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Site selection for microalgae farming on an industrial scale in Chile

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ABSTRACT

Scientific research and commercial projects into the use of microalgae as a source of energy have increased markedly over the last decade. The economic feasibility and overall sustainability of operations based on farming of microalgae on an industrial scale will largely depend on their geographic location. Criteria concerning selection of sites from which diverse local resources can be optimized have to be also considered. The present study leads the analysis of relevant factors (i.e. natural resources, road infrastructure, geographic characteristics and industrial activities which generate greenhouse gas emissions) that support proper decision-making process for selecting potential areas of large-scale microalgae farming in Chile. Based on an eight-step methodology, ten potential sites were identified as meeting all necessary requisites for the industry across the country. Sites cover 103,600 ha, capable of producing an estimated volume of 1.5 Mm^3 per year of biodiesel, and replacing 17% of the annual diesel consumption in Chile.

1. Introduction

In terms of energy, Chile depends on the international fossil fuel market. Of the 285,400 Tcal consumed in 2012 [1,2], almost 60% is imported and 66% originates from fossil fuels, 31% of them being related to petroleum derivatives. Transport represents the largest consumer sector (56%) of fossil fuels [2]. Other percentage of hydrocarbons is used by the electric generation sector, where thermal power plants complete the national demand. Electricity is transmitted along the country via six independent systems, known as SING, SIC, SMLL, SMA, SMM and IP. Given the growing energy demand (30%) in the industrial and mining sectors (I&M) over the last decade, transmission alternatives are being evaluated which could have a significant impact on carbon footprints, prices and supply [2].

Projections from the Chilean Ministry of Energy estimate that energy consumption in the country will increase by 23% in 2020 [1,2]. Given the scale and urgency of this problem, specific policy guidelines on energy must be devised in the short term. This projection is of the same order as the estimate for the global primary energy demand for the same period, which foresees an increase of around 20% [3]. Regarding the most relevant issues, the energy policy should define the composition of the national power grid, design a new national system of electricity transmission, guarantee security of supply, establish energy efficiency requirements, determine guidelines on the sustainable location of new power plants and boost sources of non-conventional renewable energy (NCRE).

Faced with similar scenarios, other countries have begun safeguarding against their oil dependency, seeking alternative methods for producing liquid fuels capable of substituting, either completely or partially, petroleum derivatives. Examples include Germany, France and Argentina, which over the last decade have implemented political campaigns, economic subsidies, regulatory frameworks and the promotion of R&D initiatives into the production of biofuels made from seasonal crops, such as soybean, corn, sugar cane or rapeseed [4]. Another case is that of Brazil and the US, which are the largest producers of biofuels in the world, but unlike the examples above, they started the incentive and production before this last decade [5]. However, current global production of biofuels has ground to a halt, reaching approximately 60 MTOE [5].

Unlike other countries on the continent, Chile is only beginning to establish a regulatory framework regarding NCREs in general and biofuels in particular; so far, its production, distribution and consumption are voluntary. The country has a limited potential of biomass sources for production of traditional biofuels. Theoretically, Chile could meet 2% of its national gasoline demand with ethanol from corn, and 5% of its diesel demand from rapeseed [6]. These percentages are taken from a nationwide territorial analysis, which shows that just 21% of its surface is used for agriculture, of which just 8% is arable or cultivable (1,266,000 ha, equivalent to 1.7% of the national land area) [7].

Other studies have exposed a shortage of economic, energy and social results originating from traditional biofuel production, such as

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corn ethanol or soy biodiesel [8–11]. This has led to research being conducted into low-intense sources of biofuel production (in terms of soil, water, energy and nutrients), which also allows for a more sustainable industry [12]. One such alternative to consider is the biomass obtained from microalgae. This alternative has also some other relevant advantages when compared with traditional biofuels such as its production does not directly compete with food [13,14] and avoid environmental (i.e. carbon balance) impacts related to land use change [15].

The first research into the use of microalgae as a source of energy dates back to 1850s, whereby researchers successfully cultivated different isolated species in the laboratory. Focus then switched to improving biomass production yields to achieve larger scale crops, in both open and closed systems. Towards the end of the 1970s, the US Department of Energy (USDOE) created a division called the Aquatic Species Program (ASP), to study the feasibility of producing bioenergy from algae. However, the low oil prices of 1980–2000 meant R&D into the so-called "microalgae farms" came to a standstill. In 1996, the ASP was discontinued and its findings were published in the 1998 book entitled, "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae" [16,17].

Microalgae are ubiquitous, unicellular organisms of diverse metabolism (photoautotrophic, heterotrophic, mixotrophic or photoheterotrophic). Some species modify their metabolism in response to changes in environmental conditions. They are generally considered photoautotrophic, with the ability to convert inorganic carbon, CO_2, into complex organic material (for example lipids, glycosides and proteins) [8,16]. These microorganisms are interesting to the field of bioenergy because they constitute a sustainable and abundant raw material for the production of biodiesel, bioethanol, biohydrogen and biogas, among other products, in the context of a biorefinery [14]. Biodiesel is obtained from the transesterification of lipids; bioethanol, from the fermentation of glycosides; biohydrogen, from the modified metabolism of the microalgae; and biogas, from the anaerobic digestion of the biomass or from the organic residue they generate during the biorefining process [14]. However, strain development and process engineering are needed to make algal biofuels practical and economically viable [18].

At the global level, the US, Germany, China, Australia, Japan and Spain are at the cutting edge countries of R&D into bioenergetic or food-related microalgae projects. In Chile during 2010, CORFO (a state entity that supports the competitiveness and productive diversification of the country) allocated funds to three public–private business consortia, AlgaeFuels S.A., Desert Biofuels S.A. and BAL Biofuels S.A., for the development of technology and research into the production of biodiesel from microalgae (the first two listed) and ethanol from macroalgae (the latter). The geographical and environmental characteristics of Chile (topographical, extension and climate) represent a potential advantage for algae production with bioenergy purposes.

One of the most important aspects to consider in the production of microalgae on an industrial scale (the central theme of this study) is the strategic location of the culture farms. These microorganisms can be cultivated in both open (raceway ponds) and closed (photobioreactors or PBRs) systems. Nevertheless, given the high investment and operating costs of the PBRs, a mixed system is proposed in which PBRs are employed as the main technology in the permanent production of mass inoculum for larger scale raceway ponds (RWP), so that growth is faster to avoid contamination [19–21]. The use of PBRs is a key factor to the success of this industry [22]. For the use of RWP, extensive land surfaces are required that comply with numerous environmental standards and design constraints, in order to optimize industrial production. For a microalgae farm of regular conditions, capable of yielding 15 m^3/ha/year of biodiesel [8,23–25], the necessary surface areas required that have been documented [26] are listed in Table 1.

The value mentioned above for the surface productivity of microalgae biodiesel (15 m^3/ha/year), is obtained from operational data associated with the farming in RWP, simplifying and gathering a large number of variables which determine this productivity (for example, solar radiation, light incidence angle, environmental and farming temperature, nutrient concentrations, gas–liquid CO_2 transfer). For its estimation it is necessary to consider a maximum concentration of biomass of 0.5 g/L [8,24] before harvest ($C_{harvest}$), ten days farming ($d_{farming}$), ponds with 30 cm depth [24,27] ($Depth_{RWP}$) and 360 of annual operation ($d_{annual/op}$ resting maintenance). Operating these values and subjecting them to unit change (volume, mass and area) biomass productivity is obtained:

$$\begin{aligned}\mathrm{Prod_{biomass}} &= \mathrm{C_{harvest}} \cdot \mathrm{d_{farming}}^{-1} \cdot \mathrm{Change_{Vol}} \cdot \mathrm{Change_{Mass}} \cdot \mathrm{Depth_{RWP}} \\ &\cdot \mathrm{Change_{area}} \cdot \mathrm{d_{annual/op}} \\ &= 54 \frac{\mathrm{ton}}{\mathrm{ha} \cdot \mathrm{year}}.\end{aligned}$$

Then, considering an average microalgae with 25% of lipids, a conversion 1:1 of lipids to biodiesel and a biodiesel density of 0.88 t/m^3($\rho_{biodiesel}$), the analyzed biodiesel surface productivity is obtained:

$$\mathrm{Prod} \cdot \mathrm{surf_{biodiesel}} = \mathrm{Prod_{biomass}} \cdot \%\mathrm{lipids} \cdot \rho_{\mathrm{biodiesel}}{}^{-1} = 15.3 \frac{\mathrm{m^3}}{\mathrm{ha} \cdot \mathrm{year}}.$$

The correct site selection for farming can help save natural and agricultural resources of the country, optimize biomass productivity, reduce the costs of transport and energy consumption, as well as improve public perception and acceptance of projects such as these. The first study or report found in this area was delivered by Maxwell and collaborators in 1985, from SERI, now NREL, covering the southwestern area of the US (Table 2). The authors compiled information according to three categories (climate, water and land) to identify potential production areas, in order to construct overlay/superposition maps [28].

The lack of studies between 1985 and 2010 relates to a dearth of research into microalgae in general, in line with the aforementioned international oil context during this period. However, since 2010 onwards, there has been extensive research into determining potential sites for microalgae production around the world (Table 2). In the same period, the USDOE published the "National algal biofuels technology roadmap", which includes an entire chapter on the evaluation of resources and potential sites [29].

In 2010, Milbrandt and Jarvis conducted an evaluation in India for the NREL. The authors conducted a survey of public and private information, culminating in a graphic of different potential sites using GIS (Geographic Information Systems) methodologies [30]. Similarly, research was conducted into potential resources in Canada and Australia in 2011 and 2012, respectively [31,32]. From this moment onwards, the use of GIS became recurrent, allowing researchers to modify, add or remove constraints and making the search for potential sites more objective in the process. These diverse studies share certain aspects, including land not being used for agriculture and areas presenting gentle slope, abundance of water resources, high levels of solar radiation and temperatures adequate for cultivating different microalgae species [33–36].

Table 1
Land sizes required for different scales of biodiesel production.

Biodiesel scale	Scale or size of plant	Surface area of microalgae farm
m^3/year	Name	ha
<8000	Pilot	<530
8000–40,000	Medium	530–2760
>40,000	Industrial	>2670

Table 2
Summary of studies of site selection for microalgae farming and based on different resources.

Year	Country	Authors	Inst.	Title
1985	US	E. Maxwell, G. Folger and S. Hogg	SERI	Resource evaluation and site selection for microalgae production systems
2010	US	J. Ferrel and V. Sarisky-Reed	USDOE	National algal biofuel technology roadmap
2010	IN	A. Milbrandt and E. Jarvis	NREL	Resource evaluation and site selection for microalgae production in India
2010	US	T. Lundquist, I. Woertz, N. Quinn and J. Benemann	EBI	A realistic technology and engineering assessment of algae biofuel production
2011	US	J. Quinn, K. Catton, N. Wagner and T. Bradley	CSU	Current large-scale US biofuel potential from microalgae cultivated in photobioreactors
2011	US	M. Wigmosta, A. Coleman, R. Skaggs, M. Huesemann, and L. Lane	–	National microalgae biofuel production potential and resource demand
2011	CA	G. Klise, J. Roach and H. Passell	SANDIA	A study of algal biomass potential in selected Canadian regions
2011	US	R. Pate, G. Klise and Ben Wub	SANDIA & USDOE	Resource demand implications for US algae biofuel production scale-up
2012	AU	M. Borowitzka, B. Boruff, N. Moheimani, N. Pauli, Y. Cao and H. Smith	CREST	Identification of the optimum sites for industrial-scale microalgae biofuel production in WA using a GIS model
2014	US	E. Venteris, R. McBride, A. Coleman, R. Skaggs and M. Wigmosta	–	Siting algae cultivation facilities for biofuel production in the United States: trade-offs between growth rate, site constructability, water availability, and infrastructure

2. Methodology

The methodology used in the present study is based on the work of Milbrandt and Jarvis [30], modified to account for the Chilean context. It consists of eight criteria for identifying potential sites for microalgae production based on a hybrid configuration of the farming process.

The elements for site selection considered in this study were:

I. Sites located close to stationary sources of CO_2 emissions, thermoelectric power plants. Appendix A gives a map of projected and current thermoelectric power plants in Chile, georeferenced and classified according to the type of fuel used [37,38].

II. Sites with daily solar radiation (annual average) greater than 4 kWh/m^2/day or 5200 MJ/m^2/year. Using the 2008 Chilean solar registry [39], a map was constructed documenting the iso-lines of total radiation on the horizontal plane MJ/(m^2/year) [38].

III. Sites with more than 6 h of daily sunshine, by annual average. Annual climatological information was consulted from the Chilean Meteorological Direction [40], specially the total hours of sunshine during the year. Chile meets these farming criteria, from the north of the country to some point between Concepción and Temuco in the central-south, where almost 2200 daily sunshine hours per year are registered.

IV. Sites located within an approximate range of 10 km from the coast. This information has been included in the same map in Appendix A.

V. Sites located outside national reserves, protected areas and wetlands. Appendix A also includes information of a compilation of several regional maps presented by the GEF Project (2012) [41]. The country's wetlands were identified via the map viewer of IDE Chile [38,41]. Only the northern half of Chilean territory is shown, as the aforementioned information can be used to discard the southern section as inadequate for farming microalgae.

VI. Sites located close to ports or railways. The ports map was constructed using information from the Chilean Navy Meteorological Service from the first, second and fourth naval zones [42]. In turn, railways were identified using maps from national tourism guides [43,44].

VII. Sites accessible from roads. As with railways, roads were identified using standard terrestrial maps [43].

VIII. Large sites and with a slope of less than 5%. Once the specific sites combining the aforementioned criteria were identified, the slopes of selected sites were evaluated.

Regarding point I, the most CO_2 emission-intensive sectors in Chile were identified. According to the baseline report of the 2007 MAPS Chile project, the three most intensive sectors are: (1) electricity generation, (2) transportation–urbanism, and (3) industrial and mining (I&M). They constitute 29%, 23% and 18% of total national CO_2 emissions, respectively [45]. Of these emissions, only those of electric generation and I&M sectors represent stationary sources. In Chile, thermoelectric power plants are usually located in coastal areas, because they are allowed to use sea water as a cooling fluid, as well as logistical issues related to fuel supplies (such as coal, that arrives by sea fright). Consequently, only thermoelectric power plants will be considered as stationary sources of CO_2 emissions in the present study.

To optimize the biomass production yield, it is considered that PBRs are operated with high concentrations of CO_2 using enriched air. This justifies the installation of culture farms close to stationary sources of CO_2. For example, Chiu et al. in 2009 found that the optimum concentration of CO_2 was 2% v/v. If concentrations are lower than 2%, or greater than 5%, the microalgae may suffer deterioration and reduced biomass productivity [46,47]. As a result, it would be necessary to establish the concentration of CO_2 at exit point of the thermoelectric power plant, treat and clean the feed gas to ensure that the desired concentration is achieved and that the particulate matter and harmful gases that deteriorate the process are removed adequately. Direct carbon-fixation from thermoelectric power plants is usually designed via the connection of the PBR aeration system to the combustion gases exiting the power plant. The design of these bioreactors allows for the optimization of gas–liquid transfer rate and, as a consequence, biomass productivity. Traditional technologies of gas–liquid transfer do not apply in the culture ponds, because their depth (20–40 cm) does not allow an adequate CO_2 transfer into the culture medium. RWP usually incorporates a paddle wheel as a traditional stirring system, so using these as CO_2 transfer mechanisms would require their design and construction in controlled environments rich in carbon (for example, CO_2 greenhouses). Alternatively, the paddle wheel could be complemented or replaced by stirring pumps, in which the gas–liquid transfer of CO_2 occurs in a confined manner.

Otherwise, Milbrandt and Jarvis [30], propose the consideration of sites adjacent to sources of underground saline water (TDS > 3000 mg/L) and wastewater treatment plants. The methodology used in the present study did not include these requirements, given the current context of water in Chile. In the last decade, the country experienced consecutive years of drought that occurred in the northern and central zones, causing a deficit of inland water levels, which has harmed agriculture and the supply of drinking water. Besides, the regulatory framework that governs water rights, prevailed for the last 30 years, has generated social inequalities and also has contributed to the aforementioned deficit [48]. Cooper mining is a major consumer of water (with rising projections) in the northern region, 13 and 2 m^3/s of inland and marine water in 2014, respectively [49]. Also it should be mentioned, that around 96% of the wastewater in Chile are treated today, using technologies of activated sludge, ponds, filters and outfalls [50]. For all these reasons, the water sources proposed by these authors for the cultivation of microalgae must be excluded from this study, because in Chile they could be used for drinking water, irrigation in agriculture or livelihoods of natural ecosystems, if they are subjected to appropriate treatment.

Despite the clarity delivered from the life cycle analysis, factors frequently ignored by many studies are the energy and economic cost of transporting supplies and final products. Dassey et al. in 2014 suggest that the average distance from microalgae production plants to the final sale point of the products should not exceed 150 km, with associated energy expenditure of 0.105 kWh/kg transported [51]. If an industrial scale biodiesel production plant produces 40,000 m^3/year, with a biodiesel density of 0.88 t/m^3, and an energy reference value of US$0.18/kWh, its operational expenditure relating to transport would exceed US$0.67 million/year. Consequently, any savings achieved in distribution and logistics, by using more economical and efficient transport, or cutting distances to the final consumers (<150 km), are measures which could reduce costs across the industry.

Accordingly, and for the specific case of Chile, analysis could be conducted into the costs associated with transporting products derived from microalgae via surface-level or underground pipes. The geographical features of the country could favor the use of pipelines over other transport means. Pipelines could follow the Chilean coastline (level zero) to pump raw materials (for example, lipids) to current infrastructure in the central zone specialized in fuel refinery (for example, the ENAP refinery in Concón). A more applicable element for site selection to the Chilean context is that the location of sea ports and railways could be the generation of distance-related indicators or maximum permissible head losses regarding pumping from the coast to the processing and production point of the biofuel, according to technical–economic bases.

3. Results and discussion

A unified map of the selection elements was built by overlapping information of different maps of Chile, as seen in Appendix A, in which ten sites were identified for the possible microalgae farming on an industrial scale in Chile (Table 3).

Using Google Earth™, ten possible culture sites were analyzed (see Fig. 1), all within a 10 km range of coastal thermoelectric power plants and discarding populated, industrial and agricultural areas. In addition, the point VIII of the methodology for site selection was included regarding land with a slope of less than 5%, thereby ruling out steeper areas.

Of all the places found, only Bahía Chascos is not a secure short or medium term option to build microalgae culture farms. This is because in that bay a project of thermoelectric power plant is proposed, known as Castilla. The Castilla project had several problems and criticisms from social, legal and environmental terms, which led to suspend its construction in 2012. For this reason the microalgae farming in the 10,700 ha detected in the Bahía Chascos, through site selection criteria, is subject to the future of Castilla project. The remaining sites are home to thermoelectric power plants of different installed capacities and operational fuel types, thereby ensuring their suitability.

Chilean road maps and all possible sites for microalgae farming were then reviewed, ensuring that access for trucks, buses and cars was possible across all cases. Accordingly, this point generates no constraints to the Chilean case study.

On a lineal projection, considering the conservative surface biodiesel productivity rate of 15 m^3/ha/year of a mixed microalgae farming plant (hybrid system, PBR as inoculum for RWP) [8,23–25], discussed in the Introduction, the potential 103,600 ha identified (see Table 3) could produce 1,554,000 m^3/year of biodiesel. With this volumetric flux it would be possible to replace 17.14% of the annual Chilean diesel consumption and reduce energy imports by 5% [2].

$$\text{Annual BD Productivity} = \text{Annual surface BD productivity} \cdot \text{Surface}.$$

In terms of territory, all potential sites combined make up 0.1% of the national land area, mainly composed of desert (with no agricultural use and natural degraded lands), and located in the northern zone of the country. Indirectly, land that is currently unfit for agriculture would be transformed into 'cultivable or arable terrain'. In this way, the proportion of cultivable land in Chile would rise by 7.9%.

It is important to note that this analysis only evaluates coastal regions, where the use and consumption of water is closely linked to enriched seawater (culture medium for marine species). The volumes of water that should be used for replacing 17.14% of the national diesel consumption would represent approximately 1 Gm^3/year of water [31, 52], considering that cultivated water could be recirculated, that the microalgae are 25% lipids, and that they reach a maximum concentration of 1 g/L in the ponds. Water loss is accounted for by evaporation during farming (2000 mm/year) and moisture remaining in the biomass after harvest (90% mass). As the ten potential sites are located in the northern half of the country, water will be a scarce resource. Preference of fresh water microalgae over seawater species may lead to a shortfall in water supplies to urban areas, agriculture, mining sector and natural habitats. This aligns with the findings of Yang et al. in 2011, where through a life cycle analysis, they calculate the water footprint of biodiesel production from marine and freshwater microalgae. Marine species preference would strongly reduce the consumption of water and nutrients during culture stage [53].

Almost all possible culture sites are located in coastal desert zones, except Los Vilos, an area with a semi-arid climate and winter rains. Huasco, on the other hand, is known for its abundant olive crops. Therefore, a more thorough evaluation should be conducted into both locations, if they are selected for the microalgae farming, to avoid competition being generated with other industrial or productive sectors.

Regarding the carbon balance and the amount of CO_2 that could be displaced with the use of microalgae biodiesel, it is necessary to analyze the biomass composition to gauge the total amount of potential carbon that can be fixed. Assuming a stoichiometry composition and formula (CHONS) of average lipids, proteins and glycosides of 25%, 50% and 25%, with the representative chemical formulas of $C_{50}H_{87}O_6$, $C_{184}H_{350}O_{86}N_{33}S$ and $C_6H_{11}O_5$, respectively [54,55]. Accordingly, the average stoichiometric formula of the microalgae biomass would be $C_{212}H_{399}O_{91}N_{33}S$, with a molecular weight of 4896 g/mol. Since the nutrients that are added to the seawater to form the culture medium are not usually carbonated products, all carbon present in the stoichiometric formula comes from the addition of CO_2. This way, for each ton of microalgae produced, around 520 kg of inorganic carbon is added (2.4 tCO_2e). However, as the microalgae are cultivated for the production of biofuel rather than for capture purposes, their definitive carbon footprints should be calculated by the life cycle analysis of

Table 3
Analysis of potential areas for microalgae farming on an industrial scale in Chile (results are shown in graphic format in Fig. 1).

	Place	Total area identified under the 8 criteria	Habited area or in use	Unsuitable area for construction due to slope	Potential area
		Surface area (ha)			
1	Arica	18,116	5307	7112	5697
2	Iquique	15,618	2881	8498	4239
3	Patache	17,318	1440	5571	10,307
4	Tocopilla	30,492	627	17,088	12,777
5	Mejillones	80,447	2129	32,425	45,893
6	Antofagasta	17,975	3735	12,067	2173
7	Taltal	17,448	31	15,435	1982
8	Bahía Chascos	12,661	0	1913	10,748
9	Huasco	24,054	2094	14,978	6982
10	Los Vilos	24,757	1189	20,727	2841
	Total	258,886	19,433	135,814	103,639

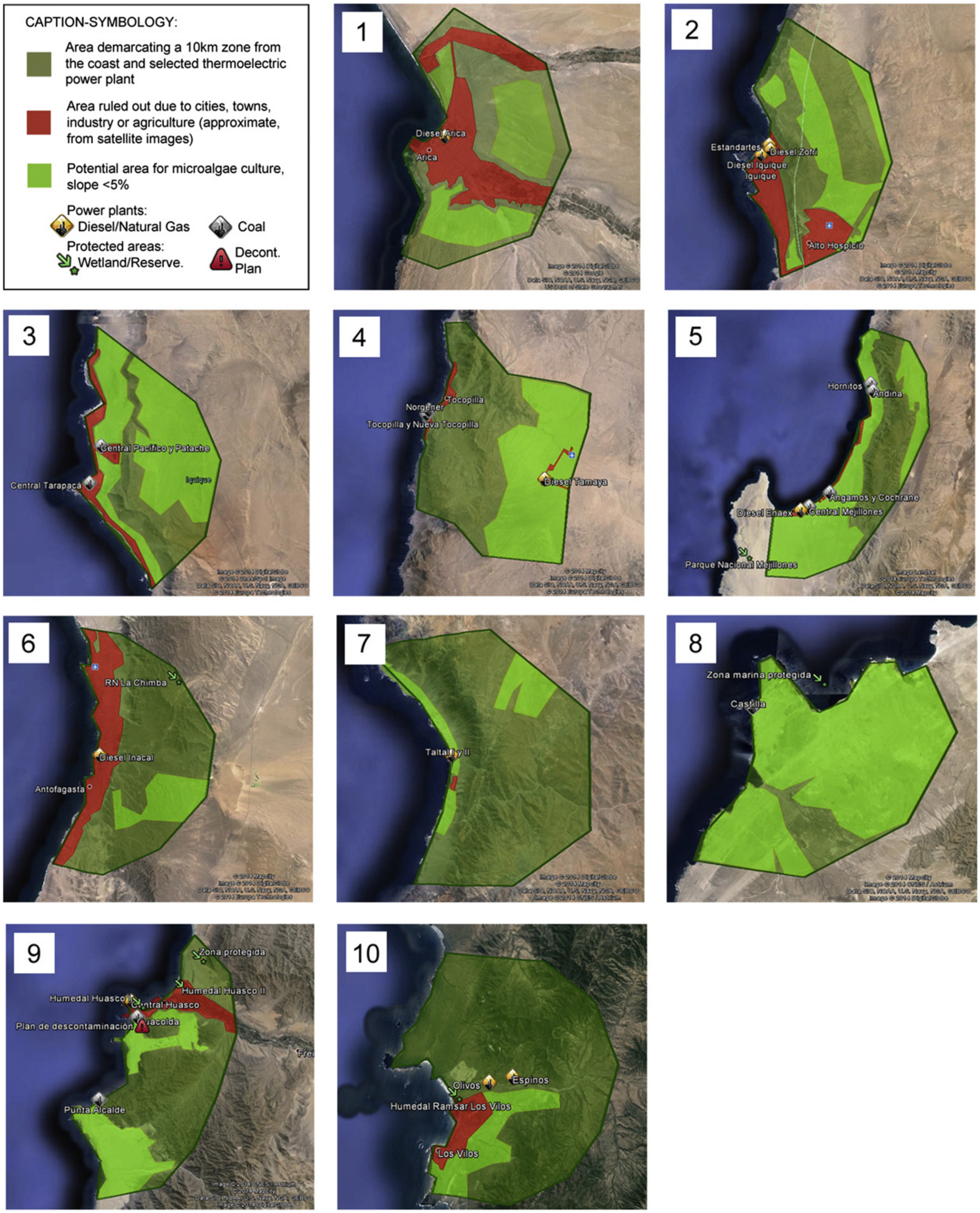

Fig. 1. Graphics of the ten sites identified in Chile with potential for microalgae cultivation on an industrial scale, for subsequent analysis of slope (elevation) in the relevant area.

their final product and by-products. There are diverse studies into carbon footprints of the production and processing of microalgae. Some authors attribute them to emission reductions, in terms of kg of CO_2/MJ of biodiesel. Others claim that they actually generate emissions, due mainly to energy consumption in the culture stage, dewatering, cell rupture, transesterification and energy recovery of by-products [56]. The indicator result usually depends on the assumptions made [47].

The uncertainty of these results depends on the precision of the current information and the depth of analysis. In this research the best ten sites for microalgae farming in Chile were located, however it is necessary to deepen in the characteristics of them, especially in the creation of maps outlining terrain with a slope of less than 5% and conduct soil surveys for proper construction of culture ponds. Additional factors to bear in mind include property rights and the value of the relevant land. The ideal case would be state-owned land, which could be subject to concessions for the periods required to sustainably exploit this resource. Also the creation of an own computer tool based on GIS to overlay information maps and requirements relevant for the microalgae farming could help identify potential areas with more accuracy [34].

4. Conclusions

Chile is characterized by its unique natural resources, resulting from its geographic and climatic diversity. Its 6435 km coastline has made possible the development of numerous human activities throughout its history. Chilean seawaters still retain unknown potential, and their exploitation could be beneficial, as long as it is undertaken in a sustainable and responsible manner. In turn, the Chilean mainland is known for its mining and energy activities, mainly in the northern area, as well as the development of a diverse and abundant agricultural and silvopasture industry in the central and southern areas.

The microalgae-based bioenergy industry represents an opportunity for interweaving several of the Chilean potentialities. It could be developed on uncultivable land, using seawater, and utilizing numerous environment factors that might help generate a differentiating factor in regard to other countries. As the present study has explained, a large part of the northern Chilean coast meets the environmental and operational standards necessary for the development of this industry.

Ten possible farming sites were identified, chosen primarily for the presence of thermoelectric power plants and areas of land conducive to the construction of culture ponds. Regarding the size of available land on which farming is possible, Mejillones Bay represents the prime area in the country for developing microalgae production farms. Like other locations on the northern Chilean coast, Mejillones presents a number of environmental problems due to intensive industrial activity in the area. The microalgae farming could help compensate the environmental impacts generated from other industries, in terms of treatment and exploitation of direct emissions, and for parties deciding to provide a CO_2 supply for the formation of biomass using PBRs.

The analysis herein determines the use of land within 10 km radius from the coast, in line with the methodology proposed by Milbrandt and Jarvis [30]. However, it is possible to pump seawater further than this distance. In fact, both in the mining industry and the research developed by Borowitzka et al. in 2012, propose a slightly more optimistic assessment that achieves longer pumping distances (over 150 km inland) [31,57]. To evaluate the energy and economic viability of these extensive pumping, it is necessary to subject the allowable maximum pumping distance to a sensitivity analysis specific to the production of microalgae in Chile. Another option which may help in the pumping of seawater is the evaluation of models which couple pumping hydroelectric plants in areas located further from the coast, making use of the intense solar radiation of the Atacama Desert during the day and, in turn, generating electricity at night.

Alternatively, the use of inland water that is not used for drinking water or agriculture, and is not subject to environmental protection could be another way to broaden the search criteria for potential sites. Highly saline inland water, either naturally or anthropically contaminated with metals, metalloids or mining and agricultural by-products could be a viable alternative for microalgae production if it is developed in a sustainable manner. The use of inland water should be accompanied with environmental impact studies and systematic work with possible affected communities in order to guarantee local understanding and participation. However, the consideration of inland water is a separate chapter, which involves a different analysis methodology and discussion from what was proposed in this research.

Future studies should conduct in-depth investigations into the possible sites identified herein, gathering new information and updating existing findings. Accordingly, it would be beneficial to rank the sites according to their individual potential in terms of biomass productivity. It is important to gauge the overall potential right along Chile. This will help in generating a holistic strategy for the development of a bioenergy industry, in which microalgae continue to represent a promising source of biomass for the future.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.algal.2015.07.012.

Abbreviations

NCRE	non-conventional renewable energy
SING	'*Sistema interconectado Norte Grande*', far north interconnected system
SIC	'*Sistema interconectado central*', central interconnected system
SMLL	'*Sistemas medianos de los Lagos*', mid-size Los Lagos system
SMA	'*Sistemas medianos Aysén*', mid-size Aysén system
SMM	'*Sistemas medianos Magallanes*', mid-size Magallanes system
IP	'*Isla de Pascua*', Easter Island
I&M	Industrial and mining
MTOE	Millions of tons of oil equivalent
GIS	Geographic information system
PBR	Photobioreactor
RWP	Raceway pond

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