Assessing the potential for macroalgae aquaculture in coastal and estuarine areas

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Abstract

Kelp aquaculture is a fast-developing biomass producing sector for food, pharmaceutical and cosmetics production, while providing ecosystem services like carbon sequestration, fish habitats and pollution remediation.

This modelling study aimed to identify the best places to install *Saccharina latissima* aquaculture inside and in the vicinity of the Tagus River estuary, in Lisbon, Portugal and at what time of the year should algae be planted to maximize their yield. For these purposes, macroalgae growth was tested with data provided by an operational model of the Tagus estuary and adjacent platform. Results show that the best location to practice aquaculture of *S. latissima* is inside the Tagus estuary right in the central part, where the best compromise between nutrients, light and salinity is found. The best time of the year to plant is by the beginning of November and harvesting can be done in May of the following year. The model is generic and can be used to simulate other species providing the appropriate parameters. To finalize the decision process of placing *S. latissima*, these growth results should be crossed with the estuary usage data as well as requesting permission from the local government to find the best possible available area.

Keywords: macroalgae; kelp; aquaculture; environmental modelling, *Saccharina latissima; Tagus River; estuary.*

Introduction

The objective of this study is to evaluate the potential growth of a brown macroalgae species named *Saccharina latissima* in the estuary of one of the greatest rivers in Portugal (either by length or drainage area), the Tagus River (*Rio Tejo*). The assumption is that the algae are fixed in longlines submerged at a specific depth. This work aims to answer the following questions:

- Where is the best location for *Saccharina latissima* to grow in the Tagus Estuary?
- When is the best time of the year to place them, in order to maximize growth?

This study starts with the hypothesis that inside the estuary *S. latissima* will have a greater availability of nutrients than in the ocean, and thus, macroalgae will grow better. The nutrients are washed from the Tagus watershed and provide a steady inflow of nutrients for the algae to grow. The river's freshwater mixes with the Atlantic Ocean saltwater, creating a mixing zone inside the estuary which might create favorable conditions for *S. latissima* proliferation. The ideal location to place the algae is where the balance of conditions such as temperature, light, salinity, and nutrients are optimized.

Saccharina latissima, also known as *Laminaria saccharina* or more commonly as sugar kelp is a species of large brown algae commonly found in Northern Atlantic coasts of Europe and America, in the northern Pacific coasts of America and Japan. It usually lives in low depths (less than 30 meters) in sublittoral zones attached to stable solid substrates and sometimes unstable substrates like rocks and boulders. Its morphology consists of a long yellowish-brown undivided blade with a wrinkled surface and frilly margins, a stipe that can reach 50 cm, a small branching holdfast that attaches to substrates and no midrib. When fully grown, it can achieve 4 m in length, live between two to four years and grow quickly from winter to April. After harvesting, these algae have several uses in the industry. They produce alginic acid that can be used to make gels, stabilizers in food, pharmaceuticals, and cosmetics. When dried, it forms a sweet white powder on the frond named mannitol, that can be used as a sweetener or in medication, hence the name sugar kelp (White and Marshall, 2007).

Three mesocosm scenarios to test the model and macroalgae sensibility to parameters were performed for this study but were not displayed here. See Reis (2021, *submitted*). The model proved to function in accordance with the parameters defined for macroalgae, revealing the best growth outcomes for the optimal values specified.

Methodology

Modeling ecosystems require to simulate each component of the environment and their interactions among themselves, so for the purpose of further understanding the dynamics between macroalgae and their surroundings, a mathematical model that can replicate natural processes with some accuracy and the interactions between the several components of water bodies was needed.

The numerical model MOHID Water modeling system provided the means to describe macroalgae and their interactions with the environment.

General growth equation

The equation that generally describes the variation of macroalgae concentration in the system, which considers the fluxes described in (Figure 1), was the following:

$$\frac{\partial M_x}{\partial t} = (\mu_x - r_x - e_x - m_x - G_x).M_x \qquad [1]$$

Where M_x ($gC.m^{-3}$) is the macroalgae concentration in the water column, μ_x (day^{-1}) is the gross growth rate or gross production rate, r_x

(day^{-1}) is the respiration rate, e_x (day^{-1}) is the excretion rate, m_x (day^{-1}) is the natural mortality rate and G_x (day^{-1}) is the grazing rate (or mortality rate by predation).

The gross production rate is given by:

$$\mu_x = \mu_x^{max}.\min(\psi(N)_x, \psi(P)_x).\psi(E)_x.\psi(T)_x.\psi(S)_x \quad [2]$$

Where $\Psi(N)_x$, $\Psi(P)_x$, $\Psi(T)_x$, $\Psi(E)_x$ and $\Psi(S)_x$ are, respectively, the limiting factors of nitrogen phosphorus, temperature, solar irradiance, and salinity and μ_x^{max} (day^{-1}) is the maximum growth rate. Each of these factors is expressed by its own equation (described in Reis (2021, *submitted*), Trancoso et al. (2005) and http://wiki.mohid.com/index.php?title=Mohid_Bibliography). Each of these factors translates the influence of their respective factor on macroalgae growth. The factors range from 0 (absence of conditions of the factor) and 1 (ideal conditions for that factor), so if all conditions are ideal, all factors are one and the growth rate μ_x is equal to the maximum growth rate μ_x^{max}.

In Figure 1 are displayed the several processes and mass exchanges of macroalgae:

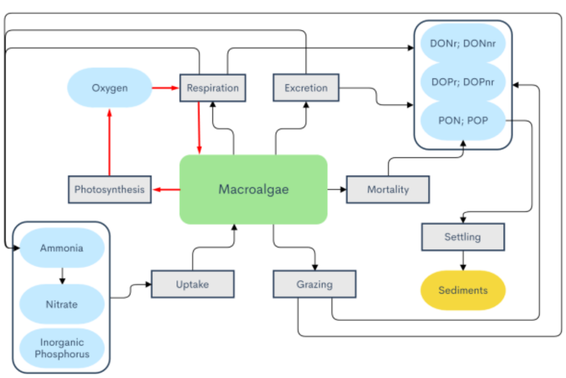

Figure 1 - Macroalgae conceptual model. Black lines represent carbon and nutrient fluxes and re lines represent oxygen fluxes.

The process of modelling *S. latissima* in the Tagus Estuary uses the results from a 3D hydrodynamic and biogeochemical operational model created, operated, and maintained by IST Maretec (http://forecast.maretec.org/), using MOHID Water modelling system for the Tagus region.

The results of this model setup have been used in multiple studies and services with good results. References and more information can be found at the website and the most recent validations can be found in de Pablo et al. (2019) and de Pablo et al. (submitted).

Data with nutrient, phytoplankton, sediment concentrations and hydrodynamic conditions was extracted for 21 locations of the operational model at three different depths for 2019 and used as conditions to simulate the biomass growth of S. latissima. Figure 2 displays the Tagus Estuary and its surroundings, as well as the bathymetry:

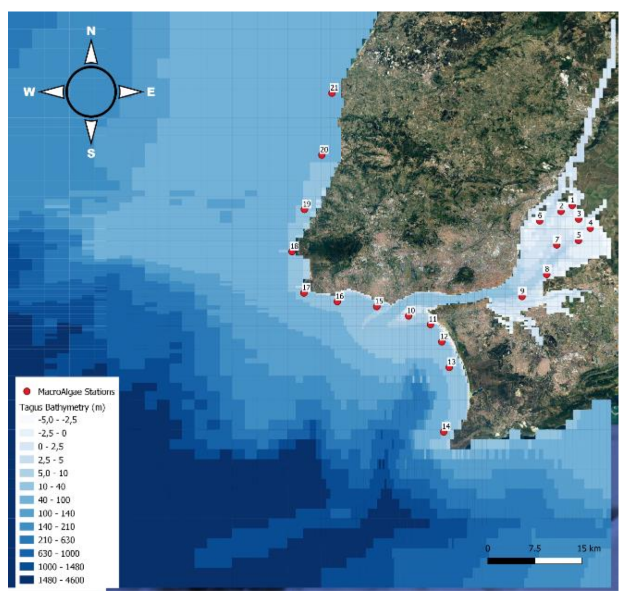

Figure 2 - Bathymetry of the Tagus Estuary and location of the 21 sites where S. latissima was simulated.

The river flows into the estuary from the North-east, bringing freshwater, nutrients and sediments washed from the soils in the Tagus watershed. The estuary itself is characterized by relatively low water depths, distributed along a 10 km wide region that divides the Lisbon Metropolitan Area and houses some wetlands, converging and getting deeper at the mouth of the estuary and discharging into the Atlantic Ocean. Table 1 displays the S. latissima parameters used on this study, their respective descriptions, and sources.

MOHID water modelling system can simulate other macroalgae species, when provided with the right parameters.

Table 1 - S. latissima parameters. Adapted from Broch and Slagstad (2012).

Parameter	Value	Unit	Description	Source
μ_{max}	0.18	d^{-1}	maximum growth rate	Chapman et al. (1978)
$Topt_{min}$	10	°C	optimum minimum temperature for growth	Fortes and Lüning (1980)
$Topt_{max}$	15		optimum maximum temperature for growth	
T_{min}	0		minimum temperature for growth	Bolton and Lüning (1982)
T_{max}	23		maximum temperature for growth	
I_{opt}	180	$W.m^{-2}$	optimum radiation value	Ozaki et al. (2001) from *Saccharina japonica*
k^{re}	0.009	d^{-1}	endogenous respiration rate	This study
k^{rp}	0.018		photorespiration rate	This study
ε_x	0.008		excretion rate	This study
m_x^{max}	0.001		natural mortality rate	This study
K_x^m	0.001	$gC.d.m^{-3}$	mortality half saturation constant	This study
G_x	0.00008	d^{-1}	grazing rate over macroalgae	This study
K_x^N	0.0373	$mg.L^{-1}$	nitrogen half-saturation constant for macroalgae	Espinoza and Chapman (1983)
K_x^P	0.0095		phosphorus half-saturation constant for macroalgae	Ozaki et al. (2001) from *Saccharina japonica*
rNC	0.18	-	macroalgae nitrogen/carbon ratio	Atkinson and Smith (1983)
rPC	0.024	-	macroalgae phosphorus/carbon ratio	
V_{crit}	2.0	$m.s^{-1}$	Critical velocity for detachment (m/s)	This study
S_{opt}	25	psu	macroalgae optimum salinity for growth	Karsten (2007)
S_{crit}	5		macroalgae critical salinity limit growth	
S_{min}	0		macroalgae minimum salinity for growth	
S_{max}	50		macroalgae maximum salinity for growth	

Results and Discussion

For each single station, growth was apparently greater in shallower depths., so results shown here in Figure 3 illustrate a comparison between S. latissima biomass development only at one-meter depth for all the sites. For the full set of results, see Reis (2021, *submitted*).

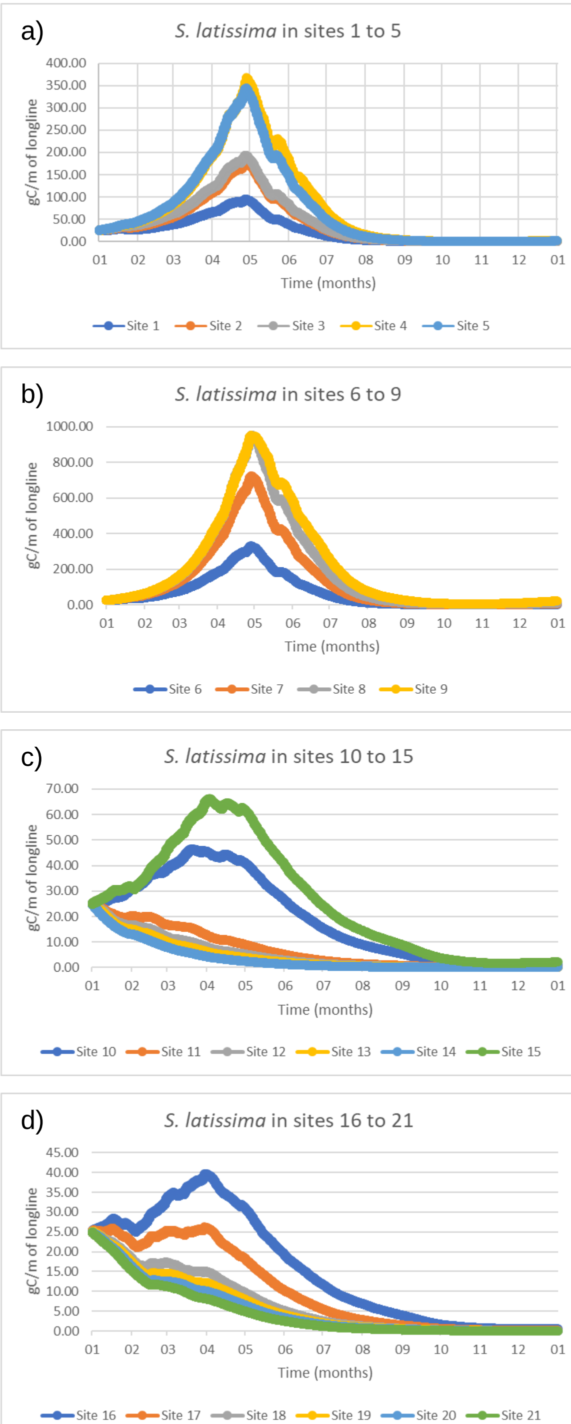

Figure 3 – S. latissima biomass in sites a) 1 to 5, b) 6 to 9, c) 10 to 15 and d) 16 to 21 at a one-meter depth.

A quick analysis of the results (Figure 3) showed that the three sites that provide the best conditions for *S. latissima* growth were sites 9, 8 and 7 at a 1 meter depth (Figure 3 b)).

All peaks of maximum growth occurring between April and the beginning of May.

Among all the results, sites 11, 12, 13, 14, 18, 19, 20 and 21 displayed no growth, only decay, implying that there's at least one factor greatly limiting growth.

In general, *L. latissima* grew the most in the middle of the estuary, followed by the stations in the surroundings of the river discharges, then near the mouth of the estuary and finally along the coast.

Nutrient concentrations inside and outside were compared and were substantially larger inside the estuary. This low concentration of nutrients in the outside of the estuary was the main factor that severely limited growth.

S. latissima proved to grow better in site 9 at a one-meter depth. Site 9 displayed high availability of nutrients from January to May and then from November to December (Figure 4 a)), as consequence of the river discharge. During those periods, temperature (Figure 4 b)), and salinity (Figure 4 c)) values inside the estuary revealed to be around the optimal range of values for growth specified in Table 1. Phytoplankton and sediments did not seem to affect light available for macroalgae inside the estuary, since their concentrations on the inside were higher than on the outside and growth proved to be much higher inside.

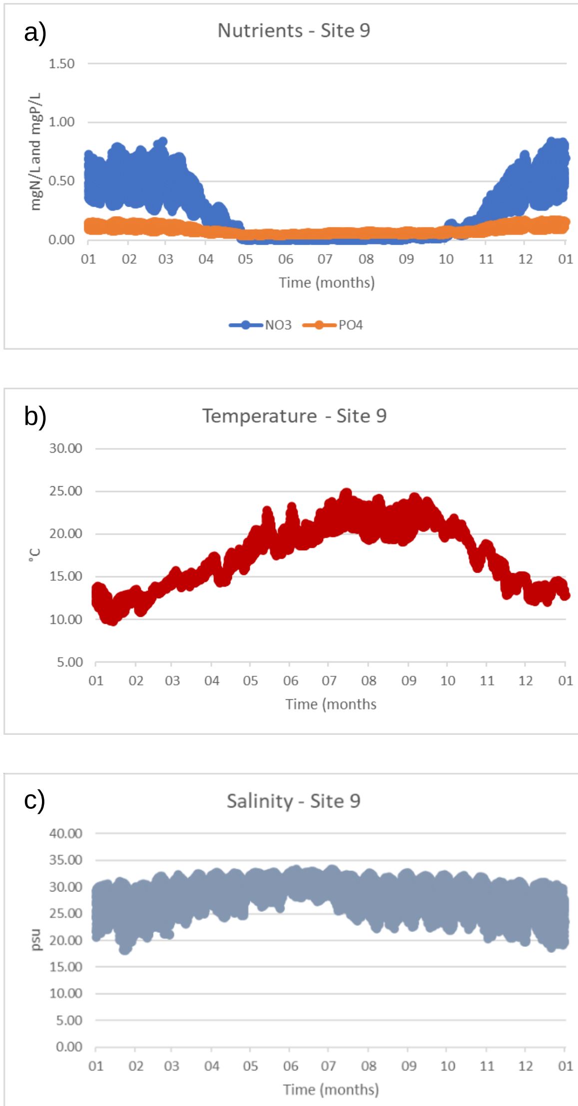

Figure 4 – a) Nutrient, b) temperature and c) salinity concentrations for site 9 at a one-meter depth.

For simplification, the previous tests were ran from January to December. To find the best time to plant and extract the macroalgae, further tests were conducted on site 9, for three straight years in order to identify the general tendencies for growth. Results showed that S. latissima biomass (Figure 5 – a)), due to the high availability during that period (Figure 5 b)), starts increasing in November and it grows until May of the following year. Exceptionally, as a consequence of abnormal salinity concentrations in year 2018 (Figure 5 c)), macroalgae failed to grow there.

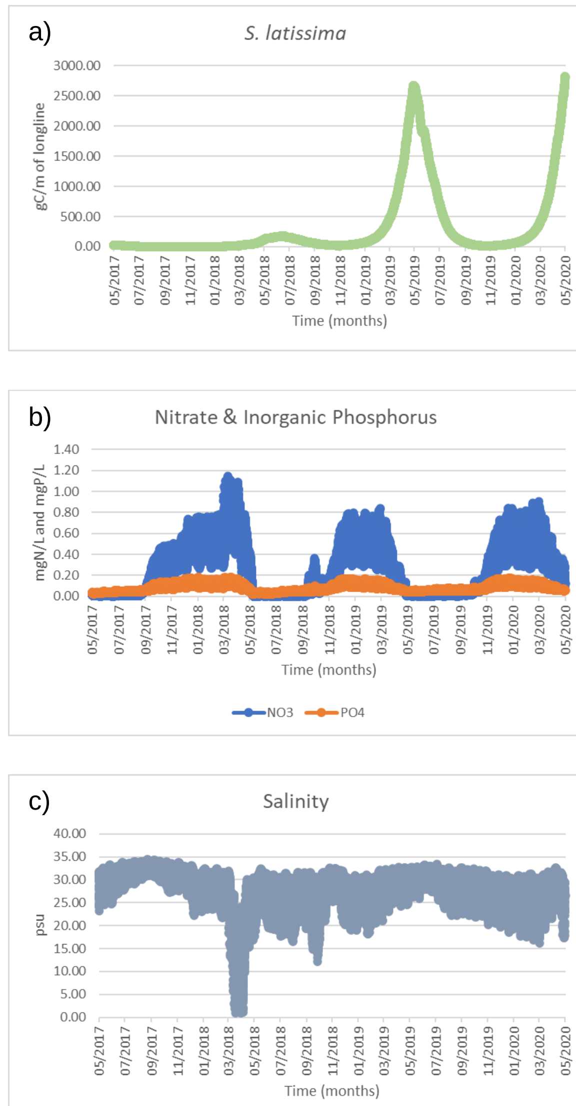

Figure 5 - a) S. latissima biomass, b) nitrate and inorganic phosphorus and c) salinity concentrations in site 9 from May 2017 to May 2020.

Conclusions

In conclusion, *S. latissima* that was planted in the interior of the estuary grew more than those placed in the outside. Inside the estuary, the macroalgae that developed the most were those close enough to the river to make use of the high concentrations of nutrients it provided but distanced enough not to be affected by the Tagus' lack of salinity. The effects of phytoplankton and sediment concentrations turned out to be negligible, not restricting light availability to *S. latissima,* since the most significant growth was in the sites where those concentrations were higher. Outside of the estuary, algae grew significantly less near the coasts, except near the estuary's mouth where some influence of nutrients from the river could still be felt. Conditions outside the estuary are mostly good for growth, apart from nutrients, which are very low, once again proving that, despite nearly all conditions being favorable, it only takes one severely unfavorable condition to inhibit growth.

So, answering the main questions, according to this study, the best location to practice aquaculture of *Saccharina latissima* in the Tagus River is in the middle of the estuary, at shallow depths of one or two meters, in the surroundings of Site 9.

The best time to attach and harvest macroalgae in order to maximize their yield is in November and then the beginning of May of the following year, where their maximum biomass is achieved before they start to die.

Of course, the possibility of actually implementing macroalgae/seaweed aquaculture depends on local government authorization and other factors such as naval traffic, operational costs, capacity of the longlines and current estuary occupation, which require further studies. As a final observation, it is worthy of mentioning that climate change is modifying the specific characteristics of each month of the year, possibly changing the conditions for macroalgae and other marine species to develop in these locations and timeframes in the future to come.

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