

1 **A modelling approach to classify the suitability of shallow Mediterranean lagoons**  
2 **for Pacific oyster, *Crassostrea gigas* (Thunberg, 1793) farming.**

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7

8 **Abstract**

9 In this study, we have developed an approach to classify the suitability of shallow coastal lagoons for  
10 pacific oyster aquaculture as the first step in a site selection process. Historical bio-physical data and  
11 local knowledge were combined to produce overall scores for biological and logistical criteria relevant  
12 for oyster farming which were then combined using Multi-Criteria Analysis (MCA) for an overall lagoon  
13 suitability score. A Dynamic Energy Budget growth model was also used to identify and rank suitability  
14 of shallow coastal lagoons to host Pacific oysters farming sites. Furthermore, modelled growth data were  
15 used to estimate the production cycle length and the potential productivity of the newly identified sites.  
16 The results indicated that biological and logistic factors were suitable for Pacific oyster farming in eleven  
17 out of twelve of the lagoons considered. However, acquiring water classification for shellfish farming  
18 and maintaining high water quality standards will be critical for any sustainable development of culture  
19 areas. Potential production figures and logistic scores, clearly indicates in which lagoons investments  
20 should be focused and what output could be realised from these very productive ecosystems. The results  
21 can be used to indicate where more detailed assessment should take place. As remote-sensing  
22 technologies continue to develop and algorithms for the interpretation of ocean colour in coastal areas  
23 keep improving, this multidisciplinary approach will increase our ability to estimate aquaculture  
24 production in complex aquatic systems. This approach will provide stakeholders, policy makers and

25 regulators with a new and powerful decision-making tool for site selection of sustainable oyster farming  
26 activities and the management of the surrounding coastal areas.

27 **Keywords:** Aquaculture, Oyster Farming, Geographic Information System, Dynamic Energy Budget,  
28 Shallow Coastal Lagoons

## 29 **1. Introduction**

30 Coastal lagoons are shallow, semi-enclosed, aquatic systems that are largely isolated from the open sea  
31 due to barriers or land features, with inlets and channels acting as the connection (Newton *et al.*, 2014;  
32 Pérez-Ruzafa *et al.*, 2019). These water bodies are amongst the most productive ecosystems in the world  
33 (Pérez-Ruzafa *et al.*, 2019), and have an important role in providing ecosystem services, including food  
34 provision through fish and shellfish culture (Newton *et al.*, 2014; Newton *et al.*, 2018). There are over  
35 100 coastal lagoons in the Mediterranean (Pérez-Ruzafa *et al.*, 2011), many of which are underutilised  
36 and could potentially be used for aquaculture. However, conditions vary and often activities such as  
37 agriculture, urban development, recreation and transport, change the biological and ecological dynamics  
38 of the systems (Pérez-Ruzafa *et al.*, 2011). Consequently, there is a need to plan and manage these  
39 activities, including aquaculture, to optimise the benefits from lagoon systems whilst minimising  
40 potential negative impacts on ecosystem health and other activities.

41 In Italy there is a high demand for seafood products, with 64% of national commercial aquaculture  
42 production coming from shellfish farming. Farmed bivalve species include the Mediterranean mussel  
43 (*Mytilus galloprovincialis*, Lamarck, 1819), grooved carpet shell (*Ruditapes decussatus* (Linnaeus,  
44 1758)), Manila clam (*Ruditapes philippinarum*, (Adams & Reeve, 1850)) and Pacific oyster  
45 (*Crassostrea gigas*, (Thunberg, 1793)). However, demand is greater than supply, and in 2017 over 1.3  
46 million tonnes of seafood were imported to the country. In particular, demand for Pacific oysters cannot  
47 be met by domestic production ~~alone,alone~~; consequently over 65,000 tonnes per year are imported from  
48 other countries to fulfil requirements (FAO, 2018). This suggests there is a considerable market for  
49 higher production of Pacific oyster in Italy if suitable locations can be identified. One such case are the  
50 highly productive coastal lagoons, which should be explored for this purpose.

51

52 Spatial models, developed using Geographic Information Systems (GIS), are often used for aquaculture  
53 site selection as they can provide an assessment based on factors which influence the suitability of a site  
54 (Falconer *et al.*, 2019). The use of Multi-Criteria Analysis (MCA)/Multi-Criteria Evaluation (MCE)  
55 within GIS models is particularly effective as it allows the combination of environmental,  
56 socio-economic and logistical parameters, providing a more holistic overview of multiple criteria, rather  
57 than considering those criteria separately (Falconer *et al.*, 2018). This supports the decision-making  
58 process by using factors, which indicate suitability of an area or production constraints, to show the limits  
59 of a given location for aquaculture development. Not all factors will be of equal importance, as some will  
60 have more influence over production than others, affecting the overall suitability. Within the MCE  
61 approach, factors are weighted based on their importance, with analytical hierarchy process (AHP)  
62 (Saaty, 1988) being the most commonly and increasingly used method for determining these weights  
63 (Nath *et al.*, 2000; Buitrago *et al.*, 2005; Longdill *et al.*, 2008; Radiarta *et al.*, 2008; Silva *et al.*, 2011;  
64 Micael *et al.*, 2015; Falconer *et al.*, 2016).

65 The ability to develop and apply a GIS-based site selection model is dependent on the availability and  
66 quality of data (Falconer *et al.*, 2018; Falconer *et al.*, 2019). As data collection can be time consuming  
67 and expensive it is efficient to use data readily available for an initial large-scale assessment, before more  
68 detailed site-specific assessment are conducted. Many spatial models rely on gridded raster data  
69 (Falconer *et al.*, 2018); however, when this is not available, alternative methodologies such as those  
70 presented in this study, are required to incorporate the available data in the most appropriate manner.

71 For a shellfish site, stock growth potential is one of the most important characteristics as this directly  
72 translates into economic performances of the venture. A range of modelling approaches have been  
73 developed to simulate the growth of shellfish (Pouverau *et al.*, 2006; Bourlès *et al.*, 2009; Barillé *et al.*,  
74 2011; Filgueira *et al.*, 2011; Hawkins *et al.*, 2013), among them, models based on dynamic energy budget

75 (DEB) theory (Kooijman, 2010) are becoming increasingly popular. DEB models can use data on  
76 temperature and food availability at a location to simulate shellfish growth; this can then be used to  
77 compare multiple locations to discover which has the most suitable stock growth potential.

78 The aim of this study was to develop, through a case study in the east coast of Sardinia, a methodology to  
79 classify the suitability of coastal shallow Mediterranean lagoons for Pacific oyster culture. This used  
80 existing environmental data, collected by government and private agencies, and logistic information  
81 collected by stakeholder interviews and satellite imagery. The use of approaches such as those presented  
82 here, could assist decision-makers and industry stakeholders with the site selection process, by  
83 prioritising the lagoons with most potential for production for more detailed assessment, to ultimately  
84 boost the growth and sustainability of Pacific oyster farming in the region.

85

## 86 **2. Study area**

87 Sardinia is the second largest island in the Mediterranean Sea and, with a coastline of 1,850 km, it offers  
88 ample opportunity for sustainable exploitation of marine resources. In particular, the coastline is dotted  
89 with approximately 10,000 ha of biologically productive lagoons which for centuries have provided  
90 employment to local communities (Bazzoni *et al.*, 2013). Most lagoons are still utilized for extensive fish  
91 farming (valliculture), but could also be potential sites for Pacific oyster farming. Pacific oyster requires  
92 shallow and relatively sheltered sites, productive waters and can withstand relatively high salinity and  
93 temperature variability. All of these conditions can be found in Sardinian lagoons and therefore many of  
94 the Italian oyster farms are already located there. Nonetheless, only 3% of the island Gross Domestic  
95 Product (GDP) is now produced by primary activities (farming and fishing) and youth unemployment  
96 has risen to 46.8% in 2017 (<http://www.sardegna statistiche.it/argomenti/istruzioneelavoro/>). Against this

97 backdrop, it would appear that sustainable aquaculture of a product in high demand, such as Pacific  
98 oysters, could provide significant development opportunities. On the other hand, over 25% of the GDP is  
99 due to tourism and related services, highlighting the critical importance of properly managing coastal  
100 land use, via appropriate site selection and decision making processes for primary industries, to assess  
101 the conflicts and opportunities arising from competing interests (Cho *et al.*, 2012).

102 Twelve Sardinian lagoons were chosen for this case study, after a detailed survey on their historical  
103 environmental parameters. The chosen lagoons are: San Giovanni, Tortolì, Feraxi, Sa Praia, San  
104 Teodoro, Tartanelle, Gravile, Stagno Longo, Colostrai, Petrosu, Sa Curcurica and Su Graneri, all located  
105 in the east coast of Sardinia (Fig. 1). These lagoons cover an area of 1,145 ha which correspond to more  
106 than 10% of the total coastal lagoon area in Sardinia (regione.sardegna.it, 2019a). All these key  
107 transitional waters are already used for extensive valliculture of grey mullet (*Mugil cephalus* and *Chelon*  
108 *auratus*), sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) with the exception of Stagno  
109 Longo, Su Graneri, Tartanelle and Gravile where no fish or shellfish farming takes place. Small scale  
110 pacific oyster production is already taking place in Tortolì, San Giovanni, Feraxi, and San Teodoro  
111 (Sardegnaagricoltura.it, 2019).

112

### 113 **3. Materials and Methods**

#### 114 3.1. Overview of modelling approach

115 The modelling approach for this study is shown in Figure 2. The overall model has two main  
116 components; lagoon suitability assessment – based on biological and logistical criteria - and growth  
117 modelling – based on DEB models over production time. In combination these were used to give the

118 potential productivity of most suitable lagoons. The model processes are described in more detail in  
119 Sections 3.2 and 3.3.

120

## 121 3.2 Lagoon suitability assessment

122 Local knowledge, shellfish farming expert focus groups and data from published literature were used to  
123 identify criteria that influence site suitability for Pacific oysters farming. These were divided into  
124 biological criteria, comprising water quality data that would directly influence oyster growth, and logistic  
125 criteria which would affect site development and farm operations. A common scoring system was  
126 established, ranging from 0 (constraint to farming) to 1 (optimal), and used to classify each criterion.  
127 Absolute constraints to farming, such as environmental parameters outside species tolerance ranges and  
128 adaptation abilities, or water microbiological classification non compatible with bivalve farming, were  
129 scored as 0. Some criteria are more important than others, as there will be greater influence on growth  
130 and farming ~~operations, operations~~; therefore weights were determined and assigned using the Analytical  
131 Hierarchical Process (AHP) first developed by Saaty (1988). Multi-Criteria Analysis (MCA) in a GIS  
132 environment was then used to combine the Biological and Logistic criteria to produce the Total  
133 Suitability layer, for each lagoon, as outlined in Figure 2.

134

### 135 3.2.1 Biological criteria

136 Bio-physical parameters (Temp °C, Sal ‰, Chl-a  $\mu\text{g L}^{-1}$ , DO  $\text{mg L}^{-1}$ ) spanning from 2002 to 2009 were  
137 extracted from the Sardinian Government Regional Environmental Information System (SIRA;  
138 SardegnaAmbiente, 2019) and used to define the environment of each lagoon and establish how suitable

139 each site was in satisfying Pacific oysters' biological requirements. Environmental data were available  
140 for three different locations in each lagoon; with the exception of Sa Praia lagoon where only one data  
141 point was available. Each parameter was considered as a mean per season and per sampling point for the  
142 data from 2002 to 2009. By averaging the values per season, we ensured that short-lived stochastic events  
143 that could perturb the local environment, such as a flash flood or a particularly cold week, that oyster  
144 would be able to withstand, would not affect our modelling outputs. Each bio-physical parameter was  
145 then assigned a suitability score between 0 (Constraint) and 1 (Optimum) as described below. These  
146 scores (for each season and sampling point within each lagoon) were averaged in order to generate an  
147 overall biological score for each lagoon.

148 In brief, each bio-physical parameter was considered independently and established the species tolerance  
149 boundary (maximum and minimum), intermediate and optimal values as illustrated in Table 1 and  
150 according to previous studies (Pagou *et al.*, 2002; Wiltshire, 2007; Patterson and [Carmichael](#), 2018; Le  
151 Moullac *et al.*, 2007). For instance, it was considered that optimal growth would be achieved at a mean  
152 temperature between 20 and 25 °C, acceptable growth would still be achieved at temperatures between 7  
153 °C and 29 °C, whilst temperatures above 30 °C and below and 6 °C would not be appropriate for Pacific  
154 oyster farming and would be considered constraints.

### 155 3.2.2 Logistic criteria

156 Logistic criteria were also taken into account (Table 2) in the model. These included accessibility to the  
157 sites (presence and type of roads), presence and type of ancillary facilities (fresh water, electricity,  
158 office/storage buildings, phone line) and presence/absence and type of microbiological water  
159 classification for shellfish farming (A, B, C, Not classified). In a similar manner to the biological criteria,  
160 the logistic criteria were selected and individually scored (between 0 and 1, where 0 represented a



161 constraint) via expert focus group discussions, consultation with local stakeholders and farmers, and by  
162 visualisation of freely available satellite images (GoogleEarth®).

163 Water classification for shellfish farming (as defined by Regulation (EC) No 854/2004, Regulation (EC)  
164 No 853/2004), was obtained from the Aquaculture and Fishery Service Office of the Sardinian Regional  
165 Government and was used to identify sites where farming could already take place (Class A scored as 1,  
166 and B scored as 0.5) and sites where farming could not take place (Class C scored as 0), as illustrated in  
167 Table 2. Importantly, because our objective was to identify potentials new sites for Pacific oyster  
168 development, which by definition do not necessarily have water classification, we decided to give a score  
169 of 0.25 to sites for which water classification was unavailable in order not to *a priori* exclude potentially  
170 suitable sites. Nonetheless, we also considered absence of water classification as a partial constraint with  
171 a value of 0.5 (Table 2) when assessing total suitability scores (Equation 3) for each lagoon. The reason  
172 for this choice lies on the administrative burden and time involved in obtaining water classification from  
173 the relevant authorities.

174

### 175 3.2.3 Analytical Hierarchy Process & Multi-Criteria Analysis

176 Once the biological criterion had been scored, they were assigned weights established by expert focus  
177 groups using analytical hierarchy process AHP (Table 1). The logistic criteria were considered to be of  
178 equal importance. Next, the overall Biological and Logistic suitability scores of each lagoon were  
179 calculated using MCA.

180 Biological Suitability ( $S_b$ ) of each site was calculated using equation 1:

181 Eq. 1: 
$$S_b = \sum(W * P)$$

182 Where W is the weight and P is the parameter.

183 The logistical suitability (Sl) was calculated using equation 2:

184 Eq. 2: 
$$Sl = \sum(P)$$

185 Total suitability scores for each lagoon were then calculated as the mean between biological and logistic  
186 scores multiplied by any constraint (0) in such a way that if a biological or logistic constraint to farming  
187 is present the overall suitability score becomes 0.

188 Total suitability (St) was calculated using equation 3:

189 Eq. 3: 
$$St = ((Sb + Sl)/2) * C$$

190 Where C is a constraint.

191 The Geo-referencing process and overall lagoon score classification was completed using the GIS  
192 software QGIS 3.14 [QGIS Development Team]. GIS outputs have then been converted into the figures  
193 using Adobe CC Illustrator<sup>®</sup>, 2019.

194

### 195 3.3 Growth modelling and sites potential productivity

196 Once total suitability was established and the growth model was validated, the length of the production  
197 cycle (from seed to market size) for each lagoon and in all sampling points of each lagoon (Table 5) was  
198 investigated to establish the potential annual productivity of all lagoons object of this study.

199 A DEB model for Pacific oysters was developed using R software (R Core Team, 2018), based on the  
200 modelling approach originally established by Pouvreau *et al.*, (2006), and calibrated to local conditions.

201 The model was validated using growth data from Pacific oyster farming sites in San Tedoro and Santa  
202 Gilla lagoons (Graham *et al.*, 2020) to ensure it represented conditions in Sardinia. Knowledge of local  
203 oyster farming practices was used to set up the model: where the production cycle started in March, the  
204 initial oyster size was 8mm, and the modelled oysters were assumed to be sterile triploids. For each  
205 location, interpolated daily values of temperature and Chl-a concentrations (used as proxy to food  
206 availability), were used to force the model. The model simulated the increase in shell length, which was  
207 then converted to weight using equation 4, which was empirically derived from morphometric data  
208 collected *in situ* (Graham *et al.*, 2020):

209 Eq. 4: 
$$W = 0.1496 * (L^{2.6681})$$

210 The endpoint of the simulation was a harvest weight of 80g per individual.

211 Using the average of temperature and Chl-a values of each sampling point, the production cycle length  
212 for each lagoon was calculated. In order to calculate the potential productivity per production cycle and  
213 per year of each lagoon, an arbitrary 25% of the surface area of each lagoon, acquired as secondary data  
214 from the Sardinian government website ([regione.sardegna.it](http://regione.sardegna.it), 2019b), was assumed as usable for Pacific  
215 oyster farming. Productivity per unit area was also considered to be 1kg/m<sup>2</sup> in accordance with local  
216 farming practices.

217 Potential production per year was then calculated using equation 5:

218 Eq. 5: 
$$PP = [(Surface\ area \times 0.25) \times (1kg / m^2)] \times (\% \text{ of production cycle per year})$$

219

## 220 4. Results

#### 221 4.1 Lagoon suitability

222 In general, all bio-physical parameters (T, Sal, DO and Chl-a) were highly suitable for Pacific oyster  
223 farming (Table 3); however, there were four exceptions: salinity in Sa Curcurica, Su Graneri and Stagno  
224 Longo, and Chlorophyll-a in Colostrai. In Sa Curcurica salinity was higher than optimal in spring,  
225 summer and autumn (score 0.46) due to low freshwater inputs from the catchment and high evaporation  
226 during the warmer months. Su Graneri and Stagno Longo lagoons had lower than optimal salinity,  
227 particularly in winter due to high fresh water inputs (scores 0.21 and 0.46 respectively). Chlorophyll-a  
228 concentrations were lower than optimal, but still suitable, throughout the year in Colostrai (score 0.5),  
229 possibly due to high water exchange rate with the Mediterranean Sea resulting in lower nutrient waters.  
230 However, all lagoons resulted in an overall score higher than 0.6, as calculated using the weights in Table  
231 1, indicating that from a strictly biological point of view all examined lagoons could potentially host  
232 Pacific oyster farming activities. These are shown in Figure 3.

233 The overall picture of Sardinian lagoons from a logistic view point (Table 4) is one of suitable overall  
234 conditions for most categories (site accessibility, utilities and building). However, only three out of  
235 twelve lagoons (Feraxi, San Giovanni and Tortoli) were serviced by a wide asphalt road which,  
236 according with local farmers, would allow for large equipment and harvest to be easily moved in and out  
237 of the farming sites (score 1). Seven lagoons had wide gravel or narrow asphalt road that could limit  
238 farming operations particularly when scope for expansion is considered (score 0.75). The remaining two  
239 lagoons (Su Graneri and Tartanelle) only had access through narrow gravel roads (score 0.5). Suitable  
240 buildings were present in all lagoons with the exception of Tartanelle (score 0.25). Only five lagoons  
241 held water classification for bivalve farming and all five were classed as A waters and scored as 1. The  
242 other sites were given a score of 0.25 as being only newly considered for bivalve culture they had no  
243 classification. The overall Logistic suitability score for each lagoon is shown in Figure 4. As neither

244 biological nor logistic considerations on their own would be enough to determine lagoon suitability and  
245 they have to be combined to generate a Total Suitability Score presented in Figure 5. This clearly  
246 indicates that although all lagoons were biologically suitable (scores from 0.63 to 0.95), and their logistic  
247 suitability was also acceptable (scores from 0.45 to 0.95) the combination of both sets of parameters  
248 creates a divide between the top five lagoons (Scores from 0.74 to 0.95) and the remaining seven (scores  
249 from 0.30 to 0.36). The difference is due to the absence of water classification for bivalve farming in the  
250 lower scoring lagoons.

251

#### 252 4.2 Oysters growth and sites potential productivity

253 The outputs from the DEB growth model for all available sampling points showed that the time to reach  
254 market size (80 g) ranged from 168 to 652 days (Table 5). Moving from a comparison between sampling  
255 points within lagoons to wider comparison between lagoons, Figure 6 showed that the time to reach 80 g  
256 ranged from 177 days in Stagno Longo to 481 days in Colostrai lagoons. Though this suggested there was  
257 growth potential for all lagoons, there were significant variations in production length between each  
258 lagoon. The potential productivity per production cycle was then calculated and predictions generated  
259 using the outputs from the DEB model and the assumptions on available area for cultivation and  
260 production density are given in Table 6. The annual potential production of each lagoon was then  
261 calculated based on the number of production cycles that could be theoretically performed within one  
262 year based on equation 5. These results are shown in Figure 7 and show that two lagoons have  
263 considerably more production potential than the rest: Tortoli (1063.4 tonnes) and San Teodoro (1025.4  
264 tonnes). The results also highlight that the size of the lagoon is not necessarily related to production  
265 capacity, as there could be more suitable environmental conditions in smaller lagoons. For example, San  
266 Giovanni lagoon (assumed cultivation area of 27.5 ha) is smaller than Colostrai (assumed cultivation area

267 of 34.25 ha) but has significantly higher annual potential production (475.7 tonnes vs 259.9 tonnes) due  
268 to the lower chlorophyll levels in the latter. The total annual combined production within the twelve  
269 lagoons was calculated to be 4113.5 tonnes/year, equal to 6.25% of the total Pacific oyster annual  
270 imports to Italy. However, more detailed lagoon-specific assessment and site selection analysis would be  
271 required to enable more robust estimates of potential production.

272

## 273 **5. Discussion**

274 This study, focused on the selection of the most suitable shallow lagoons for Pacific oyster farming in  
275 Sardinia, and demonstrated an approach that decision makers can use to prioritise areas with potential for  
276 development and where to target resources. The approach described here is composed of two  
277 complementary processes, each providing a separate piece in the decision making system: 1)  
278 Classification of lagoon suitability based on biological and logistical criteria, combined using an MCA  
279 approach and 2) Biological data through the DEB (to give production cycles per year) and size of the  
280 lagoon to give potential productivity for each lagoon.

### 281 5.1 Lagoon suitability

282 The analysis of biological factors allows for clear identification of potential constraints to farming linked  
283 to unsuitable bio-physical parameters, which would exclude any such site from further consideration on  
284 development of farming activities. The analysis of logistic factors and constraints, allows for detailed  
285 consideration of limiting factors for economic sustainable development, highlighting where investment  
286 may be needed and where these would be more effective to achieve production potentials. This approach,  
287 therefore, allows for the combination of multiple criteria and, using historical environmental data,  
288 generates predictions on potential productivities even where oyster farming activities have never taken

289 place. It is interesting to note that despite the use of historical environmental data, the results presented  
290 here are consistent with the current landscape in Sardinia and the most suitable lagoons identified via the  
291 process presented here are already involved in Pacific oyster farming. Furthermore, lagoons where  
292 oysters had never been farmed, such as Sa Praia and Tartanelle, and with a relatively low logistic score  
293 (0.62 and 0.45), would appear to show annual production potentials (300 and 258 tonnes respectively)  
294 comparable or higher than other lagoons where farming already takes place and with higher suitability  
295 scores, such as such as Feraxi (115 tonnes annual potential production and 0.89 total suitability score).  
296 These data clearly indicate that potential investments and further investigation would be very valuable in  
297 those locations.

298 The combined modelling approach presented here can be used by industry and policymakers to identify  
299 the most suitable lagoons and resources needed to support development within them. For example,  
300 improving site accessibility in Tartanelle and Sa Praia lagoons would improve their logistic suitability  
301 and allow for easier scale up of future production. Also, granting building consent or upgrade, would  
302 improve logistic suitability and help achieve their potential annual productions. Importantly, however,  
303 the combination of lagoon size, logistic and biological factor and ultimately production potential, would  
304 indicate that investment in some lagoons may not be appropriate. For example, due to the limited scope  
305 for production output in Petrosu and Su Graneri lagoon, despite their relatively high biological suitability  
306 scores (0.70 and 0.66 respectively) would indicate that investment may not be appropriate.  
307 Consequently, combination of lagoon suitability and growth modelling approaches can be used to  
308 highlight the most important challenges and the trade-offs to be considered for the effective use of public  
309 investment to maximise production outputs.

310 An important consideration in this study was the water classification for shellfish farming and the  
311 consequent critical importance of keeping a class A or B status. Indeed, the most effective way to

312 improve logistic suitability of most lagoons would be to streamline the administrative process required  
313 for the acquisition of water classification. Indeed, as water classification is depended on constant  
314 monitoring and can change, the scores employed in this study should be re-evaluated at for all lagoons  
315 when new information becomes available On the other hand, if microbiological quality of the farming  
316 water was to decline this would have immediate and severe repercussions on the overall suitability of any  
317 lagoon. Once again, this combined modelling approach helps with the prioritisation of investment  
318 towards the lagoons with the highest production potential. For instance, if all lower production potential  
319 lagoons such as: Su Graneri, Petrosu, Sa Curcurica, Feraxi, Gravile, Stagno Longo and Tartanelle (988  
320 tonnes of combined potential production) were to be classed as C waters, the loss in potential production  
321 would be lower than 50% of the loss that would be expected if San Teodoro and Tortoli' (2,088 tonnes  
322 combined annual potential production) were to be downgraded to Class C. Once again, this consideration  
323 would urge policymakers to invest in water quality protection initiatives particularly for the most  
324 productive sites.

## 325 5.2 Oysters growth and sites potential productivity

326 The observed differences in modelled growth rates are more likely due to the variability in temperature  
327 and Chl-a concentrations (main drivers of the growth model) between lagoons but also between areas  
328 within each lagoon. Indeed, distance of the sampling points from fresh water inputs, the lagoon opening  
329 to the sea, the specific bathymetry, and the position of the sampling point within the overall lagoon  
330 circulation are all critical parameters able to influence the model's main drivers. Other factors, which  
331 were not included in the DEB model, may also influence growth and overall production potential, but  
332 would require further data collection and site-specific information. The approach presented here can be  
333 used to identify not only the lagoon with most potential, but also areas within a lagoon. The ability to  
334 distinguish which area within the lagoon offer the best opportunity for growth is obviously of great



335 importance during the site selection process. This is clearly exemplified by one location in Sa Curcurica  
336 and one location in Feraxi where growth prediction is significantly longer than the other sampling points  
337 considered, within the same lagoons. It is tempting to look at the potential production figures presented  
338 here and simply scale them up to include the reminder 90% of lagoon surface area in Sardinia, and the  
339 other lagoons on the Italian national territory. By doing so, it would appear that Italy has the potential to  
340 meet the demand for Pacific oyster through domestic production, rather than relying on imports.  
341 However, not all lagoons will be suitable and differences within lagoons will also impact potential  
342 production which further highlights the need to employ methodologies such as those presented here.  
343 Equally, it would be tempting to use spatial analysis of shellfish aquaculture suitability based on its  
344 contribution to pollution mitigation (Theuerkauf *et al.*, 2019), however the approach presented here  
345 highlights the important fact that aquaculture is a food production industry and an important economic  
346 activity. Therefore, environmental services provided by this activity needs to be counterbalanced by the  
347 requirement for the main output of this food production sector to find its place on the market,  
348 consequently prioritising pollution mitigation might limit the possibility for the product to be sold.

349 The strength of the combined modelling approach presented here is that it is a cost-effective and efficient  
350 way of prioritising the lagoons that are most likely to be suitable for production, and to estimate what that  
351 production could be. However, within an area such as a lagoon, there can be spatial variation in  
352 suitability and production potential (Barillé *et al.*, 2020; Gernez *et al.*, 2017). In this study, useful  
353 information on what areas within each lagoon are likely to provide better growth have been identified,  
354 however this output has been generated but using point data source and to investigate this further would  
355 require more detailed spatial datasets (grid data). Therefore, once the most appropriate lagoons have been  
356 identified as potential for Pacific oyster culture, further analysis can take place. Earth observation and  
357 remote sensing technology are becoming increasingly used and can provide data on environmental

358 parameters relevant for oyster production at coastal (Barillé *et al.*, 2020) or farm scale (Gernez *et al.*,  
359 2017). Additional data on other factors may have to be collected, although the development and  
360 implementation of marine spatial plans in many areas is a good source of information. To assess the  
361 long-term production potential of the sector, it may also be important to consider potential implications  
362 of climate change on the suitability of production areas for oysters.

363 Even when data collection and modelling is optimised it is important to consider the potential  
364 consequences of any future increase in production. Shallow Coastal lagoons are one of the most sensitive  
365 environments to biological perturbation and examples of bivalve farming contributing to dystrophic  
366 events are mostly located in coastal lagoons (e.g. Sacca di Goro lagoon, Italy; Vincenzi *et al.*, 2006).  
367 Therefore, careful monitoring of environmental impact from oyster farming, aimed at keeping stocking  
368 densities within sustainable ranges, must be integral component of any future development. Furthermore,  
369 our data did not take into account the potential for persistent pollutants or other toxic discharges from  
370 other anthropic activities into the lagoons. These would severely limit marketability of the product and  
371 suitability of the sites and potentially drastically impact on the island's production potential. Therefore,  
372 data on any toxic compounds present, their concentrations and on future risks associated with their  
373 discharge remain to be gathered and analysed.

374 Any increase in production will also need to be sustained by the strengthening of the entire supply chain,  
375 from seed to farming equipment availability, development of modern and large-scale depuration units to  
376 products distribution to retailers and seafood operators. For the most part seed is currently sourced from  
377 French hatcheries; however, increased demand for seed may put unforeseen pressure on current seed  
378 suppliers. Furthermore, increased production may result in disease outbreaks, particularly of the Oyster  
379 Herpes Virus (OsHV-1 $\mu$ var). It will therefore be critical that seed sourced from hatcheries possess  
380 disease free-status or will originate from selectively bred lines for disease resistance. The development of

381 a local commercial hatchery may become a requirement and, in that case, investments towards triploids  
382 seed production to ensure sterility and the development of in-house selective breeding may be required.

383 Market demand and consumer acceptance is also a major factor in the economic viability of oyster  
384 production. At present, most imported oysters are sourced from France and consumers are familiar with  
385 this product so there may be a market penetration issue for locally produced oysters. Importantly, oyster  
386 farming is not formulaic and farmers' expertise is critical in the delivery of a high quality product.  
387 Mechanisms by which the already available local and international knowledge and experience can be  
388 made available to new entries in the industry will have to be strengthened or developed from scratch to  
389 ensure that local products could compete with the currently perceived better quality of imported product.  
390 This in turn will involve branding development via specific marketing intervention. Finally, increased  
391 production and competition between local farming companies may contribute to product depreciation  
392 that could only partially be compensated by economy of scale. This would potentially have a negative  
393 impact on product value and, as a consequence, affect the profitability of the businesses involved.

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Figure 1. Study area: twelve lagoons chosen for this case study and their locations in the East coast of Sardinia.

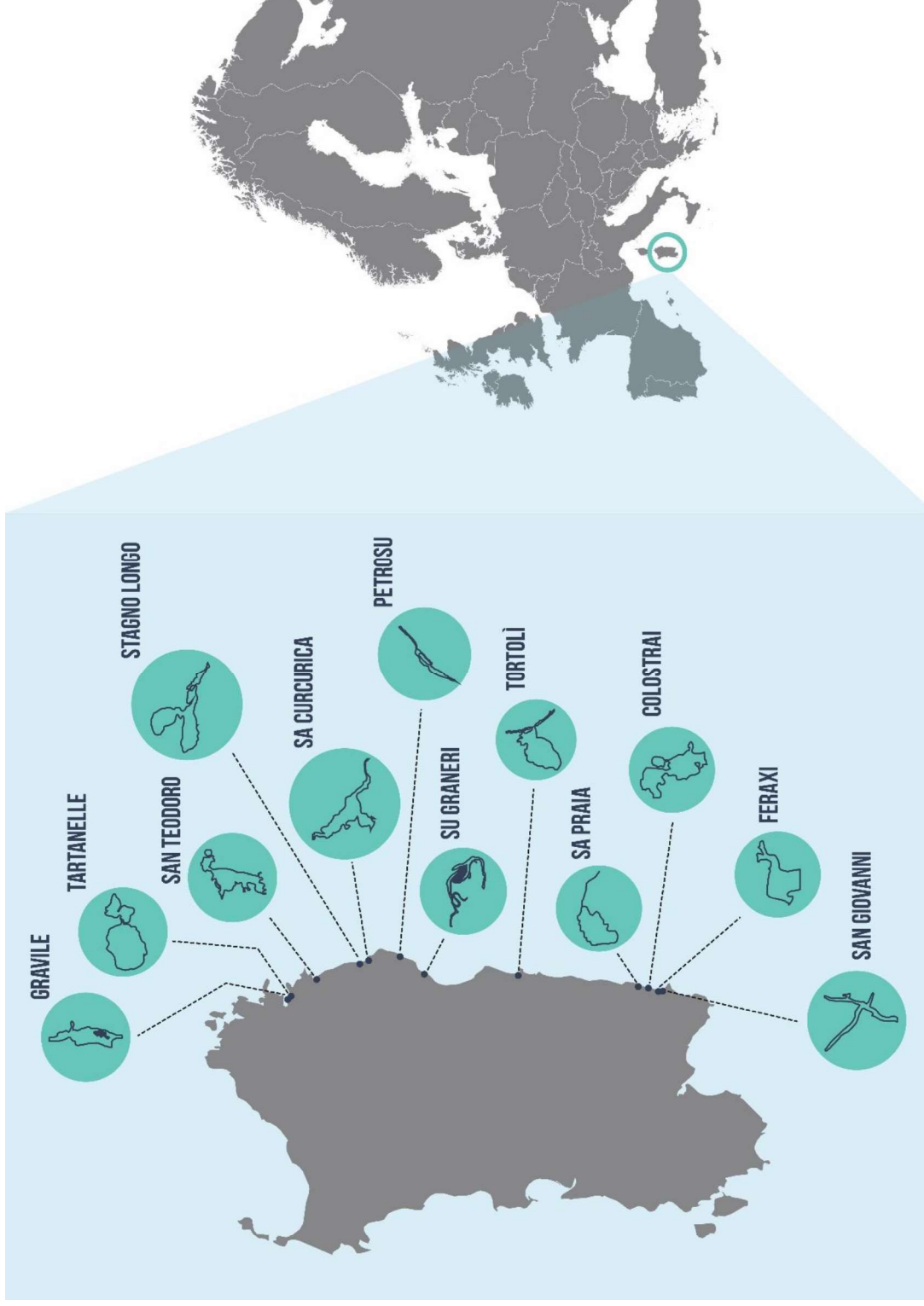




Figure 2. Diagram of the lagoons suitability classification approach

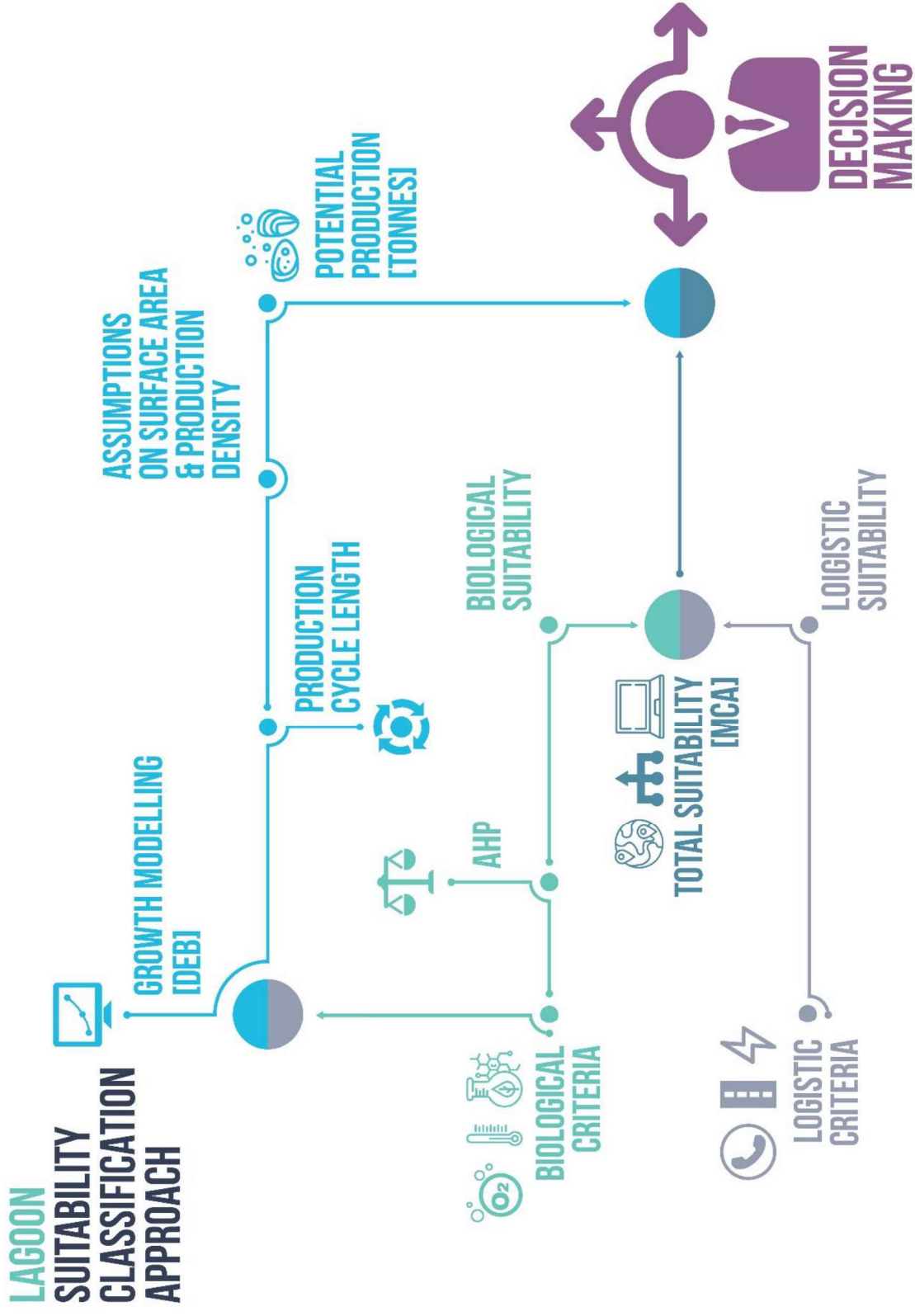


Figure 3. Biological suitability as calculated by AHP. Size of the circles and numbers are indicative of suitability scores and ranking



Figure 4. Logistic suitability. Size of the circles and numbers are indicative of suitability scores and ranking



Figure 5. Total suitability as calculated by MCA. Size of the circles and numbers are indicative of suitability scores and ranking



Figure 6. Production cycle length expressed in number of days to reach market size of 80 g for each lagoon as predicted by the DEB model. The coloured number in the chart are the production cycle length in days.

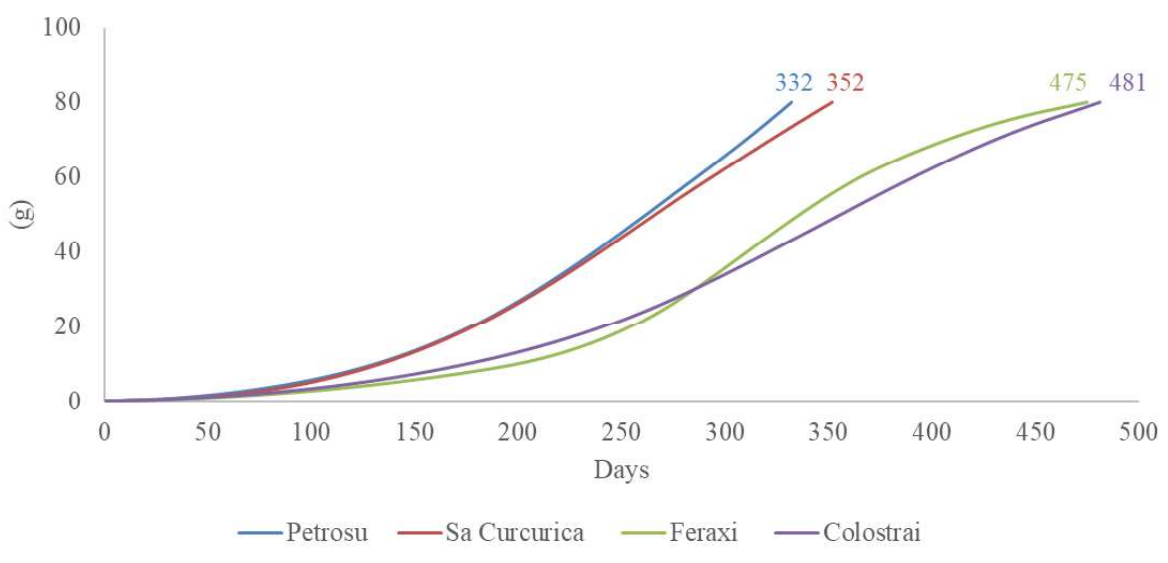
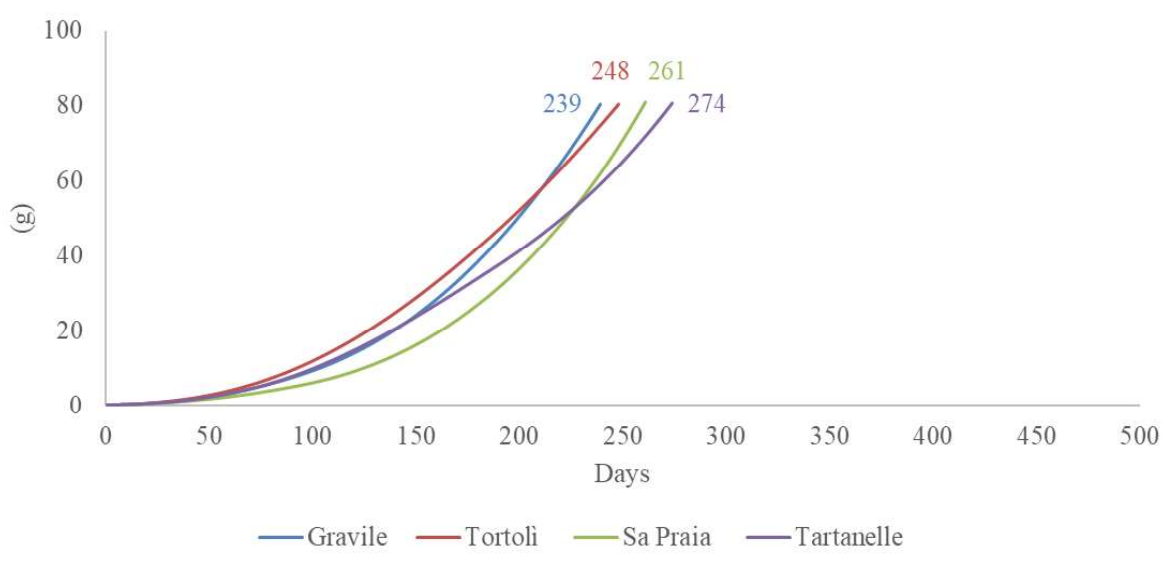
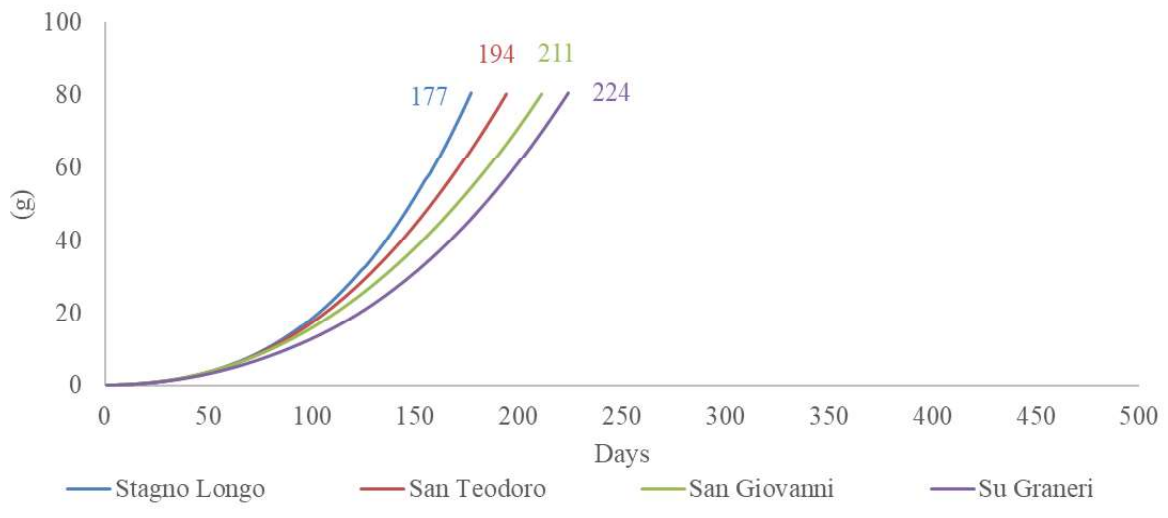


Figure 7. Total potential annual production (Tonnes). Size of the circles and numbers are indicative of production volumes

**POTENTIAL  
PRODUCTION  
PER YEAR  
[TONNES]**

