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

Philip Graham [a,b], Lynne Falconer [b], Trevor Telfer [b], Paolo Mossone [a], Iolanda Viale [c], Stefano Carboni

[b][a]IMC - International Marine Centre, Loc. Sa Mardini, 09170, Oristano, Italy

[b]University of Stirling, Institute of Aquaculture, Pathfoot Building, FK94LA, Stirling, UK

[c]Laore Sardegna, Regional Government Department for Agriculture, Via Caprera, 09123, Cagliari, Italy

## Abstract

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

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

## 1. Introduction

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

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

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

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

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

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

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

## 2. Study area

Sardinia is the second largest island in the Mediterranean Sea and, with a coastline of 1,850 km, it offers ample opportunity for sustainable exploitation of marine resources. In particular, the coastline is dotted with approximately 10,000 ha of biologically productive lagoons which for centuries have provided employment to local communities (Bazzoni *et al.,* 2013). Most lagoons are still utilized for extensive fish farming (valliculture), but could also be potential sites for Pacific oyster farming. Pacific oyster requires shallow and relatively sheltered sites, productive waters and can withstand relatively high salinity and temperature variability. All of these conditions can be found in Sardinian lagoons and therefore many of the Italian oyster farms are already located there. Nonetheless, only 3% of the island Gross Domestic Product (GDP) is now produced by primary activities (farming and fishing) and youth unemployment has risen to 46.8% in 2017 (http://www.sardegnastatistiche.it/argomenti/istruzionelavoro/). Against this backdrop, it would appear that sustainable aquaculture of a product in high demand, such as Pacific oysters, could provide significant development opportunities. On the other hand, over 25% of the GDP is due to tourism and related services, highlighting the critical importance of properly managing coastal land use, via appropriate site selection and decision making processes for primary industries, to assess the conflicts and opportunities arising from competing interests (Cho *et al*., 2012).

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

## 3. Materials and Methods

### 3.1. Overview of modelling approach

The modelling approach for this study is shown in Figure 2. The overall model has two main components; lagoon suitability assessment – based on biological and logistical criteria - and growth modelling – based on DEB models over production time. In combination these were used to give the potential productivity of most suitable lagoons. The model processes are described in more detail in Sections 3.2 and 3.3.

## 3.2 Lagoon suitability assessment

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

### 3.2.1 Biological criteria

Bio-physical parameters (Temp °C, Sal ‰, Chl-a μg $L^{-1}$, DO mg $L^{-1}$) spanning from 2002 to 2009 were extracted from the Sardinian Government Regional Environmental Information System (SIRA; SardegnaAmbiente, 2019) and used to define the environment of each lagoon and establish how suitable each site was in satisfying Pacific oysters' biological requirements. Environmental data were available for three different locations in each lagoon; with the exception of Sa Praia lagoon where only one data point was available. Each parameter was considered as a mean per season and per sampling point for the data from 2002 to 2009. By averaging the values per season, we ensured that short-lived stochastic events that could perturb the local environment, such as a flash flood or a particularly cold week, that oyster would be able to withstand, would not affect our modelling outputs. Each bio-physical parameter was then assigned a suitability score between 0 (Constraint) and 1 (Optimum) as described below. These scores (for each season and sampling point within each lagoon) were averaged in order to generate an overall biological score for each lagoon.

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

3.2.2 Logistic criteria

Logistic criteria were also taken into account (Table 2) in the model. These included accessibility to the sites (presence and type of roads), presence and type of ancillary facilities (fresh water, electricity, office/storage buildings, phone line) and presence/absence and type of microbiological water classification for shellfish farming (A, B, C, Not classified). In a similar manner to the biological criteria, the logistic criteria were selected and individually scored (between 0 and 1, where 0 represented a constraint) via expert focus group discussions, consultation with local stakeholders and farmers, and by visualisation of freely available satellite images (GoogleEarth®).

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

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

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

Biological Suitability (Sb) of each site was calculated using equation 1:

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

Where W is the weight and P is the parameter.

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

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

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

Total suitability (St) was calculated using equation 3:

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

Where C is a constraint.

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

3.3 Growth modelling and sites potential productivity

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

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

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

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

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

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

Potential production per year was then calculated using equation 5:

Eq. 5: $$PP = \lfloor (Surface\ area\ x\ 0.25)\ x\ (1kg\ /\ m^2) \rfloor\ x\ (\%\ of\ production\ cycle\ per\ year)$$

## 4. Results

4.1 Lagoon suitability

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

The overall picture of Sardinian lagoons from a logistic view point (Table 4) is one of suitable overall conditions for most categories (site accessibility, utilities and building). However, only three out of twelve lagoons (Feraxi, San Giovanni and Tortolì) were serviced by a wide asphalt road which, according with local farmers, would allow for large equipment and harvest to be easily moved in and out of the farming sites (score 1). Seven lagoons had wide gravel or narrow asphalt road that could limit farming operations particularly when scope for expansion is considered (score 0.75). The remaining two lagoons (Su Graneri and Tartanelle) only had access through narrow gravel roads (score 0.5). Suitable buildings were present in all lagoons with the exception of Tartanelle (score 0.25). Only five lagoons held water classification for bivalve farming and all five were classed as A waters and scored as 1. The other sites were given a score of 0.25 as being only newly considered for bivalve culture they had no classification. The overall Logistic suitability score for each lagoon is shown in Figure 4. As neither biological nor logistic considerations on their own would be enough to determine lagoon suitability and they have to be combined to generate a Total Suitability Score presented in Figure 5. This clearly indicates that although all lagoons were biologically suitable (scores from 0.63 to 0.95), and their logistic suitability was also acceptable (scores from 0.45 to 0.95) the combination of both sets of parameters creates a divide between the top five lagoons (Scores from 0.74 to 0.95) and the remaining seven (scores from 0.30 to 0.36). The difference is due to the absence of water classification for bivalve farming in the lower scoring lagoons.

## 4.2 Oysters growth and sites potential productivity

The outputs from the DEB growth model for all available sampling points showed that the time to reach market size (80 g) ranged from 168 to 652 days (Table 5). Moving from a comparison between sampling points within lagoons to wider comparison between lagoons, Figure 6 showed that the time to reach 80 g ranged from 177 days in Stagno Longo to 481 days in Colostrai lagoons. Though this suggested there was growth potential for all lagoons, there were significant variations in production length between each lagoon. The potential productivity per production cycle was then calculated and predictions generated using the outputs from the DEB model and the assumptions on available area for cultivation and production density are given in Table 6. The annual potential production of each lagoon was then calculated based on the number of production cycles that could be theoretically performed within one year based on equation 5. These results are shown in Figure 7 and show that two lagoons have considerably more production potential that the rest: Tortoli (1063.4 tonnes) and San Teodoro (1025.4 tonnes). The results also highlight that the size of the lagoon is not necessarily related to production capacity, as there could be more suitable environmental conditions in smaller lagoons. For example, San Giovanni lagoon (assumed cultivation area of 27.5 ha) is smaller than Colostrai (assumed cultivation area of 34.25 ha) but has significantly higher annual potential production (475.7 tonnes *vs* 259.9 tonnes) due to the lower chlorophyll levels in the latter. The total annual combined production within the twelve lagoons was calculated to be 4113.5 tonnes/year, equal to 6.25% of the total Pacific oyster annual imports to Italy. However, more detailed lagoon-specific assessment and site selection analysis would be required to enable more robust estimates of potential production.

## 5. Discussion

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

### 5.1 Lagoon suitability

The analysis of biological factors allows for clear identification of potential constraints to farming linked to unsuitable bio-physical parameters, which would exclude any such site from further consideration on development of farming activities. The analysis of logistic factors and constraints, allows for detailed consideration of limiting factors for economic sustainable development, highlighting where investment may be needed and where these would be more effective to achieve production potentials. This approach, therefore, allows for the combination of multiple criteria and, using historical environmental data, generates predictions on potential productivities even where oyster farming activities have never taken place. It is interesting to note that despite the use of historical environmental data, the results presented here are consistent with the current landscape in Sardinia and the most suitable lagoons identified via the process presented here are already involved in Pacific oyster farming. Furthermore, lagoons where oysters had never been farmed, such as Sa Praia and Tartanelle, and with a relatively low logistic score (0.62 and 0.45), would appear to show annual production potentials (300 and 258 tonnes respectively) comparable or higher than other lagoons where farming already takes place and with higher suitability scores, such as such as Feraxi (115 tonnes annual potential production and 0.89 total suitability score). These data clearly indicate that potential investments and further investigation would be very valuable in those locations.

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

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

## 5.2 Oysters growth and sites potential productivity

The observed differences in modelled growth rates are more likely due to the variability in temperature and Chl-a concentrations (main drivers of the growth model) between lagoons but also between areas within each lagoon. Indeed, distance of the sampling points from fresh water inputs, the lagoon opening to the sea, the specific bathymetry, and the position of the sampling point within the overall lagoon circulation are all critical parameters able to influence the model's main drivers. Other factors, which were not included in the DEB model, may also influence growth and overall production potential, but would require further data collection and site-specific information. The approach presented here can be used to identify not only the lagoon with most potential, but also areas within a lagoon. The ability to distinguish which area within the lagoon offer the best opportunity for growth is obviously of great importance during the site selection process. This is clearly exemplified by one location in Sa Curcurica and one location in Feraxi where growth prediction is significantly longer than the other sampling points considered, within the same lagoons. It is tempting to look at the potential production figures presented here and simply scale them up to include the reminder 90% of lagoon surface area in Sardinia, and the other lagoons on the Italian national territory. By doing so, it would appear that Italy has the potential to meet the demand for Pacific oyster through domestic production, rather than relying on imports. However, not all lagoons will be suitable and differences within lagoons will also impact potential production which further highlights the need to employ methodologies such as those presented here. Equally, it would be tempting to use spatial analysis of shellfish aquaculture suitability based on its contribution to pollution mitigation (Theuerkauf *et al.,* 2019), however the approach presented here highlights the important fact that aquaculture is a food production industry and an important economic activity. Therefore, environmental services provided by this activity needs to be counterbalanced by the requirement for the main output of this food production sector to find its place on the market, consequently prioritising pollution mitigation might limit the possibility for the product to be sold.

The strength of the combined modelling approach presented here is that it is a cost-effective and efficient way of prioritising the lagoons that are most likely to be suitable for production, and to estimate what that production could be. However, within an area such as a lagoon, there can be spatial variation in suitability and production potential (Barillé *et al.,* 2020; Gernez *et al.,* 2017). In this study, useful information on what areas within each lagoon are likely to provide better growth have been identified, however this output has been generated but using point data source and to investigate this further would require more detailed spatial datasets (grid data). Therefore, once the most appropriate lagoons have been identified as potential for Pacific oyster culture, further analysis can take place. Earth observation and remote sensing technology are becoming increasingly used and can provide data on environmental parameters relevant for oyster production at coastal (Barillé *et al.,* 2020) or farm scale (Gernez *et al.,* 2017). Additional data on other factors may have to be collected, although the development and implementation of marine spatial plans in many areas is a good source of information. To assess the long-term production potential of the sector, it may also be important to consider potential implications of climate change on the suitability of production areas for oysters.

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

Any increase in production will also need to be sustained by the strengthening of the entire supply chain, from seed to farming equipment availability, development of modern and large-scale depuration units to products distribution to retailers and seafood operators. For the most part seed is currently sourced from French hatcheries; however, increased demand for seed may put unforeseen pressure on current seed suppliers. Furthermore, increased production may result in disease outbreaks, particularly of the Oyster Herpes Virus (OsHV-1µvar). It will therefore be critical that seed sourced from hatcheries possess disease free-status or will originate from selectively bred lines for disease resistance. The development of a local commercial hatchery may become a requirement and, in that case, investments towards triploids seed production to ensure sterility and the development of in-house selective breeding may be required.

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

## 5. Acknowledgments

This study is part of the Sardinian project "OSTRINNOVA, Valorisation of sustainable production of oysters in the shellfish production system in Sardinia", funded by the Sardinia Region, Det. DG n ° 566 of 27/04/2016. The authors would like to thank LAORE Sardinian government agency for providing the logistic data, the Sardinian government for providing historical biological data and Dr Staci Rowlison for the graphic elaboration of the figures.

## References

1. Barillé, L., Le Bris, A., Goulletquer, P., Thomas, Y., Glize, P., Kane, F., Falconer, L., Guillotreau, P., Trouillet, B., Palmer, S., Gernez, P. (2020). Biological, socio-economic, and administrative opportunities and challenges to moving aquaculture offshore for small French

oyster-farming companies. *Aquaculture* **521**, 735045. https://doi.org/10.1016/j.aquaculture.2020.735045.

2. Barillé, L., Lerouxel, A., Dutertre, M., Haure, J., Barillé, A. L., Pouvreau, S., Alunno-Bruscia, M. (2011). Growth of the Pacific oyster (*Crassostrea gigas*) in a high-turbidity environment: Comparison of model simulations based on scope for growth and dynamic energy budgets. *Journal of Sea Research* **66 (4)**, 392-402. https://doi.org/10.1016/j.seares.2011.07.004.
3. Bazzoni, A. M., Pulina, S., Padedda, B. M., Satta, C. T., Lugliè, A., Sechi, N., Facca, C. (2013). Water quality evaluation in Mediterranean lagoons using the Multimetric Phytoplankton Index (MPI): Study cases from Sardinia. *Transitional Waters Bulle*tin **7 (1),** 64-76. https://doi.org/10.1285/i1825229Xv7n1p64.
4. Bourlès, Y., Alunno-Bruscia, M., Pouvreau, S., Tollu, G., Leguay, D., Arnaud, C., Goulletquer, P., Kooijman S. A. L. M. (2009). Modelling growth and reproduction of the Pacific oyster *Crassostrea gigas*: Advances in the oyster-DEB model through application to a coastal pond. *Journal of Sea Research* **62 (2-3)**, 62-71. https://doi.org/10.1016/j.seares.2009.03.002.
5. Buitrago, J., Rada, M., Hernandez, H.,Buitrago E. A. (2005). Single-use site selection technique, using GIS, for aquaculture planning: choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela. *Environmental Management* **35**, 544-556. https://doi.org/10.1007/s00267-004-0087-9.
6. Cho, Y., Lee, W-O., Hong, S., Kim, H-C., Kim, J. B. (2012). GIS-based suitable site selection using habitat suitability index for oyster farms in Geoje-Hansan Bay, Korea. *Ocean & Coastal Management* **56**, 10-16. https://doi.org/10.1016/j.ocecoaman.2011.10.009.
7. Falconer, L., Middelboe, A. L., Kaas, H., Ross, L., Telfer, T. (2019). Use of geographic information systems for aquaculture and recommendations for development of spatial tools. *Reviews in Aquaculture*. https://doi.org/10.1111/raq.12345.
8. Falconer, L., Telfer, T., Pham, K. L., Ross, L. (2018). GIS Technologies for Sustainable Aquaculture. In: Huang B (ed.) *Comprehensive Geographic Information Systems, Vol. 2*. Reference Module in Earth Systems and Environmental Sciences. Oxford: Elsevier, pp. 290-314.
9. Falconer, L., Telfer, T. C., Ross, L. G. (2016). Investigation of a novel approach for aquaculture site selection. *Journal of Environmental Management* **181**, 791-804. https://doi.org/10.1016/j.jenvman.2016.07.018.
10. FAO (2018). Food and Agriculture Organization of the United Nations [Online] Available from: http://www.fao.org/3/i9540EN/i9540en.pdf [Accessed: 02th July 2019].
11. FAO (2011-2018). Fisheries and aquaculture software. FishStatJ - software for fishery statistical time series. In: *FAO Fisheries and Aquaculture Department* [online]. Rome. Updated 21 July 2016. [~~Cited~~ Accessed 1 July 2019]. http://www.fao.org/fishery/
12. Filgueira, R., Rosland, R., Grant, J. (2011). A comparison of scope for growth (SFG) and dynamic energy budget (DEB) models applied to the blue mussel (*Mytilus edulis*). *Journal of Sea Research* **66 (4)**, 403-410. https://doi.org/10.1016/j.seares.2011.04.006.
13. Gernez, P., Doxaran, D., Barillé, L. (2017). Shellfish aquaculture from space: potential of Sentinel2 to monitor tide-driven changes in turbidity, chlorophyll concentration and oyster

physiological responses at the scale of an oyster farm. *Frontiers in Marine Science* **4**, 137. https://doi.org/10.3389/fmars.2017.00137.

14. Graham, P., Brundu, G., Scolamacchia, M., Giglioli, A., Addis, P., Artioli, Y., Telfer, T., Carboni, S. (2020). Improving Pacific Oyster (*Crassostrea gigas*, Thunberg, 1793) Production in Mediterranean Coastal Lagoons: Validation of the growth model "ShellSIM" on traditional and novel farming methods. *Aquaculture* **516***,* 734612. https://doi.org/10.1016/j.aquaculture.2019.734612.
15. Hawkins, A. J. S., Pascoe, P. L., Parry, H., Brinsley, M., Black, K. D., Mcgonigle, C., Moore, H., Newell, C. R., O'Boyle, N., Ocarroll, T., O'Loan, B., Service, M., Smaal, A. C., Zhang, X. L., Zhu, M. Y. (2013). Shellsim: A Generic Model of Growth and Environmental Effects Validated Across Contrasting Habitats in Bivalve Shellfish. *Journal of Shellfish Research* **32 (2)**, 237-253. https://doi.org/10.2983/035.032.0201.
16. Kooijman, S. A. L. M. (2010). *Dynamic Energy Budget Theory for Metabolic Organization, 3rd edn. Cambridge, UK: Cambridge University Press.*
17. Le Moullac, G., Quéau, I., Le Souchu, P., Pouvreau, S., Moal, J., Le Coz, J., R., Samain, J. F. (2007). Metabolic adjustments in the oyster *Crassostrea gigas* according to oxygen level and temperature. *Marine Biology Research* **3 (5)**, 357-366. https://doi.org/10.1080/17451000701635128.
18. Longdill, P. C., Healy, T. R., Black, K. P. (2008). An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management* **51**, 612-624. https//doi.org/10.1016/j.ocecoaman.2008.06.010.
19. Micael, J., Costa, A. C., Aguiar, P., Medeiros, A., Calado, H. (2015). Geographic information system in a multi-criteria tool for mariculture site selection. *Coastal Management* **43 (1)**, 52-6. https://doi.org/10.1080/08920753.2014.985178.
20. Nath, S. S., Bolte, J. P., Ross, L. G., Aguilar-Manjarrez, J. (2000). Applications of geographical information systems (GIS) for spatial decision support in aquaculture. *Aquacultural Engineering* **23 (1-3)**, 233-278. https://doi.org/10.1016/S0144-8609(00)00051-0.
21. Newton, A., Brito, A. C., Icely, J. D., Derolez, V., Clara, I., Angus, S., Schernewski, G., Inácio, M., Lilebø, A. I., Sousa, A. I., Béjaoui, B., Solidoro, C., Tosic, M., Cañedo-Argüelles, M., Yamamuro, M., Reizopoulou, S., Tseng, H. C., Canu, D., Roselli, L., Maanan, M., Cristina, S., Ruiz-Fernández, A. C., De Lima, R. F., Kjerfve, B., Rubio-Cisneros, N., Pérez-Ruzafa, A., Marcos, C., Pastres, R., Pranovi, F., Snoussi, M., Turpie, J., Tuchkovenko, Y., Dyack, B., Brookes, J., Povilanskas, R., Khokhlov, V. (2018). Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation* **44**, 50-65. https://doi.org/10.1016/j.jnc.2018.02.009.
22. Newton, A., Icely, J., Cristina, S., Brito, A., Cardoso, A. C., Colijn, F., Riva, S. D., Gertz, F., Hansen, J. W., Holmer, M., Ivanova, K., Leppäkoski, E., Canu, D. M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, A., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schubert, H., Carr, L., Solidoro, C., Viaroli, P., Zaldívar, J. M. (2014). An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal

systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* **140**, 95-122. https://doi.org/10.1016/j.ecss.2013.05.023.

23. Pagou, K., Siokou-Frangou, I., Papathanassiou, E. (2002). Nutrients and their ratios in relation to eutrophication and HAB occurrence. The case of Eastern Mediterranean coastal waters. Second Workshop on “Thresholds of Environmental Sustainability: The case of nutrients”, 18-19 June, Brussels, Belgium.
24. Patterson, H. K., Carmichael, R. H. (2018). Dissolved oxygen concentration affects δ15N values in oyster tissues: implications for stable isotope ecology. *Ecosphere* **9 (3)**, 1-16. https://doi.org/10.1002/ecs2.2154.
25. Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I. M. (2011). Mediterranean coastal lagoons in an ecosystem and aquatic resources management context. *Physics and Chemistry of the Earth, Parts A/B/C* **36 (5-6)**, 160-166. https://doi.org/10.1016/j.pce.2010.04.013.
26. Pérez-Ruzafa, A., Pérez-Ruzafa, I. M., Newton, A., Marcos, C. (2019). Coastal Lagoons: Environmental Variability, Ecosystem Complexity, and Goods and Services Uniformity. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. eds. *Coasts and Estuaries*. Elsevier, Amsterdam. pp. 253-276. https://doi.org/10.1016/B978-0-12-814003-1.00015-0.
27. Pouvreau, S., Bourles, Y., Lefebvre, S., Gangnery, A., Bruscia, M. A. (2006). Application of a dynamic energy budget model to the Pacific oyster, *Crassostrea gigas*, reared under various environmental conditions. *Aquaculture* **56 (2),** 156-167. https://doi.org/10.1016/j.seares.2006.03.007.
28. R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
29. Radiarta, I. N., Saitoh, S. I., Miyazono, A. (2008). GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. *Aquaculture* **284 (1-4)**, 127-135. https://doi.org/10.1016/j.aquaculture.2008.07.048.
30. Regione.Sardegna.it (2019a). Regione Autonoma della Sardegna [Online] Available from: https://www.regione.sardegna.it/documenti/1_73_20091210120722.pdf [Accessed: 10th June 2019].
31. Regione.Sardegna.it (2019b). RegioneAutonomadellasardegna [Online] Available from: https://www.regione.sardegna.it/documenti/1_73_20091210120722.pdf [Accessed: 18th June 2019].
32. Saaty, T. L. (1988). What is the Analytic Hierarchy Process?In: Mitra G., Greenberg H.J., Lootsma F.A., Rijkaert M.J., Zimmermann H.J. (eds) *Mathematical Models for Decision Support*. NATO ASI Series (Series F: Computer and Systems Sciences), vol 48. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-83555-1_5.
33. Sardegnaagricoltura (2019). Sardegna Agricoltura, il sistema agricolo della Sardegna. [Online] Available from: http://www.sardegnaagricoltura.it/documenti/14_43_20140613123850.pdf [Accessed: 01th June 2019].

34. SardegnaAmbiente (2019). Sardegna Ambiente, il sistema ambientale della Sardegna. [Online] Available from: https://portal.sardegnasira.it/web/sardegnaambiente/progetto [Accessed: 5th June 2019].
35. SardegnaStatistiche (2019). Istruzione e Lavoro [Online] Available from: http://www.sardegnastatistiche.it/argomenti/istruzionelavoro [Accessed: 15th October 2019]
36. Silva, C., Ferreira, J. G., Bricker, S. B., Delvalls, T. A., Martín-Díaz, M. L., Yañez, E. (2011). Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. *Aquaculture* **318**, 444-457. https://doi.org/10.1016/j.aquaculture.2011.05.033.
37. Theuerkauf, S. J., Morris, J. A. Jr., Waters, T. J., Wickliffe, L. C., Alleway, H. K., Jones, R. C. (2019). A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS ONE* **14 (10)**, e0222282. https://doi.org/10.1371/journal.pone.0222282.
38. Vincenzi, S., Caramori, G., Rossi, R., De Leo, G. A. (2006). A GIS based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy). *Ecological Modelling* **193 (1-2)**, 90-104. https://doi.org/10.1016/j.ecolmodel.2005.07.039.
39. Wiltshire, J. H., (2007). Ecophysiological tolerances of the Pacific oyster, *Crassostrea gigas*, with regard to the potential spread of populations in South Australian waters. *SARDI Research Report Series* **222**, Adelaide.

# Figures

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

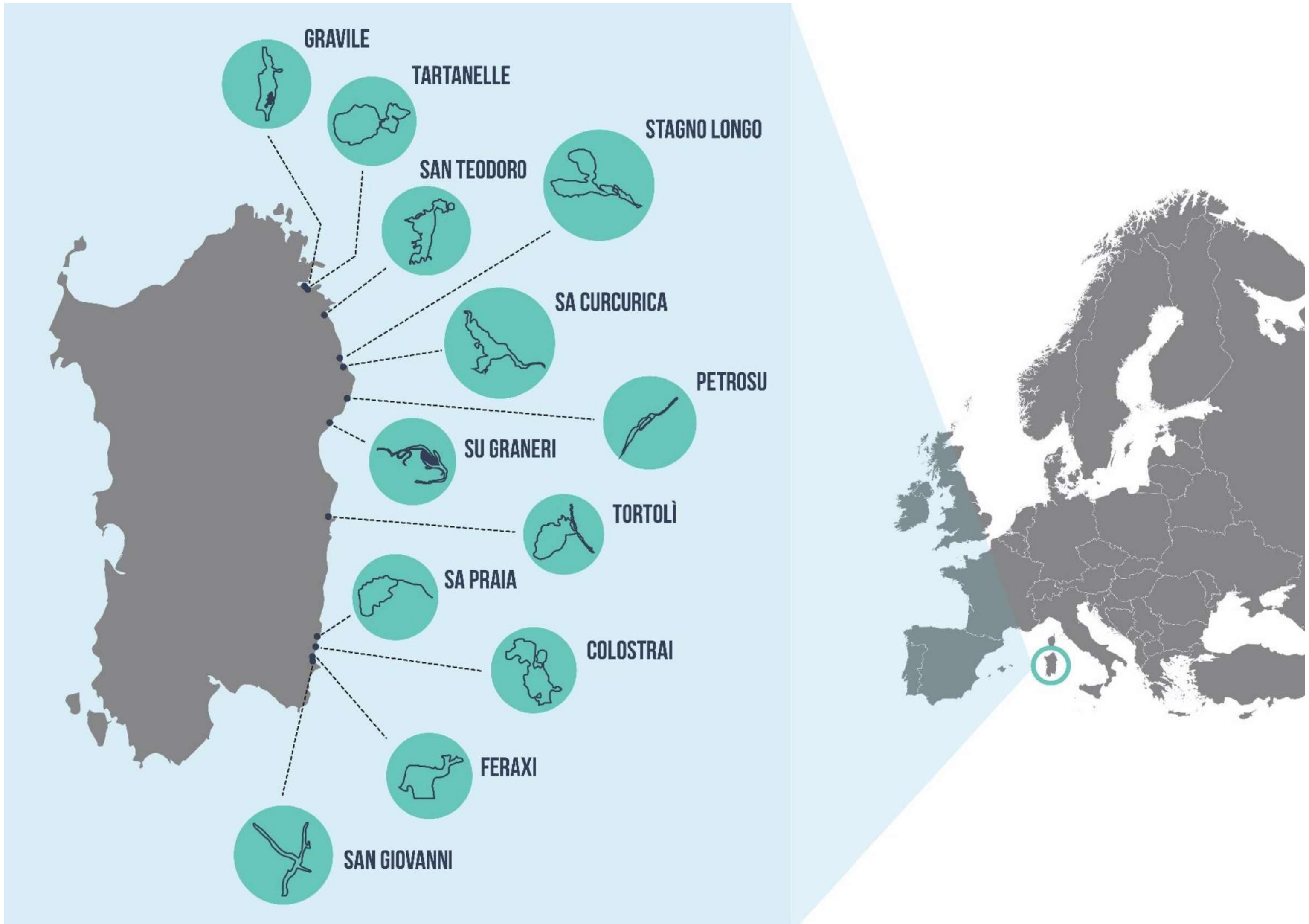

Figure 2. Diagram of the lagoons suitability classification approach

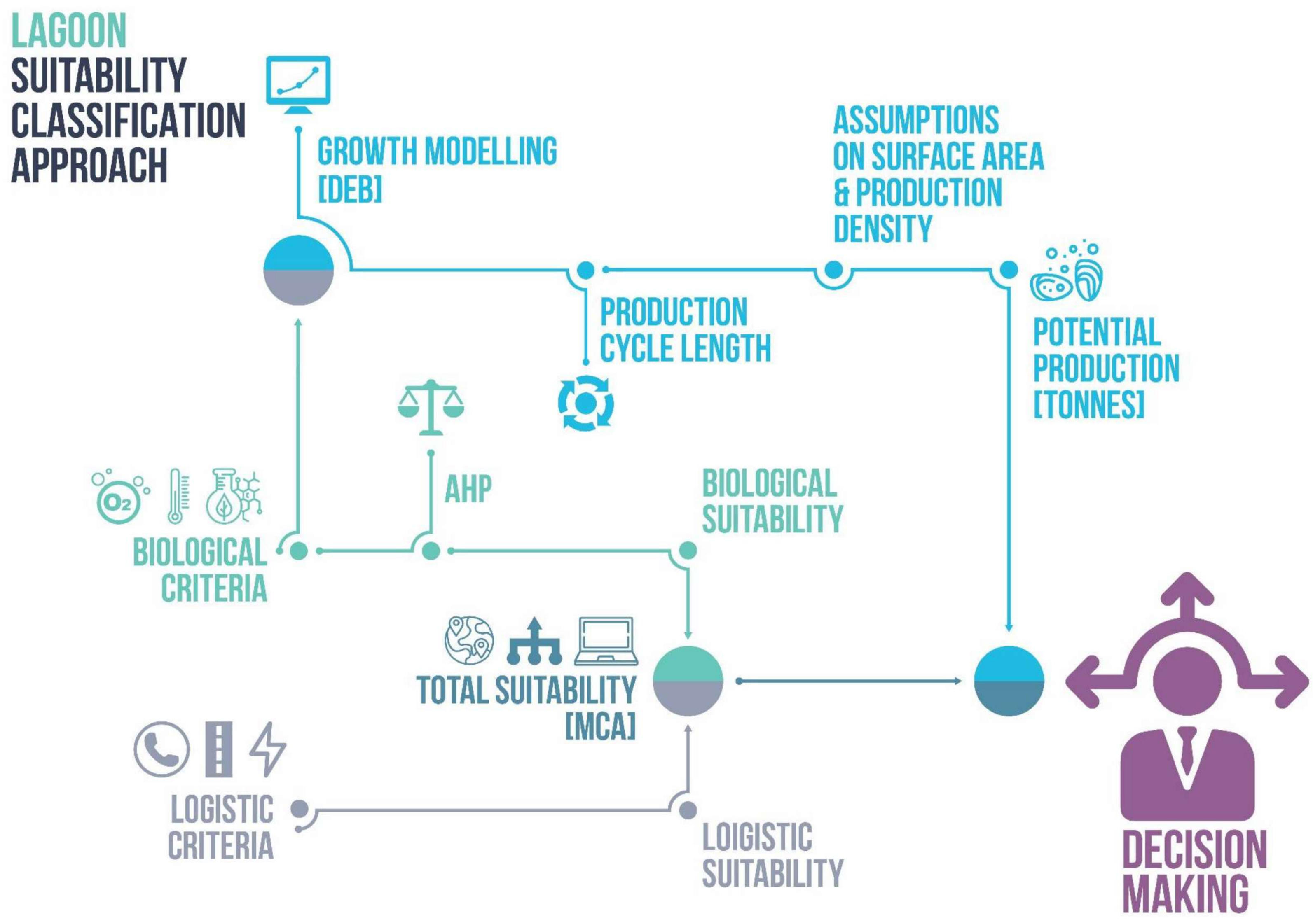

Figure 3. Biological suitability as calculated by AHP.  Size of the circles and numbers are indicative of suitability scores and ranking

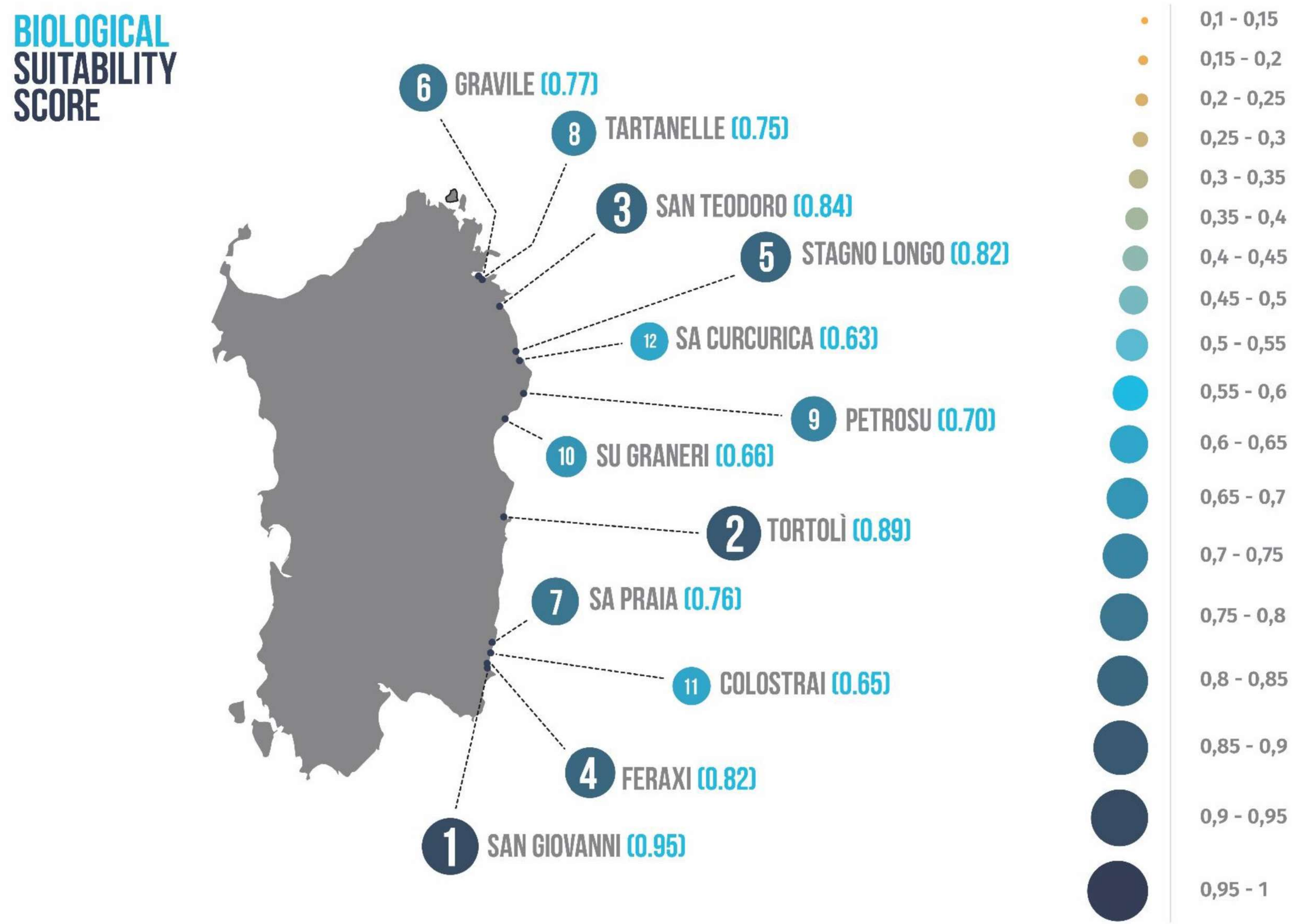

Figure 4. Logistic suitability. Size of the circles and numbers are indicative of suitability scores and ranking

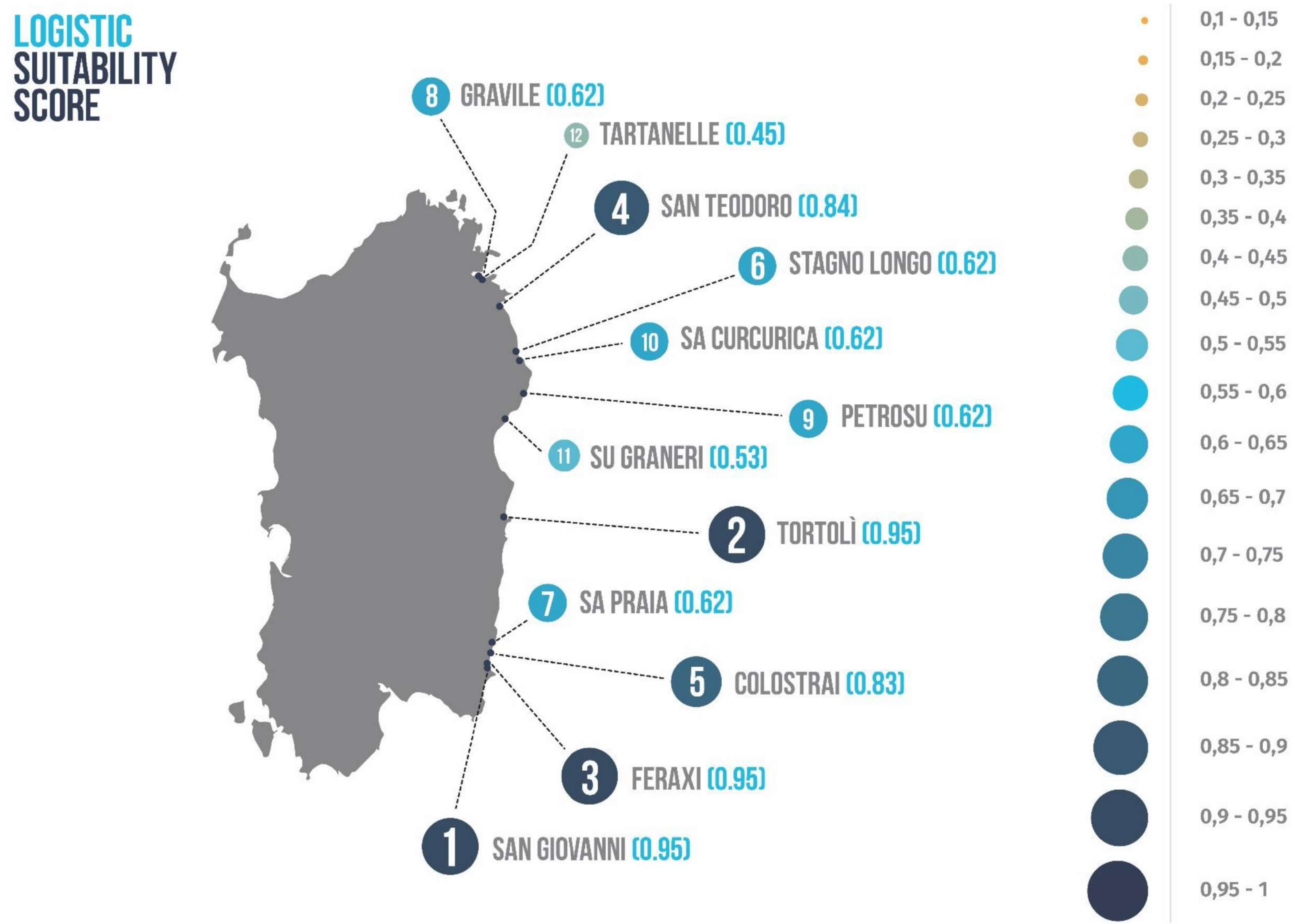

Figure 5. Total suitability as calculated by MCA. Size of the circles and numbers are indicative of suitability scores and ranking

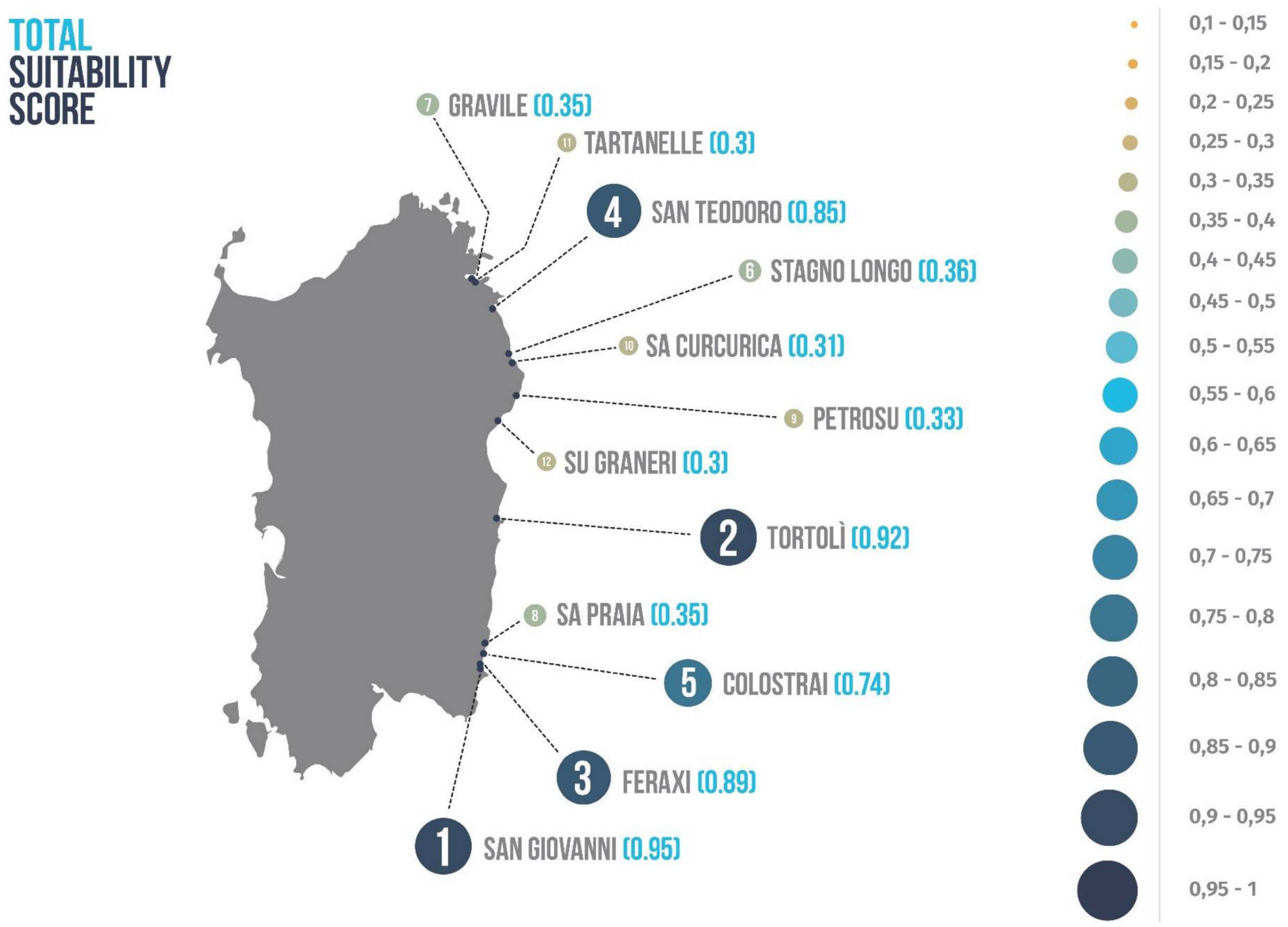

Figure 6. Production cycle length expressed in number of days to reach market size of 80 g for each lagoon as predicted by the DEB model. The coloured number in the chart are the production cycle length in days.

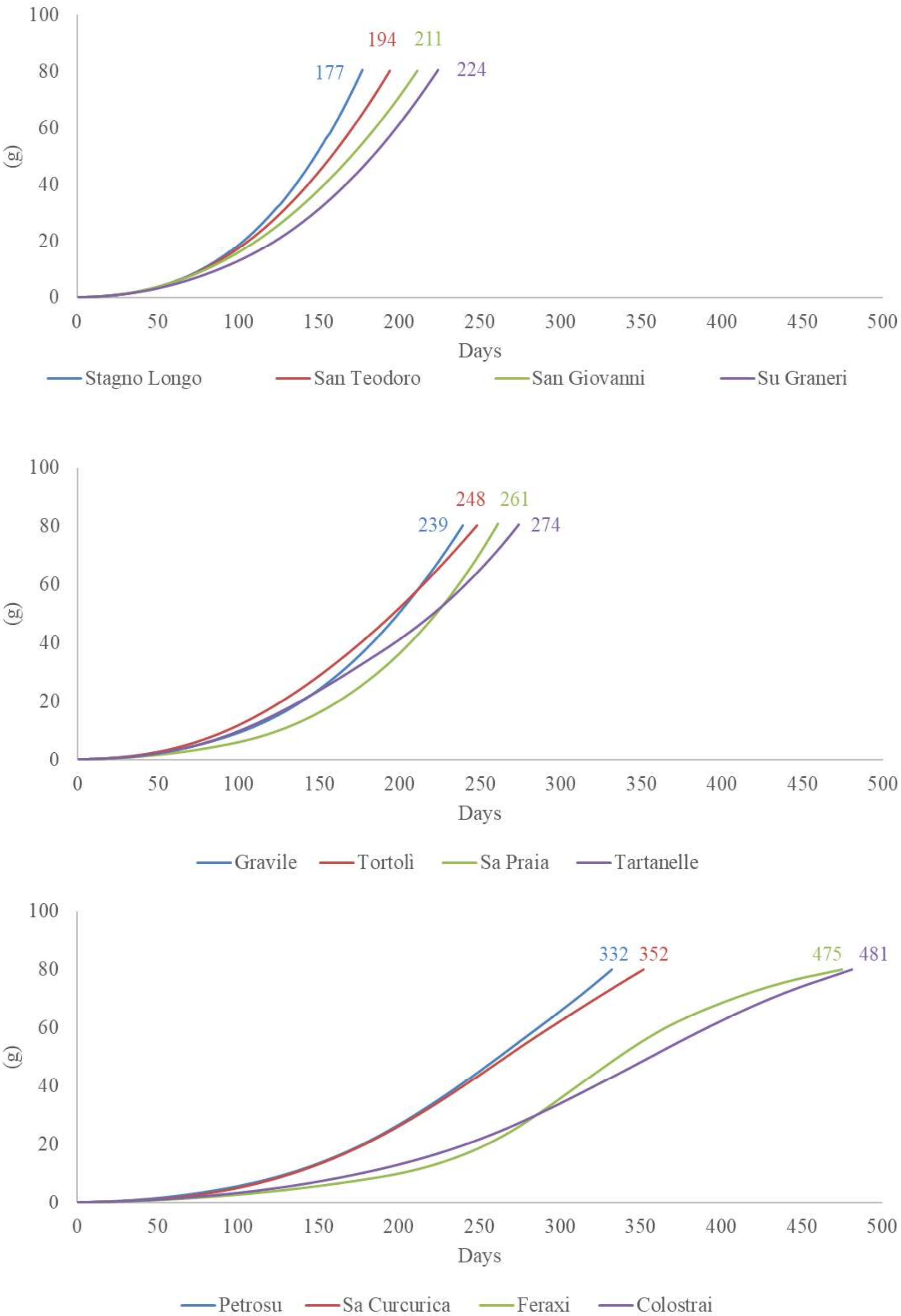

Figure 7. Total potential annual production (Tonnes). Size of the circles and numbers are indicative of production volumes