Improving Pacific Oyster (*Crassostrea gigas*, Thunberg, 1793) Production in Mediterranean Coastal Lagoons: Validation of the growth model "ShellSIM" on traditional and novel farming methods

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Abstract

Bivalve farming is a major European aquaculture activity, representing 48.5% of total biomass produced. Italy is one of the largest consumers of oysters but local production does not meet the market demand. Italy has approximately 384 000 ha of shallow lagoons in its coastal area, already devoted to extensive aquaculture activities which could also represent potential locations for Pacific oyster (*Crassostrea gigas*, Thunberg, 1793) farming.

The aim of this study is to enhance Pacific oyster farming in shallow coastal lagoons by testing novel farming technologies and validating an existing bioenergetic growth model (ShellSIM).

Commercial performance of Pacific oysters and associated environmental parameters were monitored in two Sardinian coastal lagoons (San Teodoro and Santa Gilla, Italy). Oyster growth and survival were compared during a production cycle for two rearing systems: traditional systems (floating bags or lanterns) and Ortac units. The latter has not been previously tested in coastal lagoons. Measured performances were compared with ShellSIM predictions to evaluate the model's ability to predict growth and the potential production in other coastal lagoons.

Results showed that at the end of a six months cycle the oysters mean weight and Condition Index were significantly higher (*p* value < 0.05) in floating bags than in Ortac, (55.8 ± 0.9 g and 50.1 ± 1.3 g; 4.6 ± 0.1 and 3.9 ± 0.1 respectively). Also, the minimum commercial size (40 g) was reached by 98 % and 68 % of the oyster farmed in floating bags and Ortac units respectively. On the other hand, oysters reared in the Ortac showed a higher survival than in the floating bags (95.8 ± 0.9 % and 82.1 ± 3.4 %, respectively).
ShellSIM growth predictions were highly correlated with the observed data in both lagoons. However, high values for RMSD indicated that ShellSIM predictions were significantly validated for San Teodoro lagoon but not for Santa Gilla suggesting further tailoring to some environmental conditions to produce more realistic growth predictions.
Results of this study indicate that both floating bags and Ortac system should be employed during the production cycle to maximise oysters' survival and growth performances. Furthermore, this study provides a new validated tool to farmers and stakeholders to monitor oysters performances and estimate productivity in local waters.

Keywords

Pacific oysters farming; Shellfish growth model; Farming technologies;

Abbreviations

POS 1, POS 2 and POS 3 are the three chosen experimental position

1. Introduction

Italy is one of the main seafood consumers in Europe and amongst the World's top 10 importers, estimated at 5.6 million US dollars in 2016 (FAO, 2016). Different species of shellfish, crustaceans and fish are farmed using both extensive and intensive methods.

In 2016, in Italy most aquaculture companies were farming shellfish contributing to over 64% of the total aquaculture production being the largest producer of Manila clam (*Venerupis philippinarum* (Adams and Reeve, 1850)) and the third producer of Mediterranean mussel (*Mytilus galloprovincialis* (Lamarck, 1819)) in Europe. A smaller production includes grooved carpet shell (*Ruditapes decussatus* (Linnaeus, 1758)) and Pacific oyster (*Crassostrea gigas* (Thunberg, 1793)) (Eurofish, 2016; FAO, 2016). Pacific oyster is native to Japan and coastal regions of Asia, and due to its wide adaptation range at different environmental conditions, is the most widespread cultured oyster species in the world (Shatkin *et al*., 1997).

In 2016, Europe produced 23000 tonnes of Pacific oysters 145 of which were of Italian origin (30 tonnes by a single Sardinian company (FAO 2011 - 2018 Fishstat.J)). Italy is one of the largest consumers of oysters in Europe importing 6500 tonnes per year primarily from France, major reason why there is an opportunity to diversify Italian shellfish farming in the future (Sardegnaagricoltura.it, 2016, FAO, 2016). Sardinia has approximately 10000 ha of shallow coastal lagoons representing the 2.6% of the total lagoon area in Italy (Bazzoni *et al.,* 2013). Many of these lagoons are used for extensive finfish farming, but are potential sites for Pacific oyster farming.

Currently, depending on environmental conditions such as water depth, tidal range, water exchange rates and bottom substrates, three main oyster farming methods are used: off-bottom culture, on-bottom culture and suspended culture (Buestel *et al*., 2009). In Sardinian lagoons suspended culture is the most commonly used due to their environmental conditions. More specifically, floating bags are designed to keep the oyster growing at the water surface where most of the food is available. These are manufactured in square and diamond mesh patterns (from 4 to 23 mm), suspended on the surface thanks to two floaters which allow periodic exposure of the oysters to the air to reduce biofouling and strengthen the adductor muscle.

Amongst suspended oyster culture methods, several new farming tools have been recently developed, for example Ortac units (ABBLOX), OysterGro© (OysterGro) and Zapco Tumbler (Zapco Aquaculture). These aim to improve oyster production by reducing manual labour, increasing growth rates and improving oysters' quality (i.e. shell shape). The Ortac system has been employed in this study. The Ortac system consists of baskets made of polypropylene plastic and divided in two halves. These operate attached to a trestle and, due to their shape, an up-welling water flow is passively generated by the surrounding water currents. Furthermore, thanks to the constant movement under currents actions, this system has been designed to reduce fouling therefore requiring less handling.

Aside from environmental conditions, also the use of different grow-out gears affects oyster performances as suggested by the recent study from Rankin *et al.,* (2018).

The only independent trial for Ortac conducted to date to compare growth, survival and physiological performances with traditional bag systems used *Ostrea edulis* in Scotland (Francouer, 2017). Results of this study indicated that there were no significant differences in growth between *Ostrea edulis* reared in the two different systems (Ortac units and traditional bags) but higher survival was observed within the Ortac units. The study presented here is the first investigation and comparison of the performance of the Ortac system in warmer climates with a smaller tidal range.

Much effort has been dedicated to generate and validate growth models for bivalves (Pouverau *et al.,* 2006). Most of the energy budget models predicting growth are net production models, which assume that energy is immediately available for the animal maintenance while the rest is used for growth or deposited as a reserve. Others are based on a dynamic energy budget approach (DEB) where energy is first stored as a reserve and then used for different metabolic processes at a catabolic rate (Kooijman, 2000; Pouvreau *et al.,* 2006; Ren and Ross, 2001; Beadman *et al.,* 2002). Most shellfish energy budget models are only able to simulate growth for locations where they have been calibrated, therefore restricting their use in areas with different environmental conditions (Hawkins *et al.,* 2013; Dowd, 1997). ShellSIM growth model has been calibrated for 16 shellfish species in different locations throughout Europe, the U.S.A, China, New Zealand, Malaysia and Australia. This includes *Mytilus edulis* and *Crassostrea gigas* (ShellSIM, 2011; Hawkins *et al*, 2013).

ShellSIM is based on principles of energy balance:

$$\text{Net energy balance} = \text{Energy ingested} - (\text{Energy egested} + \text{Energy excreted} + \text{Energy expended})$$

and was developed as a tool to be used by farmers, scientist and environmental regulators (Hawkins *et al.,* 2013). Consequently, this growth model was considered to be appropriate to provide growth forecasts in Sardinian coastal lagoons with suitable validation for local conditions.

The aim of this study is to validate this existing bioenergetic growth model in two ecologically different Mediterranean coastal lagoons and for two different oyster farming systems: the Ortac and the traditional floating bags and to compare the production efficiency between these two farming systems.

2. Materials and Methods

2.1. Growth Trial: Ortac *vs* floating bags

This trial was performed between June 2017 and December 2017 in the lagoon of San Teodoro (northeast Sardinia: 40°48’ 38.08’’N, 9°40’26.99’’E). A total of 2400 Pacific oyster seeds (1.7 ± 0.1 g, 2.9 ± 0.2 cm), from a French hatchery located in the Loire region of France, were randomly divided between 6 Ortac units and 6 Floating bags (200 individual per unit, mean total biomass per unit was 260.7 ± 5.6 g). Thirty oysters from each unit were tagged with an underwater curing epoxy resin (AquaScape) and biometric parameters were measured every two weeks (i.e. weight, length, depth and width) using a portable scale (Steinberg SBS-LW-2000A, 0.01g) and callipers

(METRICA, 0.05 mm). At each sampling point, mortality was also recorded and 5 oysters per unit were selected for dry weight measurements (Mo and Neilson, 1994) and Condition Index (CI) calculations using the protocols described by Mo and Neilson (1994) for the dry weight and Davenport and Chen (1987) and Walne and Mann (1975) for CI calculations where:

$$\mathrm{CI} = (\text{Dry weight meat (g)}/\text{Dry weight meat (g)} + \text{Dry weight shell (g)}) \times 100$$

The oyster culture systems were positioned in two rows of three Ortac units and three floating bags (fig.1). Ortac units were mounted onto two trestles (3 units per trestle), floating bags were attached to ropes as in the usual commercial setting of the Compagnia Ostricola Mediterranea, host of these trials.

Oysters of both systems were cultured following the standard conditions of the company, with 24hrs of air exposure every two weeks to prevent biofouling, changing of the floating bags mesh (4, 9, 14 and19 mm) according to oysters' size, and based on the increasing Pacific Oysters biomass. Grading was performed for both Ortac units and floating bags keeping similar biomass in both systems.

2.2. ShellSIM validation for floating Bag units (San Teodoro Lagoon)

A survey of the dominant currents in the area was conducted during the neap (minimum) and spring (maximum) tides using GPS tracking drifters (drogues) (Cromey and Black, 2005). The drifters were released at the same time at three different points, one hour before the tidal peak until one hour after. During the survey the wind direction and speed was recorded by a fixed weather station (La Crosse WS3650). These information was fed to ShellSIM model to account for the hydrodynamic and ecological conditions within the lagoon.

Three floating bags per each area were stocked with *C. gigas* (838 ± 36.4 g, 811.5 ± 17.8 g and 709.8 ± 40.1 g total biomass) with a mean size in weight and length of 4.5 ± 0.3 g and 4.0 ± 0.2 cm

(POS 1), 4.5 ± 0.3 g and 3.9 ± 0.2 cm (POS 2), 3.9 ± 0.2 g and 3.9 ± 0.2 cm (POS 3). The oysters were cultured following the standard procedures described above.

Sampling for oyster growth was performed monthly for 5 months. Each month 80 individuals unit^{-1} were randomly measured for wet weight 30 of which also measured for length, depth and width. Other 10 individuals unit^{-1} were collected for dry weights measurements.

Environmental data: temperature (T, °C), salinity (Sal, ‰), dissolved oxygen (DO, mg L^{-1}), total particulate matter (TPM, mg/L), particulate organic matter (POM, mg L-1), particulate organic carbon (POC, mg m^{-3}) and Chlorophyll-a (Chl-a, µg L^{-1}) were collected in the immediate vicinity of the farming gears. Temperature, salinity and dissolved oxygen were collected at a depth of 15 cm, with a multiparametric probe (HACH HQ40d) and data loggers (HOBO: UTBI-001, U26-001 and U24-002-C respectively for T, DO and Sal). Temperature data loggers were set-up to take measurements every 30 minutes, while the Sal and DO probes measured values every 2 hrs.

Water for the TPM, POM, POC was collected using 1L pre-rinsed in sample water plastics bottles, while 5L pre-rinsed in sample water plastic bottles were used to collect water for Chl-a analysis. Laboratory analysis for TPM and POM were performed according to Hawkins *et al.* (2013), while Chl-a analysis according to Lorenzen (1967). For POC measurements water was collected in 1 L pre-rinsed plastic bottles then filtered in 47-mm diameter GF/F filters previously combusted at 450 °C. POC samples were analysed with a CEI Flash smart elemental analyser. The average values of each environmental parameter were used to run the model, excluding September 2017, when no data were collected due to farmers' activities and weather constraints.

2.3. ShellSIM validation for lantern systems (Santa Gilla Lagoon)

In order to validate the growth model in a different location, a growth trial was performed between May 2017 and September 2017, in Santa Gilla lagoon (39°12'28.2''N 9°05'53.5''E). Three lanterns with five compartments each and a mesh size of 3.5 x 5 mm, were stocked with 500 oysters per compartment (mean weight = 4.4 ± 0.1 g; mean length = 3.6 ± 0.6 cm). The oysters were farmed following the standard production protocols, grading and changing the mesh size according to oysters' size and biomass. Growth was measured monthly when 70 individuals per lantern were randomly sampled and weighted, 30 of which were also measured for shell length, depth and width. Furthermore, 10 individuals per lantern were collected for dry weight measurements. Environmental data sampling and analysis were conducted as described above. The monthly means of all the environmental data were used to run the growth model.

2.4. ShellSIM Validation for Ortac units and floating Bags (San Teodoro Lagoon)

In order to validate the model for different gear types, a new experiment was set up in the lagoon of San Teodoro (July 2017 – December 2017). In this occasion the model performance were also tested on a different farming system i.e. the Ortac units.

Farming methods, growth measurements, sample collection and analysis of all environmental parameters were conducted as described previously. A bi-weekly mean of all the environmental data were used to run the ShellSIM, except for November and December, when data were collected only one per month due to farmers' activities and weather constraints.

2.5. Statistical Analysis

Prior to analyses, data were tested for normality and homogeneity of variance Weight gain, biometrics measures differences, survival rate and Condition index differences, over time were analysed by general linear model followed by a Tukey post-hoc test where significant differences occurred.

End points of all biometrics measures, survival rate and condition index, were analysed by one-way ANOVA followed by post-hoc Tukey's Multiple Comparison tests where significant differences occurred.

To assess fitness between the prediction made by ShellSIM and observed data, Taylor diagrams and skill scores (S) were used (Taylor, 2001). A Taylor diagram is a way to show graphically how well a model prediction fits the observed data, using correlation, centred root mean square difference (RMSD) and amplitude of their variation (standard deviations). The skill score proposed by Taylor (2001) quantifies model performance against observed data.

3. Results

3.1. Growth Trial: Ortac *vs* floating bags

At the end of the of the production cycle (October to December), the Pacific oysters farmed in the floating bags had a significantly higher weight and shell depth (*p* value = 0.001, 0.001 respectively) to those in the Ortac units (55.8 ± 0.9 g, 50.1 ± 1.3 g; 26.6 ± 0.2 g, 24.2 ± 0.3 g) (figs.2a, 2c). Oysters farmed into the Ortac units showed instead a significant higher growth in shell length (86.9 ± 1, 75.4 ± 0.6, *p* value = 0.001 Ortac and floating bags respectively), and shell width (46.2 ± 0.5 mm, 44.6 ± 0.4 mm, *p* value = 0.017) (fig.2b, d).

Survival was significantly higher (p = 0.001) in the Ortac units compared to the floating bags (95.8 ± 0.9%, 82.1 ± 3.4 %) (fig.3). The highest mortality occurred between June and July (3.8 ± 1 %, 16.3 ± 3.3 % Ortac units and floating bags respectively).

The condition index at the end of the production cycle was significantly higher (*p* value = 0.001) in the floating bags compared to the Ortac units (4.6 ± 0.1, 3.9 ± 0.1) (fig.4) and the smallest commercial size (40 g) was reached by the 98 % and 69 % of the oyster farmed in the floating bags and Ortac units respectively (fig.5).

3.2. ShellSIM validation in San Teodoro Lagoon

Three areas with different current speed (POS1 0.15 m s^{-1}, POS2 0.07 m s^{-1}; POS 3 0.04 m s^{-1}) were identified in San Teodoro. A decreasing speed gradient from the sea mouth to the internal part of the lagoon was identified. Consequently, these areas were used as experimental locations to monitor the oysters' growth and the environmental parameters required by the growth model.

Environmental data are illustrated in Table 1. ShellSIM predicted, during a 6 months production cycle, a final weight and length of 19.7 g, 48.4 g and 121.6 g; 6.0 cm, 8.3 cm and 11.5 cm, respectively for POS 1, POS 2 and POS 3.

The measured weight and length at the end of this production cycle, was 16.4 ± 1.1 g, 46.9 ± 2.1 g, 48.9 ± 1.5 g and 5.4 ± 0.3 cm, 8.2 ± 0.3 cm, 9 ± 0.2 cm, respectively in POS 1, POS 2 and POS 3.

Figure 6 shows that measured growth in weight and length, fitted the predicted growth curve in POS 2, while in POS 1 and POS 3 ShellSIM overestimate the final mean growth in weight and length respectively 20.5, 12.1, 148.8 and 27.9 %. The calculated skill score for the three different areas indicate the best fitting between observed and predicted measures of weight and length, respectively in POS 2 (S=1; S=1), POS 1 (S=0.87; S=0.81) and POS 3 (S=0.42; S=0.79).

Standard deviation, Centred Root Mean square difference (RMSD), correlation and the overall skill score of the performance of the predicted growth curve to fit the observed data in the lagoon of San Teodoro are shown in Figure 7 and Table 2.

3.3. ShellSIM validation in Santa Gilla Lagoon

Environmental data collected in the lagoon of Santa Gilla and their seasonal variations are illustrated in Table 3.

The measured growth in weight and length (79.5 ± 1.8 g and 9.1 ± 0.1 cm) did not fit the predicted growth curve (data not shown), and the calculated skill score indicates a very poor fit between observed and predicted measures of weight and length, respectively S=0.003 and S=0.17 (Table 2).

Standard deviation, Centred Root Mean square difference (RMSD) and correlation are shown in Figure 8 and Table 2.

3.4 ShellSIM Validation on Ortac *vs* floating bags

Environmental data collected to run ShellSIM and their changes are shown in Table 4.

In this trial, ShellSIM was run in POS 2 for two different farming systems. It predicted a growth of 48.6 g and 8.3 cm in weight and length respectively for the Ortac system, and a growth of 49.1 g and 8.2 cm for the floating bags over a 6 months production cycle. At the end of this production cycle, the measured weight and length were 50.1 ± 1.3 g and 8.7 ± 0.1cm for the Ortac and 55.8 ± 0.9 g and 7.5 ± 0.1 cm for the floating bags. Figure 9 shows that during the production cycle, the measured mean weight and length in the Ortac units and floating bags were underestimated by ShellSIM, except for the final length farmed in the floating bags which was accurate. Indeed, in November there was a change in trend of the model prediction, from underestimation to overestimation (the model overestimated the final mean length of 8.2 %), while the final weight was still overestimated by 11.9%.

Moreover Figure 9 shows that ShellSIM at the end point of the production cycle of the oysters reared inside the Ortac units, unlike the rest of the predictions, slightly underestimated growth in weight and length by 3% and 4.4% respectively.

The calculated skill score indicates that the best fitting between observed and predicted measures of weight and length, respectively in Ortac (S=0.95, S=0.93) compared to floating bags (S=0.90, S=0.89). Standard deviation, Centred Root Mean square difference (RMSD), correlation and the overall skill score of the performance of the predicted growth curve to fit the observed data in this trial in the San Teodoro lagoon are shown in Figure 10 and Table 2.

4. Discussion and conclusions

The results of this study provide new information to improve *C. gigas* farming and a growth prediction tool in shallow coastal lagoons. The higher survival rate in the Ortac units for the first two months and the higher growth in weight and CI in the floating bags, suggest a potential mixed use of the two systems during the production cycle. Specifically, the Ortac units may be employed when Pacific oysters are more susceptible to stress and during the stressful period (e.g smaller size and hottest periods) and floating bags thereafter. In this way it would be possible to reduce the costs of the equipment, avoiding several floating bags with different meshes depending on the oysters' sizes, and a minor loss of individuals due to mortality.

There was no statistically significant difference in growth between Ortac units and floating bags, but at the end of the production cycle there was a significant higher mean weight in the floating bags than in the Ortac units. Comparison of these results with previous studies are difficult due to difference in culture techniques and effects of other experimental variables such as initial oyster size and the production season.

In many studies it is reported that shell morphology in bivalves is influenced by population density, predation responses, handling and grow-out methods (Telesca *et al*., 2018; Seed, 1968; Brake *et al*., 2003; Kube *et al*., 2011; Griffiths and Buffenstein, 1981; Van Erkom Schurink and Griffiths, 1993; Bayne, 2000; Sheridan *et al.,* 1996). We also observed a difference in shape between the animals reared in floating bags or Ortac with the latter longer and wider compared to the former which were instead thicker and with a higher C.I.

The morphological differences found between individuals farmed in the two different farming gears, are probably due to the different interaction that these tools have with the currents. Under low current speed typical of shallow lagoons, the shape of the Ortac units may have not promoted the rocking motion required to generate enough rubbing between oysters and the farming gear, causing less shell chipping, which is widely recognised as a factor promoting shell depth and a higher meat content (Brake *et al*., 2003; Holliday, 1991; O'Meley, 1995; Robert *et al*., 1993).

Moreover, the fact that the animals did not move enough inside the Ortac units probably induced those in the innermost part to grow more in length and width in order to increase the filtering surface. Nonetheless, results of this study are comparable with those obtained by Francouer *et al*., (2017) who reared *Ostrea edulis* using the Ortac system in Scotland.

Mortality may depend on the farming system (Pernet *et al.*, 2012). Improved survival in the Ortac system could be due to the shading effect provided by a more solid structure, which would shelter farmed individuals from direct sunlight and desiccation, particularly during the earlier part of the growth cycle and during air exposure periods. (Potter and Hill, 1982; Spencer-Davies, 1970). Moreover, different studies report that one of the stress factors associated to mortalities is temperature, and sudden small changes may have a large effect on the survival of bivalves (Pernet *et al*., 2018; Pernet *et al*., 2012; Petton *et al*., 2015; Le Deuff *et al*., 1994, Le Deuff *et al*., 1996; Sauvage *et al*., 2009; Kennedy and Mihursky, 1971). Again the more solid structure of the Ortac may have promoted more stable temperature and reduced stress.

Results of this study indicate that the predicted growth by ShellSIM, fitted well with field measurements in the lagoon of San Teodoro. However, results from the growth trial in Santa Gilla lagoon indicate that the model would require further tailoring to local conditions to produce realistic growth projections. In particular, we tested the hypothesis that the assumption ShellSIM makes to convert concentration of food into energy available to animals does not apply to Santa Gilla Lagoon. To do this, we run the model reducing the amount of POC available to one quarter of the measured POC and the model prediction was more accurate ($S = 0.97$ and $S = 0.95$ respectively for weight and length). Indeed, POC can be considered as a very heterogeneous nutrient source composed by different materials with large variations in digestible energy content. (Mazzola and Sarà, 2001; Lawacz, 1977; Watanabe and Kuwae, 2015).

Further studies to identify the real digestible energy content of the Particulate Organic Carbon in Santa Gilla area is required to modify the model assumption and improve its performances. Our data also suggest that seasonality and farming system used can influence the accuracy of ShellSIM providing scope for further tailoring of the model under the local conditions.

During the first-year trial in the lagoon of San Teodoro the measured growth closely fitted the predicted growth in POS 2, while in POS 1 ShellSIM slightly overestimated and in POS 3 considerably overestimated the growth, both in weight and length. Similar results in POS 2 were observed in the second-year validation trial. The growth in weight and length of the oyster was different between the two farming tools, with a higher growth in weight recorded for oysters reared in the floating bags and a higher growth in length for oysters reared in the Ortac units. In this trial, ShellSIM underestimated the weight and length during the production cycle except at the end point where it only slightly underestimated weight and length in the Ortac units providing a better accuracy at harvest time. While in the floating bags the final mean weight was underestimated and the length was overestimated.

These overestimation and underestimation can be potentially associated with a less than optimal rearing method (the Ortac), combined with the potential different production capacity of the different farming areas within the lagoon. Furthermore, as reported by several authors, the grow-out methods employed could affect oyster growth (Bayne, 2000; Sheridan *et al*., 1996). ShellSIM does not consider different grow-out methods in its variables possibly generating the discrepancy between observed and predicted growth measured in this study. Overall, ShellSIM predictions correspond with the growth trends observed by the farmers over the years (POS 3 with higher growth rates and POS 1 with lower growth rates) suggesting the good accuracy of the model with the general growth dynamics in the different areas of San Teodoro lagoon. This is reflected in the calculated skill scores (Taylor, 2001), for both validation trials in the fore mentioned lagoon.

Taken together, the results of this study provide information to improve bivalve growth prediction tools for Mediterranean lagoons. They could be applied to study the productivity of different sites to potentiate the oyster's aquaculture industry and for coastal spatial planning. Moreover, the presented results indicate that Ortac units improve the oyster's survival in the production early stage. The use of Ortac units also reduces reliance on multiple mash bags therefore simplifying production protocols.

Acknowledgments

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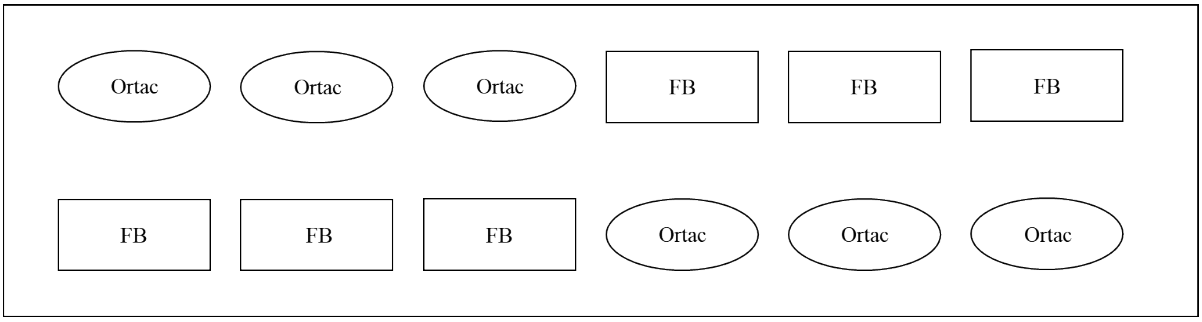

Figure 1. Diagram of the experimental layout of the Ortac and Floating Bags (FB) in the San Teodoro Lagoon.

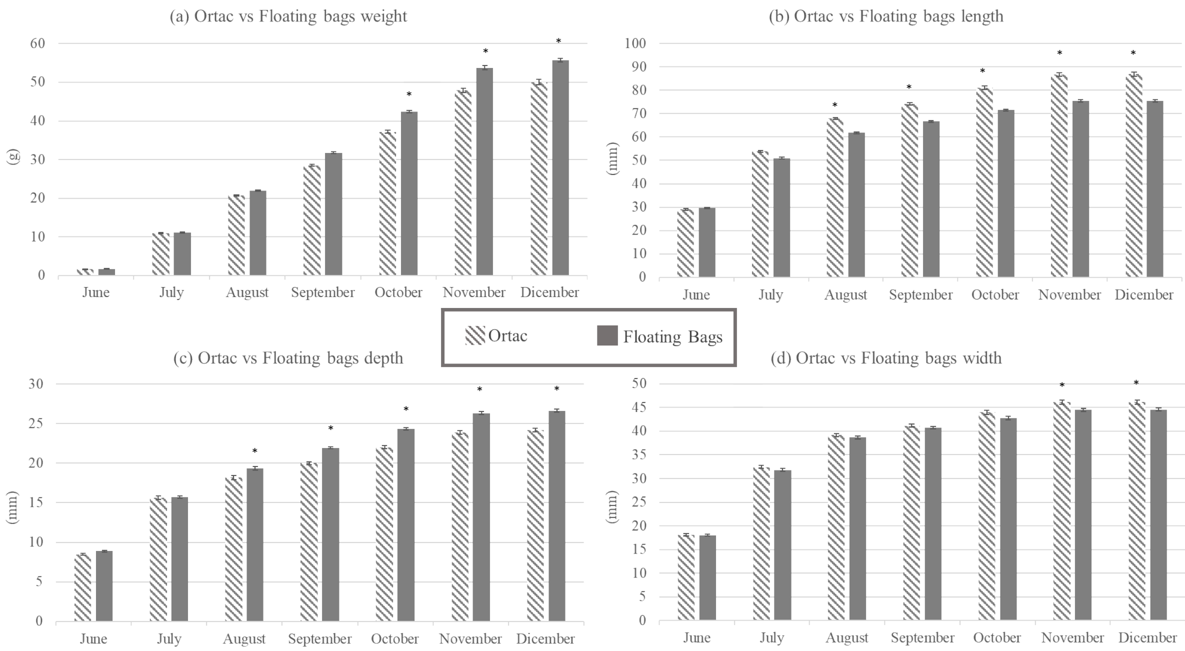

Figure 1. (a) Difference growth in weight between *C. gigas* farmed in two different tools (Ortac units and Floating bags). (b) Difference growth in length between *C. gigas* farmed in two different tools (Ortac units and Floating bags). (c) Difference growth in width between *C. gigas* farmed in two different tools (Ortac units and Floating bags). (d) Difference growth in depth between *C. gigas* farmed in two different tools (Ortac units and Floating bags). Stars indicate where significant difference occurs. (*p-value* < 0.05). Data are presented as mean ± SE; n=6.

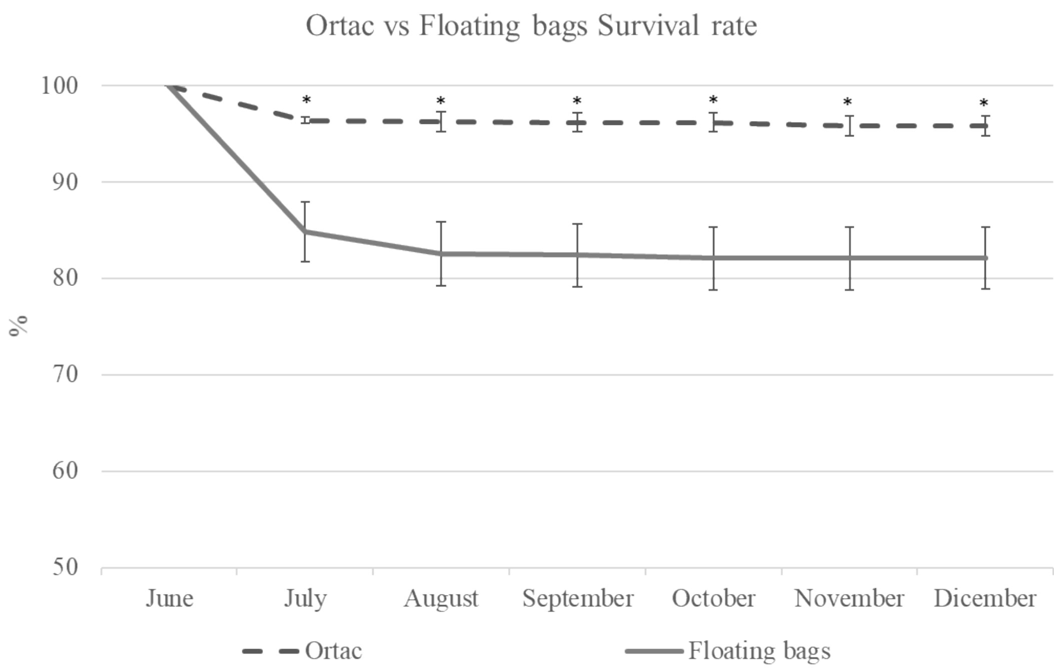

Figure 2. Comparison of survival rate between *C. gigas* farmed into Ortac units and Floating bags. Stars indicate where significant difference occurs. (p-value < 0.05). Data are presented as mean ± SE; n=6.

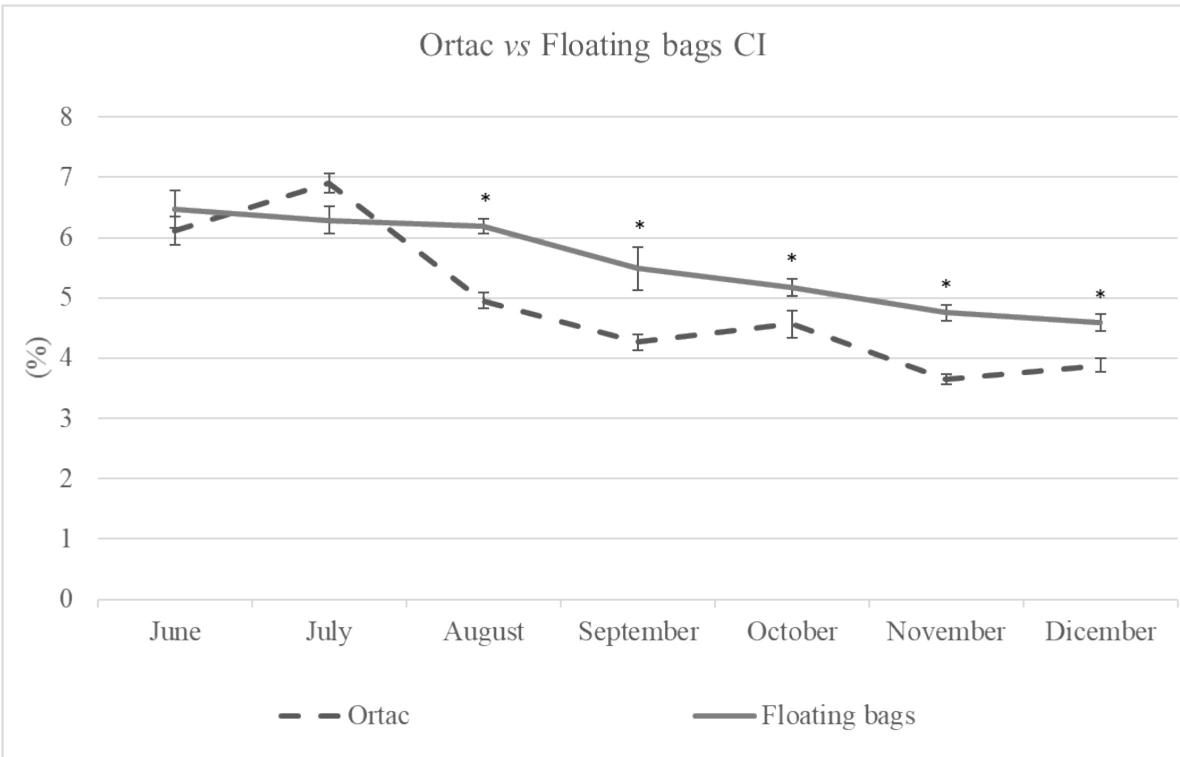

Figure 3. Comparison of condition index (CI) calculated as (Dry weight Meat (g)/ Dry weight Meat + Dry weight shell) *100, between *C. gigas* farmed into Ortac units and Floating bags. Stars indicate where significant difference occurs. (p-value < 0.05). Data are presented as mean ± SE; n=6.

Figure 4. Comparison of size class distribution between *C. gigas* farmed into Ortac units and Floating bags.

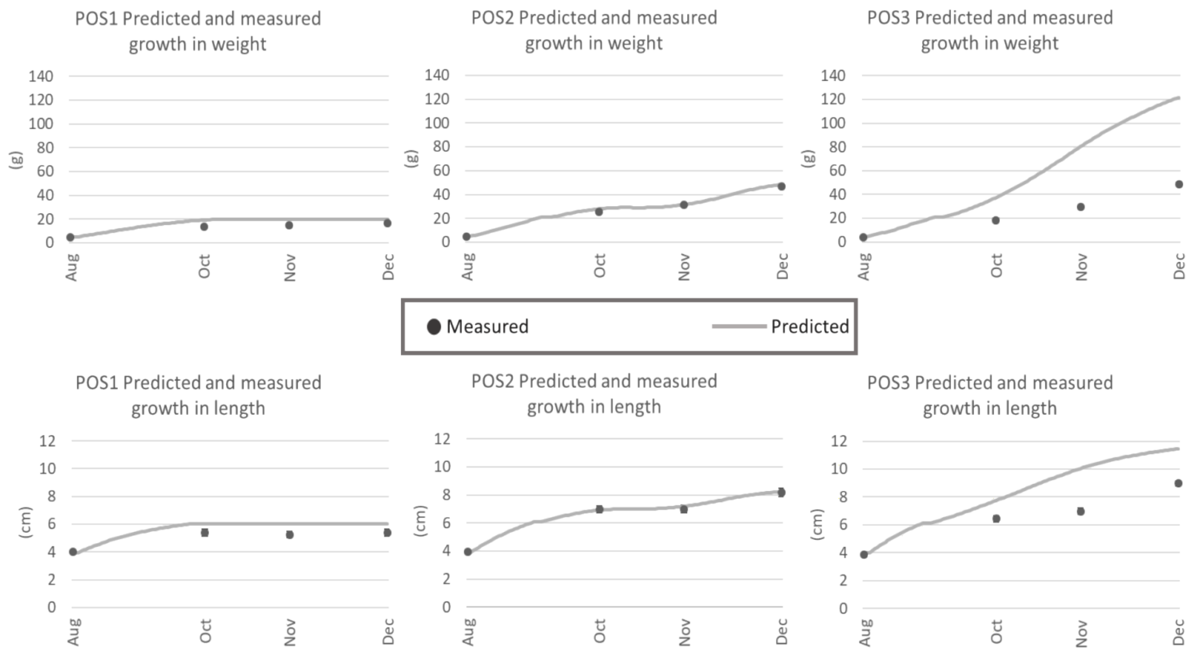

Figure 5. ShellSIM growth prediction compared to the measured oyster growth in weight and length, during a production cycles performed in to three different areas (POS1, POS2 and POS3) of the San Teodoro lagoon. Measured growth data are presented as mean ± SE; n=3.

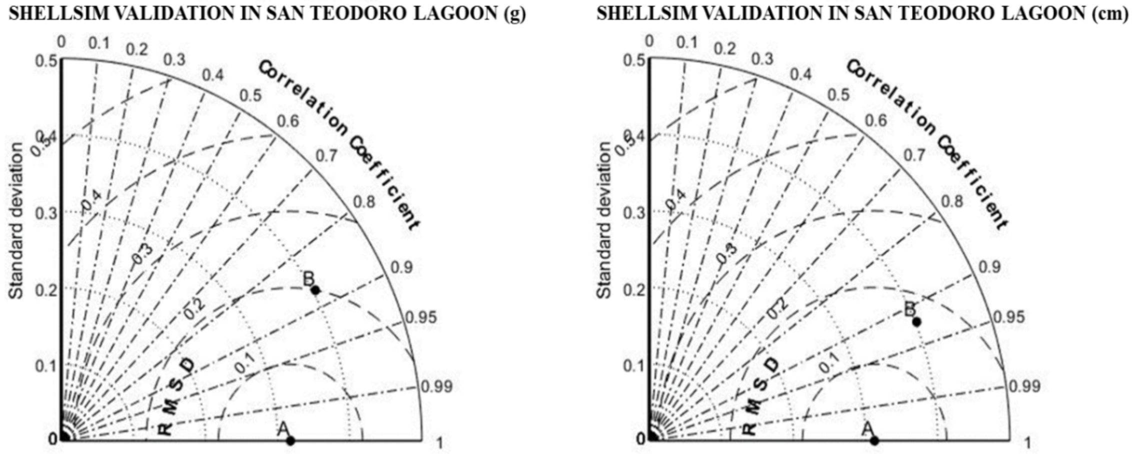

Figure 6. Taylor diagrams representing how closely model performance (B) match the observed data (A). The similarity between model prediction and observed data is quantified in terms of their correlation, the amplitude of their variation (normalised standard deviation) and their root mean square difference (RMSD) (dashed circular arcs). The left panel contain the results for the ShellSIM validation in the san Teodoro lagoon in terms of predicting the growth in weight of the *C.gigas*. The right panel contain the results for the ShellSIM validation in the san Teodoro lagoon in terms of predicting the growth in length of the *C.gigas*.

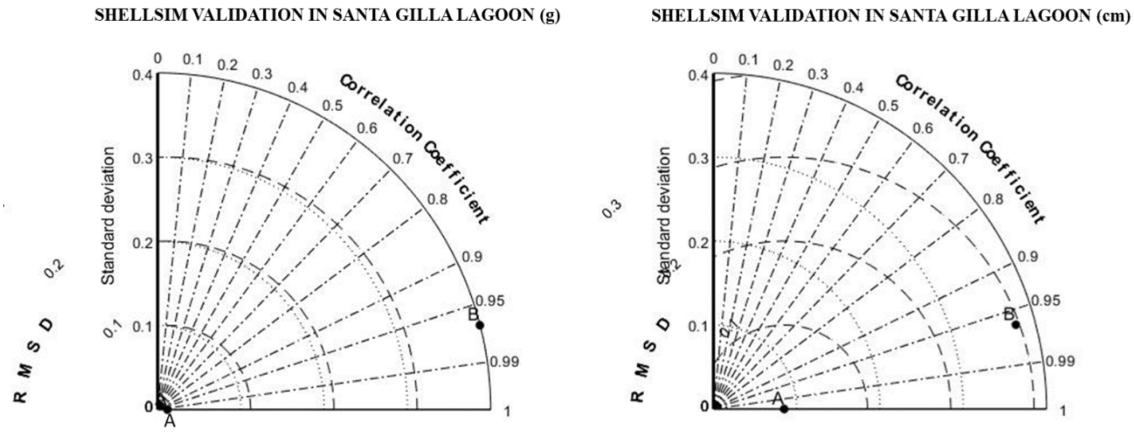

Figure 8. Taylor diagrams representing how closely model performance (B) match the observed data (A). The similarity between model prediction and observed data is quantified in terms of their correlation, the amplitude of their variation (normalised standard deviation) and their root mean square difference (RMSD) (dashed circular arcs). The left panel contain the results for the ShellSIM validation in the Santa Gilla lagoon in terms of predicting the growth in weight of the *C.gigas*. The right panel contain the results for the ShellSIM validation in the Santa Gilla lagoon in terms of predicting the growth in length of the *C.gigas*.

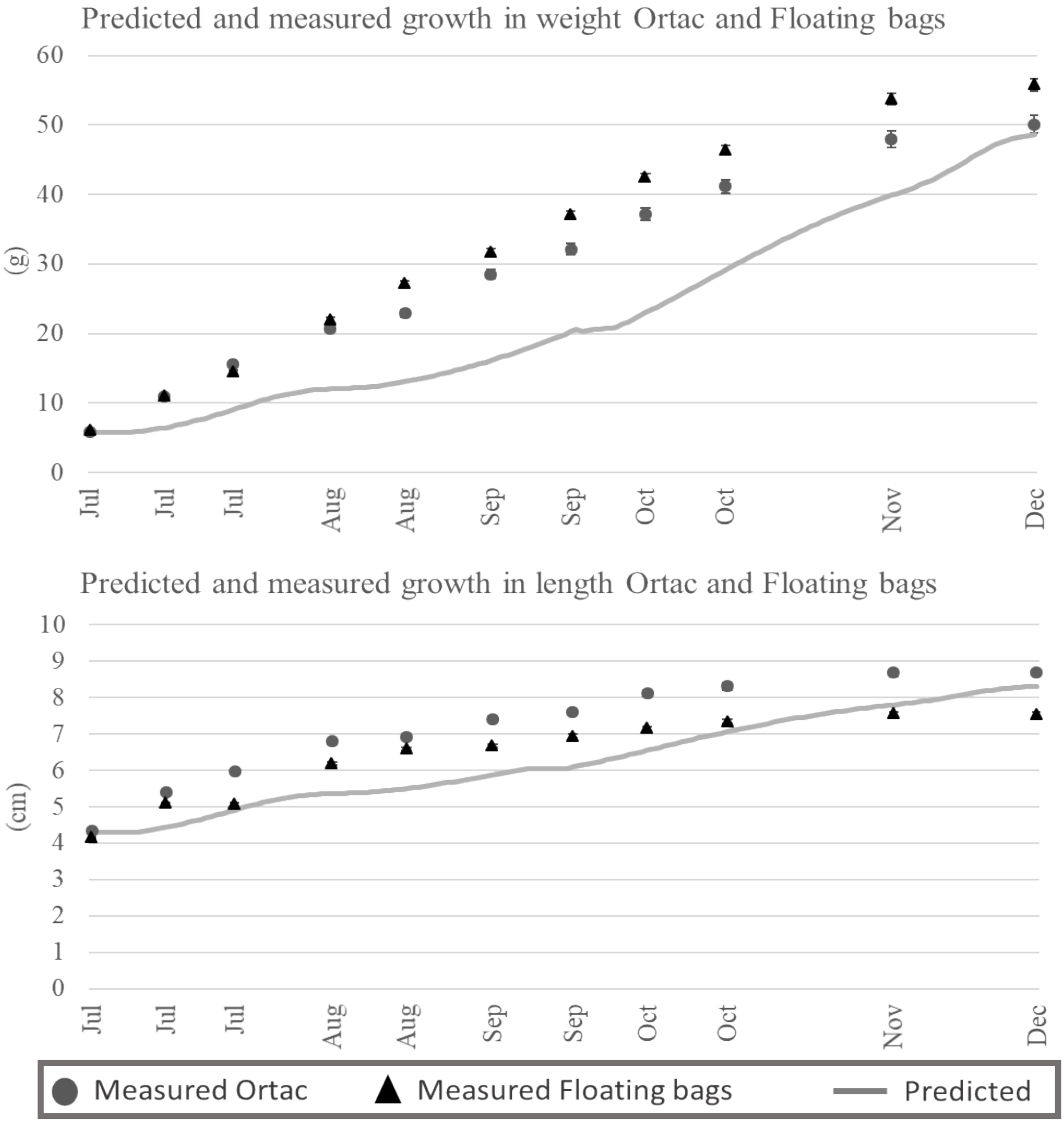

Figure 9. ShellSIM growth prediction compared to the measured oyster growth in weight and length, during a production cycles performed in to two different farming systems (Ortac units and Floating bags) in the San Teodoro lagoon (July 2017 – December 2017). Measured growth data are presented as mean ± SE; n=6.

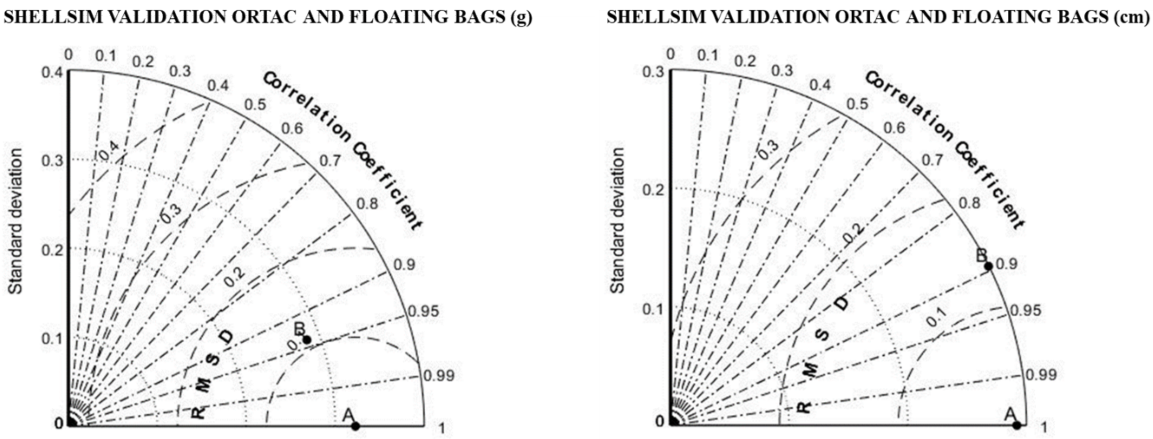

Figure 10. Taylor diagrams representing how closely modelled performances (B) matched the observed data (A). The similarity between model prediction and observed data is quantified in terms of their correlation, the amplitude of their variation (normalised standard deviation) and their root mean square difference (RMSD) (dashed circular arcs). The left panel contain the results for the ShellSIM validation in the San Teodoro lagoon on Ortac and Floating bags in terms of predicting the growth in weight of the *C.gigas*. The right panel contain the results for the ShellSIM validation in the San Teodoro lagoon on Ortac and Floating bags in terms of predicting the growth in length of the *C.gigas*.

Table 1. Summary of the environmental data collected to run ShellSIM. These data were collected during the production cycles started in August 2016, in three different areas (POS1, POS2 and POS3) of the San Teodoro lagoon. Data are presented as mean ± SE.

	T °C	*Sal ‰*	*DO mg/L*	*TPM mg/L*	*POM mg/L*	*POC mg/m³*	*Chl-a µg/L*
				August 2016			
POS 1	*27.1 ± 0.1*	*39.3 ± 0.1*	*7.2 ± 0.2*	*31.5 ± 12.4*	*5.3 ± 1.9*	*848.2 ± 18.6*	*2.1 ± 0.2*
POS 2	*27.2 ± 0.1*	*39.7 ± 0.1*	*7.5 ± 0.1*	*15.5 ± 1.6*	*3.2 ± 0.3*	*1213.1 ± 67.9*	*4.3 ± 0.7*
POS 3	*27.2 ± 0.2*	*39.5 ± 0.1*	*6.8 ± 0.1*	*19.4 ± 1.1*	*3.6 ± 0.2*	*1421.9 ± 68.5*	*4.1 ± 0.1*
				October 2016			
POS 1	*23.5 ± 0.1*	*39.2 ± 0.1*	*8.7 ± 0.1*	*5.2 ± 0.2*	*1 ± 0.1*	*206.9 ± 6*	*0.3 ± 0.1*
POS 2	*24.1 ± 0.1*	*38.8 ± 0.1*	*8.5 ± 0.1*	*5 ± 0.2*	*1 ± 0.1*	*211.3 ± 18.1*	*0.3 ± 0.1*
POS 3	*23.1 ± 0.3*	*38.8 ± 0.1*	*8.9 ± 0.3*	*21.1 ± 2.4*	*3.9 ± 0.2*	*1192.5 ± 55.8*	*3.7 ± 0.3*

			November 2016				
POS 1	*17.1 ± 0.1*	*39.2 ± 0.1*	*9.3 ± 0.1*	*0.6 ± 0.03*	*0.5 ± 0.1*	*167.3 ± 9.1*	*0.4 ± 0.02*
POS 2	*15.8 ± 0.5*	*37.7 ± 0.5*	*8.8 ± 0.2*	*2.3 ± 0.1*	*1 ± 0.1*	*485.2 ± 33.9*	*2.8 ± 0.2*
POS 3	*14.5 ± 0.2*	*38.8 ± 0.1*	*9.6 ± 0.1*	*3.0 ± 0.04*	*1.1 ± 0.1*	*473.4 ± 20.4*	*2.9 ± 0.1*
			December 2016				
POS 1	*16 ± 0.1*	*36.4 ± 0.2*	*10 ± 0.2*	*1.7 ± 0.1*	*0.6 ± 0.1*	*232.8 ± 21*	*0.7 ± 0.1*
POS 2	*17.5 ± 0.3*	*37 ± 0.3*	*10.7 ± 0.4*	*1.0 ± 0.1*	*0.6 ± 0.1*	*199.1 ± 28.4*	*0.4 ± 0.1*
POS 3	*15.1 ± 0.3*	*36.2 ± 0.2*	*9.2 ± 0.6*	*4.8 ± 0.2*	*1.2 ± 0.1*	*408.4 ± 24*	*0.9 ± 0.03*

Table 2. Summary of how well observed data match predicted data by ShellSIM in terms of their correlation, their root-mean square difference (RMSD), the ratio of their variances and skill score (Taylor, 2001).

SHELLSIM VALIDATION IN SAN TEODORO LAGOON (FLOATING BAGS)					
	St.dev Obs.	***St.dev Pred.***	***RMSD***	***Correlation***	***Skill score***
POS 1 (g)	*0.3*	*0.43*	*0.14*	*0.98*	*0.87*
POS 1 (cm)	*0.27*	*0.43*	*0.16*	*1*	*0.81*
POS 2 (g)	*0.35*	*0.36*	*0.02*	*1*	*1*
POS 2 (cm)	*0.36*	*0.37*	*0.02*	*1*	*1*
POS 3 (g)	*0.14*	*0.38*	*0.24*	*0.99*	*0.42*
POS 3 (cm)	*0.24*	*0.38*	*0.16*	*0.97*	*0.79*
OVERALL (g)	*0.32*	*0.4*	*0.2*	*0.87*	*0.83*
OVERALL (cm)	*0.31*	*0.4*	*0.17*	*0.92*	*0.87*
SHELLSIM VALIDATION ON ORTAC AND FLOATING BAGS IN SAN TEODORO LAGOON					

ORTAC (g)	*0.32*	*0.30*	*0.1*	*0.95*	*0.95*
ORTAC (cm)	*0.31*	*0.28*	*0.11*	*0.93*	*0.93*
FLOATING BAGS (g)	*0.33*	*0.27*	*0.12*	*0.94*	*0.9*
FLOATING BAGS (cm)	*0.27*	*0.31*	*0.13*	*0.9*	*0.89*
OVERALL (g)	*0.32*	*0.29*	*0.11*	*0.94*	*0.93*
OVERALL (cm)	*0.29*	*0.30*	*0.14*	*0.89*	*0.9*
SHELLSIM VALIDATION IN SANTA GILLA LAGOON					
SANTA GILLA (g)	*0.01*	*0.4*	*0.39*	*0.97*	*0*
SANTA GILLA (cm)	*0.08*	*0.38*	*0.3*	*0.96*	*0.18*

Table 3. Summary of the environmental data used to run ShellSIM. These data were collected during the production cycles started in June 2017, in the Santa Gilla lagoon. Data are presented as mean ± SE.

	T °C	***Sal ‰***	***DO mg/L***	***TPM mg/L***	***POM mg/L***	***POC mg/m³***	***Chl-a µg/L***
June 2017	*24.7 ± 0.02*	*37.6 ± 0.03*	*7 ± 0.03*	*2.3 ± 0.2*	*0.9 ± 0.1*	*413.1 ± 8.2*	*0.7 ± 0.1*
July 2017	*24.8 ± 0.02*	*43.3 ± 0.1*	*6.1 ± 0.04*	*4.6 ± 1.1*	*1 ± 0.1*	*349.5 ± 3.3*	*0.7 ± 0.1*
August 2017	*27 ± 0.01*	*35.4 ± 0.03*	*5.2 ± 0.04*	*6.6 ± 0.9*	*1.4 ± 0.1*	*451.4 ± 12.6*	*1.8 ± 0.1*
September 2017	*24.4 ± 0.02*	*36 ± 0.03*	*6 ± 0.03*	*8.1 ± 0.7*	*2.1 ± 0.3*	*561.6 ± 19.9*	*1.9 ± 0.1*

Table 4. Summary of the environmental data used to run ShellSIM. These data were collected during the production cycles started in July 2017, in the San Teodoro lagoon. Data are presented as mean ± SE.

	T °C	***Sal ‰***	***DO mg/L***	***TPM mg/L***	***POM mg/L***	***POC mg/m³***	***Chl-a µg/L***

July 2017	*27.5 ± 0.2*	*38.9 ± 0.4*	*9.6 ± 0.3*	*6.1 ± 4.0*	*1.7 ± 1.2*	*358.2 ± 62.7*	*1.7 ± 0.7*
August 2017	*28.4 ± 0.3*	*41.1 ± 0.4*	*7.8 ± 0.3*	*3.9 ± 0.8*	*1.5 ± 0.2*	*557.6 ± 94.2*	*3.1 ± 1.1*
September 2017	*21.5 ± 0.1*	*40.2 ± 1.1*	*9.2 ± 0.1*	*5.4 ± 0.3*	*1.5 ± 0.2*	*491.1 ± 30.1*	*1.7 ± 0.6*
October 2017	*18 ± 2.1*	*40.7 ± 0.1*	*8.3 ± 0.3*	*5.2 ± 0.3*	*1.4 ± 0.1*	*769.2 ± 99*	*2.8 ± 0.6*
November 2017	*18.3 ± 0.3*	*38.4 ± 0.3*	*9.4 ± 0.1*	*23.2 ± 3.3*	*3 ± 0.4*	*151.3 ± 23.9*	*0.5 ± 0.03*
December 2017	*14.7 ± 0.1*	*36.7 ± 0.5*	*10 ± 0.1*	*12.3 ± 9.5*	*1.9 ± 1.3*	*222.4 ± 67.4*	*0.8 ± 0.3*

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