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.

27 Results showed that at the end of a six months cycle the oysters mean weight and Condition Index

28 were significantly higher (p value< 0.05) in floating bags than in Ortac, (55.8 ± 0.9 g and 50.1 ± 1.3

29 g; 4.6 ± 0.1 and 3.9 ± 0.1respectively). Also, the minimum commercial size (40 g) was reached by

30 98 % and 68 % of the oyster farmed in floating bags and Ortac units respectively. On the other

31 hand, oysters reared in the Ortac showed a higher survival than in the floating bags (95.8 ± 0.9 %

32 and 82.1 ± 3.4 %, respectively).

33 ShellSIM growth predictions were highly correlated with the observed data in both lagoons.

34 However, high values for root mean square deviation (RMSD) indicated that ShellSIM predictions

35 were significantly validated for San Teodoro lagoon but not for Santa Gilla suggesting further

36 tailoring to some environmental conditions to produce more realistic growth predictions.

37 Results of this study indicate that both floating bags and Ortac system should be employed during

38 the production cycle to maximise oysters' survival and growth performances. Furthermore, this

39 study provides a new validated tool to farmers and stakeholders to monitor oysters' performances

40 and estimate productivity in local waters.

41

44

Abbreviations

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

47

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 shellfish farming was the main aquaculture industry, contributing to over 64% of the total Italian production. This country is 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 77,000 tonnes of Pacific oysters, 145 of which were of Italian origin (30 tonnes by a single Sardinian company (FAO 2011-2018Fishstat.J). Italy is one of the largest consumers of oysters in Europe importing 6,500 tonnes per year primarily from France; this could represent an opportunity to diversify Italian shellfish farming in the future (Sardegnaagricoltura.it, 2016, FAO, 2016). Sardinia has approximately 10,000 ha of shallow coastal lagoons. This surface represents 2.6% of the total lagoons area in Italy (Bazzoni*et al.,* 2013). Many of these lagoons are used for extensive finfish farming, but could be potential sites for Pacific oyster farming.

Currently, in the world, three main oyster farming methods are used depending on environmental conditions such as water depth, tidal range, water exchange rates and bottom substrates: off-bottom culture, on-bottom culture and suspended culture (Buestel*et al*., 2009). In Sardinian lagoons suspended culture is the most commonly used method due to the local 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

73 to 23mm), suspended on the surface thanks to two floaters which allow periodic exposure of the

74 oysters to the airto reduce biofouling and strengthen the adductor muscle.

75 Amongst suspended oyster culture methods, several new farming tools have been recently

76 developed, for example Ortac units (ABBLOX), OysterGro© (OysterGro) and Zapco Tumbler

77 (Zapco Aquaculture). These systems aim at improving oyster production by reducing manual

78 labour, increasing growth rates and improving oysters' quality (i.e. shell shape). The Ortac system

79 has been employed in this study. The Ortac system consists of baskets made of polypropylene

80 plastic and divided in two halves. These operate attached to a trestle and, due to their shape, an up-

81 welling water flow is passively generated by the surrounding water currents. Furthermore, thanks to

82 the constant movement under currents actions, this system has been designed to reduce fouling

83 therefore requiring less handling.

84 Aside from environmental conditions, the use of different grow-out gears affects oyster

85 performances as suggested by the recent study from Rankin *et al.,* (2018).

86 To date, only one independent trial has been conducted in Scotland to compare growth, survival and

87 physiological performances of *Ostrea edulis* between Ortac and traditional bag systems (Francouer,

88 2017). Results of this study indicated that there were no significant differences in growth between

89 *Ostrea edulis* reared in the two different systems (Ortac units and traditional bags) but higher

90 survival was observed within the Ortac units. The study presented here is the first investigation and

91 comparison of the performance of the Ortac system in warmer climates with a smaller tidal range.

92 Much effort has been dedicated to generate and validate growth models for bivalves (Pouvrerau *et*

93 *al.,* 2006). Most of the energy budget models predicting growth are net production models, which

94 assume that energy is immediately available for the animal maintenancewhile the restis usedfor

95 growth or deposited as a reserve. Others are based on a dynamic energy budget approach (DEB)

96 where energy is first stored as a reserve and then used for different metabolic processes at a

97 catabolic rate (Kooijman, 2000; Pouvreau *et al.,* 2006; Ren and Ross, 2001;Beadman*et al.,* 2002).

98 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 the principles of energy balance:

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

This 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 three different oyster farming systems: the Ortac units, the traditional floating bags and the lantern nets, and furthermore to compare the production efficiency between the traditional and new farming tools (Ortac and floating bags).

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 (north-east Sardinia: 40°48' 38.08''N, 9°40'26.99''E). A total of 2,400 triploid 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:

$$CI = (Dry\ weight\ meat\ (g)/Dry\ weight\ meat\ (g) +\ Dry\ weight\ shell\ (g))\ x\ 100$$

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 in 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 and 19mm) according to oysters' size, and based on the increasing Pacific Oysters biomass. Grading was performed when the biomass in each farming unit reached about 4kg live weight and generally once every three months for both Ortac units and floating bags in order to keep 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 were fed to ShellSIM model to account for the hydrodynamic and ecological conditions within the lagoon.

150   Three floating bags per each area were stocked with *C. gigas* (838 ± 36.4 g, 811.5 ± 17.8 g and

151   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

152   (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

153   were cultured following the standard procedures described above.

154   Sampling for oyster growth was performed monthly for 5 months. Each month 80 individuals unit^{-1}

155   were randomly measured for wet weight, 30 of which also measured for length, depth and width.

156   Other 10 individuals unit^{-1} were collected for dry weights measurements.

157   Environmental data: temperature (T,°C), salinity (Sal, ‰), dissolved oxygen (DO, mgL^{-1}), total

158   particulate matter (TPM, mg/L), particulate organic matter (POM, mgL^{-1}), particulate organic

159   carbon (POC, mg m^{-3}) and Chlorophyll-a (Chl-a, µgL^{-1}) were collected in the immediate vicinity of

160   the farming gears. Temperature, salinity and dissolved oxygen were collected at a depth of 15 cm,

161   with a multi-parametric probe (HACH HQ40d) and data loggers (HOBO: UTBI-001, U26-001 and

162   U24-002-C respectively for T, DO and Sal). Temperature data loggers were set-up to take

163   measurements every 30 minutes, while the Sal and DO probes measured values every 2 hrs.

164   Water for the TPM, POM, POC was collected using 1L pre-rinsed in sample water plastics bottles,

165   while 5L pre-rinsed in sample water plastic bottles were used to collect water for Chl-a analysis.

166   Laboratory analysis for TPM and POM were performed according to Hawkins *et al.* (2013), while

167   Chl-a analysis according to Lorenzen (1967). For POC measurements water was collected in 1L pre-

168   rinsed plastic bottles then filtered in 47-mm diameter GF/F filters previously combusted at 450 °C.

169   POC samples were analysed with a CEI Flash smart elemental analyser. The average values of each

170   environmental parameter were used to run the model, excluding September 2017, when no data were

171   collected due to farmers' activities and weather constraints.

172

173   2.3. ShellSIM validation for lantern systems (Santa Gilla Lagoon)

174   In order to validate the growth model in a different location, a growth trial was performed between

175   May 2017 and September 2017, in Santa Gilla lagoon (39°12'28.2''N 9°05'53.5''E). Three lanterns

176 with five compartments each and a mesh size of 3.5 x 5 mm, were stocked with 500 oysters per

177 compartment (mean weight = 4.4 ± 0.1 g; mean length = 3.6 ± 0.6 cm). The oysters were farmed

178 following the standard production protocols, grading and changing the mesh size according to

179 oysters' size and biomass. Growth was measured monthly when 70 individuals per lantern were

180 randomly sampled and weighted, 30 of which were also measured for shell length, depth and width.

181 Furthermore, 10 individuals per lantern were collected for dry weight measurements.

182 Environmental data sampling and analysis were conducted as described above. The monthly means

183 of all the environmental data were used to run the growth model.

184

185 2.4. ShellSIM Validation for Ortac units and floating Bags (San Teodoro Lagoon)

186 In order to validate the model for different gear types, a new experiment was set up in the lagoon of

187 San Teodoro (July 2017 – December 2017) where the model performance was also tested on a

188 different farming system, the Ortac units.

189 Farming methods, growth measurements, sample collection and analysis of all environmental

190 parameters were conducted as described previously. A bi-weekly mean of all the environmental data

191 were used to run the ShellSIM, except for November and December, when data were collected only

192 once per month due to farmers' activities and weather constraints.

193

194 2.5. Statistical Analysis

195 Prior to analyses, data were tested for normality and homogeneity of variance Weight gain,

196 biometrics measures differences, survival rate and Condition index differences, over time were

197 analysed by general linear model followed by a Tukey post-hoc test where significant differences

198 occurred.

199 End points of all biometrics measures, survival rate and condition index, were analysed by one-way

200 ANOVA followed by post-hoc Tukey's Multiple Comparison tests where significant differences

201 occurred.

202 To assess fitness between the prediction made by ShellSIM and observed data, Taylor diagrams and

203 skill scores (S) were used (Taylor, 2001). A Taylor diagram is a way to show graphically how well a

204 model prediction fits the observed data, using correlation, centred root mean square difference

205 (RMSD) and amplitude of their variation (standard deviations). The skill score proposed by Taylor

206 (2001) quantifies model performance against observed data.

207

208 **3. Results**

209 3.1. Growth Trial: Ortac *vs* floating bags

210 At the end of the production cycle (October to December), the Pacific oysters farmed in the floating

211 bags had a significantly higher weight and shell depth (*p* value =0.001, 0.001 respectively) to those

212 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

213 inside the Ortac units showed instead a significant higher growth in shell length (86.9 ± 1, 75.4 ±

214 0.6, *p* value = 0.001, Ortac and floating bags respectively), and shell width (46.2 ± 0.5 mm, 44.6 ±

215 0.4 mm, *p* value = 0.017) (fig.2b,d).

216 Survival was significantly higher (*p* value= 0.001) in the Ortac units compared to the floating bags

217 (95.8 ± 0.9%, 82.1 ± 3.4 %) (fig.3). The highest mortality occurred between June and July (3.8 ± 1

218 %, 16.3 ± 3.3 % Ortac units and floating bags respectively).

219 The condition index at the end of the production cycle was significantly higher (*p* value = 0.001) in

220 the floating bags compared to the Ortac units (4.6± 0.1, 3.9± 0.1) (fig.4) and the smallest

221 commercial size (40 g) was reached by the 98 % and 69 % of the oyster farmed in the floating bags

222 and Ortac units respectively (fig.5).

223

224 3.2. ShellSIM validation in San Teodoro Lagoon

225 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

226 identified in San Teodoro. A decreasing speed gradient from the sea mouth to the internal part of

227   the lagoon was identified. Consequently, these areas were used as experimental locations to monitor

228   the oysters' growth and the environmental parameters required by the growth model.

229   Environmental data are illustrated in Table 1. ShellSIM predicted, during a 6 months production

230   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,

231   respectively for POS1, POS2 and POS3.

232   The measured weight and length at the end of this production cycle, was 16.4 ± 1.1 g, 46.9 ± 2.1 g,

233   48.9 ± 1.5 g and 5.4 ± 0.3 cm, 8.2 ± 0.3 cm, 9 ± 0.2 cm, respectively in POS1, POS2 and POS3.

234   Figure 6 shows that measured growth in weight and length, fitted the predicted growth curve in

235   POS2, while in POS1 and POS3 ShellSIM overestimate the final mean growth in weight and length

236   respectively 20.5, 12.1, 148.8 and 27.9 %. The calculated skill score for the three different areas

237   indicate the best fitting between observed and predicted measures of weight and length, respectively

238   in POS2 (S=1; S=1), POS1 (S=0.87; S=0.81) and POS3 (S=0.42; S=0.79).

239   Standard deviation, Centred Root Mean square difference (RMSD), correlation and the overall skill

240   score of the performance of the predicted growth curve to fit the observed data in the lagoon of San

241   Teodoro are shown in Figure 7 and Table 2.

242

243   3.3. ShellSIM validation in Santa Gilla Lagoon

244   Environmental data collected in the lagoon of Santa Gilla and their seasonal variations are

245   illustratedin Table 3.

246   The measured growth in weight and length (79.5 ± 1.8 g and 9.1 ± 0.1 cm) did not fit the predicted

247   growth curve (data not shown), and the calculated skill score indicates a very poor fit between

248   observed and predicted measures of weight and length, respectively S=0.003 and S=0.17 (Table 2).

249   Standard deviation, Centred Root Mean square difference (RMSD) and correlation are shownin

250   Figure 8 and Table 2.

251

252   3.4 ShellSIM Validation on Ortac *vs* floating bags

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

254 In this trial, ShellSIM was run in POS2 for two different farming systems. It predicted a growth of

255 48.6 g and 8.3 cm in weight and length respectively for the Ortac system, and a growth of 49.1 g

256 and 8.2 cm for the floating bags over a 6 months production cycle. At the end of this production

257 cycle, the measured weight and length were 50.1 ± 1.3g and 8.7 ± 0.1cm for the Ortac and $55.8 \pm$

258 0.9 g and 7.5 ± 0.1 cm for the floating bags. Figure 9 shows that during the production cycle, the

259 measured mean weight and length in the Ortac units and floating bags were underestimated by

260 ShellSIM, except for the final length farmed in the floating bags which was accurate. Indeed, in

261 November there was a change in trend of the model prediction, from underestimation to

262 overestimation (the model overestimated the final mean length of 8.2 %), while the final weight was

263 still overestimated by 11.9%.

264 Moreover, Figure 9 shows that ShellSIM at the end point of the production cycle of the oysters

265 reared inside the Ortac units, unlike the rest of the predictions, slightly underestimated growth in

266 weight and length by 3% and 4.4% respectively.

267 The calculated skill score indicates that the best fitting between observed and predicted measures of

268 weight and length was respectively obtained in Ortac (S=0.95, S=0.93) compared to floating bags

269 (S=0.90, S=0.89). Standard deviation, Centred Root Mean square difference (RMSD), correlation

270 and the overall skill score of the performance of the predicted growth curve to fit the observed data

271 in this trial in the SanTeodoro lagoon are shown in Figure 10 and Table 2.

272

273 **4. Discussion and conclusions**

274 The results of this study provide new information to improve *C. gigas* farming and a growth

275 prediction tool in shallow coastal lagoons. The higher survival rate in the Ortac units for the first two

276 months and the higher growth in weight and CI in the floating bags, suggest a potential mixed use of

277 the two systems during the production cycle. Specifically, the Ortac units may be employed when

278 Pacific oysters are more susceptible to stress and during the stressful period (e.g smaller size and

279   hottest periods) and floating bags thereafter. As a result, by combining the two farming gears within

280   one production cycle, it would be possible to reduce the capital costs of equipment by reducing the

281   need for several meshes sizes in the floating bag system, and achieve a significantly higher survival

282   rate from seed to market size individuals.

283   There was no statistically significant difference in growth between Ortac units and floating bags, but

284   at the end of the production cycle there was a significant higher mean weight in the floating bags

285   than in the Ortac units. Comparison of these results with previous studies is difficult due to

286   difference in culture techniques, local environment, species used, initial oyster size and the

287   production season.

288   Many studies report that the shell morphology in bivalves is influenced by population density,

289   predation responses, handling and grow-out methods (Telesca *et al*., 2018; Seed, 1968; Brake *et al*.,

290   2003; Kube*et al*., 2011; Griffiths and Buffenstein, 1981; Van Erkom Schurink and Griffiths, 1993;

291   Bayne, 2000; Sheridan *et al.,* 1996). As in these studies, we observed a difference in shape between

292   the animals reared inside the floating bags or Ortac units, with the latter showing longer and wider

293   shells compared to the former which were instead thicker and with a higher C.I.

294   The morphological differences found between individuals farmed in Ortac and floating bags are

295   probably due to the shape of these different tools, and consequently the different interaction of these

296   with the currents. Under low current speed typical of shallow lagoons, the shape of the Ortac units

297   may have not promoted the rocking motion required to generate enough rubbing between oysters

298   and the farming gear, causing less shell chipping, which is widely recognised as a factor promoting

299   shell depth and a higher meat content (Brake *et al*., 2003; Holliday, 1991; O'Meley, 1995; Robert *et*

300   *al*., 1993).

301   Moreover, the fact that the animals did not move enough inside the Ortac units probably induced

302   those in the innermost part to grow more in length and width in order to increase the filtering

303   surface. Nonetheless, results of this study are comparable with those obtained by Francouer *et al*.,

304   (2017). In his study, performed in Scotland, oysters' growth differences were found to be not

305 statistically significant between the two systems, consistently with data reported here. Mortality may

306 depend on the farming system (Pernet *et al.*, 2012). Improved survival in the Ortac system could be

307 due to the shading effect provided by a more solid structure, which would shelter farmed individuals

308 from direct sunlight and desiccation, particularly during the earlier part of the growth cycle and

309 during air exposure periods (Potter and Hill, 1982; Spencer-Davies, 1970). Moreover, different

310 studies report that one of the stress factors associated to mortalities is temperature, and sudden small

311 changes may have a large effect on the survival of bivalves (Pernet *et al*., 2018; Pernet *et al*., 2012;

312 Petton *et al*., 2015; Le Deuff *et al*., 1994, Le Deuff *et al*., 1996; Sauvage *et al*., 2009; Kennedy and

313 Mihursky, 1971). Again the more solid structure of the Ortac may have promoted more stable

314 temperature and reduced stress.

315 Results of this study indicate that the predicted growth by ShellSIM fitted well with field

316 measurements in the lagoon of San Teodoro. However, results from the growth trial in Santa Gilla

317 lagoon demonstrate that the model would require further tailoring to local conditions to produce

318 realistic growth projections. In particular, we tested the hypothesis that ShellSIM assumptions on the

319 conversion of food concentration into available/digestible energy for the oysters, may not apply to

320 Santa Gilla Lagoon. In order to do this, we run the model reducing the amount of POC available to

321 one quarter of the measured POC and the model prediction was more accurate ($S = 0.97$ and $S =$

322 0.95 respectively for weight and length). Indeed, POC can be considered as a very heterogeneous

323 nutrient source composed by different materials with large variations in digestible energy content

324 (Mazzola and Sarà, 2001; Lawacz, 1977; Watanabe and Kuwae, 2015).

325 Further studies to identify the real digestible energy content of the Particulate Organic Carbon in

326 Santa Gilla area is required to modify the model assumption and improve its performances. Our data

327 also suggest that seasonality and farming system used can influence the accuracy of ShellSIM

328 providing scope for further tailoring of the model to reflect gear types and local environmental

329 conditions.

During the first-year trial in the lagoon of San Teodoro the measured growth closely fitted the predicted growth in POS2, while in POS1 ShellSIM slightly overestimated and in POS3 considerably overestimated the growth, both in weight and length. Similar results in POS2 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 each 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 (POS3 with higher growth rates and POS1 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, for both validation trials in the fore mentioned lagoon.
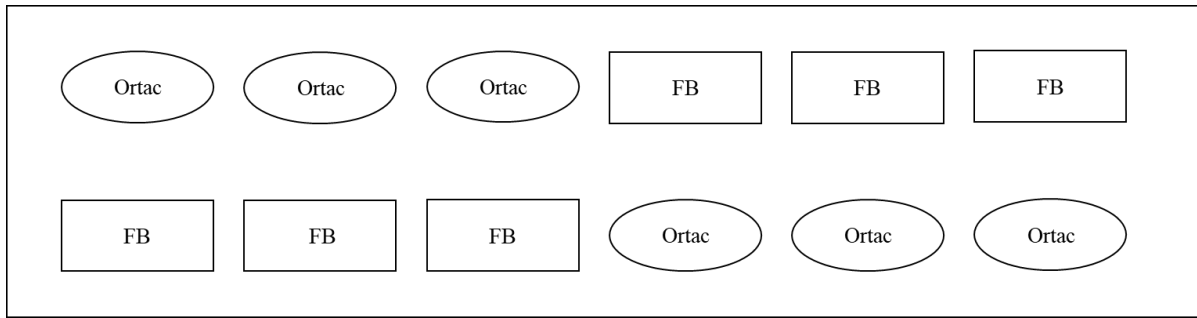
Taken together, the results of this study provide information to improve bivalve growth prediction tools for Mediterranean lagoons. They could be applied to study the productivity of different sites to potentiate the oyster's aquaculture industry and for coastal spatial planning. Moreover, the presented 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 mesh bags therefore simplifying production protocols.
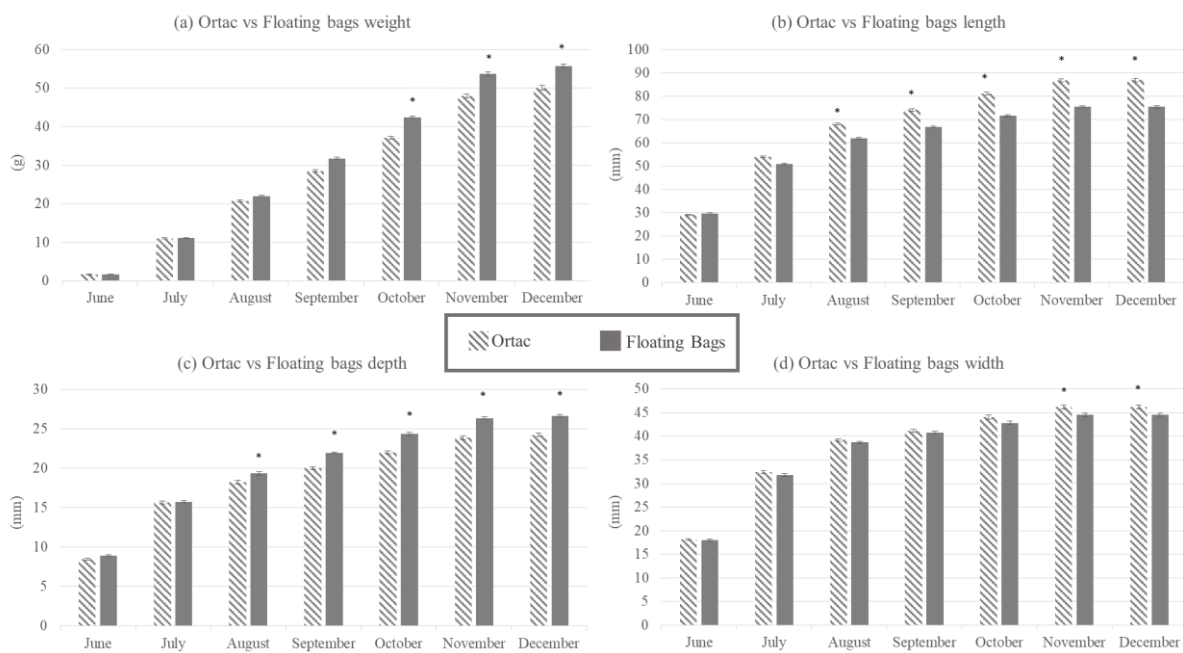
356

369

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

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373

374   *Figure 1.* (a) Difference growth in weight between *C. gigas* farmed in two different tools (Ortac units and Floating bags).
375   (b)Difference growth in length between *C. gigas* farmed in two different tools (Ortac units and Floating bags). (c)Difference growth
376   in width between *C. gigas* farmed in two different tools (Ortac units and Floating bags). (d)Difference growth in depth between *C.*
377   *gigas* farmed in two different tools (Ortac units and Floating bags). Stars indicate where significant difference occurs. (*p-value*<
378   0.05). Data are presented as mean ± SE; n=6.

379

Ortac vs Floating bags Survival rate

380
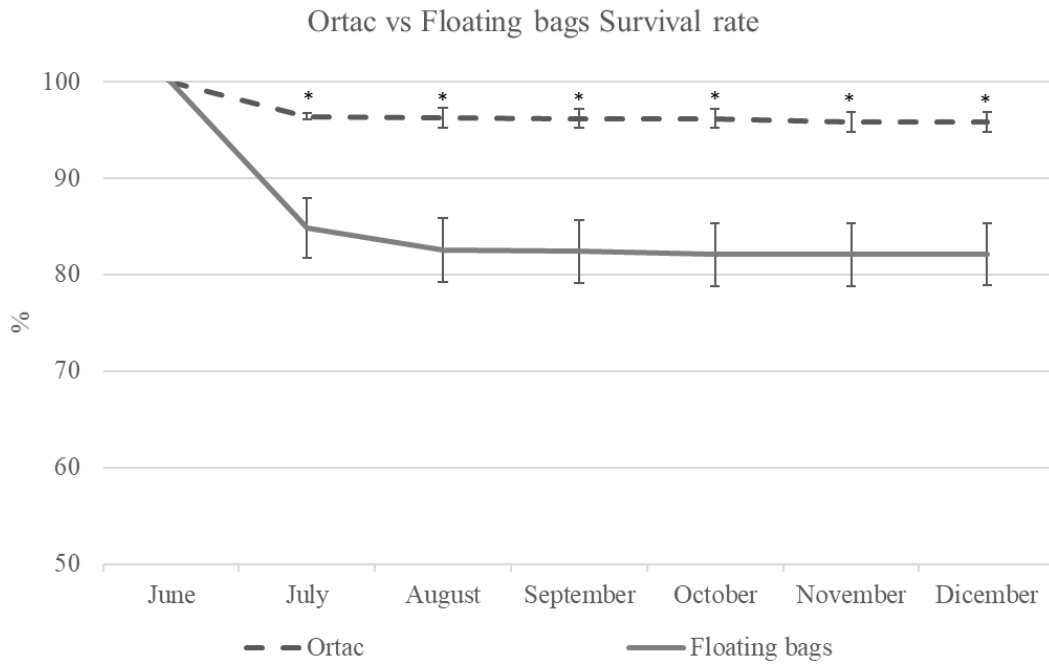
Figure 2. Comparison of survival rate between *C. gigas*farmed inside theOrtac units and Floating bags.Stars indicate where significant difference occurs. (p-value< 0.05). Data are presented as mean ± SE; n=6.

383

Ortac *vs* Floating bags CI

384

Figure 3. Comparison of condition index (CI) calculated as(Dry weight Meat (g)/ Dry weight Meat + Dry weight shell) *100, between *C. gigas*farmed inside theOrtac units and Floating bags.Stars indicate where significant difference occurs. (p-value< 0.05). Data are presented as mean ± SE; n=6.
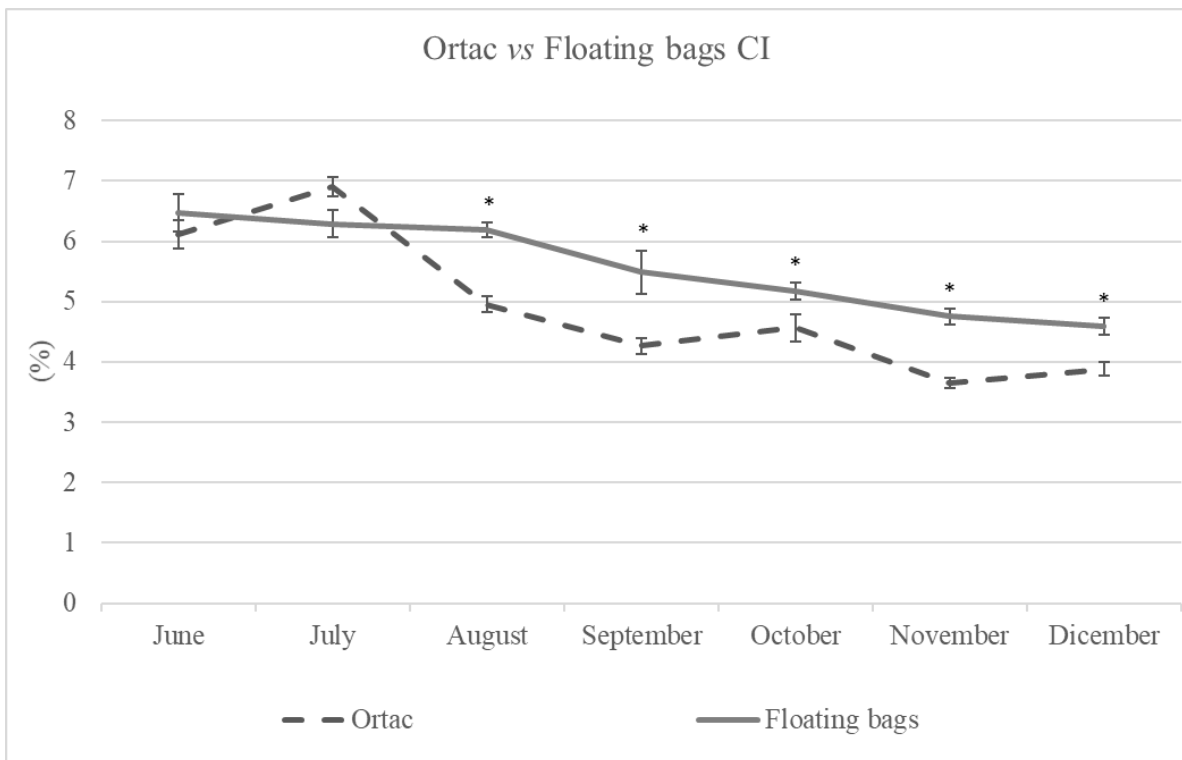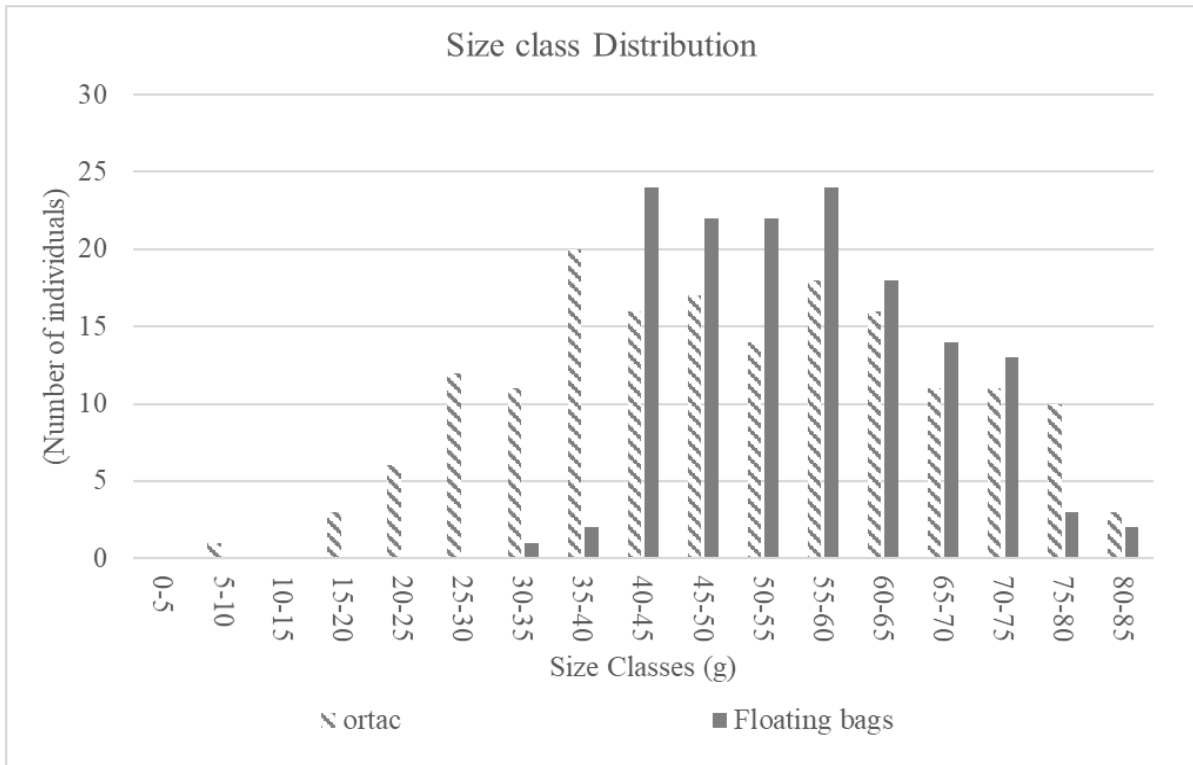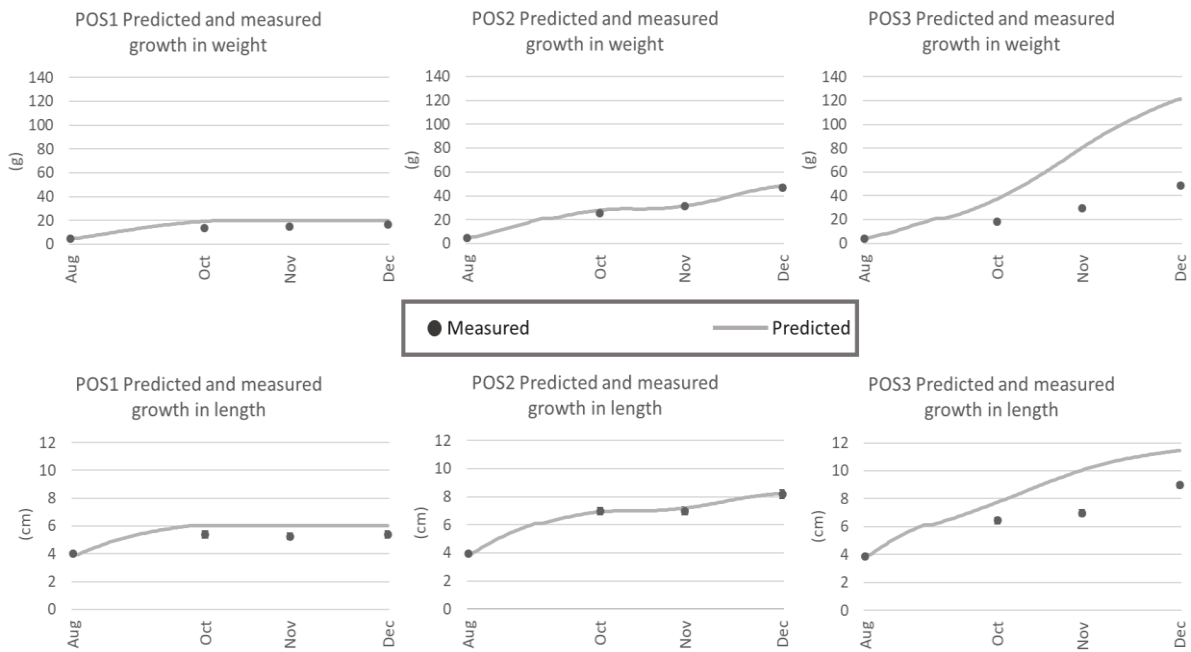
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389

390   *Figure 4.* Comparison of size class distribution between *C. gigas* farmedinsidethe Ortacunits and Floating bags.
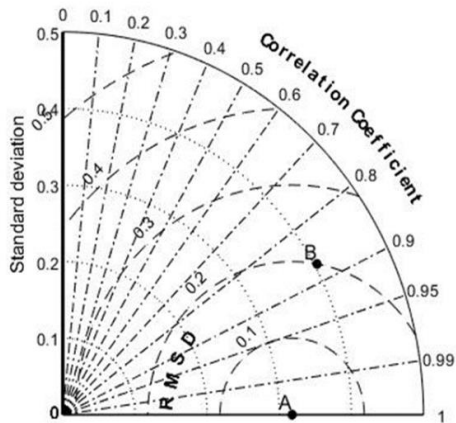
391

392

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

396

SHELLSIM VALIDATION IN SAN TEODORO LAGOON (g)

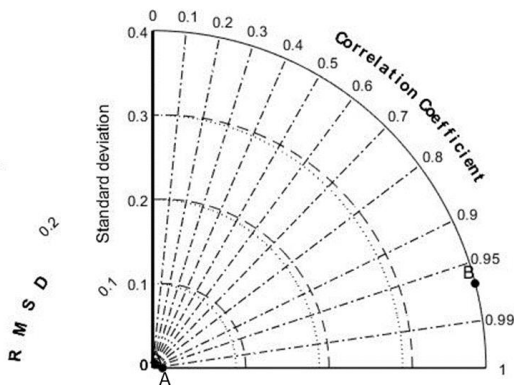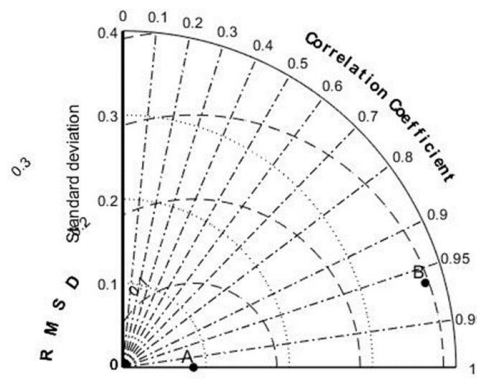**SHELLSIM VALIDATION IN SAN TEODORO LAGOON (cm)**
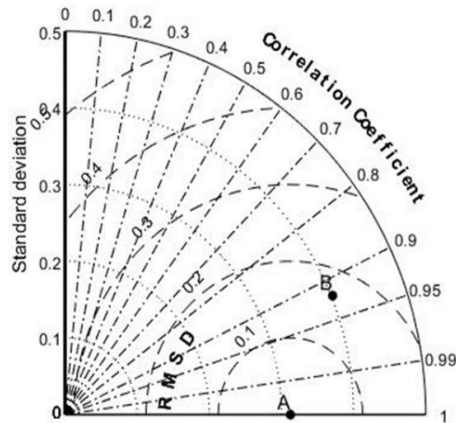
397

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

404

SHELLSIM VALIDATION IN SANTA GILLA LAGOON (g)

SHELLSIM VALIDATION IN SANTA GILLA LAGOON (cm)

405

406 *Figure 8.* Taylor diagrams representing how closely model performance (B) match the observed data (A). The similarity between
407 model prediction and observed data is quantified in terms of their correlation, the amplitude of their variation (normalised standard
408 deviation) and their root mean square difference (RMSD) (dashed circular arcs). The left panel contain the results for the ShellSIM
409 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
410 the ShellSIM validation in the Santa Gilla lagoon in terms of predicting the growth in length of the *C.gigas*.

411

Predicted and measured growth in weight Ortac and Floating bags

Predicted and measured growth in length Ortac and Floating bags

● Measured Ortac   ▲ Measured Floating bags   — Predicted

412
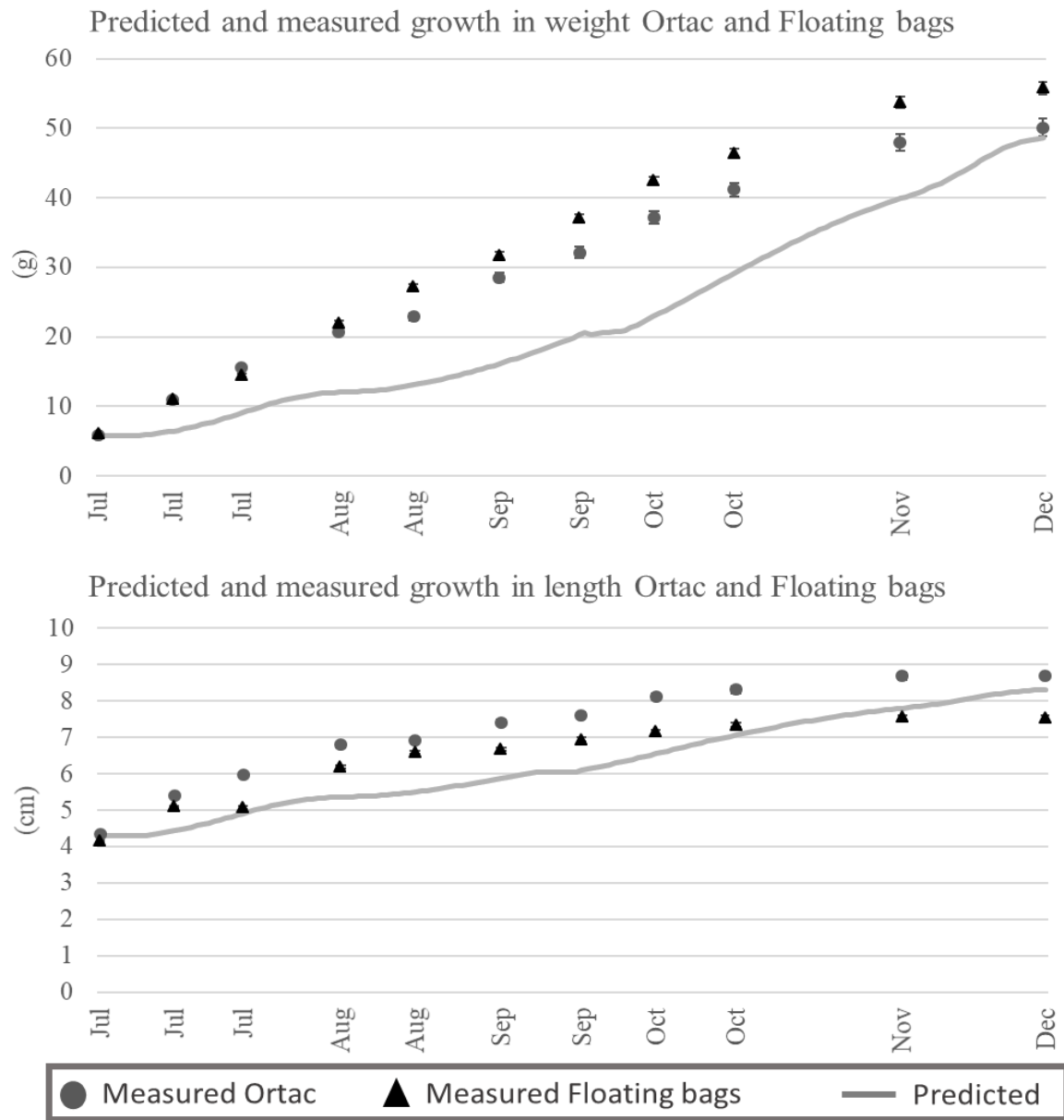
*Figure 9.*ShellSIM growth prediction compared to the measured oyster growth in weight and length,during a production cycles performed in to two different farming systems (Ortac units and Floating bags) in the San Teodoro lagoon (July 2017 – December 2017).Measured growth data are presented as mean ± SE; n=6.
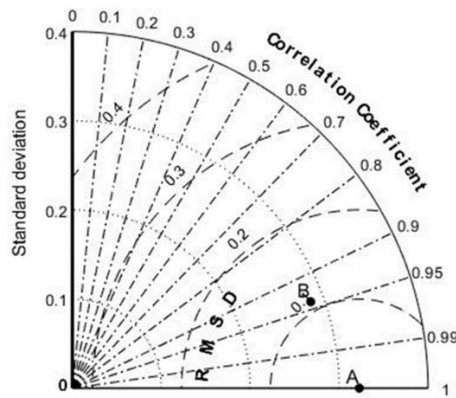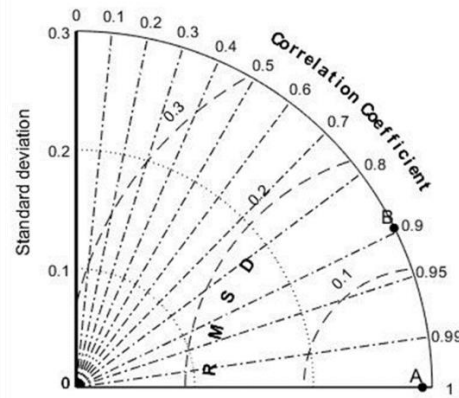
416

417

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

429

430

431 *Table 2.* Summary of how well observed data match predicted data by ShellSIM in terms of their correlation, their root-mean square
432 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
POS1 (g)	0.3	0.43	0.14	0.98	0.87
POS1 (cm)	0.27	0.43	0.16	1	0.81
POS2 (g)	0.35	0.36	0.02	1	1
POS2 (cm)	0.36	0.37	0.02	1	1
POS3 (g)	0.14	0.38	0.24	0.99	0.42
POS3 (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

433

434

435

436 *Table 3.* Summary of the environmental data used to run ShellSIM. These data were collected during the production cycles started in
437 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

438

439

440 *Table 4.* Summary of the environmental data used to run ShellSIM. These data were collected during the production cycles started in
441 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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