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Research Article

Dynamic simulation of diploid *vs.* triploid Pacific oyster (*Crassostrea gigas*) productive performance in northwestern Mexico

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ABSTRACT. The Pacific oyster *Crassostrea gigas* was introduced in northwestern Mexico for aquaculture purposes. Although its cultivation has been successful, this species has shown high mortalities during summer. To mitigate this problem, producers have resorted to biotechnology (triploidy), whose performance -regarding diploid seedling- depends on site conditions and stocking time. Hence, uncertainty exists on its benefits under real production conditions. This research evaluates triploidy performance by implementing a dynamic simulation model considering environmental effects (temperature and chlorophyll) on culture production. The dynamic simulation was based on systems theory, dividing the productive system into two sub-models (environmental and biological), including temperature and chlorophyll effects, growth, mortality, and condition index parameterized in the function of the environmental parameters. The dynamic simulation results suggest that implementing triploid culture is advantageous in zones under high stress associated with high temperature and low productivity; likewise, triploid spat tends to show better performance independently of the site. Nevertheless, performance by ploidy varies depending on the environmental conditions of the sites.

Keywords: *Crassostrea gigas*; polyploidy; biotechnology; numerical simulation; systems theory

INTRODUCTION

The Pacific oyster *Crassostrea gigas* (Thunberg, 1973) has been introduced worldwide for aquaculture purposes because of its high tolerance to adverse environmental conditions, growth potential, market size, unit price, or improvement of collapsed/overexploited stocks (Mann 1979, 1991). World aquaculture production was 5 million tons for all oyster species in 2018 (FAO 2019).

For aquaculture purposes, the Pacific oyster was introduced in the 1970s in northwestern Mexico to promote national aquaculture development (Islas-Olivares 1975). Despite the success obtained at several production sites, high mortalities were frequently recorded during the summer. This problem has been attributed to a combination of factors, such as high temperature, low phytoplankton production in some farming sites, and pathogens (Chávez-Villalba et al. 2010, Ibarra et al. 2017).

To mitigate this problem, genetic improvement and biotechnologies (e.g. polyploidy) are among the existing alternatives (Clark & Langmo 1979). Aquaculture production using triploid organisms (3N) is a better alternative than diploid culture (2N). Since the first ones -partially or sterile- do not develop gametes and grow more because this energy is redirected towards more somatic tissue formation (Allen &

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Downing 1986, Allen et al. 1989, Ibarra et al. 2017, Wadsworth et al. 2019). On a global scale, 3N spat shows an advantage in growth, meat quality, and survival. Additionally, its performance varies with environmental conditions and handling practices carried out during farming- sometimes without having apparent performance advantages concerning 2N (Allen & Busheck 1992, Wadsworth et al. 2019). In northwest Mexico, the only reported work that determined the performance of 3N *C. gigas* -validated by flow cytometry- was performed by Ibarra et al. (2017), where 2N *vs.* 3N performance was assessed in oysters reared in tropical and temperate environments. These authors found that under temperate conditions, 3N individuals attained a 4% lower growth rate measured by shell height and a 6% greater weight increase than those of 2N individuals. Whereas in sites with tropical environments, slow growth was observed in both 2N and 3N compared to those farmed in temperate sites. However, 3N in this condition gained 64-70% more weight per month than 2N.

Currently, in Mexico, the productive sector has been facing uncertainty about using 3N organisms (BCS Oyster Product System Master Program 2011; Ibarra et al. 2017) since performance varies depending on the seeding date and environmental characteristics of each cultivation site (Ascencio-Michel 2008). This situation has caused several new aquaculture oyster farms to fail by not considering the possible scenarios previously outlined (Kam et al. 2003, Molina et al. 2012). However, decisions, in general, continue to be made under assumptions of certainty, especially through previous experience or that of other farmers.

Thus, for aquaculture purposes in Mexico, some authors have recommended that spat should be stocked in winter and harvest time done in early summer, avoiding low growth rate and high mortality associated with summer months (Chávez-Villalba et al. 2005). This suggestion implies a reduction in risks and farm productivity concerning maintaining production throughout the year and stocking in April and October, dates in which spat is available in the region (Chávez-Villalba 2014).

Several research works have been performed in northwestern Mexico to optimize *C. gigas* production, among which studies on growth, reproduction, productive systems and temperature tolerance are found (Ochoa-Araiza & Fimbres-Peña 1984, Cáceres-Martínez et al. 1988, 1990, Hoyos-Chairez 2004, Sicard et al. 2006, Góngora-Gómez et al. 2012, Chávez-Villalba 2014). However, the decision on the type of spat to use on a production scale becomes complex due to mixed growth results and the higher price of 3N seedlings. Hence, the spat selection decision carries a financial risk in biotechnology (Chávez-Villalba 2014). Aquaculture dynamic simulation is a valuable and easy-to-use tool for decision-making (Pomeroy et al. 2008, Araneda et al. 2011, Molina et al. 2012). Simulations are generated from mathematical models parameterized with historical information on production (data) or technical information and pilot-experimental studies. Dynamic simulation allows a cost-effective evaluation of different productive scenarios "*in silico*" that generate valuable insight for decision-making (Araneda & Rodger 2013). Consequently, simulating production scenarios is an option for generating information for decision-making related to oyster spat selection in different management scenarios and site conditions (Perez 2014).

Therefore, in this study, the growth and survival experimental data of the article by Ibarra et al. (2017) was used to parameterize mathematical models that describe the most relevant biological processes and environmental parameters of oyster production in northwestern Mexico. Subsequently, 3N spat performance should be evaluated through a dynamic simulation concerning 2N spat for Pacific oyster production at a commercial scale in sites showing different environmental conditions and two stocking dates depending on spat availability by oyster production laboratories in northwestern Mexico.

MATERIALS AND METHODS

Data collection

As previously mentioned, the experimental growth and survival data used in this study come from Ibarra et al. (2017), where an experiment was performed in three production sites in Mexico: Bacorehuís, Sonora (Baco), Ceuta, Sinaloa (CEU), and Rancho Bueno, Baja California Sur (RB). However, for this study, the CEU location was ruled out since, as mentioned by the author, mortality was due to a pathogen recorded in the area (OsHV-1). Only were two Baco and RB (Fig. 1) farming sites used to parameterize a model and project dynamic simulations at commercial-scale performance for diploid and triploid oysters. Monthly satellite-derived datasets (1 km resolution) of sea surface temperature (SST) [2000-2016] (merged data from MODIS-Aqua and MODIS-Terra) and chlorophyll-*a* (Chl-*a*) [1997-2016] (multisensor merged Chl-*a*, from SeaWiFS, MERIS, MODIS-Aqua, and MODIS-Terra) were used.

Productive performance: a conceptual and mathematical model

The production model describes the individual growth and survival of 2N and 3N *Crassostrea gigas* in two

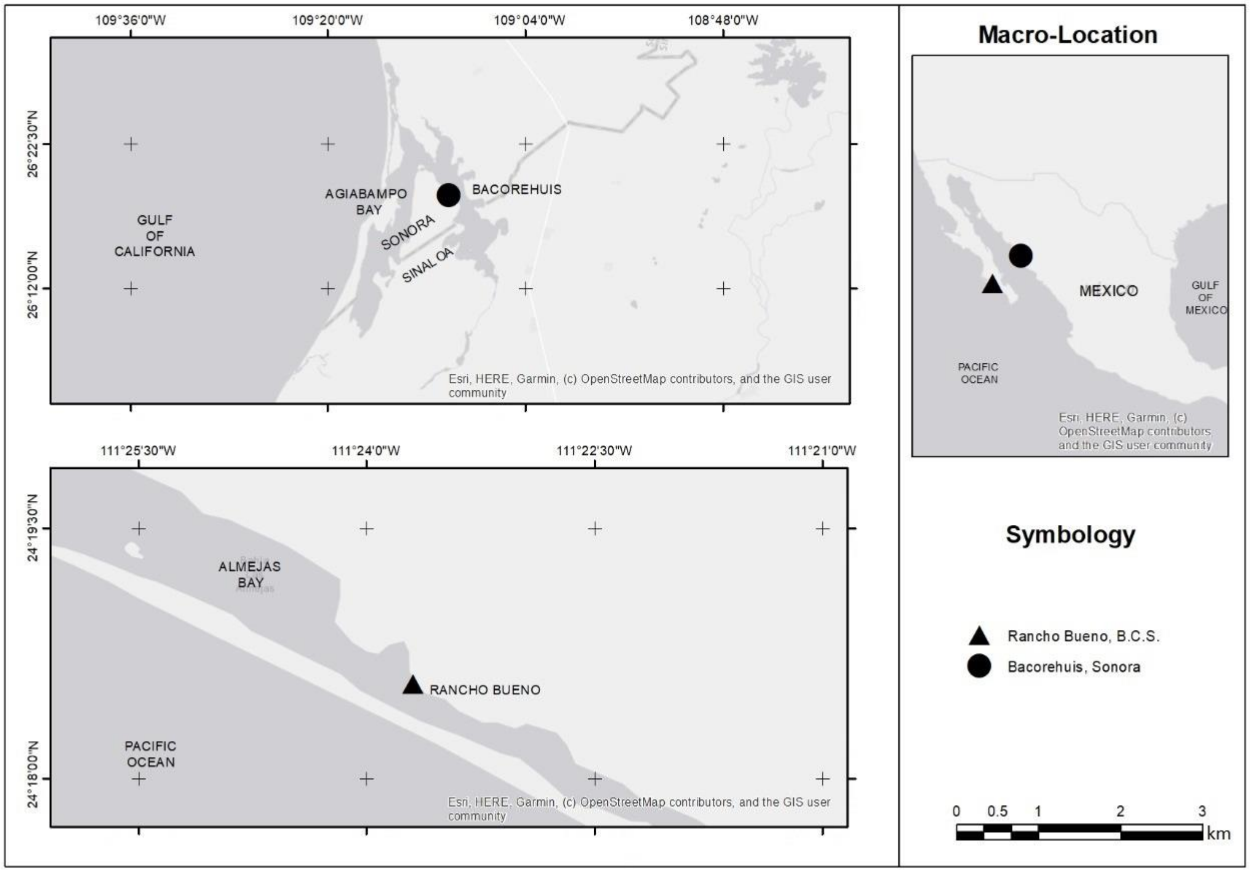

Figure 1. Location of the rearing sites where Pacific oyster *Crassostrea gigas* growth was evaluated in northwest Mexico. ▲: Rancho Bueno (RB), Baja California Sur; ●: Bacorehuís (Baco), Sonora, México.

farming zones. For this purpose, the model includes three sub-models: a) environmental, b) biological, and c) technological. The environmental sub-model influences the performance of the biological sub-model (growth, survival, and condition index). On the other hand, the technological sub-model comprises harvest decisions, such as minimum harvest size and meat quality (condition index) for commercialization at each site (Fig. 2).

Environmental sub-model

Surface sea temperature

SST seasonality was simulated for each site through a cyclical function for 12 months. The equation was modified from Anderson & Seijo (2011):

$$SST_t = \tau + \alpha Sine\left(2\pi \frac{t}{12}\right)$$

where τ is the ten-year average of the estimated temperature for each location; $\boldsymbol{\alpha}$ corresponds to amplitude, and *t* is time in months.

Chlorophyll-*a* (Chl-*a*) concentration

A circular function with the sine and cosine element and 12 months was parameterized to simulate Chl-*a* fluctuations. From observed data, different functions follow for each location.

Bacorehuís:

$$\text{Chl-}a = \alpha + \beta * \sin\left(\frac{2\pi t}{12}\right) + \delta \cdot \cos\left(\frac{2\pi t}{12} \text{Chl-}a\right)$$

Rancho Bueno:

$$\text{Chl-}a = \frac{1}{\alpha + \beta * \sin\left(\frac{2\pi t}{12}\right) + \delta * \cos\left(\frac{2\pi t}{12}\right)}$$

where in both functions, *t* represents the month of the year; β and δ describe the oscillation magnitude, and α is the intercept.

Biological sub-model

Growth

Three models that describe growth in *C. gigas* height (von Bertalanffy, logistic, and Gompertz) were compa-

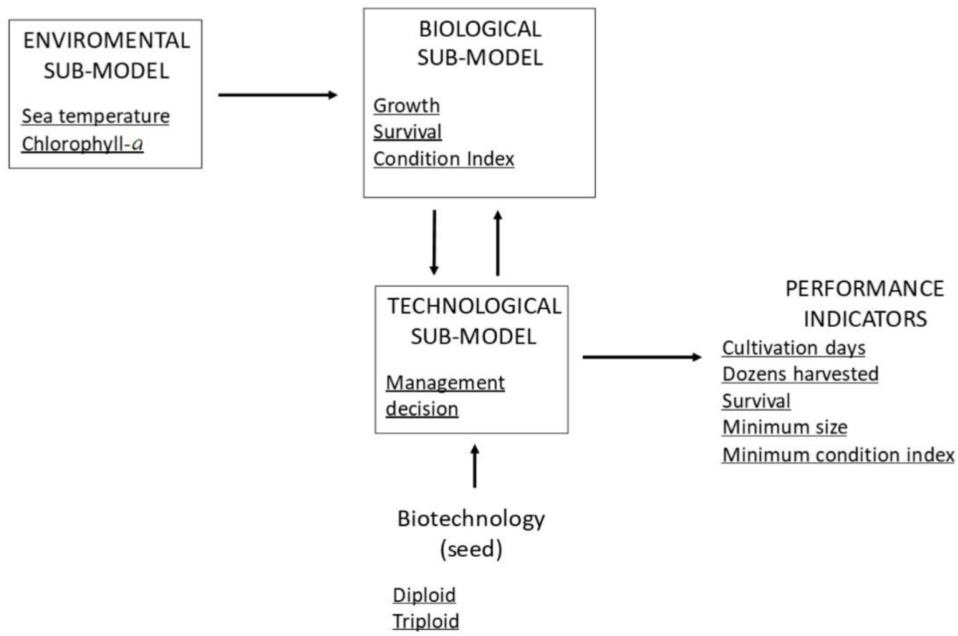

Figure 2. The conceptual diagram with the structure of the environmental, biological, and technological sub-models represents the operation of the Pacific oyster *Crassostrea gigas* production unit and its relationship with the environment.

red, modifying the equations to include seasonal behavior of the growth constant (K) in response to food availability (Chl-*a*).

von Bertalanffy

$$L_t = L_\infty \times (1 - exp^{(-(K) \times t)})$$

Logistic

$$L_t = \frac{L_\infty}{(1 + \gamma \times exp^{(-(K) \times t)})}$$

Gompertz

$$L_t = L_\infty \times exp^{(-\gamma * \exp(-(K) \times t)})$$

where L_∞: asymptotic mean size; *K*: growth rate related with Chl-*a*; γ: serves as a free parameter for equation fit, and *t*: time in days.

As mentioned earlier, the effect of Chl-*a* on oyster growth was included by modifying the *K* parameter of von Bertalanffy, logistic, and Gompertz functions. This correction represented the change in growth influenced by Chl-*a* and expressed as the linear function:

$$K = \alpha + \beta \times \text{Chl-}a$$

where α and β correspond to the intercept and slope, respectively.

Survival

Survival during the rearing cycle, data come from the counts of stocking and recovered organisms, monthly adjusting densities as described by Ibarra et al. (2017). The monthly survival observations allowed parameterizing an exponential extinction function:

$$N_t = N_0 \times \exp(-(M) \times t)$$

where N_t represents the number of organisms at time *t*; N_0, stocking quantity; *M* instantaneous mortality coefficient, which was related to *SST* by the following linear function:

$$M = \alpha + \beta \times SST$$

where SST corresponds to observed sea surface temperature; α and β to the intercept and slope of the equation, respectively.

Condition index

Condition index is useful for recognizing mollusk nutritional condition and determining meat quality for commercialization (Crosby & Gale 1990). Thus, the condition index was represented using the following exponential equation:

$$CI = \alpha \times L_t{}^{\beta} \times \gamma^{ln(SST)}$$

where *CI* denotes condition index; L_t, growth parameter in height; *SST* mean temperature; and *α, β,* and *γ,* free parameters for equation fit.

Technological sub-model

Staff from different spat production laboratories were interviewed, and traders from each production zone were to establish consumer preferences at each location. From the above, harvest decision variables were established for each zone, such as minimum harvest size (Baco: 6 cm, RB: 8 cm) and minimum condition index (Baco: 0.15%, RB: 0.16%).

The goodness of fit and validation of simulation models

Each function fit was performed using non-linear regression methods (Seber & Wild 1989) by reassigning a loss function (v. gr. minimum squares). The significant fit of the functions was evaluated through a one-way analysis of variance (ANOVA) ($\alpha = 0.05$). The statistical significance of the free parameters was evaluated using the t-Student test ($\alpha = 0.05$).

Three information criteria were used to choose between the three growth functions (i.e. R2a, Akaike information criterion (AIC), and bayesian information criterion (BIC)). The goodness of fit indicators used were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistics. The acceptable proportional reduction of PRMSE was assumed in values lower than 30%, and Thiel statistics in less than 0.2, following the recommendations of Roff (1983) and Power (1993). The latter is a non-parametric estimator with an interval of possible values ranging from 0 to 1. It measures the discrepancy between observed and simulated data, where 0 indicates a perfect fit. This estimator is related to the mean squared error (MSE), which is composed of the mean (Bias), variance (VAR), and covariance (COV) (Barlas 1989, Saber & Wild 1989, Pindyck & Rubinfeld 1991, Power 1993, Loría 2007).

Model implementation: performance projections

A one-year simulation was carried out to compare the rearing performance of 2N *vs.* 3N, to understand the dynamics of SST, Chl-*a*, survival, growth in height, and the condition index. A production scenario was proposed for two locations in northwestern Mexico, Baco, and RB, and two stocking dates are given by spat availability from oyster spat production labs (May and October). A simulation of the farm operation was carried out with one million seeds per ploidy using the mean parameters from Ibarra et al. (2017), as well as harvest decision variables, such as minimum harvest size (Baco = 6 cm and RB = 8 cm), and minimum condition index (Baco = 0.15% and RB = 0.16%).

RESULTS

Productive model parameterization

Environmental sub-model.

SST and Chl-*a* concentration

The fit of the environmental function parameters at both sites was statistically significant (Table 1). The

Table 1. Value and statistical significance for sea surface temperature (SST) equation in Bacorehuís, Sonora and Rancho Bueno Baja California Sur, México. $^*P < 0.001$. The free parameter for equation fit were α and τ. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc).

	Bacorehuís	Rancho Bueno
α	-5.322*	-4.238*
τ	25.53	22.26
Goodness of fit validation		
R^2	0.6835	0.8161
r	0.8267	0.9034
RMSE	2.2117	1.2222
PRMSE	1.02%	0.06%
Theil (U)	0.0000	0.0001
Bias	0.0001	0.0034
Us(var)	0.1035	0.0552
Uc(cov)	0.9051	0.9460

Table 2. Value and statistical significance for chlorophyll-*a* equation in Bacorehuís, Sonora and Rancho Bueno Baja California Sur, México. $^*P < 0.001$. The free parameter for equation fit were α, β and δ. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc).

	Bacorehuís	Rancho Bueno
α	2.815*	0.883*
β	1.742*	-0.189*
δ	1.185*	0.679*
Goodness of fit validation		
R^2	0.9410	0.9462
r	0.9701	0.9727
RMSE	0.3736	0.4131
PRMSE	4.35%	58.45%
Theil (U)	0.0020	0.0346
Bias	0.0001	0.0485
Us(var)	0.0179	0.1473
Uc(cov)	0.9835	0.8165

proposed productive model suggests that the minimum temperature at both sites occurred during April (Baco = 20.2°C; RB = 18.02°C), while the maximum temperature occurred during October (Baco = 30.8°C; RB = 26.4°C).

Likewise, the function and fit of parameters for the Chl-*a* function were statistically significant at both sites (Table 2), showing the highest Chl-*a* in February at Baco (4.92 mg m^{-3}), while RB Chl-*a* peaked during

Table 3. Value and statistical significance of free parameters for each *Crassostrea gigas* growth equation in Bacorehuís, Sonora, México. *$P < 0.001$, **$P < 0.05$, ***$P = 0.05$. L_∞ is the average asymptotic length. The free parameter for equation fit were α, β and γ. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc). The used information criteria for model selection were the adjusted R-square statistic (R^2a), Akaike information criterion (AIC) and Bayesian information criterion (BIC).

	Von Bertalanffy		Logistic		Gompertz	
	2N	3N	2N	3N	2N	3N
L_∞	6.3556*	8.2907*	6.6596*	8.5009*	6.7127*	8.6383*
α	0.0279*	0.0204*	2.2181*	2.9638*	1.2819*	1.4901*
β	-0.0017**	-0.0013*	0.0224*	0.0234*	0.0183*	0.0179*
γ	-	-	-0.0000***	-0.0005**	-0.0002***	-0.0007*
Validation						
R^2	0.7488	0.8545	0.7604	0.8636	0.7655	0.8799
r	0.8653	0.9244	0.8720	0.9293	0.8749	0.9380
RMSE	0.8457	0.8737	0.8281	1.0540	0.8062	0.7807
PRMSE	18.47%	18.31%	19.52%	23.44%	21.44%	15.59%
Theil (U)	0.0025	0.0050	0.0033	0.0071	0.0002	0.0018
Bias	0.0023	0.0280	0.0285	0.3793	0.0000	0.0189
Us(var)	0.0119	0.0014	0.0404	0.0023	0.0708	0.0211
Uc(cov)	0.9859	0.9706	0.9311	0.6184	0.9293	0.9600
Selection criteria						
R^2a	0.7482	0.8539	0.7598	0.8631	0.7649	0.8794
AIC	2954.3569	2820.8364	2926.1283	3062.8308	2890.2012	2678.8410
BIC	2968.4107	2839.3274	2940.1821	3081.3218	2904.2550	2697.3319

June (5.62 mg m^{-3}). The lowest Chl-*a* for Baco was in August (0.70 mg m^{-3}), while that of RB was in December (0.62 mg m^{-3}).

Biological sub-model

Growth, survival, and condition index

Estimated and observed data sets were contrasted at both sites and in both ploidies (2N and 3N) with growth functions (Von Bertalanffy, logistic, and Gompertz) that showed significant relationships in all cases (Tables 3-4); the Von Bertalanffy function was selected for subsequent simulations.

The survival function in both production sites and ploidies was statistically significant ($P < 0.001$) in all parameters (Table 5). In the case of the condition index, the adjustment of the parameters in both rearing sites and ploidies was also statistically significant ($P < 0.001$) (Table 6).

Productive performance: comparison between 2N *vs*. 3N

The projected production results in estimated SST and Chl-*a* indicate different behavior at each site and stocking date (Fig. 3). In this dynamic simulation, Baco showed a temperature peak during August-October with values exceeding 30°C and low Chl-*a* availability (0.70 mg m^{-3}). However, during February-April, low temperatures (22°C) and high Chl-*a* availability (4.92 mg m^{-3}) were projected. Thus, the model shows that more food is available at low temperatures and vice versa.

Unlike Baco, the period with low Chl-*a* availability in RB is longer, spanning over five months compared with three of Baco. Lower temperatures (18°C) were expressed during March-April and lower Chl-*a* availability (0.62 mg m^{-3}) during October-February. On the other hand, RB dynamic simulation placed high temperatures (26°C) during September-November and high [Chl-*a*] availability (5.62 mg m^{-3}) during May-July.

The tallest projected shells were those of 3N oysters farmed at RB (9.51 cm), followed by 2N oysters from RB (9.19 cm). However, at Baco, the 2N shell height (6.35 cm) was significantly lower than 3N (8.20 cm) and lower than that of 2N and 3N from RB (Fig. 4).

The highest condition index was estimated for 2N individuals from RB (17.93%), followed by 3N from the same site (17.24%). Baco's 3N condition index was higher than its 2N counterpart, although it was lower than 2N and 3N in RB (Fig. 5).

The dynamic simulation indicates that both RB ploidies show higher survival than those from Baco.

Table 4. Value and statistical significance of free parameters for each *Crassostrea gigas* growth equation in Rancho Bueno Baja California Sur, México. **P* < 0.001, ***P* < 0.05. L_∞ is the average asymptotic length. The free parameter for equation fit were α, β and γ. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc). The used information criteria for model selection were the adjusted R-square statistic (R^2a), Akaike information criterion (AIC) and Bayesian information criterion (BIC).

	Von Bertalanffy		Logistic		Gompertz	
	2N	3N	2N	3N	2N	3N
L_∞	9.2071*	9.5167*	8.9878*	9.3760*	9.0721*	9.4385*
α	0.0190*	0.0223*	4.0331*	3.5999*	1.9063*	1.7967*
β	-0.0004*	-0.0003**	0.0366*	0.0390*	0.0270*	0.0295*
γ			-0.0011*	-0.0010*	-0.0007*	-0.0005**
Validation						
R^2	0.8457	0.9004	0.8290	0.8837	0.8366	0.8914
r	0.9196	0.9489	0.9105	0.9401	0.9147	0.9441
RMSE	0.9814	0.8136	1.0501	0.8814	1.0245	0.8510
PRMSE	18.84%	14.73%	20.27%	16.92%	18.91%	15.71%
Theil (U)	0.0001	0.0013	0.0023	0.0015	0.0022	0.0014
Bias	0.0000	0.0172	0.0284	0.0198	0.0256	0.0192
Us(var)	0.0376	0.0133	0.0231	0.0113	0.0242	0.0127
Uc(cov)	0.9625	0.9695	0.9486	0.9689	0.9502	0.9681
Selection criteria						
R^2a	0.8453	0.9001	0.8284	0.8832	0.8360	0.8908
AIC	3172.8022	2276.1032	3268.7965	2362.5806	3234.4766	2325.3706
BIC	3186.8710	2289.4260	3287.5549	2380.3444	3253.2350	2343.1344

Table 5. Value and statistical significance for survival equation in productive performance of Pacific oyster *Crassostrea gigas*. **P* < 0.001. The free parameter for equation fit were α and β. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc).

	Bacorehuís		Rancho Bueno	
	2N	3N	2N	3N
α	0.0113*	0.0037*	0.0003*	-0.0017*
β	-0.0002*	-0.0000*	0.0000*	0.0001*
Validation				
R^2	0.7488	0.8545	0.8457	0.9004
r	0.8653	0.9244	0.9196	0.9489
RMSE	0.8457	0.8737	0.9814	0.8136
PRMSE	18.47%	18.31%	18.84%	14.73%
Theil (U)	0.0025	0.0050	0.0001	0.0013
Bias	0.0023	0.0280	0.0000	0.0172
Us(var)	0.0119	0.0014	0.0376	0.0133
Uc(cov)	0.9859	0.9706	0.9625	0.9695

Table 6. Value and statistical significance for condition index equation in productive performance of Pacific oyster *Crassostrea gigas*. **P* < 0.001. ***P* < 0.05. The free parameter for equation fit were α and β. The goodness of indicators were the correlation coefficient (r), determination coefficient (R^2), mean square error (RMSE), percentage mean square error (PRMSE), and Theil statistic (U). Which is composed of the mean (Bias), variance (Us), and covariance (Uc).

	Bacorehuís	Rancho Bueno
α	0.359*	0.170*
β	0.118**	0.145**
γ	0.718*	0.896*
Validation		
R^2	0.3185	0.0924
r	0.5643	0.3040
RMSE	0.0129	0.0156
PRMSE	1.04%	1.61%
Theil (U)	0.0004	0.0005
Bias	0.0000	0.0000
Us(var)	0.2898	0.5582
Uc(cov)	0.7162	0.4535

However, 2N survival (87%) at RB was greater than 3N (66%) at the same location. Contrastingly, 2N from Baco showed lower survival (27%) than their 3N counterparts (55%). Therefore, the model suggests that survival varies by ploidy and site (Fig. 6).

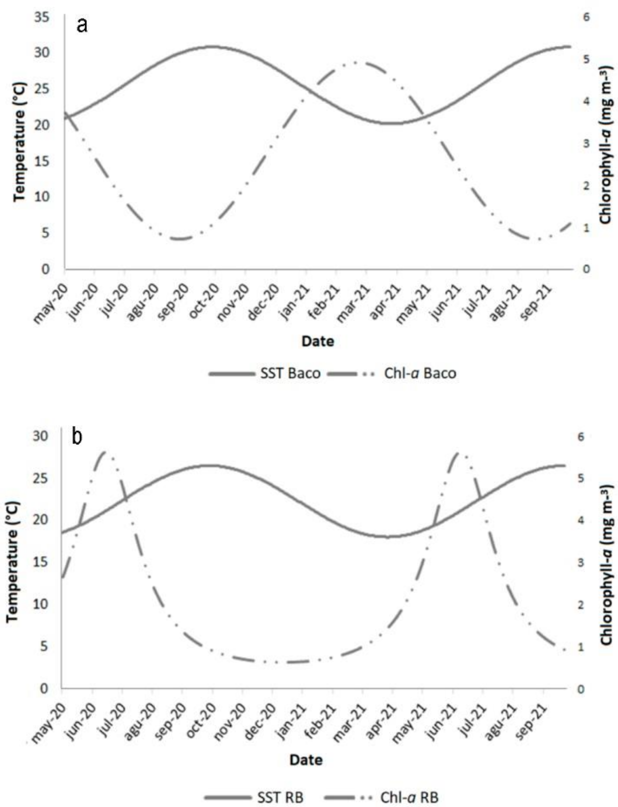

Figure 3. The sea surface temperature (SST) monthly dynamics adjustment model and chlorophyll-*a* in two Pacific oyster *Crassostrea gigas* farming locations in northwest Mexico; a) Bacorehuis, b) Rancho Bueno.

Productive performances on different dates and locations

The results showed growth and performance differences between 2N and 3N stocking at different times (March and October). Generally speaking, 3N showed higher productive performance because of its faster growth, which reduced culture time span; the yield advantage of 3N was observed by the low mortality they showed in contrast to 2N, which showed high mortalities on both cultivation dates.

Nevertheless, regarding the stocking dates carried out in Baco, 3N stocking in May had greater advantages, reducing rearing time and reaching its market size in 52 days with a performance of 74,835 dozen harvested, which agrees with high survival (89.8%) and a condition index of 0.15%. The 3N organism stocking in May was followed by 3N stocked in October, which reached its market size in 69 days, and had a performance of 73,217 dozen harvested and 87.9% survival rate, maintaining the same condition index. On the other hand, 2N organisms showed productive disadvantages when stocking both in October and May. For example, those stocked in October took 129 days to yield 41,225 dozen harvested, with a 49.5% survival rate and a condition index of 0.15%. The lowest productive performance of 2N organisms in May coincided with a long rearing time (256 days) with a performance of 23,885 dozen harvested and a 29% survival, maintaining a 0.15% condition index (Table 7).

Unlike RB, the productive advantage of the Baco model (dozens harvested and survival) occurred mainly with 2N at both stocking dates (May and October). However, the shortest rearing lapse to market size was attained by 3N organisms stocked in October, followed by 3N stocked in May. On the other hand, 2N organisms required longer culture times when stocked in October (117 days) and in May, where culture time was the longest (198 days).

On the one hand, in RB, the 2N stocking in October showed greater survival (95.6%), which resulted in an advantage in dozens harvested (79,678), maintaining a condition index of 17%. In the case of 2N stocking in May, a performance of 76,982 dozen harvested with a 92.4% survival rate and meat index of 0.16% was observed. On the other hand, 3N from RB stocking in October proved more advantageous, with a performance of 72,344 dozen harvested, 86.8% survival, and 0.16% condition index; while its May counterpart showed the lowest productive performance (70,836 dozen harvested, 85% survival, and 0.16% condition) (Table 7).

DISCUSSION

Growth and survival by site

Through dynamic simulation, this study showed *Crassostrea gigas* growth when it was farmed in northwestern Mexico (Bacorehuís and Rancho Bueno) on two commonly used stocking dates by producers (May and October). In this sense, 3N oysters showed productive advantages when cultivated in Baco, such as growth in height, meat index, and survival over 2N and in both stocking dates, same as that concluded before by Ibarra et al. (2017) for the same cultivation sites. These authors evaluated rearing during one season in a seven-month experiment. They only assumed the effect of environmental conditions (SST and Chl-*a*) on growth and survival; therefore, simulating the potentially achievable production as a commercial business in the growing seasons was important in the function of spat availability.

Performing dynamic simulations in growth and survival -in stocking seasons and each cultivation site- is of utmost importance for decision-making, reflected in per dozen harvested and meat index production.

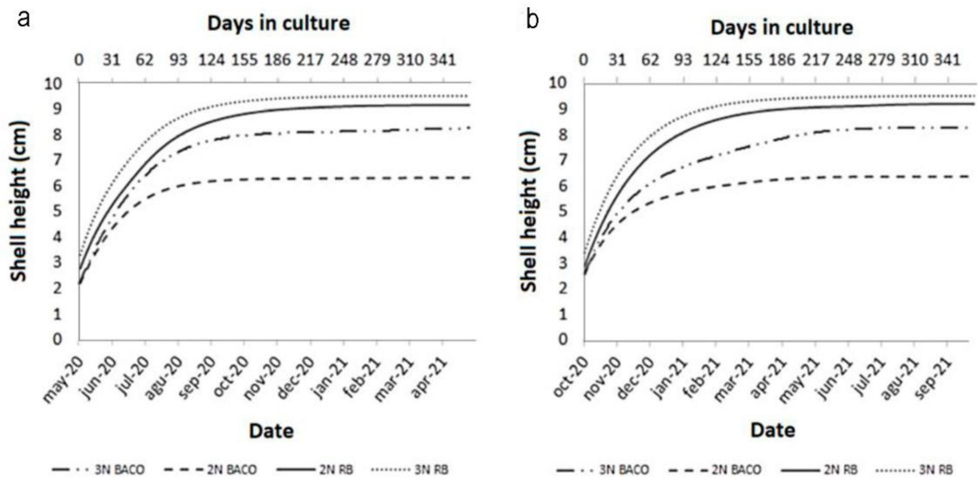

Figure 4. Result of the dynamic simulation of diploid (2N) and triploid (3N) Pacific oyster *Crassostrea gigas* high shell model in two stocking dates and locations in northwest Mexico. Stocking in a) May, b) October.

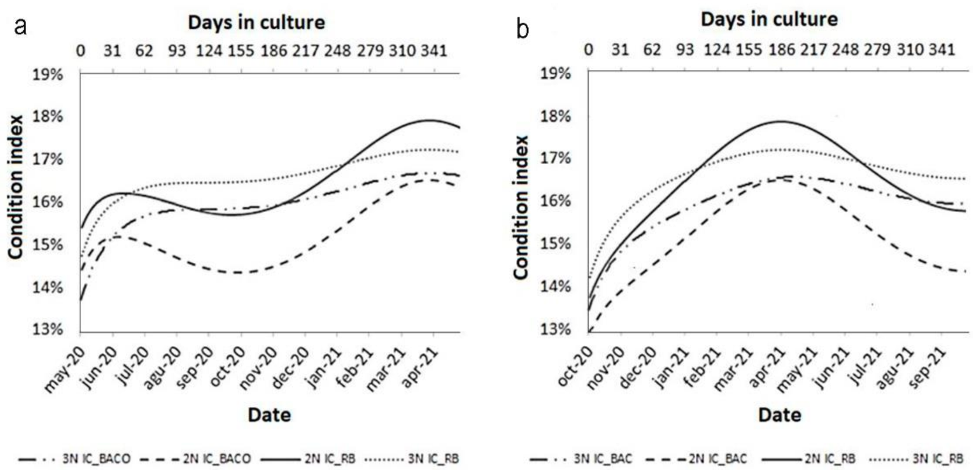

Figure 5. Result of the dynamic simulation of the model in condition index of diploid (2N) and triploid (3N) Pacific oyster *Crassostrea gigas* in two stocking dates and different localities in northwest Mexico. Stocking in a) May, b) October.

When the model was implemented in Baco, it showed that 3N oysters are a better option for production on both cultivation dates because they showed consistent meat quality throughout their growth and the advantage in dozens harvested by the end of the culture cycle projected. This result is mainly due to the breeding season, where partial or total spawning occurs in 2N. Unlike 3N, that are partially sterile, meat quality decreases significantly in 2N (Allen & Downing 1986, Guo et al. 1996, Dégremont et al. 2012), which reflects that 3N can have a shorter growing season and reach market size in less time than 2N (Nell 2002, Molina et al. 2012, Ibarra et al. 2017, Wadsworth et al. 2019).

Concerning RB, similar to Baco, meat quality in 3N was maintained throughout rearing time, unlike 2N. Nonetheless, it did not occur in the same manner in the harvested dozens of oysters where advantage was observed in 2N over 3N, which was reflected in survival and in the high food availability peaks that occur in RB (Martinez-López & Verdugo-Díaz 2000, Ibarra et al. 2017, Wadsworth et al. 2019). A similar report was made by Maldonado-Amparo et al. (2014) with lion's paw scallop (*Nodipecten nodosus*) reared in Rancho Bueno, where 3N did not differ from 2N in growth, arguing that the high food availability in this site allowed diploid clams not to use reserve energy for gonadic maturation.

Therefore, the results in this study showed that implementing dynamic simulations over time for the projection of 2N and 3N *C. gigas* rearing adhered to a

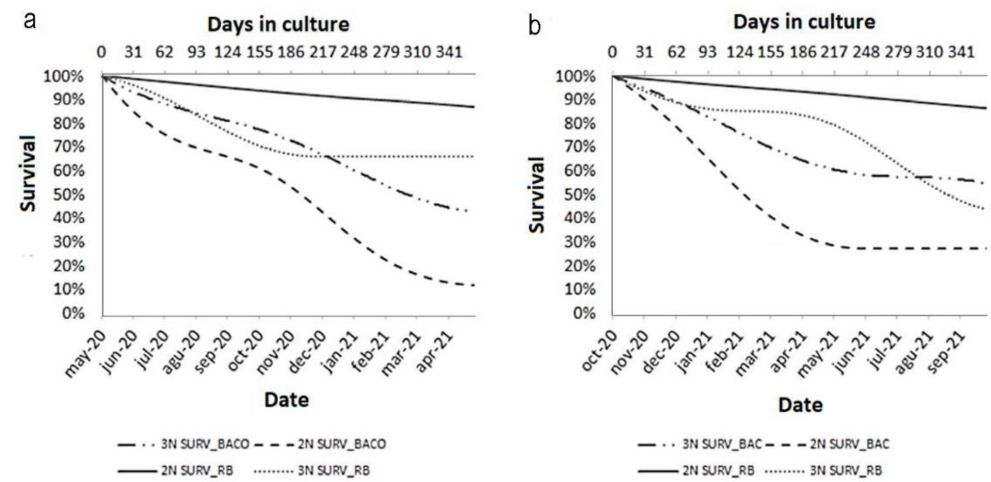

Figure 6. Result of the dynamic simulation of the model in the survival of diploid (2N) and triploid (3N) Pacific oyster *Crassostrea gigas* in two stocking dates and different locations in northwest Mexico. Stocking in a) May, b) October.

Table 7. Productive performance of Pacific oyster *Crassostrea gigas* in Bacorehuís, Sonora and, Rancho Bueno, Baja California Sur, México.

Bacorehuís, Sonora				
Stocking date	May, 1		October 1	
Ploidy	2N	3N	2N	3N
Days culture	256	52	129	69
Harvest date	12/01/2021	22/06/2020	07/02/2021	09/12/2020
Dozen harvest	23,885	74,835	41,225	73,217
Survival (%)	29%	89%	49%	87%
Harvest size (cm)	6.33	6.01	6.00	6.29
Condition index (%)	0.15	0.15	0.15	0.15
Rancho Bueno, Baja California Sur				
Stocking date	May, 1		October, 1	
Ploidy	2N	3N	2N	3N
Days culture	198	86	117	82
Harvest date	15/11/2020	26/07/2020	26/01/2021	22/12/2020
Dozen harvest	76,982	70,836	79,678	72,344
Survival (%)	92%	85%	95%	86%
Harvest size (cm)	9.05	8.52	8.50	8.52
Condition index (%)	0.16	0.16	0.17	0.16

biological reality at both dates and cultivation sites. This information is useful for oyster production because producers can schedule stocking and harvest dates based on environmental conditions. On the other hand, dynamic simulations implementing growth functions and the effect of environmental variables, such as TSS and Chl-*a*, are useful for decision-making, given that yields may be forecasted in each growing site, thus reducing financial risks. Therefore, this research shows that using 3N, according to the projections by dynamic simulation, approximates reality in each rearing site.

In conclusion, 3N rearing did not show a significant growth compared to 2N in the total *C. gigas* production, but productive yields may vary depending on each cultivation site's environmental characteristics (SST, Chl-*a*). Therefore, choosing rearing according to the most important environmental variables is important to decide which type of ploidy to use, either 2N or 3N, to obtain higher yields in the farming cycle. In addition to the above, the spat selection decision becomes even more complex for the producers since it also needs to consider that seedlings from different hatcheries are expected to have different performances, which may vary depending on the areas and dates of harvesting (Reynaga-Franco et al. 2019a,b)

Soon, further research can complement this study by evaluating the anomalies due to climate change or climate events (e.g. ENSO) to assess the farming risks associated with climate change. In addition, an economic analysis could provide information, projecting the production value and economic returns they would offer for better decision-making in the oyster and governmental sectors. Moreover, improvements in production justify the investment in a genetically improved seed.

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