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Research Article

Bioeconomic modeling of optimal harvest time in Nile tilapia (*Oreochromis niloticus*) considering size heterogeneity and minimum marketable size

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ABSTRACT. Size dispersion in farmed fish has a substantial impact on production's bioeconomic performance, directly affecting net profits. This work's objective was to develop a bioeconomic model based on experimental data to identify the optimal harvest time (OHT) for Nile tilapia *Oreochromis niloticus*. The bioeconomic model considered four minimum marketable sizes (*Mms* = 350, 400, 450, and 500 g). Organisms were selected by size with different coefficients of variation (CV). Therefore, they were reared under two growth strategies: heterogeneous size (HT = 44-155 g; CV 25.5%) and homogeneous size (HM = 87-112 g; CV 5.9%). The HT system-generated tradable biomass of 99.30% in an OHT of 196 days with a net profit of USD 3,551.61 and a *Mms* of 350 g. However, the HM system achieved greater marketable biomass (99.53%) in less time (OHT = 181 days) with a net profit of USD 3,327.96 for the same *Mms*. The *Mms* of 500 g had the lowest net benefit in both systems. The HM strategy earned an additional 10.66% of incomes, indicating that the reduction in size dispersion positively impacted profits. The developed model provides a new perspective regarding the management of heterogeneity and size homogeneity in commercial production of Nile tilapia in intensive systems.

Keywords: *Oreochromis niloticus*; tilapia; bioeconomic; size heterogeneity; optimal harvest time; aquaculture

INTRODUCTION

Aquaculture is an essential agricultural practice for food security worldwide (Klinger & Naylor, 2012; FAO, 2016; Føre *et al*., 2018) and Nile tilapia (*Oreochromis niloticus*) is one of the most popular species (Cai *et al*., 2018). Size dispersion occurs naturally in the population of tilapia (Barki *et al*., 2000; Borrego-Kim *et al*., 2020), and directly affects the profitability (Arnason *et al*., 1992), since there is a minimum marketable size (*Mms*) with commercial value. The effect of size dispersion is a recurring phenomenon beyond the inherent stochastic; such as stocking density, feeding conditions, temperature, and ration size (Barbosa *et al*., 2006; Peacor *et al*., 2007; Santos *et al*., 2008; Gullian *et al*., 2012; Gullian-Klanian & Arámburu-Adame, 2013; Domínguez-May *et al*., 2020). The problem of size heterogeneity in aquaculture has been addressed with various management practices, including pre-selection or partial harvests (Palada de Vera & Eknath, 1993; Pérez, 2014) as well as some market strategies (Huang & Chiu, 1997; Gasca-Leyva *et al*., 2008; Domínguez-May *et al*., 2011, 2020).

Population dynamics studies and the determination of the optimal harvest time (OHT) have allowed managing and reducing uncertainty in aquaculture production (Llorente & Luna, 2016). Stochastic bioeconomic models for structured populations based on the weight of organisms make it possible to simulate production and economic performance through the use of probability functions (Martínez & Seijo, 2001; Seijo, 2004; Sánchez-Zazueta & Martínez-Cordero, 2009; Shamshak & Anderson, 2009; Moreno-Figueroa *et al*., 2018; Núñez-Amao *et al*., 2019). For this purpose, discrete and continuous models are used; for example,

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discrete models have been used for Atlantic salmon (Forsberg, 1996, 1999) and continuous models for shrimp and tilapia, which have considered the initial population density (Gasca-Leyva *et al*., 2008; Domínguez-May *et al*., 2011; Araneda *et al*., 2013). Continuous models compared to discrete models offer the advantage of predicting future values because they can simulate population variation based on weight and time by using a normal distribution, which is relevant for sowing and selective harvesting (Arnason *et al*., 1992). Other authors have applied for the same purpose, the Generalized Linear Model Method (Briceño *et al*., 2010) and quantile regressions (Mayer *et al*., 2009; Estruch *et al*., 2017; Jover, 2017).

Most of the current bioeconomic models consider the effect of the initial variation of organisms' size, neglecting the influence that this effect can have over time. Incorporating this factor into models can improve the estimation of marketable biomass, relevant information to determine the OHT. Nile tilapia models have not yet considered a continuous approach structured by weight to address this problem.

In previous works, we calculated the bioeconomic effect of size heterogeneity on commercial production of Nile tilapia. We demonstrated that the quasi-benefit of variable costs had an inversely proportional relationship with the minimum market size (Borrego-Kim *et al*., 2020). In this study, we use the results obtained previously to develop a bioeconomic model that includes the dispersion of size and *Mms* in the production of Nile tilapia and thus provide data on net profit.

MATERIALS AND METHODS

Data source

The data used to perform the bioeconomic modeling comes from an experimental study conducted in a commercial tilapia farm (Yaxchilam Farm, Yucatan, Mexico) from February 2015 to January 2016 for 330 days (Borrego-Kim *et al*., 2020). The organisms were obtained from a batch of 100,000 sex-reversed Nile tilapia (*Oreochromis niloticus*) fingerlings (Spring Genetics). Briefly, the experimental design consisted of two treatments with the same population density (40 org m^{-3}; 180 fish) and three replication *per* treatment. Two seeding strategies were used: heterogeneous seeding (HT) (44-115 g body weight (BW)) and homogeneous seeding (HM) (87-112 g BW). The experimental units consisted of 1,700 L tanks with a depth of 0.75 m and a diameter of 2.13 m. A 5.0 HP blower was used to maintain aeration. The area was covered with a shade mesh (70% sun protection). The feeding rate was 3% of the biomass distributed three times during the day. The fish were fed a commercial floating pellet containing 35% crude protein and 3,152 kcal kg^{-1} as metabolizable energy. During the first 26 weeks, the fish were fed 3% of initial biomass; after, the feeding rate was adjusted to 2% until ending the experiment.

All the fish of each treatment were weighed every 15 days. The procedure consisted of lowering the water level of each tank, taking out all the fish with a net of 1.0, and dividing them between rectangular tanks of 72×40×35 cm with aeration to reduce stress. The mortality rate at the final of the experiment was 3.89 and 2.33% for HM and HT, respectively. For more details, see Borrego-Kim *et al*. (2020).

Model description

The experimental data was used to build a bio-economic model. The variables considered were weight, stocking density, feed conversion ratio, and marketable sizes.

Biologic sub-model

The von Bertalanffy model (Von Bertalanffy, 1957) was applied to describe the growth of fish in each population. This model was selected according to the results obtained by previous authors for several commercial tilapia strains (Allaman *et al*., 2013; Zuniga & Goycolea-Homann, 2014).

The biological sub-model included the effect of the variation in size in the instantaneous individual growth rate.

This effect considers the dispersion of size in growth during a specific period (Pérez, 2014).

$$\frac{dx}{dt} = g(x) \pm \varepsilon \qquad x(0) = x_0 \tag{1}$$

where $g(x)$ represents the growth rate, $\varepsilon \equiv \eta(t,x)$ represents the deviation of the instantaneous individual growth rate, and $x_0 > 0$ represents the initial size of the individual at $t = 0$. It is assumed that $g(x)$ it is continuously differentiable and has a positive value in the $[0,\omega]$ interval, $g(0) = g(\omega) = 0$ where ω represents the maximum size of the fish $(\omega > 0)$. The deviation of the growth rate (Equation 1), was modeled as follows, with an equation similar to the one proposed by Pauly & Gaschutz (1979):

$$\eta(t,x) = w_0(x_0) + Ae^{-\delta x}\cos\left(2\pi(t-B)/\mathrm{C}\right) \tag{2}$$

where $w_0(x_0)$ represents the linear effect of the variation (initial deviation) of the initial size x_0, which is similar to the linear function for average absolute value for variation proposed by Gulland (1971). A, B, and C are parameters, while δ is the average change rate of the variation coefficient for the empirical data and can be described as $\delta = \Delta CV(t)/t$; the used coefficient is defined as $CV(t) = s_{x(t)}/\overline{x}$, where $s_{x(t)}$ represents the standard deviation of fish size and $\overline{x}$ represents the average fish size. The change of *CV(t)* in time was described as $\frac{d(CV(t))}{dt}$. To find the linear relationship of w_0, the following equation was used

$$w_0(x_0) = mx_0 - n \tag{3}$$

where m is the slope (rate of change) and n is the y-intercept; Equation 3 represents the initial variation in sizes.

Equation 1 was integrated by the Microsoft Excel Software through the Euler method assuming a time value of one day $(d\tau = 1)$

$$x(t) = x_0 + \int_0^t \{g(x(\tau)) + \eta(\tau, x(\tau))\} d\tau \tag{4}$$

Management sub-model

The initial population density represented as N_0 had the same value for the HT and HM system. The observed variance for this parameter was higher in the HT system (HM variance < HT variance, $P < 0.05$), as was expected. The *Mms* delimited the $x(t)$ value.

The model by Gasca-Leyva *et al.* (2008) describes the function for the number of organisms with different *x* sizes at a time *t*, as:

$$N_t(t,x) + (g(x)N(t,x))_x = -\mu N(t,x)$$
$$0 < x < \omega,\ t > 0 \tag{5}$$
$$N(0,x) = N_0 \nu_0(x)$$
$$N(t,0) = 0$$

where μ represents the instantaneous mortality rate $(\mu \geq 0)$, which is assumed to be independent of the organism's size.

The two conditions followed by this model are a) the distribution of sizes N_0 is dependent on the probability density function (PDF) $\nu_0(x)$, and b) there is no introduction of new organisms to the system. The partial derivatives of the model indicate that through time the growth of the organisms follows Equation 1; this suggests that the initial variability of the system determines heterogeneity. The β coefficient, a PDF, considers the different *Mms*; this can be seen in the following equation:

$$\nu_0(x) = \frac{1}{x_1 - x_0} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{x - x_0}{x_1 - x_0}\right)^{\alpha-1} \left(1 - \frac{x - x_0}{x_1 - x_0}\right)^{\beta-1} \tag{6}$$

with $\Gamma(\alpha) = \int_0^\infty e^{-x} x^{\alpha-1} dx$; $x_0 < x < x_1$; $\alpha, \beta > 0$.

where x represents the fish size, Γ represents the gamma function, x_0 and x_1 represents the initial range for the deduction period of growth, α and β are defined by $\alpha(x) = \alpha_1 e^{-\alpha_2 x}$ and $\beta(x) = \beta_1 e^{-\beta_2 x}$. These equations indicate that size heterogeneity over a determined period depends on the initial variability of the organisms and other factors involved in the population dynamics of fish.

The equation for the biomass of the organisms over time *t* is:

$$B(t) = \int_0^\omega x(t) N(t,x) dx \tag{7}$$

where ω represents the maximum size of the fish ($\omega > 0$).

Economic sub-model

Biomass value: the assumptions used for the economic sub-model are found in Table 1. The value of biomass over time was determined by the sum of all individual values (by size) at a specific time in time once organisms reach the *Mms*. Biomass was established as independent of size.

This equation is represented as

$$V(t) = p\int_0^w x(t) N(t,x) dx \tag{8}$$

The considered costs are the feeding costs f(x), the labor cost c_L, and the energy cost c_E. Therefore, the total accumulated at *t* days is given by

$$C(t) = \int_0^t e^{-\rho\tau} \left(\int_0^\omega f(x) N(\tau,x) dx + c_L + c_E \right) d\tau + c_0 + c_F \tag{9}$$

where ρ represents the daily discount rate, c_0 represents the cost of the fry, and c_F represents the fixed costs (depreciation of the infrastructure and the motor pumps). For calculating the feeding costs the feed conversion index ξ was used, this indicates the ratio between food intake and the size increase of an organism, as shown in the following equation:

$$f(x) = c_f \xi \{g(x) + \eta(t,x)\} \tag{10}$$

c_M is the cost of individual maintenance of the fish per kg C_f represents the cost per kg of food.

Net benefit: for this model, a single production cycle is considered. The discounted profits function is given by:

Table 1. Assumptions used for bioeconomic modeling optimal harvesting time in Nile tilapia (*Oreochromis niloticus*) considering size heterogeneity and minimum marketable size. [a]Includes the maintenance costs of the infrastructure. [b]Includes the investment interests and the depreciation of the infrastructure and the motor pumps.

Parameter	Symbol	Unit	Value
Maximum selling price	p	USD kg^{-1}	2.31
Fry cost	C_S	USD fry^{-1}	0.28
Labor cost	C_L	USD d^{-1}	10.28
Energy cost	C_E	USD d^{-1}	3.25
Feeding costs	C_f	USD kg^{-1}	0.64
Maintenance cost[a]	C_M	USD kg^{-1}	0.001
Fixed cost[b]	C_F	USD cycle^{-1}	1,232.31
Instantaneous mortality rate	μ	Fish d^{-1}	0.00067
Discount rate	r	% year^{-1}	7.5

$$\begin{aligned} &\text{Max} \quad \prod_{t\geq 0}(t) = e^{-\rho t}V(t) - C(t) \\ &s.a. \\ &x(t) \geq x_{TMM} \end{aligned} \tag{11}$$

where $\prod$ is the net benefit at time t, e is the base of the Napierian logarithm, $p = (1+r)^{1/365}-1$ is the daily discount rate, $V(t)$ is the value of the biomass, $C(t)$ is the total cost of the production cycle, $\chi(t)$ is the size of fish through time, and χ_{TMM} is the minimum marketable size.

Statistical analysis

The growth model's parameterization was performed with Statistica version 12 (StatSoft Inc., Tulsa, OK, USA). The bioeconomic model was made in Microsoft Excel. The accuracy of the model was validated by the prediction of known patterns (Power, 1993; Hernández & Gasca-Leyva, 2003). The coefficient of determination (R^2), the mean square error (RMSE), and the Theil's inequality coefficient (U) were used to adjust the growth model (Barlas, 1989). The RMSE is usually divided into three factors that measure the proportion of bias in the average, variance, and covariance. The inequality coefficient U is limited between 0 and 1; a value of zero indicates that the model accurately predicts real values, while a value of 1 means the opposite (Pindyck & Rubinstein, 1998).

Ethical approval

The experiments performed were following the National and Institutional guidelines for animal welfare. The tests described complying with the Manual of Good Practices in Aquaculture Production of Tilapia for Food Safety described by García-Ortega & Calvario-Martínez (2008).

RESULTS

Growth model

Table 2 shows the values of the parameters of the von Bertalanffy growth model. All parameters were statistically significant. The statistical indicators of the Theil inequality index and its components are in Table 3. In HT and HM systems, the growth simulation model explained between 92 to 98% of the observed data variation, except for in HM with 89.4%.

Optimal harvest time

Figure 1 shows the relative proportion in time between the HM and HT systems of individuals that did not reach the minimum market size. After 150 days and until the end of growth, the HT system had a higher percentage of organisms that did not reach the limit reference point identified as the *Mms*.

Figure 2 shows the distribution of organisms by *Mms* for each system, where the vertical dashed line represents the OHT; the HT system shows greater dispersion.

In the HT system, the highest gain was obtained in the *Mms* 350 g in an OHT of 196 days and a net profit of USD 3,551.61, while the profit generated in 500 g was negative (Table 4). The CV in HT showed a significant decrease. Marketable biomass varied between 91.1 and 98.3% between HT and HM.

Table 5 shows the estimates of OHT in a culture cycle in the HM system. The results show that OHT increases as the *Mms* increases. The maximization of the net gain indicated a higher profit with USD 3,327.96 in the *Mms* of 350 g and a harvest time of 181 days. The lowest benefit of USD 615.43 was obtained in the *Mms* = 500 g and with an OHT of 221 days. The CV remained around 30% and decreased slightly as the harvest day increased. Although the range of marketable

Table 2. Estimated parameters of the von Bertalanffy growth model of Nile tilapia (*Oreochromis niloticus*) from two seeding strategies: homogeneous seeding size (HM) and heterogeneous seeding size (HT). [a]Values estimated from the experimental data. [b]Values estimated with Excel's function solver by the least-squares method. PDF: Probability density function.

Parameter	Symbol	HM		HT	
		Estimated value	*t*-value	Estimated value	*t*-value
Catabolism parameter	a	0.1651	3.56	0.1464	4.39
Anabolism parameter	b	0.0155	2.82	0.0132	3.39
Initial variation slope	m	0.1078	18.15	0.0212	15.07
Ordinate of the initial variation	n	-10.67	-17.94	-2.04	-13.89
Average instantaneous rate	δ	0.00049[a]		0.00003[a]	
Calibration parameter	A	1.24[b]		0.75[b]	
Calibration parameter	B	124.26[b]		93.48[b]	
Calibration parameter	C	230.93[b]		281.79[b]	
Constants for the (α)	α_1	3.76	11.40	2.52	16.71
Parameter of the (α) PDF	α_2	0.00041	2.16	0.00029	2.50
Constants for the (β)	β_1	4.18	3.95	3.62	12.59
Parameter of the (β) PDF	β_2	0.00090	1.47	0.00101	5.53

Table 3. Results of the validation of the von Bertalanffy growth model of Nile tilapia (*Oreochromis niloticus*) from two seeding strategies: homogeneous seeding size (HM) and heterogeneous seeding size (HT).

Statistical validation parameters	Symbol	HM				HT			
		Estimated value				Estimated value			
		Q_1	Q_2	Q_3	X_{MAX}	Q_1	Q_2	Q_3	X_{MAX}
Root mean square error	RMSE	52.74	64.70	38.63	135.01	41.72	32.05	37.16	116.17
Theil index	U	0.1234	0.1303	0.0671	0.1810	0.1039	0.0654	0.0647	0.1579
Average component	U^M	0.7649	0.7859	0.4091	0.3645	0.6371	0.5023	0.0482	0.4375
Variance component	U^S	0.0532	0.0022	0.0325	0.4017	0.0895	0.0076	0.3903	0.4793
Covariance component	U^C	0.1818	0.2119	0.5584	0.2339	0.2733	0.4901	0.5614	0.0832

biomass was 93.9-99.4%, it was maximized based on the minimum size.

Sensitivity analysis

The sensitivity analysis results are summarized in Table 6, in which the most influential economic factors in the tilapia culture system are established. This analysis showed that for both HT and HM, the product's price is the commercial parameter that most contributes to the variation in net profit. To a lesser extent, changes in the OHT impact on the *Mms* 350 and 400 g, while for 450 and 500 g, it did not reflect any changes.

DISCUSSION

This work's main contribution is a bioeconomic model for size heterogeneity using a continuous population model that reflects the effect of economic performance on tilapia (*Oreochromis* spp.) farming. The proposed growth model is not linear and includes the deviation factor of the similar size used by Pérez (2014). The model more accurately predicts the size range at the end of the growth period, which is useful for the industry. Understanding size dispersion lowers economic risk, especially at the time of return on investment.

The problem of heterogeneity was previously addressed for tilapia and white shrimp (*Penaeus vannamei*) using size-structured bioeconomic models, where the leading cause of this phenomenon was environmental (Araneda *et al*., 2008, 2011; Gasca-Leyva *et al*., 2008; Domínguez-May *et al*., 2011). Most known models for size dispersion only consider the total biomass harvested, without analyzing the effect that minimum marketable sizes have on this value (Forsberg & Guttormsen, 2006; Araneda *et al*., 2011; Domínguez *et al*., 2011). Our bioeconomic model simulates size dispersion and heterogeneity, focusing on the minimum marketable size, which helps farmers estimate their earnings based on these parameters.

The work results showed a direct positive relationship between the dispersion of the fish size and the optimal harvest time. The benefits generated by the

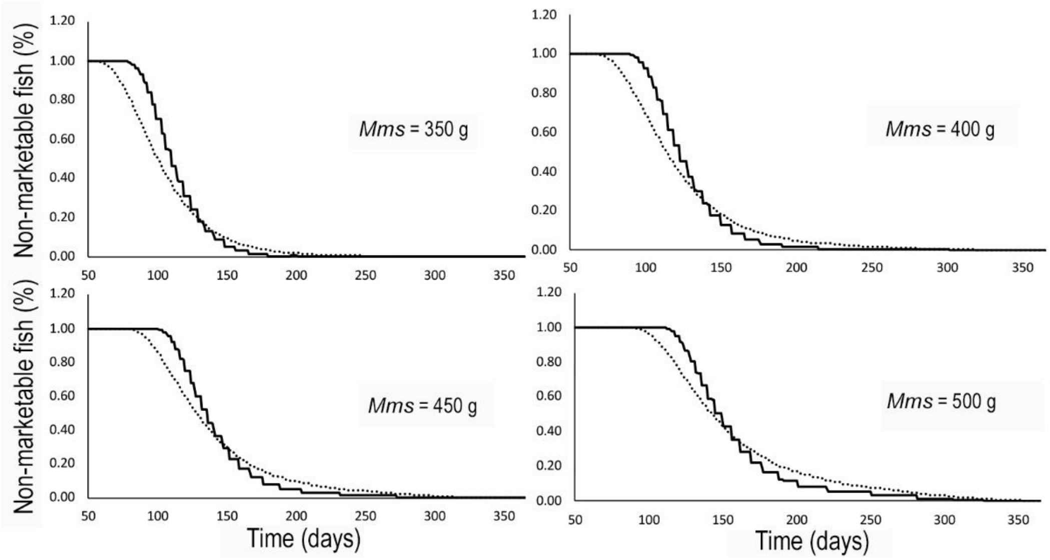

Figure 1. Percentage of fish that do not reach the minimum marketable size in homogeneous (-) and heterogeneous (..) stocking strategies.

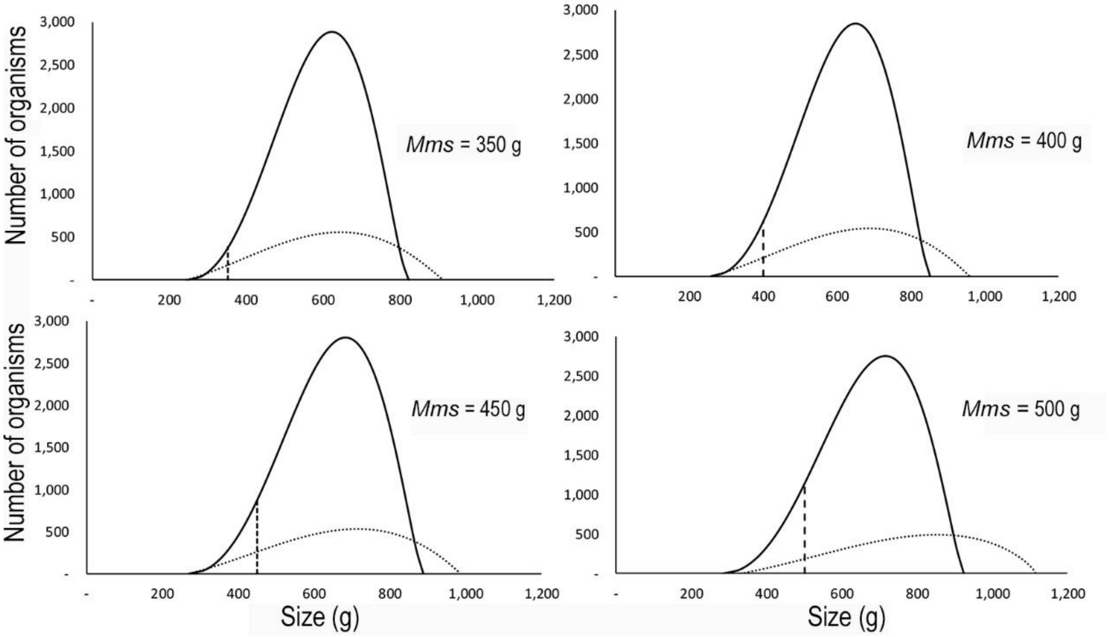

Figure 2. Organisms distribution by minimum marketable size (*Mms*) in the homogeneous (-) and heterogeneous (..) seeding strategies. The vertical dashed line represents the optimal harvest time (OHT).

HT system were lower than those obtained by the HM, possibly due to the reduction in marketable biomass and its impact on economic performance. The OHT for the HT system was 196-229 days for the *Mms* of 350, 400, and 500 g. This time was shorter in the HM strategy, where the OHT was 181-221 days for *Mms* 350, 400, and 450 g. The *Mms* = 500 g presented a negative net profit of USD 235.96 in the HT system, while in the HM, the net profit was USD 615.40. The economic results are consistent with the conclusions of Pérez *et al.* (2012) and Borrego-Kim *et al.* (2020), in which they indicated that heterogeneity harms the optimization of biomass and yield as a function of time.

The OHT and final weight were higher in the HT system than in the HM. The average sizes observed in the HT system for the *Mms* of 350, 400, 450, and 500 g were 628.84, 664.30, 685.04, and 793.05 g, while in HM, the observed values were 570.31, 593.63, 619.57 and 647.28 g. Bjørndal (1988), deduced that the OHT and size increase with variable prices. The present model

Table 4. Optimal harvest time (OHT) of Nile tilapia (*Oreochromis niloticus*) from heterogeneous seeding size (HT) considering minimum marketable sizes.

Parameter	Unit	Minimum marketable sizes			
		350 g	400 g	450 g	500 g
Production					
Optimal harvest time (OHT)	d	196	216	229	296
Min and max weight	g	350.2-912.9	400.9-958.9	450.2-985.8	500.1-116.5
CV	%	29.55	29.14	28.91	27.13
Survival rate	%	87.75	86.58	85.84	82.08
Total biomass	kg	25,243.33	26,470.20	27,639.95	30,516.67
Viable biomass at the OHT	%	99.1	98.3	96.9	98.3
Sales revenue					
Price	USD kg^{-1}	2.35	2.35	2.35	2.35
Biomass value	USD	56,389.48	58,390.06	58,811.39	66,288.58
Costs					
Fixed costs	USD	1,232.31	1,232.31	1,232.31	1,232.31
Food	USD	33,426.31	35,604.51	36,863.14	43,163.18
Maintenance	USD	2,771.64	3,268.49	3,602.07	5,432.52
Labor	USD	1,987.07	2,184.50	2,312.41	2,966.44
Energy	USD	628.04	690.44	73.87	937.58
Fry	USD	12,792.50	12,792.50	12,792.50	12,792.50
Total	USD	52,837.87	55,772.75	56,876.30	66,524.53
Profits					
Net profit	USD	3,551.61	2,617.31	1,278.09	-235.96

Table 5. Optimal harvest time (OHT) of Nile tilapia (*Oreochromis niloticus*) from homogeneous seeding size (HM) considering minimum marketable sizes.

Parameters	Unit	Minimum marketable sizes			
		350 g	400 g	450 g	500 g
Production					
Optimal harvest time (OHT)	d	181	191	204	221
Min and max weight	g	353.1-822.9	400.8-852.9	450.1-887.2	500.7-925.3
CV	%	29.90	29.55	29.31	29.23
Survival rate	%	88.62	88.02	87.26	86.27
Total biomass	kg	24,221.01	25,092.29	25,932.75	26,959.47
Viable biomass at the OHT	%	99.4	98.2	96.2	93.4
Sales revenue					
Price	USD kg^{-1}	2.31	2.31	2.31	2.31
Biomass value	USD	53,902.69	55,416.43	56,751.98	57,700.89
Costs					
Fixed costs	USD	1,232.31	1,232.31	1,232.31	1,232.31
Food	USD	31,873.33	33,390.35	35,075.49	36,873.62
Maintenance	USD	2,257.65	2,495.40	2,815.13	3,247.29
Labor	USD	1,838.48	1,937.59	2,066.14	2,233.74
Energy	USD	581.08	612.40	653.03	706.00
Fry	USD	12,792.50	12,792.50	12,792.50	12,792.50
Total	USD	50,574.73	52,460.55	54,634.60	57,085.46
Profits					
Net profit	USD	3,327.96	2,955.88	2,117.38	615.43

Table 6. Sensitivity analysis considering the price and the main production costs at different minimum marketable sizes (*Mms*). HT: heterogeneous seeding size, HM: homogeneous seeding size; OHT: optimal harvest time.

Mms	Parameter	Concept	Variation (%)	System			
				HT		HM	
				OHT (%)	Net profit (%)	OHT (%)	Net profit (%)
350 g	p	Price	-10	-0.55	-161.42	-3.06	-158.0
			+10	11.05	169.46	8.67	163.17
	c_f	Feeding costs	-10	11.05	101.33	8.67	96.95
			+10	-0.55	95.34	0	-94.12
	c_M	Maintenance cost	-10	1.10	6.85	4.08	-7.80
			+10	-0.55	-6.77	0	8.30
400 g	p	Price	-10	0	-187.48	-6.48	-218.46
			+10	12.57	189.40	7.41	225.46
	c_f	Feeding cost	-10	0.52	112.97	3.70	137.16
			+10	0	-112.96	-6.48	-133.78
	c_M	Maintenance cost	-10	0	8.44	0	12.49
			+10	0	-8.44	0	-12.49
450 g	p	Price	-10	0	-268.03	-3.06	-456.24
			+10	0	268.03	10.04	481.25
	c_f	Feeding cost	-10	0	165.66	10.04	326.85
			+10	0	-165.65	-3.06	-287.01
	c_M	Maintenance cost	-10	0	13.30	0	31.48
			+10	0	-13.30	10.04	-28.18
500 g	p	Price	-10	0	-937.57	-	-
			+10	0	37.57	-	-
	c_f	Feeding cost	-10	0	599.15	-	-
			+10	0	-599.15	-	-
	c_M	Maintenance cost	-10	0	52.76	-	-
			+10	0	-52.76	-	-

did not consider different prices by size in the bioeconomic analysis because in the local tilapia market, the production is sold on-farm through intermediaries, and at a single sale price. However, the studies addressed in these lines of work may be considered in the future. The HM and HT systems' dependence assumed at $t = 0$ and the initial sizes in the 87-112 and 44-155 g intervals, respectively, were similar to the initial sizes considered in our previous work (Borrego-Kim *et al.*, 2020).

The 10% increase in food cost and maintenance showed significant differences in OHT in both strategies. When the price increases (10%), it induces an increase in the growth period in the *Mms* of 350 and 400 g. The OHT of the *Mms* 450 and 500 g were independent of the price changes. The analysis coincided with other short-term bioeconomic studies, where the sale price and food costs are sensitive factors for optimal management (Hernández-Llamas *et al.*, 2004; Saiti *et al.*, 2007; Sánchez-Zazueta & Martínez-Cordero, 2009; Zuniga-Jara & Goycolea-Homann, 2014).

Regarding the selection process, the results coincide with the reports by Azaza *et al.* (2013), and Khaw *et al.* (2016), in which the organisms with less dispersion contributes to obtaining more significant economic benefits. A common practice in aquaculture is to repeatedly select organisms during culture to reduce size variation during growth. This strategy only occurs due to market demand for organisms of uniform size (Sae-Lim *et al.*, 2013). Some authors have suggested that this handling affects the health and well-being of fish (Sanches & Piana, 2019) and generates higher labor costs. The results of the HM strategy in this work demonstrate that the size dispersion is smaller when the biological model considers a low initial distribution.

On the other hand, the observed relationship between OHT and heterogeneity contradicts the results obtained by Araneda *et al.* (2011), and Domínguez-

May *et al*. (2011), for shrimp and tilapia, respectively. Following the recommendation of Peacor *et al.* (2007), those authors considered the dependency period in the data analysis (days affected after storage, $t > 0$), to evaluate the effect of population density and portion size, concluding that heterogeneity reduces the harvest time. Those studies considered the average size of the population, unlike the present work, where we used dispersion indicators. Another difference with the previously cited models is that the current model considers heterogeneity over time, a closer approach to reality than in a specific period.

Growth models that include size dispersion lead to useful and practical recommendations for the tilapia industry. The results showed that the net benefits were significantly higher in the HM system than the HT, which indicates that it is advisable to select individuals of homogeneous sizes to obtain higher profits. Fish that do not reach *Mms* are likely to become an economic loss rather than a benefit. Therefore, it is not recommended to keep them in production as they will negatively affect profitability in the short term. This model can become a reference for practical management decisions in fish populations with heterogeneous growth.

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