Aquaculture 283 (2008) 43–49

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Productivity and profitability of *Mithraculus forceps* aquaculture

Joana Figueiredo [a,*], Gil Penha-Lopes [a], Junda Lin [b], Luís Narciso [a]

[a] Laboratório Marítimo da Guia, Faculdade de Ciências da Universidade de Lisboa, Avenida Nossa Senhora do Cabo, 939, 2750-374 Cascais, Portugal
[b] Florida Institute of Technology, 150W. University Boulevard, Melbourne, FL 32901, U.S.A.

ARTICLE INFO

Article history:
Received 13 March 2008
Received in revised form 27 June 2008
Accepted 29 June 2008

Keywords:
Mithraculus forceps
Management
Model
Ornamental
Production
Profitability

ABSTRACT

Red-clinging crabs *Mithraculus forceps* are used for their ability to control nuisance algae in marine aquariums. Their larval and juvenile culture protocol has already been successfully developed. The objective of this work is to build a model that integrates the effect of different abiotic and biotic factors (temperature, stocking density, prey density), as well as space (number and volume of tanks) in production and economic parameters (costs of feed, labour and maintenance, market price and profit). The model aimed to be used as a tool to support management decisions. Overall, the model was able to integrate previously collected data and produce expected forecasts of *M. forceps* larval and juvenile culture reared under different combinations of temperature, stocking density, and prey density. Sensitivity analysis revealed that temperature was the most important factor regulating survival and growth, and consequently profit. According to the model, a batch of 1500 larvae reared in ten 10 L tanks in optimal conditions (10 prey mL^{-1} and 28 °C) and then, as juveniles, in a 3 m^2 water table at 28 °C, is expected to reach commercial size in 225 days.

1. Introduction

The demand for marine ornamentals has increased exponentially in the past decade (Wood, 2001; Green, 2003). In 2000, the global total wholesale and retail values of live ornamentals were estimated at US$900 million and US$3 billion, respectively (FAO, 2006). However, most trade in marine ornamentals comes from wild-caught stock (Moe, 2003; Olivier, 2003; FAO, 2006). Compared with the culture of freshwater ornamentals, marine ornamental culture is still in its infancy and is limited to few species (Arvedlund et al., 2003; Wabnitz et al., 2003; FAO, 2006). Interest from the governments in promoting the culture and trade of non-food aquatic species, particularly ornamentals, has been spurred by their growing potential for increasing rural employment and generating income among small rural and even urban families (FAO, 2006). Therefore, there is a widespread interest in predicting product yield as well as culture profitability. The ultimate measure of economic viability of a commercial operation is its profit. Profitability is influenced by productivity, but it is also subjected to economic factors such as production costs and market price (Yu et al., 2006).

Application of modelling has increased in aquaculture management (Nunes and Parsons, 2006) and it has been used to describe and predict the effects of biological and environmental factors on survival, growth, production, profitability and economic feasibility of aquaculture operations (Hanson et al., 1985; Yi, 1998; Zhu et al., 1998; Hernández et al., 2003; Christensen et al., 2004; Halachmi et al., 2005; Halachmi, 2006; Yu et al., 2006; Grant et al., 2007). A model is able to encompass our knowledge about the system, integrating the interaction between components and important processes (Jorgensen and Bendoricchio, 2001). Models can yield a better management plan and can be used for decision support contributing to reduce production costs and increase product quality in aquaculture facility (Forsberg and Guttormsen, 2005).

Marine ornamental red-clinging crabs *Mithraculus forceps* (A. Milne Edwards, 1875) are popular in the aquarium industry for its ability to control nuisance algae, particularly bubble algae *Valonia* sp. and *Ventricaria ventricosa* (Figueiredo et al., 2008). Their larval and juvenile culture feasibility has already been proved (Penha-Lopes et al., 2005, 2006; Rhyne et al., 2005) and it can be used to minimize collection from the wild (Penha-Lopes et al., 2007). The protocol developed by Penha-Lopes et al. (2007) intends to increase productivity per tank but does not account for the interaction between different factors, nor addresses the economic perspective of an aquaculture (operation costs and market price).

The objective of the model was to maximize the production and profit of raising one batch of *Mithraculus forceps* larvae to market size in an aquaculture facility, under different conditions of temperature, stocking density, and prey density and using different number and size of tanks. The aquaculture operation costs (feed, labour and maintenance) and market price were addressed to predict culture profitability.

2. Model description

The model was built using differential equations with a 1 day time step in Matlab 7.0, The MathWorks, Inc. The model represents the larval

* Corresponding author. Tel.: +351 214 869 211; fax: +351 214 869 720.
E-mail address: joana_figueiredo@portugalmail.pt (J. Figueiredo).

0044-8486/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.aquaculture.2008.06.043

and juvenile culture of *Mithraculus forceps*. The effect of temperature, stocking density and prey density on the processes of larval mortality, metamorphosis to juvenile, juvenile mortality and growth to commercial size are addressed; the model incorporates and economic submodel which variables are culture costs (labour, feed and maintenance) and profit (Fig. 1). Previously published data on the culture of this species (Penha-Lopes et al., 2005, 2006, 2007; Rhyne et al., 2005) were used to construct and calibrate/validate the model (Table 1).

2.1. Assumptions and conditions

The following assumptions are made in the model:

1) Tank volume does not significantly affect larval survival or growth;
2) Rearing temperature is constant throughout larval culture;
3) Rearing temperature is constant throughout juvenile culture;
4) Larval and juvenile water temperature might be different but there is no negative impact (stress) of changing temperatures from larval to juvenile culture (perfect acclimation).

Table 1
Combinations of temperature, stocking density and prey density previously tested on the larval and juvenile culture of *Mithraculus forceps* (NHA — newly hatched *Artemia* nauplii)

	Temperature	Diet	Stocking density	Prey density	Replicates	Reference
Larval culture	25 °C	NHA	10 L^{-1}	7 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	10 L^{-1}	7 mL^{-1}	10 (6)	Rhyne et al., 2005
					(4)	Penha-Lopes et al., 2005
	28 °C	NHA	10 L^{-1}	12 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	20 L^{-1}	12 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	40 L^{-1}	1 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	40 L^{-1}	4 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	40 L^{-1}	7 mL^{-1}	4	Penha-Lopes et al., 2005
	28 °C	NHA	40 L^{-1}	12 mL^{-1}	8	Penha-Lopes et al., 2005
	28 °C	NHA	80 L^{-1}	12 mL^{-1}	4	Penha-Lopes et al., 2005
Juvenile culture	25 °C	NHA	225 m^{-2}	10 mL^{-1}	30	Penha-Lopes et al., 2006
	28 °C	NHA	225 m^{-2}	10 mL^{-1}	30	Penha-Lopes et al., 2006
	28 °C	NHA	225 m^{-2}	20 mL^{-1}	30	Penha-Lopes et al., 2006
	28 °C	NHA	1130 m^{-2}	20 mL^{-1}	10	Penha-Lopes et al., 2006
	28 °C	NHA	3390 m^{-2}	20 mL^{-1}	5	Penha-Lopes et al., 2006
	28 °C	NHA	6790 m^{-2}	20 mL^{-1}	5	Penha-Lopes et al., 2006
	28 °C	NHA	13580 m^{-2}	20 mL^{-1}	5	Penha-Lopes et al., 2006

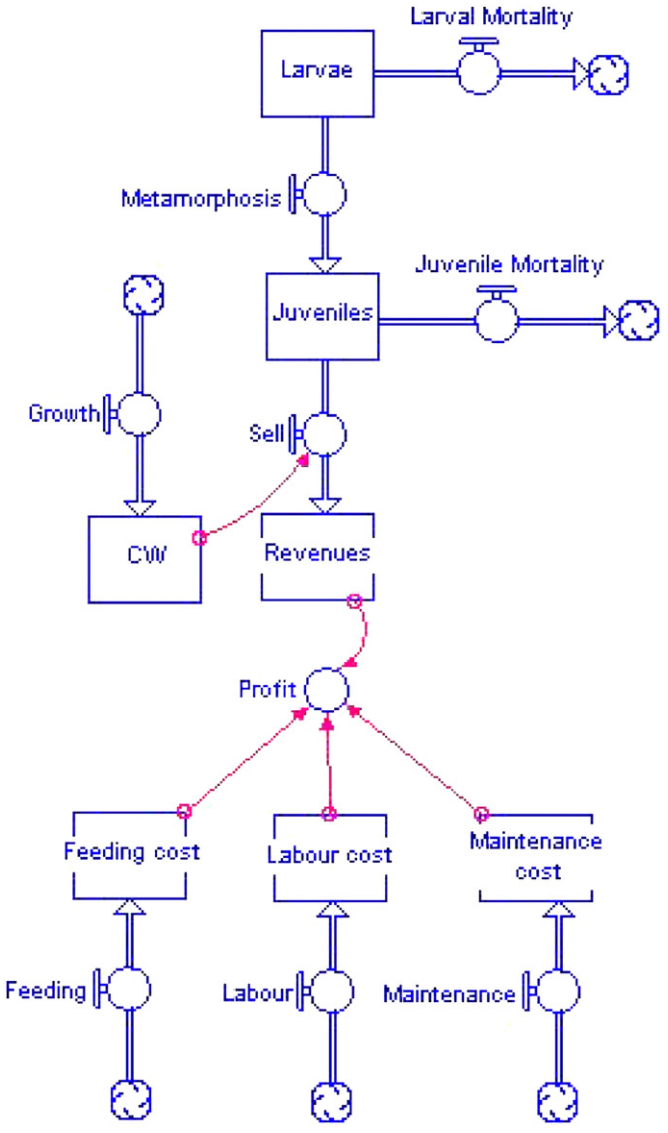

Fig. 1. Simplified conceptual diagram of the model (state variables and processes) (drawn in STELLA, Isee Systems, Inc.).

The following culture conditions were used:

1) Photoperiod is 14 L:10 D, salinity is 33–35, pH is 8–8.2 and water quality is optimal: good filtration and sterilization systems that allow ammonia, nitrites and nitrates levels are maintained below detectable levels;
2) Newly hatched *Artemia* nauplii were used as larval and juvenile diet; this diet was proved to be the best until juveniles are one month old and it is assumed to be adequate until the animal reaches commercial size (10 mm CW). Feeding is conducted once per day;
3) Larvae are reared in cylindrico-conical tanks, and its main features are the "upwelling" flow that allows larvae and prey to be maintained in suspension and the use of screens that allows removing the prey from the tank without manipulation of the larvae (described by Calado et al., 2003);
4) Juvenile rearing is done in water tables (described by Penha-Lopes et al., 2005).

2.2. State variables and forcing functions

The biological state variables of this model are Larvae (L, number), Juveniles (J, number) and individuals carapace width (CW, mm), and economic state variables are Revenues (R), Feeding cost (FC), Labour cost (LC), Maintenance cost (MC). The initial value of Larvae is an input of the user (number of larvae that hatched and that will be raised). Individuals CW's initial size is 0.60 mm (newly hatched larvae). Juveniles, Profit and Feeding cost start as zero; Maintenance and Labour costs might start as zero or with another input decided by the user in case they want to include assumed costs before the culture starts (for instance, cost of tanks, machinery, purchase, collection and maintenance of the adult broodstock can be added to the initial value of Maintenance cost) (Table 2).

Temperature (LT for larval temperature and JT for juvenile temperature, °C), stocking density (LSD for larval stocking density in number of larvae L^{-1} and JSD for juvenile stocking density in number of crabs m^{-2}) and prey density (LPD, number of *Artemia* nauplii mL^{-1} in larval tanks and JPD, number of *Artemia* nauplii mL^{-1} in juvenile tanks) are the forcing functions affecting the processes. Larval stocking density (LSD) is calculated as the number of larvae that initiate culture (iL) divided by number of larval tanks (nLt) and larval tank volume (VLt): LSD = iL/(nLt × VLt). Juvenile stocking density (JSD) is calculated as the maximum number of larvae that metamorphose (MM) divided by number of juvenile tanks (nJt) and juvenile tank area (AJt): JSD = MM/(nJt × AJt).

Table 2
Model parameters unit, value/estimate and description (* — user input)

State Variable	Unit	Initial value	Description
L	Individuals	*	Number of Larvae
J	Individuals	*	Number of Juveniles
R	Euro	0*	Revenues
FC	Euro	0*	Feeding cost
LC	Euro	0*	Labour cost
MC	Euro	0*	Maintenance Cost
CW	mm	0.60	Individuals carapace width
Forcing Function	Unit	Value	Description
LT	°C	*	Larval rearing temperature
JT	°C	*	Juvenile rearing temperature
LSD	Individuals L^{-1}	*	Larval stocking density
JSD	Individuals m^{-2}	*	Juvenile stocking density
LPD	*Artemia* nauplii mL^{-1}	*	Prey density in larval tanks
JPD	*Artemia* nauplii mL^{-1}	20*	Prey density in juvenile tanks (water tables)
Parameter	Unit	Value/Estimate	Description
iL	Individuals	*	Initial number of larvae
nLt	Tanks	*	Number of larval tanks
VLt	L	*	Larval tank volume
nJt	Tanks	*	Number of juvenile tanks
AJt	m^2	*	Juvenile tank area
HJt	m	0.05	Juvenile tank height
MRsp		0.12	Larval mortality rate in starvation parameter
MRs	Individuals day^{-1}	If LT>20 then MRs=MRsp, else MRs=−MRsp×(LT-21).	Larval mortality rate in starvation
MR	Individuals day^{-1}	If LT<15 or LT>35, then MR=4, else if LPD<1, then MR=MRs×LT, else MR=0	Larval mortality rate
iLM	DPH	4	Time larval mortality due to starvation
LMt		1.18	Larval mortality time parameter
aLd		21.1373	Regression parameter constant on Ld
bLd		−0.47549	Regression parameter of the effect of LT on Ld
Ld	DPH	aLd+bLd×LT	Larval duration (time metamorphosis begins)
aMM		−2810.07	Polynomial multiple regression constant parameter on MM
bMM		202.4	Polynomial multiple regression parameter of the effect of LT on MM
cMM		−3.61	Polynomial multiple regression parameter of the effect of LT^2 on MM
dMM		−0.73	Polynomial multiple regression parameter of the effect of LSD on MM
eMM		15	Polynomial multiple regression parameter of the effect of PD on MM
fMM		−0.78	Polynomial multiple regression parameter of the effect of PD^2 on MM
MM	Individuals	If ((aMM+bMM×LT+cMM×LT^2+dMM×LSD+eMM×LPD+fMM×LPD^2)/100×iL)>0, then MM=(aMM+bMM×LT+cMM×LT^2+dMM×LSD+eMM×LPD+fMM×LPD^2)/100×iL, else MM=0	Maximum number of larvae that metamorphosis to juvenile
LMb	Individuals day^{-1}	If LPD≥1 and t>iLM and t≤LMt×Ld and (L-MM)>0, then LMb=0.05, else LMb=0	Larval mortality rate before metamorphosis
LMa	Individuals day^{-1}	If LPD≥1 and t>(LMt×Ld) and L>0, then LMa=1, else LMa=0	Mortality rate of incompetent larvae
aRM		−27.7826	Polynomial multiple regression constant parameter on RM
bRM		2.0064	Polynomial multiple regression parameter of the effect of LT on RM
cRM		−0.0359	Polynomial multiple regression parameter of the effect of LT^2 on RM
dRM		−0.0069	Polynomial multiple regression parameter of the effect of LSD on RM
eRM		0.1555	Polynomial multiple regression parameter of the effect of PD on RM
fRM		−0.0081	Polynomial multiple regression parameter of the effect of PD^2 on RM
RM	Individuals day^{-1}	If t>Ld and ((aRM+bRM×LT+cRM×LT^2+dRM×LSD+eRM×LPD+fRM×LPD^2)×iL>0 and MM>0 and J≥0, then RM=(aRM+bRM×LT+cRM×LT^2+dRM×LSD+eRM×LPD+fRM×LPD^2)×iL, else RM=0	Rate of metamorphosis
aJMR		0.0054	Polynomial regression constant parameter on JMRsd
bJMR		0.000001	Polynomial regression parameter of the effect of JSD on JMRsd
JMRsd		JMRsd=aJMR×JDS+bJMR×JSD^2	Juvenile mortality rate due to JSD
JMRt		If JT>34 or JT<22, JMRt=$(28-JT)^2$/36, else JMRt=1	Juvenile mortality rate due to JT
JMRpd		If JPD<15, JMRpd=$(20-JT)^2$/36, else JMRpd=1	Juvenile mortality rate due to JPD
JMR	Individuals day^{-1}	If t>(LMt×Ld) and J>0, then JMR=JMRsd×JMRt×JMRpd, else JMR=0	Juvenile mortality rate
mS	mm	10	Minimum market size
Sr	Individuals day^{-1}	If CW>mS, then Sr=*, else Sr=0	Sell rate
aLGR		-1.379×10^{-3}	Polynomial multiple regression constant parameter on LGR
bLGR		1.7×10^{-4}	Polynomial multiple regression parameter of the effect of LT on LGR
cLGR		-1.4×10^{-5}	Polynomial multiple regression parameter of the effect of LSD on LGR
dLGR		1.5×10^{-5}	Polynomial multiple regression parameter of the effect of LPD on LGR
eLGR		-7.09×10^{-10}	Polynomial multiple regression parameter of the effect LPD^2 on LGR
LSf		If LT>32 or LT<22, then LSf=0, else LSf=1	Larvae stressful factor
aJGR		−0.00141	Polynomial multiple regression constant on JGR
bJGR		0.0002	Polynomial multiple regression parameter of the effect of JT on JGR
cJGR		-2.9×10^{-7}	Polynomial multiple regression parameter of the effect of JSD on JGR
dJGR		1.43×10^{-11}	Polynomial multiple regression parameter of the effect of JSD^2 on JGR
JSf		If JT>34 or JT<20 or JPD<5, then JSf=0, else JSf=1	Juvenile stressful factor

(continued on next page)

Table 2 (*continued*)

Parameter	Unit	Value/Estimate	Description
GR	mm day^{-1}	If $t \leq$Ld, then GR=(aLGR+bLGR×LT+cLGR×LSD+dLGR×LPD+eLGR×LPD^2)×LSf, else GR=(aJGR+bJGR×JT+cJGR×JSD+dJGR×JSD^2)×JSf	Growth rate (daily increment in the carapace width)
mP	Euro	6*	Market price per individual
Lp	Euro day^{-1}	*	Labour daily price per worker
W	Individuals	*	Number of workers
LF		If L>1, LF=1, else LF=0	Larval feeding parameter
Ap	Euro nauplii^{-1}	*	*Artemia* nauplii price
JF		If J>1, JF=1, else JF=0	Juvenile feeding parameter
Ep	Euro day^{-1}	*	Electricity price
Sp	Euro day^{-1}	*	Salt price
Wp	Euro day^{-1}	*	Water price
Profit	Euro	R−FC−MC−LC	Profit of one batch of *M. forceps* larvae

The differential equations of the model that regulate the changes over time (t) in each variable are:

$$\frac{dL}{dt} = -\textit{Larval mortality} - \textit{Metamorphosis} \quad (1)$$

$$\frac{dJ}{dt} = +\text{Metamorphosis} - \textit{Juvenile mortality} - \textit{Sell} \quad (2)$$

$$\frac{dCW}{dt} = +\text{Growth} \quad (3)$$

$$\frac{dFC}{dt} = +\text{Feeding} \quad (4)$$

$$\frac{dLC}{dt} = +\text{Labour} \quad (5)$$

$$\frac{dMC}{dt} = +\text{Maintenance} \quad (6)$$

$$\frac{dR}{dt} = +\text{Sell} \times \text{mP} \quad (7)$$

where mP is the crab market price.

2.3. Processes

2.3.1. Larval mortality

During larval period, the number of larvae decays logistically (inverse logistic model). Mortality rate depends mainly on temperature; the higher the temperature, the higher the mortality rate (MR) (Table 2). In lethal temperatures (below 15 or above 35 °C), larval mortality rate (MR) is very high and development does not occur (Table 2). When fed, larval mortality usually starts 4 day post hatch — DPH (iLM) with a low mortality rate (LMb). Mortality rate increases a few days after the metamorphosis begins (LMt×Ld) since some larvae never metamorphose (incompetent larvae) and end up dying as megalopa (Penha-Lopes et al., 2005) (Table 2). Rhyne et al. (2005) found that starved larvae (LPD<1.mL^{-1}) will display low mortality in the earlier days of culture (3 DPH), probably since they still have some lecitothrophic capacity; however, mortality accelerates on 4 DPH. By 8 DPH, there are few remaining larvae.

$$\begin{aligned}\text{Larval Mortality} &= \text{Mortality during larval period} \\ &\quad + \text{Mortality during metamorphosis} \\ &\quad + \text{Mortality of incompetent larvae} \\ &= (\text{MR} \times \text{L} \times ((\text{iL}+1)-L)/(\text{iL}+1)) \\ &\quad + (\text{LMb} \times (\text{L}-MM)) + (\text{LMa} \times \text{L}),\end{aligned}$$

where MR is the larval mortality rate, L is the number of larvae, iL is the initial number of larvae, LMb is the larval mortality rate before metamorphosis, LMa is the larval mortality rate after metamorphosis and MM is the maximum number of larvae that metamorphoses to juvenile. Mortality rate (MR) depends on larval temperature (LT) and prey density (LPD) (Table 2); LMa and LMb depend on prey density (Table 2); MM depends on larval temperature (LT), stocking density (LSD) and prey density (LPD) (Table 2).

2.3.2. Metamorphosis

According to Penha-Lopes et al. (2007), the asymptotic model fits well the *M. forceps* metamorphosis to crab stage. The three parameters that shape the asymptotic model are larval duration (Ld), rate of metamorphosis (RM) and maximum metamorphosis (MM). Based on Penha-Lopes et al. (2007), we assume temperature (LT), stocking density (LSD) and prey density (LPD) to significantly affect RM and MM, but Ld to be only significantly affected by larval temperature (Table 2). RM is equal to zero when $t \leq$Ld. Multiple polynomial regressions were used to estimate RM, MM and Ld in different combinations of LT, LSD and LPD (for t>Ld), using literature data (Penha-Lopes et al., 2005, 2006, 2007; Rhyne et al., 2005) (Table 2).

$$\text{Metamorphosis} = \text{RM} \times \text{L} \times (1-((J+1)/(MM+1)))$$

2.3.3. Juvenile mortality

According to data and models published by Penha-Lopes et al. (2006 and 2007, respectively), we can simplify juvenile mortality as linear decay. Juvenile mortality rate (JMR) is expected to increase with juveniles stocking density and to increase as the temperature (JT) and prey density (JPD) become more deviate from the optimal conditions (28 °C and 20 *Artemia* nauplii mL^{-1}) (Table 2).

$$\text{Juvenile mortality} = \text{JMR},$$

where JMR is the juvenile mortality rate and depends on JT, JSD and JPD (Table 2).

2.3.4. Growth

M. forceps grows asymptotically, with growth rate (GR), during both larval period (GR=LGR when t<Ld) and juvenile grow-out period (GR=JGR when $t \geq$Ld), being dependent of larval stocking density (LSD and JSD), temperature (LT and JT) and prey density (LPD and JPD)(Table 2, Penha-Lopes et al., 2007) (Table 2). Multiple polynomial regressions were used to estimate their effect on CW growth rate (LGR and JGR), using published data (Rhyne et al., 2005; Penha-Lopes et al., 2005, 2006).

$$\text{Growth} = \text{GR} \times (\text{CWmax}-CW) \times (1-(CW/CWmax)),$$

where CW max is the maximum CW of the species (20.73 mm).

2.3.5. Sell

In ornamental trade, the product is traded by the number rather than by weight (FAO, 2006). Once crabs achieve minimum commercial size (mS), they can be sold at market price (mP).

$$\text{Sell} = \text{Sr} \times J,$$

where Sr is the sell rate and J is the number of juveniles.

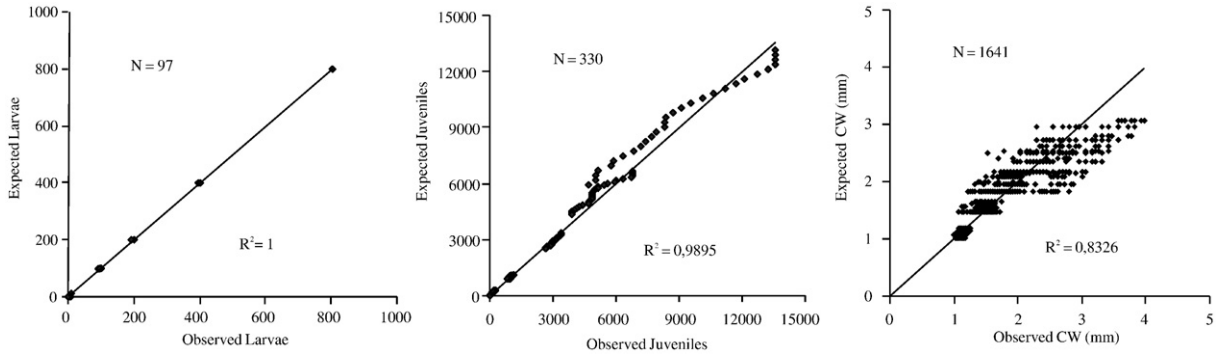

Fig. 2. Model calibration: observed vs. expected number of Larvae, number of Juveniles and carapace width (CW); line represents observed = expected (perfect fitness).

2.3.6. Feeding

Feeding cost depends on number and volume of larval (nLt and VLt) and juvenile tanks (nJt and AJt) with animals in each day, prey density (LPD and JPD) used on those tanks and *Artemia* price (Ap).

$$\text{Feeding} = (\text{LF} \times \text{LPD} \times \text{nLT} \times \text{VLt} \times 1000 + \text{JF} \times \text{JPD} \times \text{Jt} \times \text{AJt} \times \text{HJt} \times 100\,000) \times \text{Ap},$$

where LF and JF are larval and juvenile feeding parameters, that can take the value 1 or 0 as there are animals or not in the tanks (Table 2). The numbers 1000 and 100 000 in the expression are conversion factors since prey density is expressed in number of preys mL^{-1} and we are calculating the total number of preys in larval and juveniles tanks, which units are L and m^3, respectively.

2.3.7. Labour

Labour cost depends on number of workers (W) and their daily payment (Lp).

$$\text{Labour} = \text{Lp} \times W$$

2.3.8. Maintenance

As maintenance we consider a multitude of topics such as electricity (Ep) and water prices (Wp). This process is included but it has to be developed by each aquaculture facility. For instance, the greater the difference between ambient temperature and rearing temperature, the greater should be the cost of electricity. Each location has different water and electricity costs that have to be addressed. Also, the distance from the sea might require the use of artificial salt water (with salt costs associated, Sp).

$$\text{Maintenance} = \text{Ep} + \text{Sp} + \text{Wp}$$

2.4. Parameter estimation

Parameters (listed in Table 2) were estimated based on relationships derived from literature and published data (Penha-Lopes et al., 2005, 2006, 2007; Rhyne et al., 2005). Polynomial regression analyses were performed with Statistica 7.0, StatSoft, Inc. to find relationships and interaction between temperature, stocking density and prey density on the different processes. Deleterious limits had to be imposed for some of the processes of the model without the support of a database; limits were based on the general assumption that as we deviate from optimal conditions, mortality and growth rates increase.

3. Profit

The Profit can be calculated has the Revenues minus the Feeding cost, Labour cost and Maintenance cost (Fig. 1) at every instant of time (t). The value of profit over time can be used to compare the suitability of different culture scenarios.

4. Sensitivity analysis

Sensitivity analyses were carried out to determine which inputs in the model contributed most for the output variability. The analysis was conducted by means of successive simulations, varying each parameter, forcing function and initial value of the state variables, included in the model 10% up and down of their initial baseline values (keeping the others equal to their baseline) and observing graphically the corresponding response on the state variables (Jorgensen and Bendoricchio, 2001).

Sensitivity analysis allowed the determination of the parameters with a major influence on disturbances of our predictions. In this model, the parameters with higher sensitivity were larval and juvenile temperature (with great impact on number of Larvae and, number of Juveniles, CW and profit, respectively). The constants (aLd, aMM, aRM) and parameters of the multiple regressions associated with the effect of temperature in larval duration (bLd), metamorphosis rate (bRM, cRM), maximum metamorphosis (bMM, cMM) and larval and juvenile mortality had greater impact in the number of Larvae (J) and Juveniles (J), and consequently in the profit, feeding cost and discounted profit. The parameter of the effect of prey density (LPD) in rate of metamorphosis (eRM) was also sensitive. The parameters associated with juvenile growth rate, particularly the effect of stocking density (bJGR), also shown to be sensitive for the CW and Revenues (R) state variables.

During the calibration process, the parameters with highest sensitivity were determined with high accuracy.

5. Calibration and validation

The model was calibrated and validated by simulating number of larvae, juveniles and individuals' CW and comparing them with previously published data. The economic part of the model was not tested since there is no available data; data are only available for 43 DPH. All combinations tested in the past (see Table 1) were compared with simulated data over time to check for fitness (Fig. 2). Model predictions closely reflect the data for most culture conditions. Regression analyses between observed and expected values (R^2) were used to test the data adjustment to the model. The number of larvae, juvenile and individuals

Table 3
Scenarios conditions of larval temperature (LT), juvenile temperature (JT), number of larval tanks (nLt), number of juvenile tanks (nJt), labour price (Lp), and maximum profit that can be achieve (MaxProfit) and in which day of culture (days of culture)

Scenario	LT	JT	nLt	nJt	Lp	MaxProfit (€)	Days of culture
1	28	28	50	10	10	40366	231
2	25	28	50	10	10	23517	227
3	28	25	50	10	10	38526	270
4	28	28	25	10	10	33031	229
5	28	28	50	5	10	30633	244
6	28	28	50	10	50	31166	231

CW throughout culture are well predicted by the model ($R^2=1$, $R^2=0.9895$ and $R^2=0.8326$, respectively)(Fig. 2).

6. Scenarios

The model was built in a way that each aquaculture manager can simulate the profitability of culturing one batch of *Mithraculus forceps* larvae (initial number of larvae) until commercial size, under different abiotic and biotic conditions (temperature, stocking density, prey density), and according to the aquaculture characteristics (number and volume of larval and juvenile tanks, electricity cost, water cost, number of workers, labour price, feed cost, etc.).

As an example, several scenarios were simulated, all considering raising an equal number of larvae (10,000), prey density (10 and 20 *Artemia* nauplii mL^{-1} during larval and juvenile culture, respectively), larval tank volume (10 L), juvenile tank area (1 m^2), juvenile tank water height (0.05 m), *Artemia* nauplii price (6×10^{-7}€), electricity price (2€ day^{-1}), salt price (0€ day^{-1}), water price (2€ day^{-1}), one worker and 50 larval tanks and 10 juvenile tanks available (can be used or not); the simulations will differ in the larval and juvenile temperature (LT and JT), number of larval and juvenile tanks used (nLt and nJt, which will be reflected in stocking density) and labour cost (which varies significantly geographically and might be important to decide where to establish an aquaculture facility) (Table 3, Fig. 3).

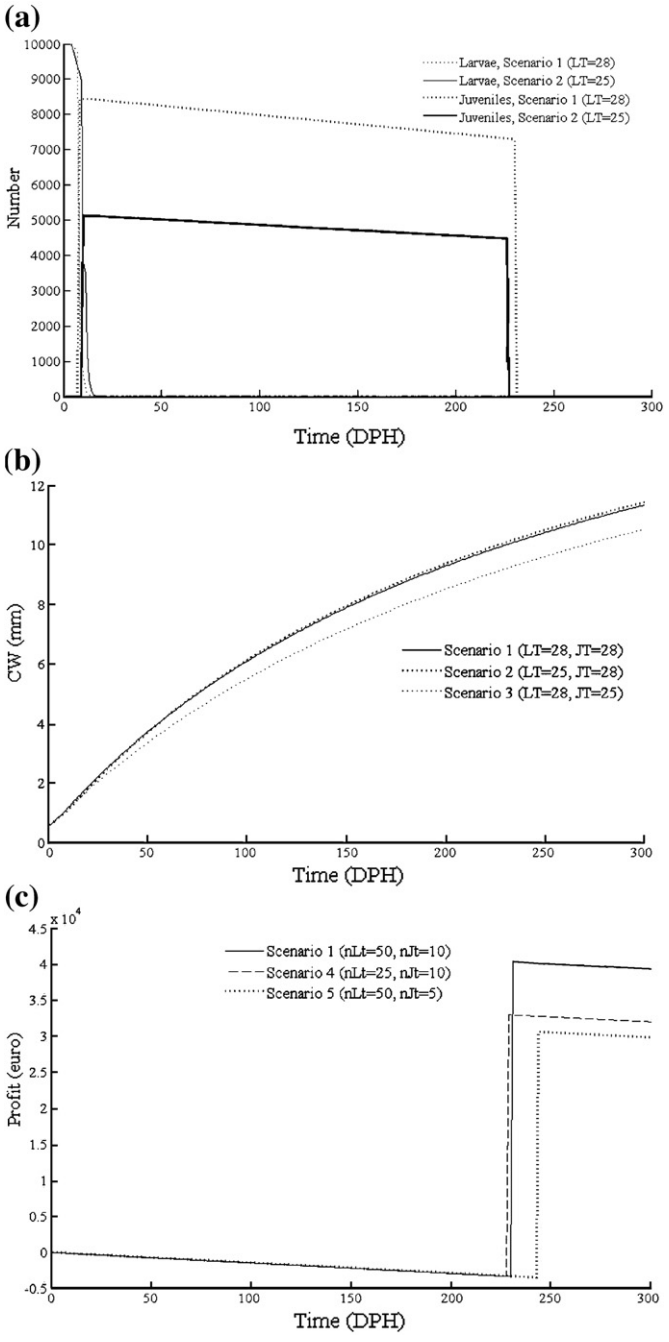

Fig. 3. Model simulations of (a) Number of larvae and juveniles in scenario 1 vs. 2 (b) CW in scenario 1 vs. 2 vs. 3; (c) Profit in scenario 1 vs. 4 vs. 5.

7. Discussion

Integration through computer modelling allows synthesis of data and simulations to be performed, facilitating the design and understanding of the system structure and its relationships (Nunes and Parsons, 2006). This model aims to support management decisions by allowing the producers to simulate not only productivity but also profit of the use of different abiotic and biotic conditions and also different number of tanks and costs associated with it according to the specificity of the facility. Although the assumptions employed during the model development offered a simplistic view of *M. forceps* culture, simulations produced expected forecasts of survival, metamorphosis and growth of this species. The management advantage of this model is addressing the issue of number and volume of tanks versus their operation costs. The model shows that although productivity per tank is higher at higher stocking densities (Penha-Lopes et al., 2007), survival and growth generally decrease with increasing stocking density (Penha-Lopes et al., 2005, 2006), so the overall productivity increases as the animals are distributed to the greater number of tanks (scenario 4 and 5). However, productivity increase is followed up by an increase in feeding, labour and maintenance costs, which can be reflected in a reduced profit (Fig. 3c). The model simulations will allow the aquaculture managers to find the most profitable combination (of number of tanks and cost associated) according to the characteristics of the aquaculture facility.

The economic sub-model needs to be developed by each aquaculture manager according to the aquaculture facility operation costs. The electricity cost (Ep) differs according to location and the number and volume of the larval and juvenile tanks available; the greater number of tanks in use the greater energy the pumps and temperature controllers will be needed. Electricity price might also increase with the difference between rearing temperature and ambient temperature since more energy will be use to warm or chill the water. Labour price (Lp) will vary among locations. Number of workers (W) required should depend on the number of active tanks. Water cost (Wp) will certainly depend on local water price, on the number and volume of the tanks (and sumps) being used and frequency and amount of water changes performed. If artificial seawater is used, the expense in artificial salt (Sp) should depend on number and volume of larval and juvenile tanks in use and frequency and amount of water changes performed. Therefore, this model still needs to receive the inputs from the aquaculture managers in regard to the economic aspects of the culture. Once implemented, a long period of aquaculture activity will generate more data that can be used to validate the prognoses (Jorgensen and Bendoricchio, 2001) and possibly improve forecasts.

Simulation by means of mathematical modelling has been the common tool in aquaculture to analyse different aspects of animals' growth (Hernández et al., 2003). In the present model, we estimate the carapace width (CW) of the crabs and we estipulate that once crabs achieve market size they are sold. However, the model only estimates the average CW and consequently does not account for the size dispersion commonly observed in natural and cultured populations, i.e. not all animals will achieve commercial size at the same time, which might fasten or delay sell day and increase or decrease aquaculture operation expenses. Also, the shrimp grow is regulated by the moult cycle which is made up of short moult periods of rapid

growth and of longer intermoult periods when no growth occurs (Franco et al., 2006), however, and as a simplification, the present model used an asymptotic growth since we are considering the average CW of all animals in culture.

According to the present model, if 1500 larvae (average batch size ranges from 500 to 2000 larvae, unpublished data) were raised in ten 10 L tanks (15 larvae L^{-1}) in optimal conditions, i.e., 28 °C and 10 *Artemia* nauplii mL^{-1} during larval culture (according to Penha-Lopes et al., 2007), crabs fed *Artemia* nauplii are expected to achieve commercial size in 225 days (Fig. 3a). This model assumes that newly hatched *Artemia* nauplii could be used as a diet throughout the culture, it is not reasonable to use one larval diet to raise an animal from hatch to commercial size. After 43 DPH, a diet adequate to crustacean decapods grow-out should be used instead to keep a similar growth rhythm or even increase it. G. Penha-Lopes (unpublished data) recorded this species to take 3 to 4 months to reach commercial size when fed a mixed diet composed by frozen squid and fish. More long term data is needed to produce better simulations during juvenile grow-out, particularly data concerning diet.

According to the model, if animals are raised in sub-optimal conditions, they will require more time to achieve commercial size (Fig. 3b), and consequently decrease the profitability. In our case, the parameters with higher sensitivity are those related with temperature, which was expected since temperature accelerates the metabolism and consequently speeds up the rates of mortality, metamorphosis and growth (Hernández et al., 2003). Lower temperatures cause an increase in mortality and increase culture time (e.g. 25 °C, Fig. 3a and b). Higher temperatures (>28 °C) are more deleterious than lower temperatures but promote a faster growth, particularly during juvenile growth, which lead to an increase of profit (less time to achieve commercial size and aquaculture operation costs reduced). Prey density during larval culture has less impact on survival than temperature and no significant impact on time to achieve commercial size.

The implementation of predictive models to wider range of species culture would allow improvement of aquaculture efficiency and profitability and therefore, protect environment by minimizing wild collection.

8. Conclusion

The model aims to provide a good management tool for aquaculturists since it allows simulating culture conditions and predict daily profit (Fig. 3d). Overall, the model was able to integrate previously collected data and produce expected forecasts of *Mithraculus forceps* larval and juvenile culture when under different combinations of temperature, stocking density, and prey density. Sensitivity analysis revealed that temperature is the most important factor regulating survival and growth. Since survival and growth decrease with stocking density, productivity increases when larvae and juveniles are split into a greater number of tanks. However, the costs associated with it (more tanks to feed and maintain) might decrease the profitability of such a strategy. So, economic parameters need to be inserted in the model by each aquaculturist considering the specific conditions of the aquaculture facility to run the model and to find the most profitable compromise between number of tanks and costs.

Long-term aquaculture data should be collected to improve simulation forecasts, particularly number of juveniles raised in high stocking densities. Data concerning juvenile grow-out diet (cost, feeding days and impact on growth, and consequently profit) should be collected. Economical data of an aquaculture facility expenses should be collected, including the cost of implementation. Several economical parameters linked with temperature and number of tanks should be collected and integrated in the sub-economic model. A comparison of the model predictions with aquaculture data needs to be performed to validate prognoses and to guaranty a higher degree of confidence in simulation results so that the model becomes acceptable for its intended use (Jorgensen and Bendoricchio, 2001; Hernández et al., 2003).

Acknowledgements

We would like to thank Justin Anto and anonymous reviewers for providing constructive criticism to this manuscript, Dr. Robert van Woesik and Kelly Kearney for helping during the modelling process and Fundação para a Ciência e Tecnologia for the financial support provided (#SFRH/BD/17130/2004 (JF) and #SFRH/BD/25277/2005 (GPL)).

References

Arvedlund, M., Craggs, J., Pecorelii, J., 2003. Coral culture — possible future trends and directions. In: Cato, J.C., Brown, C.L. (Eds.), Marine Ornamental Species: Collection, Culture and Conservation. Iowa State Press, Iowa, USA, pp. 233–248.
Calado, R., Narciso, L., Morais, S., Rhyne, A.L., Lin, J., 2003. A rearing system for the culture of ornamental decapod crustacean larvae. Aquaculture 218, 329–339.
Christensen, S.M., Macintosh, D.J., Phuong, N.T., 2004. Pond production of the mud crabs *Scylla paramamosain* (Estampador) and *S. olivacea* (Herbst) in the Mekong Delta, Vietnam, using two different supplementary diets. Aquac. Res. 35, 1013–1024.
FAO, 2006. State of world aquaculture. FAO Fisheries Technical Paper. No. 500. FAO, Rome. 134pp.
Figueiredo, J., Narciso, L., Turingan, R., Lin, J., 2008. Efficiency of using emerald crabs *Mithraculus sculptus* (Lamarck, 1818) to control bubble algae *Ventricaria ventricosa* (sin *Valonia ventricosa*) (J. Agardh, 1887) in aquaria habitats. J. Mar. Biol. Assoc. U.K. 88 (1), 95–102.
Forsberg, O.I., Guttormsen, A.G., 2005. A pigmentation model for farmed Atlantic salmon: Non linear regression analysis of published experimental data. Aquaculture 253, 415–420.
Franco, A.R., Ferreira, J.G., Nobre, A.M., 2006. Development of growth model for penaeid shrimp. Aquaculture 259, 268–277.
Grant, J., Curran, K.J., Guyondet, T.L., Tita, G., Bacher, C., Koutitonsky, V., Dowd, M., 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec. Ecol. Model. 200, 193–206.
Green, E., 2003. International trade in marine aquarium species: using the global marine aquarium database. In: Cato, J.C., Brown, C.L. (Eds.), Marine Ornamental Species: Collection, Culture and Conservation. Iowa State Press, Iowa, USA, pp. 31–47.
Halachmi, I., 2006. Systems engineering for ornamental fish production in a recirculating aquaculture system. Aquaculture 259, 300–314.
Halachmi, I., Simon, Y., Guetta, R., Hallerman, E.M., 2005. A novel computer simulation model for design and management of recirculating aquaculture systems. Aquac. Eng. 32, 443–464.
Hanson, J.S., Griffin, W.L., Richardson, J.W., Nixon, C.J., 1985. Economic feasibility of shrimp farming in Texas: an investment analysis for semi-intensive pond grow-out. J. World Aquac. Soc. 16, 129–150.
Hernández, J.M., Gasca-Leyva, E., León, C.J., Vergara, J.M., 2003. A growth model for gilthead seabream (*Sparus aurata*). Ecol. Model. 165, 265–283.
Jorgensen, S.E., Bendoricchio, G., 2001. Fundamentals of ecological modelling, 3rd ed. Developments in Environmental Modelling, vol. 21. Elsevier, Amsterdam. 530 pp.
Moe, M.A., 2003. Culture of marine ornamentals: for love, for money, and for science. In: Cato, J.C., Brown, C.L. (Eds.), Marine Ornamental Species: Collection, Culture and Conservation. Iowa State Press, Iowa, USA, pp. 11–28.
Nunes, A.J.P., Parsons, G.J., 2006. A computer-based statistical model of the food and feeding patterns of the Southern brown shrimp *Farfantepenaeus subtilis* under culture conditions. Aquaculture 252, 534–544.
Olivier, K., 2003. World trade in ornamental species. In: Cato, J.C., Brown, C.L. (Eds.), Marine Ornamental Species: Collection, Culture and Conservation. Iowa State Press, Iowa, USA, pp. 49–63.
Penha-Lopes, G., Rhyne, A., Lin, J., Narciso, L., 2005. The larval rearing of the marine ornamental crab, *Mithraculus forceps* (A. Milne Edwards) (Decapoda: Brachyura: Majidae). Aquac. Res. 36, 1313–1321.
Penha-Lopes, G., Rhyne, A.L., Lin, J., Narciso, L., 2006. Effects of temperature, stocking density and diet on the growth and survival of juvenile *Mithraculus forceps* (A. Milne Edwards) (Decapoda: Brachyura: Majidae). Aquac. Res. 37, 398–408.
Penha-Lopes, G., Figueiredo, J., Narciso, L., 2007. Modelling survival and growth of *Mithraculus forceps'* larvae and juveniles (A. Milne Edwards, 1875) (Decapoda: Brachyura: Majidae) in aquaculture. Aquaculture 264, 285–296.
Rhyne, A., Penha-Lopes, G., Lin, J., 2005. Growth, development and survival of larval *Mithraculus sculptus* (Lamark) and *M. forceps* (A. Milne Edwards) (Decapoda: Brachyura: Majidae): economically important marine ornamental crabs. Aquaculture 245, 183–191.
Wabnitz, C., Taylor, M., Green, E., Razak, T., 2003. From Ocean to Aquarium. UNEP-WCMC, Cambridge, UK. 64 pp.
Wood, E.M., 2001. Collection of Coral Reef Fish for Aquaria: Global Trade, Conservation Issues and Management Strategies. Marine Conservation Society, United Kingdom. 80 pp.
Yi, Y., 1998. A bioenergetics growth model for Nile tilapia (*Oreochromis niloticus*) based on limiting nutrients and fish standing crop in fertilized ponds. Aquac. Eng. 18, 157–173.
Yu, R., Leung, P., Bienfang, P., 2006. Optimal production schedule in commercial shrimp culture. Aquaculture 254, 426–441.
Zhu, S., Deltour, J., Wang, S., 1998. Modeling the thermal characteristics of greenhouse pond systems. Aquac. Eng. 18, 201–217.