MODELLING MUSSEL GROWTH IN TAGUS ESTUARY: A PRELIMINARY APPROACH

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CHAPTER SYNOPSIS

Background
In recent years, considerable research has been carried out on the application of the DEB theory to simulate growth and bio-energetics of bivalve species. DEB theory describes the individual in terms of two state variables, structural body and reserves, describing energy flow through organisms from assimilation to allocation to growth, reproduction and maintenance. The advantages of DEB model lies in its versatility and generality, with its applications to other species only requiring a new set of parameters. DEB models have been successfully applied to several shellfish species including *Mytilus edulis* and *Crassostrea gigas*.

Results
A model based on the DEB theory was integrated in MOHID model and applied to the Tagus estuary. The model was applied to the Tagus estuary to simulate the potential growth potential of the *Mytilus edulis* in the system. In order to identify the preferential growth zones of the bivalves, the discussion of the results were focused on the shell allometry (structural volume, shell length, dry weight) and mussel bioenergetics (energy in the reserves, reproductive energy).

Conclusions
A model capable of examining environmental sustainability and productivity of a system is a powerful tool to support sustainable management of shellfish culture. The present model can reproduce a system behavior and is capable to assess the impact of mussel culture on the dynamics of the system. Therefore it can be used to estimate the potential for growth, the ecological and the capacity of a system to support shellfish production.

1 INTRODUCTION

Growth of bivalve species with economic value has been widely studied due to their role in aquaculture and other ecosystem services such as water filtration [1]. The need for tools to understand ecological interactions and processes of relevance for estimating carrying capacity in shellfish aquaculture has promoted the development of individual bivalve growth models. Individual bivalve growth has been modelled using a range of energetic models, from empirical based net-production models [2] to the recent use of more mechanistic models based on the Dynamic Energy Budget (DEB) theory [3].

In recent years, considerable research has been carried out on the application of the DEB theory [4] to simulate growth and bio-energetics of bivalve species. DEB theory describes the individual in terms of two state variables, structural body and reserves [5], describing energy flow through organisms from assimilation to allocation to growth, reproduction and maintenance. The advantages of DEB model lies in its versatility and generality, with its applications to other species only requiring a new set of parameters. DEB models have been successfully applied to several shellfish species including *Mytilus edulis* [6,7] and *Crassostrea gigas* [3,8]. Also, some authors have coupled DEB models with biogeochemical models to supply feedbacks from aquaculture farms to phytoplankton and nutrient dynamics [9,10,11].

Dabrowski et al. [11] developed a Fortran 90 implementation of the DEB algorithm for *Mytilus edulis*. The developed model includes physiological interactions with the ecosystem and it has been coupled with a Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD). Afterwards, the coupled model was subsequently embedded within a numerical physical model for hydrodynamics and transport of passive tracers. The modelling system was applied to Bantry Bay (Ireland) and successfully reproduced the biogeochemical cycles and growth of mussel cultures in the system. The DEB model developed by [11] is generic and it can be coupled to any hydrodynamic model for estuarine, coastal and ocean waters.

In the present study, the DEB model developed by [11] was integrated by the authors in MOHID water modelling system (http://www.mohid.com), and applied to the Tagus estuary (Portugal), to simulate the potential growth of *Mytilus edulis* in the system. The aim of the study was to identify the preferential potential growth zones of the bivalves in the modelled domain.

2 DEB MODEL INTEGRATION WITH MOHID

In this section, a brief description of the integration in MOHID model of the DEB model developed by [11] is given. The detailed description of the DEB model formulation and validation is not reported in this study, but it can be found in [11].

The DEB model was integrated in MOHID model through the module BenthycEcology. To run the DEB model with MOHID the user has to turn on at least the modules Hydrodynamic, WaterQuality, BenthicEcology and InterfaceSedimentWater. The DEB model parameters handled by ModuleInterfaceSedimentWater and by ModuleBenthicEcology, are listed in Table 1 and Table 2, respectively.

A schematic diagram of the integrated model is presented in Figure 1. The DEB model calculates bivalve's volume, energy, reproductive energy, individual dry weight and total dry weight. The model accounts of feedbacks to the ecosystem (Chlorophyll-a consumption, oxygen consumption, ammonia excretion, nitrogen egestion). The biogeochemical fields are updated by taking into account the following processes: Oxygen (O_2) is consumed by bivalves' respiration, Phytoplankton (Phyto) is consumed by benthic grazing, ammonia (NH_4) increases due to excretion, Particulate Organic Matter (POM) increases due to mortality and egestion processes.

3 MODEL APPLICATION

3.1 Study area

The Tagus estuary is the largest estuary in Portugal and one of the largest in Europe, covering an area of 320 km^2 (Figure 2). The Tagus estuary is a semi-diurnal mesotidal estuary, with tidal range varying from 1 m during neap tides up to almost 4 m in the spring tides. The tide propagates up to almost 80 km upstream and the estuary mean resident time is 25 days [12]. In this area the wind blows predominantly from south and southwest during winter, rotating progressively to northwest and north during spring and maintaining this direction during summer.

Table 1. *List of parameters required for the initialization of DEB model.*

Parameter	Unit	Description
bivalve volume	m^3	Individual bivalve volume
bivalve energy	J	Energy reserve of individual bivalve
bivalve reproductive energy	J	Reproductive energy of individual bivalve

Table 2. *Input parameters required for the chosen species.*

Parameter	Unit	Description
NINDM2	-	Number of individuals per m^2
EGCC	$J\ m^{-3}$	Energetic growth cost per unit growth in structural body volume
MAXSAING	$J\ m^{-2}\ s^{-1}$	Max. surface-area-specific ingestion rate
ASSEFFIC	-	Assimilation efficiency (= Pam/Pxm)
SOMACOST	$J\ m^{-3}\ s^{-1}$	Somatic maintenance cost
FLUXRESFRAC	-	Fraction of flux from reserve spent on somatic maintenance
SATCOEF	mg (chl-a) m^{-3}	Saturation coefficient - food density at which ingestion rate is half the maximum
REPOREFFIC	-	Reproduction efficiency
ENERCONT	-	Energy content of 1g of reserve
WWTODW	-	WW to DW converter
SPAWEFFIC	-	proportion of the reproductive buffer emptied at each spawning
TSPAWN	ºC	temperature threshold trigeering spawning
GSOMINDEX	-	Gonado-somatic index triggering spawning (fraction)
NSPAWND		Number of spawning days in a year (MUST be same as SpawnDay array dimension)
JDAYSPAWN	D	Julian day
VOLADULT	m^3	Volume specifying a change from juvenile to adult
SHAPEPARAM	-	shape parameter
REFTEMP	K	Ref. temp. for rate constants
TEMPARRH	K	Arrhenius temperature
TEMPLOW	K	Lower boundary of tolerance range
THRESP	K	Upper boundary of tolerance range for respiration
THING	K	Upper boundary of tolerance range for ingestion
TAL	K	Arrhenius temp. for rate of decrease at lower boundary
TAHRESP	K	Arrhenius temp. for rate of decrease at upper boundary for respiration
TAHING	K	Arrhenius temp. for rate of decrease at upper boundary for ingestion
FECALDECAY	s^{-1}	Corresponds to T_{90} of 0
ENERGPHY	$J\ mg^{-1}$ C	energetic value of phyt C
ENERGO2		energetic value of oxygen ($J\ mg^{-1}\ O_2$)
CCHLABIV		C to Chla ratio used to convert Phyto to Chla
NH4EXCFRAC		define NH4 excretion as a fraction of N ingested
BILENINIC	m	Initial bivalve length

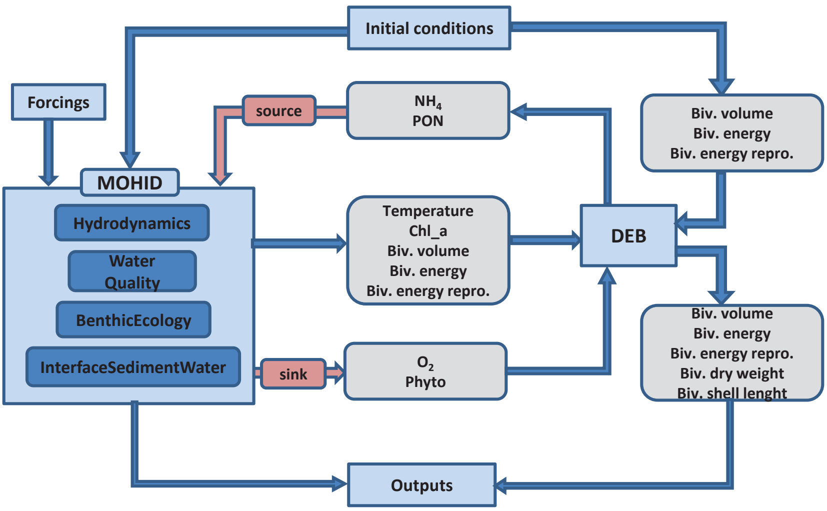

Figure 1. *Flowchart presenting the integration of the DEB model with the MOHID model.*

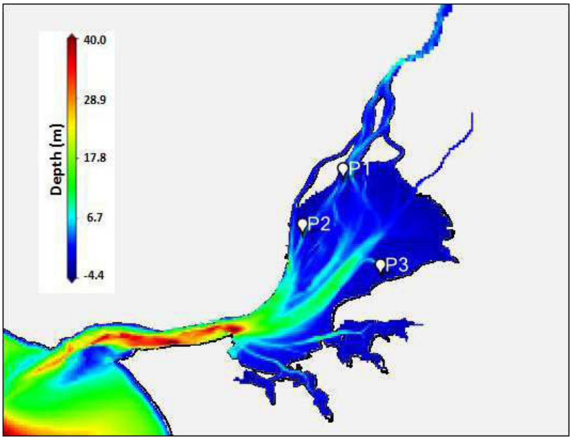

Figure 2. *Tagus estuary bathymetry.*

Morphologically the estuary can be divided into three main areas: a straight narrow and deep W-E oriented channel with about 16 km long and 2 km wide, with maximum depths of about 45 m; an inner bay with 25 km long and 15 km wide SW-NE oriented with depths between 5 and 10 m and; an upper shallow estuary with an area of 100 km^2, encompassing large mudflats and salt marshes separated by shallow channels.

The main freshwater source to the estuary is the Tagus River, with flow rates varying typically between 50 and 2000 m^3 s^{-1}, showing a strong seasonality and the actual discharge is also controlled by dam releases. The Sorraia and the Trancão rivers are the second and third main estuarine tributaries with mean discharges of 39 and 6 m^3 s^{-1}, respectively.

The combined effect of low average depth, strong tidal currents and low freshwater input make Tagus a globally well-mixed estuary, with significant stratification occurring only during specific situations such as neap tides or after heavy rains.

Until the 1970's Portugal and specifically the Tagus estuary, was the major exporter of oysters in Europe. Factors like TBT and oysters gill disease caused the end of the shellfish aquaculture in the Tagus estuary. Mesotidal estuaries, like Tagus, are favorable areas for shellfish culture, offering good trophic conditions due to strong tidal currents that ensure an intensive food renewal within the area [13]. Thus, the Tagus estuary provides the conditions to implement the aquaculture of bivalves, as existed for decades, until the collapse 40 years ago of the fishery of the Portuguese oyster *Crassostrea angulate*.

3.2 Numerical model

The MOHID modelling system was applied to the Tagus estuary by using a 2-D configuration, with a downscaling scheme with three nested domains was used (Figure 3). The first domain covers the entire Portuguese coast with a 0.06^o horizontal resolution and is forced with the FES2004 global tide solution [14]. To obtain a smooth grid variation, an intermediate domain with 0.02^o resolution was created to supply hydrodynamic ocean open boundary conditions to the Tagus estuary model. The third domain encompasses the Tagus estuary with a variable horizontal resolution ranging from 0.02^o off the coast up to 0.002^o inside the estuary. Figure 2 shows the bathymetry of the Tagus estuary used in the simulations.

For the atmospheric conditions, the system is one-way coupled offline with the MM5 atmospheric forecast model for the west Iberian coast, running at IST (http://meteo.ist.utl.pt). This model provides wind speed, air temperature, mean sea level pressure, surface humidity, cloud cover, downward long wave radiation and solar radiation hourly data with a 9 km spatial resolution. Water proprieties were simulated only on the Tagus estuary model (third domain) and constant values were imposed in the ocean open boundary, considering a low seasonal variation of these proprieties in the ocean. The simulated proprieties were: water temperature, salinity, oxygen, ammonia, nitrite, nitrate, phosphorus, phytoplankton, zooplankton, and cohesive sediment.

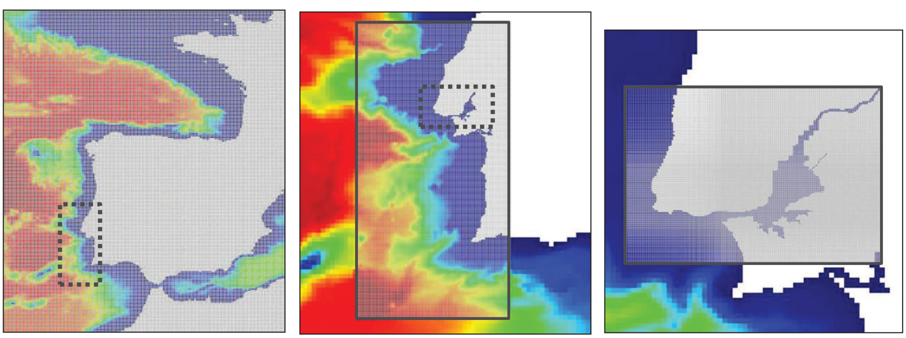

Figure 3. *Downscaling scheme used for the Tagus estuary model with three nested domains: a) first domain; b) second domain; c) third domain the Tagus estuary.*

Tagus river freshwater discharges measured at the Almourol hydrometric station were used as the main river boundary conditions (http://snirh.pt). For Sorraia and Trancão rivers, flow and water properties were obtained from climatological data. Other 15 discharges related with urban waste water treatment plants were included in the model.

The DEB model was applied only for the Tagus estuary model (third domain) and the same parameterization used by [11] for the *Mytilus edulis* simulations was employed. A value of 100 individuals per m^2 was applied in all the domain cells and the initial values of bivalve volume, energy and reproductive energy was set to 2.95×10^{-6} m^3, 5177 J and 1000 J, respectively.

The model was executed over a time period of 1 year from January 2009 to January 2010. The validation of hydrodynamic and biogeochemical model for this period can be found in [15].

4 RESULTS AND DISCUSSION

The model was applied to the Tagus estuary to simulate the potential growth of the *Mytilus edulis* in the system. In order to identify the preferential growth zones of the bivalves, the discussion of the results were focused on the shell allometry (structural volume, shell length, dry weight) and mussel bioenergetics (energy in the reserves, reproductive energy).

Figure 4 shows the spatial distribution of predicted structural volume and energy in the reserves of an individual bivalve after one year of simulation. Results obtained for the structural volume shows two distinct regions: an offshore area and the lower estuary where the potential mussel growth is almost null, and the upper estuary as a preferential zone for the potential mussel growth. Initially the mussel volume was 2.95 cm^3 (shell length of 5 cm) and in the upper estuary after one year of simulation the volume reached values of 8 cm^3 (shell length of 7 cm). Shell allometry and mussel depend on the consistent supply of high quality food, particularly phytoplankton [16]. Thus the level of shellfish production that can be sustained in a body of water is determined by the level and supply of primary production.

The upper estuary is the area with higher phytoplankton concentrations and consequently the area with more potential for the mussel growth. However, salinity can also be a limitation factor for the *Mytilus edulis* growth. This species is euryhaline and occurs in marine as well as in brackish waters down to 4‰, although it does not thrive in salinities of less than 15‰ and its growth rate is reduced below 18‰ [17]. This factor was not considered in the simulation and in the case of the present application the results can be affected, due to the range of salinities that can occur in the system. Another growth limiting factor not considered in the model is the sediment concentration. In some way these are model limitations that should be solved in the future.

The time series of predicted shell length and mussel dry weight (DW) in three stations (P1, P2, P3) located in the upper estuary (Figure 2) are shown in Figure 5. Results of the phytoplankton concentration are also represented in the mussel dry weight plot. The model recreated the annual pattern of growth: growth in the spring and summer and little or no growth in the autumn and winter. However, after one year different potential growth rates are predicted for the three stations, with the maximum rate at P1 and similar rates at P2 and P3. The final shell length varies from 7.0 cm in P1 and 5.68 cm in P3, showing a significant variation in the potential growth depending on the zone of the upper estuary.

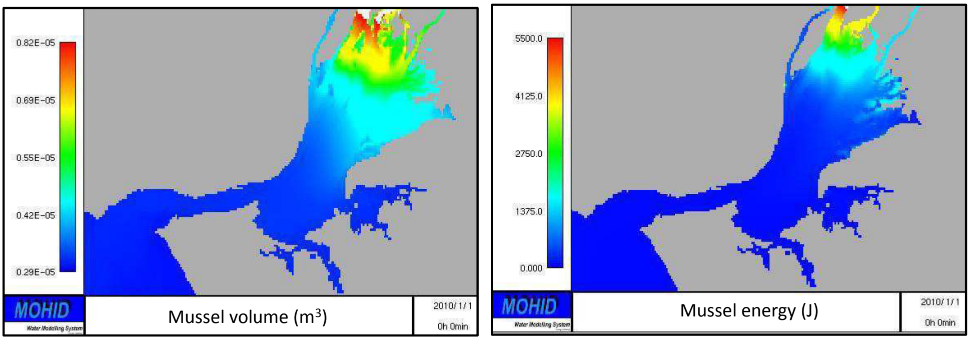

Figure 4. *Results after one year of simulation: a) potential mussel volume, and b) potential mussel energy.*

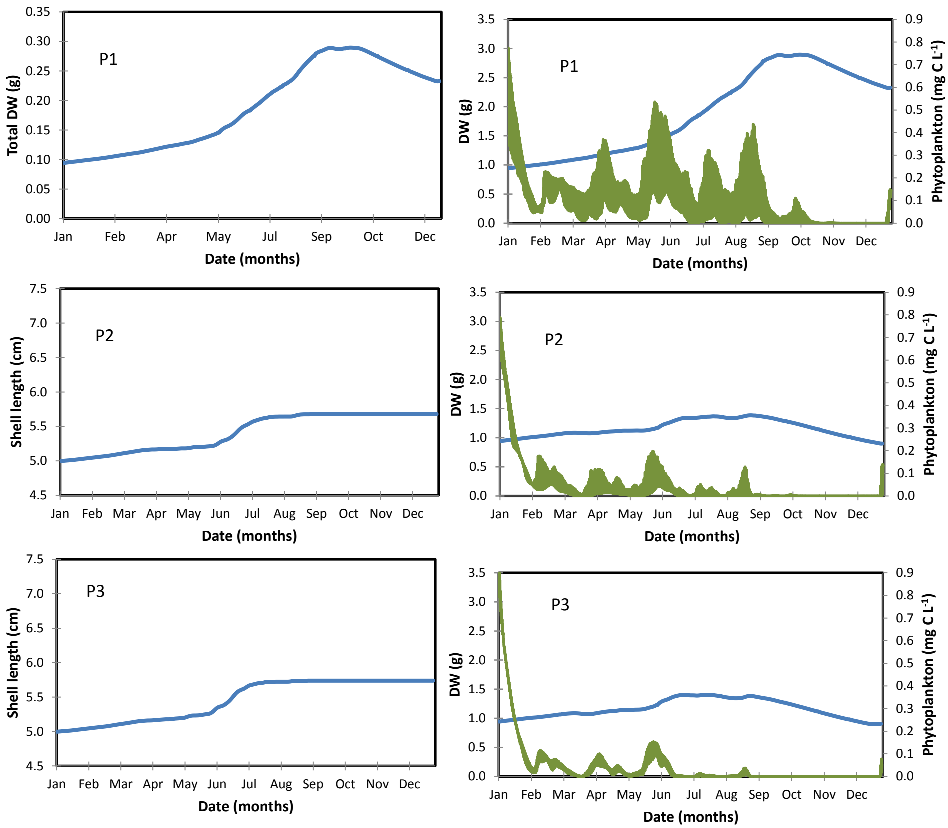

Figure 5. *Time series of simulated shell lengths, dry weights and phytoplankton concentration (green line) in three stations located in the upper estuary area (see Figure 2 for stations location).*

In terms of dry weight (DW), the model results shows an increase from 1.0 g to between 2.9 g at P1 and to 1.4 g in P2 and P3, and a reduction of DW in autumn and in winter in the three stations. This reduction is associated with starvation (very low phytoplankton concentration). The time series of the phytoplankton concentration show high values of phytoplankton concentration in station P1 than in stations P2 and P3 and consequently, high final shell length and dry weight are predicted in P1.

5 CONCLUSIONS

A model based on the DEB theory was coupled with the MOHID model and applied to the Tagus estuary. The one year simulation results showed that the upper estuary is the area with more potential for mussel growth. However, within the upper estuary different potential growth rates are obtained depending on the phytoplankton concentration. Results also showed that some improvements can be done to the model, namely the inclusion of salinity and sediment concentration as limiting factors for *Mytilus edulis* growth.

A model capable of examining environmental sustainability and productivity of a system is a powerful tool to support sustainable management of shellfish culture. The present model can reproduce a system behavior and is capable to assess the impact of mussel culture on the dynamics of the system. Therefore it can be used to estimate the potential for growth, the ecological and the capacity of a system to support shellfish production.

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