MODELLING THE ENVIRONMENTAL AND PRODUCTIVE CARRYING CAPACITY OF A GREAT SCALE AQUACULTURE PARK IN THE MEDITERRANEAN COAST AND ITS IMPLICATIONS

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CHAPTER SYNOPSIS

Background

Mohid Modelling System was used to assess the carrying capacity of a Marine Culture Park located on the coast of Murcia (SE Spain). This location includes seven facilities with a global production of near 7000 tons of finfish. To assess the Productive Carrying Capacity (PCC), three distinct scenarios of increasingly unfavourable hydrodynamic conditions were modelled using toxic ammonia levels and hypoxia risk as indicators. The Environmental Carrying Capacity (ECC) was evaluated under different production scenarios. In this case, the ECC was assessed by means of eutrophy levels in sediments and water column and the tolerance of benthic organisms to organic matter sedimentation.

Results

Ammonia concentrations would not reach toxic levels for the culture under the analysed distribution scheme. However, oxygen consumption due to fish breath could result in first symptoms of hypoxia stress in downstream located cages when coinciding with prolonged low hydrodynamic periods.
In any of the studied scenarios, modelled dissolved nutrient concentrations were found significantly different from local average values. Eulerian and lagrangian model results showed moderate benthic impact. The benthic effects were mainly due to uneaten feed.

Conclusions

The effect on culture and environment could be reduced by means of simple distance rules obtained from the production and environmental carrying capacity analysed in this work. An efficient feeding management that decrease the unconsumed feed would significantly improve the environmental compatibility, on the contrary mismanagement would produce very high impact on the bottom. The followed methodology in this work is highly adaptable to any area and cultured species.

1 INTRODUCTION

1.1 The San Pedro Marine Culture Park

Mariculture production in the Region of Murcia has grown since the mid 90's, with just over half a ton, up to the current 10,000 tons of fish placed on the market. Murcia has become in little more than 15 years in one of the leaders of the offshore aquaculture in Spain. This activity produced in 2008 revenues of more than 60 million Euros due to the degree of specialization achieved by companies through continuous improvement of facilities, equipment, technical training and research. Thus, marine finfish culture has become a strategic economic sector at regional level, with growing potential and able to generate a significant number of jobs.

In order to prevent socioeconomic and environmental conflicts local authorities delimited an aquaculture coastal area where facilities were grouped. Currently, this area named "Polígono de Cultivo Marinos" (the Spanish term for Marine Culture Park, hereafter referred as MCP) (Law 2/2007 on Marine Fisheries and Aquaculture of the Region of Murcia). The

MCP includes seven administrative concessions authorized to produce annually around 7000 tons of Atlantic bluefin tuna (*Thunnus thynnus*), gilthead seabream (*Sparus aurata*, hereafter referred as seabream), and European seabass (*Dicentrarchus labrax*, hereafter referred as seabass) among other species present in a testimonial number. The production is achieved by an estimated cultured biomass around 11,000 tons of fish, depending on species proportion, commercial size and conversion rates. The San Pedro MCP could be regarded as one of the biggest open sea facilities dedicated to caged fish production in the Mediterranean Sea.

In spite that every facility has a different owner; the MCP could be regarded as a single environmental and sanitary unit in management terms. To date, the facilities operation has not led to any environmental impact above the permissible levels as the environmental monitoring plans results has been showing since the beginning of the activity. Thus, according to the adaptive monitoring approach [1] adopted in Murcia [2] the production in the study area could be increased.

The San Pedro MCP is an interesting study case to test the ability of modern hydrodynamic and ecological models to deal with multipurpose and multisource discharges and evaluate resilient capacity at local and regional scales.

1.2 Numerical models as a tool for aquaculture management

Mathematical models were used on the last thirty years as an administrative tool for aquaculture management. Initial applications were simple dispersion models [3], without any regard to the systems' hydrodynamics, centred on the benthos impact by particulated materials accumulation. Lagrangian models, i.e. DEPOMOD [4], soon were considered as adequate tools for the particulated discharges study due to its high spatial resolution, but their incapacity to simulate neither the hydrodynamic fields nor the biology of the water column restricted them to very local scale applications and to scenarios where impact of soluble waste could be neglected. For these reasons, fully 3D hydrodynamic models as the Mohid Modelling System [5], able to simulate both the dissolved and particulated discharges and to represent heterogeneous hydrodynamic fields, were found suitable for this study purposes. The Mohid model included, in addition to the eulerian and lagrangian dispersion modules, several modules than could resolve sediment biochemistry, zooplankton communities (NPZD) models, pathogen dispersion from fish faeces as faecal coliforms, floating oils derived from feed pellets, etc.

1.3 Mariculture and its effects in the environment

Impacts of aquaculture activity are mainly related with the nature and quantity of wastes and oxygen consumption from the water column. Any generic input-output flow schema should comprise (Figure 1):

- Particulate Discharges: integrated by different fractions of decomposing faeces and uneaten feed. The smallest fraction is incorporated into the suspended particulate matter or detritus, which is also composed of faecal matter, waste substances, and the body remains of planktonic organisms. These particles are readily colonized by bacteria, protozoa and heterotrophs that actively remineralise organic matter releasing mainly ammonium, which is incorporated into the water column, while consuming oxygen for the aerobic metabolism. In contrast, larger particulate matter settles in the substrate at a distance which is a function of its sedimentation speed, distance to the seabed and ambient currents. Once the solids have settled in the bottom, a small part could return to the water column in dissolved form, as a result of microbial activity and invertebrates feeding. These processes are simultaneous to the cages discharge.

- The dissolved discharge: composed mainly of ammonium excreted by fish and from remineralised organic matter. Ammonia is excreted as un-ionised form (NH_3), and depending of pH, salinity and temperature in seawater, it could be ionised forming NH_4^+. Microbial and invertebrate metabolism releases nitrogen as ammonium (NH_4), although the amount of ammonia entering the water column through remineralisation is much less than which enters directly in dissolved form by excretion and fish feed. A side effect of the particulate fraction is increasing turbidity and therefore the inadequacy of photo-synthetically active fraction of light available in the water column. Lethal concentration for 50% of the population (96h-LC_{50}) in marine caged fish has been estimated in 40 $mg\ l^{-1}$ for seabass [6]. The un-ionised ammonia is 300 to 400 times more toxic than ionised form [7]. Independently of ammonia toxicity, the final effect of both types of discharges, particulate and dissolved, would be an increase in the dissolved nitrogen availability. There is a clear relationship between nutrient enrichment and water quality deterioration. Eutrophication takes place when nutrient discharge rate exceeds the processing capacity or elimination from the system and exceeding nutrients stimulate excessive biological production. Once ammonia is oxidized to nitrate is directly assimilated by phytoplankton and stimulates the development of planktonic communities, including mesoplankton, provided there is no limitation by phosphorus and silica. An increase in plankton biomass entails even greater risk of increasing populations of certain toxic algae which extreme event are red tides. Within this scheme, changes on nutrient concentration could be regarded as an undesirable water quality disturbance [8] which could significantly alter the planktonic production, increasing the risk of eutrophication or red tides events.

- Oxygen consumption: In addition to the nutrient supply, oxygen concentrations could be regarded as an indicator of aquaculture impact. Settled organic matter remineralisation imply a series of associated processes including oxygen consumption that could lead to hypoxia and anoxia events, and the rise of the red-ox potential discontinuity, that could lead to sulphide production, with the consequent impoverishment of the benthic macrofauna diversity, richness and biomass following the spatial and temporal gradients according to the Pearson and Rosenberg model [9]. Particulated matter deposited on the sediment should be considered as an undesirable disturbance when the sedimentary oxygen demand increases significantly, which could imply a benthic simplification at the community level. Thousands of tons of fish breathing in a constrained net-pen could produce a marked reduction in the water column dissolved oxygen concentration. Moderated water column hypoxia would limit growth rates and high levels would conduce to brachicardia and extreme levels to death [10].

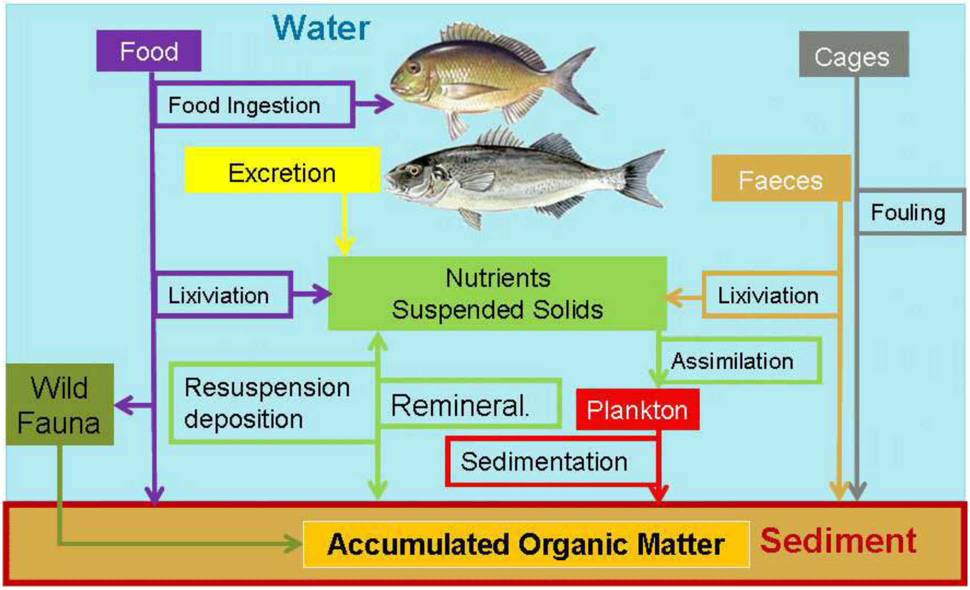

Figure 1. *Conceptual model for the aquaculture nutrient including the actors (filled boxes) and their associated processes (empty boxes). In this study, all the processes were modelled except the wild fauna (in dark green) and the cages (in grey) processes.*

In general, aquaculture facilities impacts produce small-scale disturbances, which isolated could be considered ecologically not significant. In offshore aquaculture, only minor impacts on nutrients concentrations and plankton communities were documented, especially in areas where, as in this case, the currents pattern promotes a high renewal rate of water masses [11]. In cases where some degree of confinement was added, such as aquaculture in fjords, bays and lakes, water quality could be altered by the aquaculture activity. In any case, the result of these small impacts should be monitored and should be regarded as undesirable on any aquaculture management context. Most of these studies refer to production scales much reduced than those analyzed in the present work [11], which exceeds 28,000 tons.

1.4 Objectives

The main objectives of this study include the evaluation of the Production Carrying Capacity (PCC) and the Ecological Carrying Capacity (ECC) as defined by the New Zealand National Institute of Water and Atmospheric Research (NIWA) [12] with the aid of numerical modelling tools.

Regardless of the methodological approach, in order to address the carrying capacity of an aquaculture development area, a number of issues should be taken into consideration: factors that could determine the environment productivity, the amount of food/waste that would be consumed / produced, the environment reaction to the waste discharge and the allowed change [8].

2 THE STUDY AREA

2.1 Localization

The aquaculture study area is located 6 km off the coast of the Autonomous Community of Murcia, in the municipality of San Pedro on the southeast coast of the Iberian Peninsula (Figure 2). The stretch of the Murcia coast from the north end to Cape Palos, with predominant exposure to the East, is characterized by a wide continental shelf of very gentle slope, up to 35 km from the coastline to reach 200 m depth. The aquaculture facilities are located 35 m over the seabed. The adjacent stretch of coast correspond to the San Pedro salt marshes natural reserve where the coast keeps the dunes belt and typical coastal vegetation thought most of neighbouring coastal area is occupied by large residential resorts.

2.2 Hydrodynamics

The study area is located in the transitional zone between the waters moving south from the Alghero-Provençal basin and the waters of the Alboran Sea influenced by the entering waters from the Atlantic Ocean. On the surface, the Mediterranean Atlantic Water (MAW), loaded with nutrients and low salinity, after entering through the Gibraltar Strait and circulating in two cyclonic eddies, is directed towards the inner Mediterranean Sea. Eventually, a third cyclonic gyre may occur in western Algerian waters leading the MAW to the study area. These waters could be responsible of planktonic blooms, contributing significantly to the production in the area, though this relation has been poorly studied. The influence of these cyclonic eddies is significant since the composition analyzed phytoplankton is apparently similar to the Alboran Sea [13].

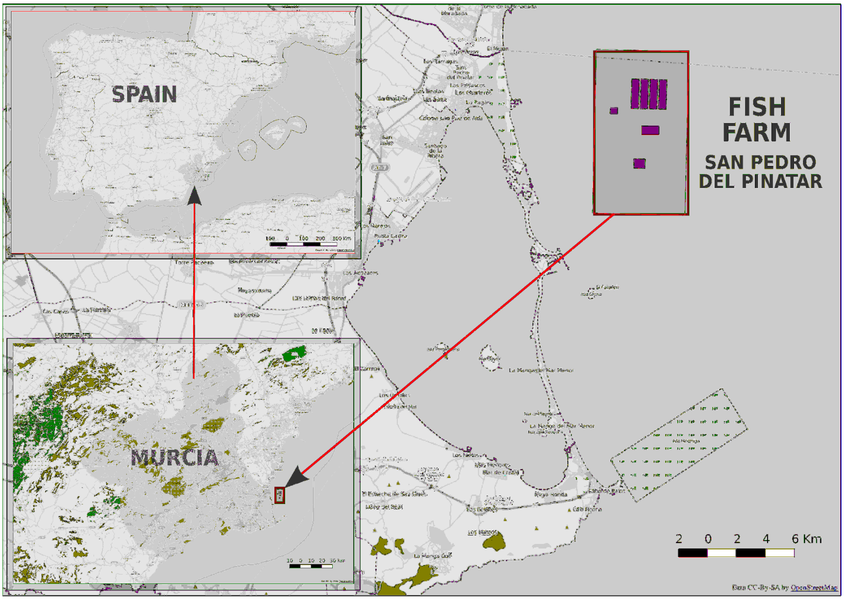

Figure 2. *Map of the SE Spanish coast where the Marine Culture Park is located.*

2.3 Water quality

The data used to characterize the regional waters come from the project MEDATLAS DS3 [14] limited to 200 m for nutrients. Nitrogen concentrations range from 0.5 mmol m^{-3} at the surface to 8.3 mmol m^{-3} in depth, with minimal seasonal deviation. The same variation occurs to phosphorus concentrations ranging from 0.3 mmol m^{-3} at the surface to 0.83 mmol m^{-3} in depth. At the local scale, data were obtained from TAXON coastal campaigns (2007-2009), in this case limited to the first 50 m depths.

The non-refractory dissolved organic matter (nrDOM) above the thermocline represents between 25-35% of dissolved organic carbon (DOC), 30-35% of the dissolved organic nitrogen (DON) and 60-80% of the dissolved organic phosphorus (DOP). The relationships between each of the elements is variable in the Mediterranean Sea, generally nrDOM concentrations are lower than refractory dissolved organic matter (reDOM), except for C:N (nrDOC:nrDON 10–19, nrDOC:nrDOP 160–530 and nrDON:nrDOP 15–38). The DOM stoichiometry in the Mediterranean Sea suggests that heterotrophic activity could probably be the dominating process in this oligotrophic sea.

2.4 Sediment quality

The seabed at the MCP is predominantly sandy, with average percentages of sand up to 74 % and a range that varies from 36 to 89% of total sand. The finer materials (silts and clays) are also quite variable, ranging between 7.7 and 57.6%, the average value for the area of 16%. The average content of organic matter is 0.7%, with a range of values in the study area ranges between 0.35% and 1.84% dry weight. These values correspond to submerged areas with some external inputs.

2.5 Trophic status

In general, the Mediterranean waters are nutrient limited, and therefore present low biological productivity, comparable to that of the Sargasso Sea and the oceanic central gyres. The oligotrophy increases from east to west with local increases based on higher nutrients supply. Medatlas data showed that nitrogen concentrations range from 0.5 mmol m-3 at the surface to 8.3 mmol m^{-3} in depth, with reduced seasonal variations. Phosphorus concentrations present a similar pattern, ranging from 0.3 mmol m-3 at surface to 0.83 mmol m^{-3} in depth [14].

Eastern Iberia coastal waters correspond to coastal subtypes characterised by the existence of a spring phytoplanktonic bloom where the planktonic biomass could double, while offshore waters generally do not present this bloom [15]. When comparing local data these waters could be regarded as productive, reaching values of 1 mg Chla m^{-3} in bloom conditions, while average Mediterranean waters do not exceed 0.28 mg Chla m^{-3}.

Trophic structure is dominated by heterotrophs over autotrophs in terms of biomass and respiration [16]. In particular, the bacterial carbon demand might exceed the primary production. Micro and mesozooplankton exhibit the ability to feed directly from the detritus, preventing its nutrients to end up in the phytoplankton compartment and producing massive blooms [17]. This ”top down” control seems to lead to a high resilience to eutrophication [18]. Thus, the autotrophic community would not be limited by nutrients availability, but by POM demand.

3 MATERIAL AND METHODS

3.1 Mohid description

The MOHID Water is an open source numerical model included in MOHID Water Modelling System [5] developed since 1985 Instituto Superior Técnico (IST), Portugal. The core of the model is a fully 3D hydrodynamic model coupled to different modules comprising water quality, atmosphere processes, discharges, oil dispersion, mixing zone model for point source discharges, and catchment area. MOHID is programmed in ANSI FORTRAN 95 using an object orientated philosophy able to simulate eulerian and lagrangian processes. Lagrangian transport model manages the evolution of water parcels and have been used to simulate different processes as near field outfall dispersion, oil dispersion and during this work the aquaculture production processes were increased to its code.

In this work, the MOHID WaterQuality module was parameterised to the specific characteristics of the Mediterranean ecology and the aquaculture activities. Particularly, a coupled application of the WaterQuality module, a nutrient-phytoplankton-zooplankton-detritus (NPZD) module, was coupled to the hydrodynamic module to simulate nitrogen, phosphorus and oxygen cycles both in the water column and the bottom sediments. This module has a phytoplankton compartment expressed in mg C l^{-1} and nutrients and organic matter compartments also expressed in mg l^{-1} of nitrogen or phosphorus. Five particulate organic nitrogen and phosphorus pools (PON_{1-5} and POP_{1-5} respectively) with independent sinking rates (Table 1) were implemented to simulate the particulated organic discharge from the fish cages. The main features of this NPZD model were:

- Independent sinking rate for each pool defined in the FreeVerticalMovement module input file;
- Conversion of PON_x to ammonium and reDON , and POP_x to phosphate and reDOP, using the same mineralization rate and PON and POP partitioning coefficients defined in the WaterQuality module input file;
- Sedimentation and resuspension of the POM pools, with bottom mineralization (PON_x conversion to NH_4, and POP_x conversion to PO_4);
- Oxygen consumption by POM mineralization;
- Zooplankton ingestion of PON_1 and POP_1.

Table 1. *Characteristics of the simulated POM pools (origin, sinking rate and volume).*

Particle	Type	Sedimentation Velocity (m/s)	% Volume
PON_1 & POP_1	Detritus	0.00905	21.2
PON_2 & POP_2	Faeces	0.0246	18.6
PON_3 & POP_3	Faeces	0.0356	32.9
PON_4 & POP_4	Faeces	0.0463	22.1
PON_5 & POP_5	Not Consumed Feed	0.15	5.2

3.2 Aquaculture waste production model

A ”production unit” was defined to deal with multiples configurations of sea cages and incremental production scenarios. This unit was based in a standard sea cage with 25 m diameter and 20 m deep, which is the most common used cage for the seabream and seabass culture. An annual production of 100 tons by net-pen (50% of seabream and 50% seabass) was estimated. All amounts here presented are related to this unit and replicated later to construct individual scenarios. Good management practices were assumed and uneaten feed was estimated as the 3% of the total feed delivered.

A simple mass balance equation between food and excretory products was used to estimate global waste inputs [3]. A detailed characterization of different wastes forms (PON_{1-5} and POP_{1-5}, ammonia and lixiviated products), temporal evolution and influence of temperature was attained by means of bioenergetic model for seabream and seabass [19]. Daily estimated waste and oxygen consumption was distributed at hourly scale according to Calderer [10]. One entire cycle, until commercial size was attained, for seabream and seabass production was modelled (Figure 3). The simulated discharge corresponded to the daily release cycle for a production unit with 100 tons of caged biomass at the end of the production cycle.

3.3 Production Carrying Capacity (PCC)

Ammonia and oxygen concentrations were selected as indicators of the PCC. The analysis of allowable limits of these variables should provide simple regulations for the aquaculture facilities design, in terms of culture density and minimum distances between cages rows.

Analysis was conducted under an hypothetical hydrodynamic scenario of a uniform 40 meter bathymetry composed with 111×29 cells of 25×25 m wide, and three sigma vertical layers (20 m, 16 m and 0.4 m). The model was fed by a uniform North-South constant current. Three scenarios with progressively worsening current conditions were defined: calm currents: $0.04\ \mathrm{m\,s^{-1}}$; average currents: $0.3\ \mathrm{m\,s^{-1}}$ and extreme currents: $1\ \mathrm{m\,s^{-1}}$. All scenarios included 60 production units aligned north-south disposed in three sets of ten pairs of cages with a separation between cages of 25 m and between rows of 50 m.

The environmental physicochemical parameters used to feed the model were: temperature, salinity, oxygen, nitrate, phosphate and silicate, whose climatological profiles were imposed at the mesh boundaries from NOAA World Ocean Atlas 2005 data [20].

3.4 Environmental Carrying Capacity (ECC)

The ECC was evaluated in terms of the risk of eutrophication and the allowable benthos degradation. Nutrient concentrations in the water column, organic matter discharge rate and organic matter percentage in the sediment were the selected indicators. The organic matter discharge rate integrated the five types of particles simulated and was converted to organic matter concentration per unit area and day. The organic matter percentage in the sediment includes besides particulates from the marine culture, the natural organic matter from the water quality module, therefore it should be regarded as the organic matter concentration often used as an indicator in monitoring plans.

An independent hydrodynamic model of PCC scenarios was constructed. In this case a two nested domains were necessary to obtain accurate local hydrodynamics (Figure 4). Level 1, or regional level, included a regular domain covering the entire Region of Murcia with a horizontal resolution of 886 m formed by 130 cells wide by 80 cells. This was a 2D simulation and its vertical dimension was discretised with a single sigma layer of variable size forced by winds and tides. Finally level 2, or San Pedro level, was composed of 73 cells wide by 73 cells wide with a horizontal resolution of 246 m defining a simulation domain 18 km^2. This domain was 3 Dimensional whose vertical dimension was discretised by a set of 10 sigma layers.

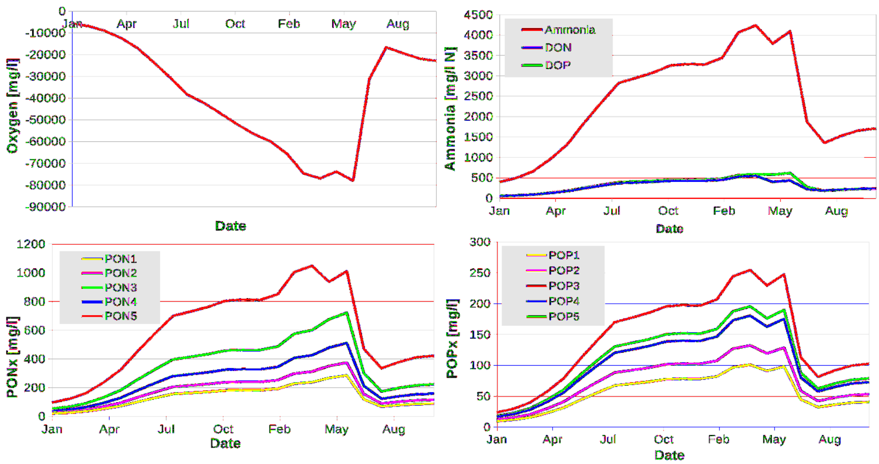

Figure 3. *Complete cycle of oxygen consumption (top left), dissolved discharges (top right), organic nitrogen particles (bottom left) and organic phosphorus particles (bottom right) for a hypothetical cage with mixed seabream and seabass culture used as input to simulate the different considered load scenarios.*

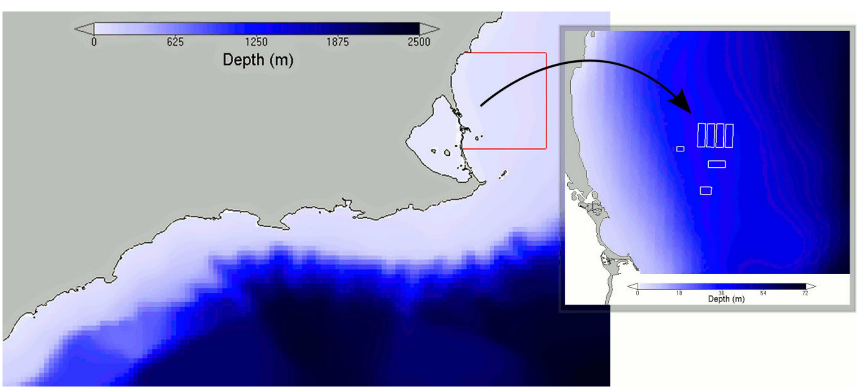

Figure 4. *Bathymetry employed for the 2D hydrodynamic domain covering the coast of the Autonomous Community of Murcia with a horizontal resolution of 886 m (Left). The red polygon corresponds to the 3D San Pedro nested domain with a horizontal resoluiton of 246 m (right). The white polygons represent the location of the aquaculture facilities in the MCP.*

For creating the model gridded bathymetries, a high-resolution digital terrain model from the ESPACE project of the Spanish Institute of Oceanography (IEO) [21] was used. Hydrodynamics were forced by local wind data from the nearby San Javier airport and by the reduced local tides, imposed in the Level 1 domain with tidal components obtained from the global tide model FES2004 [22]. At the San Pedro level the model was coupled with the water quality module where the environmental physicochemical parameters used to feed the model were the same as in the channel model described in the above section.

This realistic San Pedro hydrodynamic level was coupled with a lagrangian dispersion model. Several dispersion scenarios based on different configurations of number and spatial distribution of the production units were analysed:

1. Caged fish biomass of 11100 Tm (Figure 5a): integrated a total of 111 production units irregularly spaced and distributed in seven groups, obtaining an estimated annual production around 4,700 tons.
2. Caged fish biomass of 14000 Tm (Figure 5b): 140 production units arranged in regular distribution of 7 rows of 10 pairs of cages, accounting for an estimated annual production of 5,850 metric tons.
3. Caged fish biomass of 28000 Tm (Figure 5c): Maintaining technical and environmental efficiency of the second alternative but doubling the number of production units.

Both, eulerian and lagrangian approaches, were followed. The eulerian approach was employed to obtain the water quality properties concentrations on the water column and in the benthos. The lagrangian approach was useful to estimate accurately the cages footprint, as lagrangian particles are not restricted by the horizontal resolution of the model.

4 RESULTS AND DISCUSSION

4.1 Modelling results from the PCC

Results from PCC scenarios reveal and addition effect of ammonia levels between successive net-pens (Figure 6). Ammonia maximum modelled concentrations, after the addition effect of the 60 production units, was 0,091 mg l^{-1} on calm conditions, 0.036 mg l^{-1} for average currents and 0.021 mg l^{-1} for extreme currents. These ammonia levels were below the interval of 0.2 to 2 mg l^{-1} that has deleterious effects on fish [7]. Although this range of values could sensibility vary depending on fish size and balance between its ionized and unionized form (NH_3) [6]. These results would indicate that the limiting concentrations could be achieved in water tanks, where the water renewal is low, but in open water conditions the nitrogen discharges would not limit the production, as the hydrodynamic conditions and red-ox process would modify the toxic forms into harmless forms.

Same addition effect was observed for oxygen depletion, although in this case some values dropped within the limit considered (Figure 6). Critical concentrations for culture growth (5.5 mg l^{-1}) [10] were reached nearly after the half of the second row of cages under calm conditions. More intense currents would imply higher renewal rates in the water column which in addition would lead to reduced decreases of dissolved oxygen partial pressure.

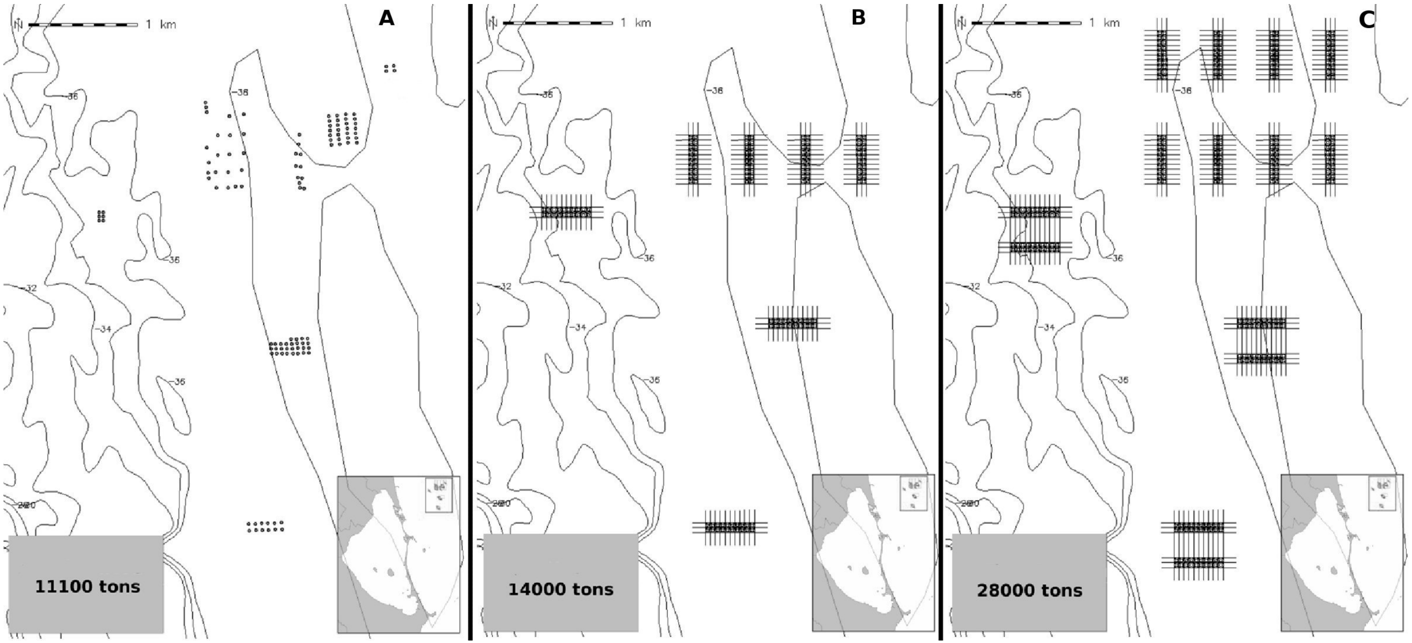

Figure 5. *Maps of the analysed alternatives for the San Pedro del Pinatar MCP environmental carrying capacity study: alternative description map: scenario I (a), scenario II (b), scenario III (c).*

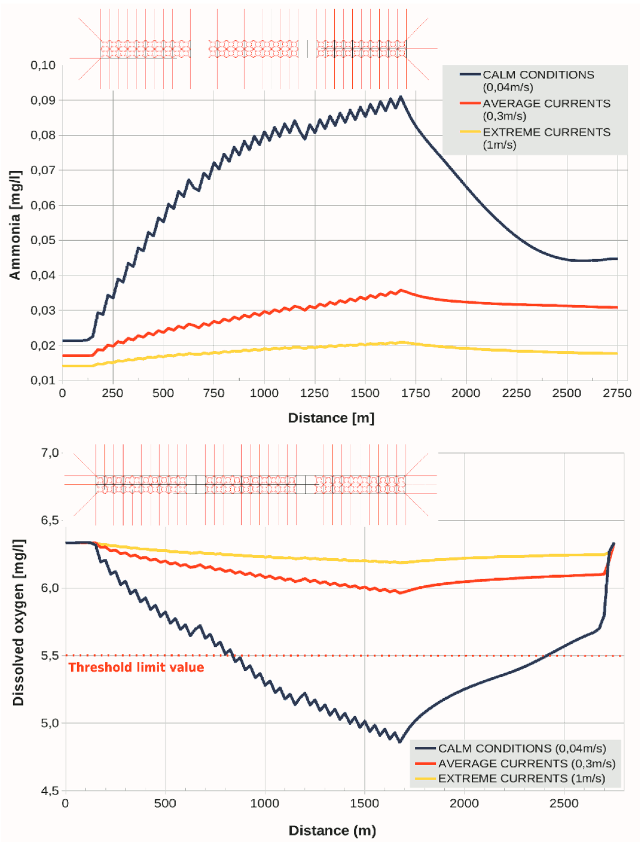

Figure 6. *Ammonia and oxygen modelled concentrations in the production carrying capacity study. The distance is measured from the beginning of the domain; the distribution of the cages is depicted on top of each figure. The threshold limit value for ammonia is out of the range of modelling results. The threshold limit value for oxygen concentration of 5.5* mg l^{-1} *is shown in the figure.*

From the results showed in figure 6, it could be estimated that the maximum number of cages that could be placed on the same row would be up to 24 cages; as from the twelfth pair of cages situations of stress might occur to the cultured fish. This curve could be used to obtain the minimum distance between installations, particularly in the case of two rows of 20 cages (ten pairs of cages) of 100 ton (Figure 6), a separation of 550 m would be necessary to ensure no negative effects due to possible hypoxia situations.

4.2 Results from the Environmental Carrying Capacity

Footprints from eulerian and lagrangian models were in agreement. Results from lagrangian approach simulations for the three different scenarios showed that footprint did not exceeded 475 meters from the facilities in the maximum amplitude axis (NW-SE) (Figure 7). Maximum rates of POM were obtained immediately below the cages (3,500 mg m^{-2} d^{-1}), being able to distinguish the individual cage footprints.

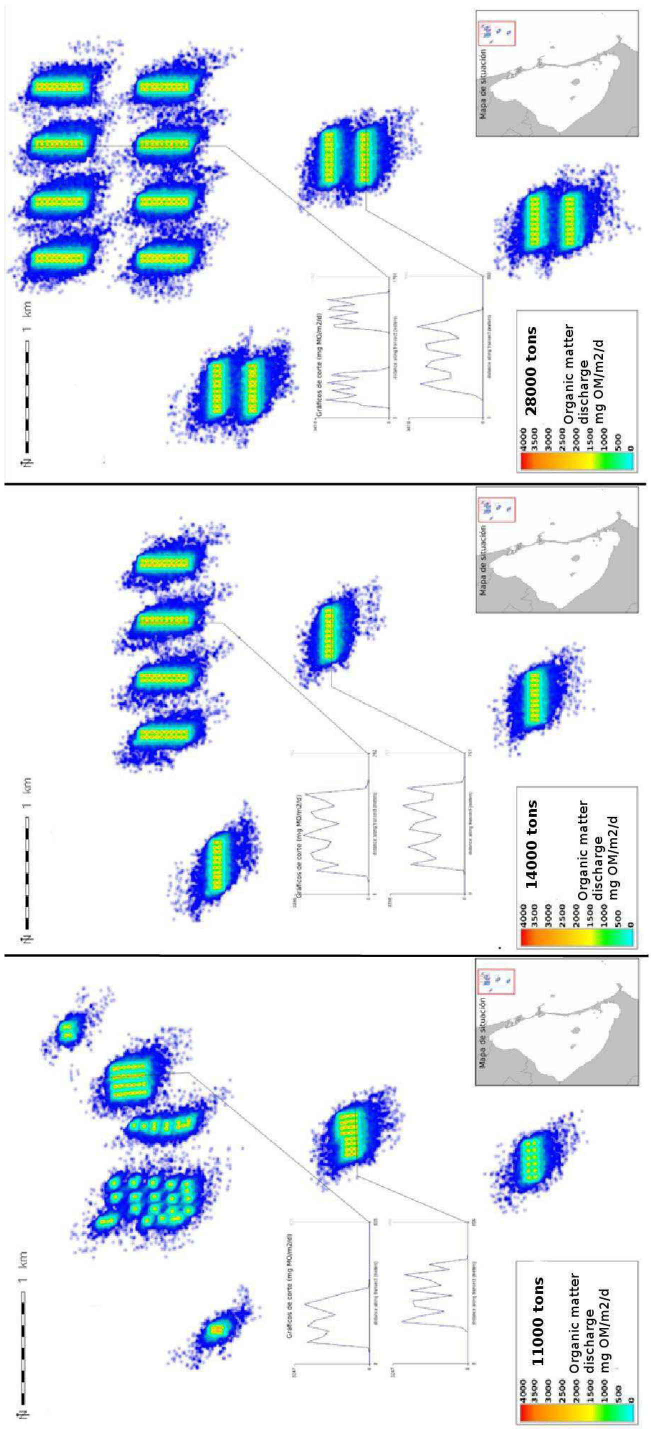

Figure 7. *Organic matter sedimentation rates obtained for the simulated alternatives (I, II and III).*

From the cages, sedimentation rates reduced rapidly, approximately 40 times in 50 m. It could be noted that facilities with low cage separation were less efficient in dispersing the discharges. Sedimentation rates around 1500 mg C m^{-2} d^{-1} would produce benthic community deterioration in mesocosm experiments [23,24]. Field experiments in East Mediterranean facilities [25] needed rates $>$4,100 mg C m^{-2} d^{-1} for altered conditions. Our modelling results reached rates between 100 and 1,000 mg C m^{-2} d^{-1}, corresponding to certain enrichment.

Results from the eulerian approach provided organic matter percentage values in sediment (Figure 8). The highest organic matter concentration in sediment was found in the ECC scenario of 28,000 tons (2.2%), surprisingly followed by the lower production case (11,100 tons) (2.1%); the 14,000 tons scenario has 1.7% of organic matter in sediments. These results could be explained because the alternatives caging higher biomass (alternative 2 and 3) spread their discharge over larger areas achieving lower sediment organic matter concentrations than the first alternative. These values would correspond to submerged areas with external inputs, slightly higher than maximum natural values in the study area. None of the simulated alternatives reaches values over the environmental quality standards ($<$2% out of the AZE; $<$4% within the AZE) established by the Region of Murcia administration [2].

5 CONCLUSIONS

Under the above assumptions and according to the MOHID model results, the discharges would not produce any significant change out of the MCP. Inside the MCP, the footprint could achieve early to moderate early stages of contamination according to the Pearson-Rosenberg model [9]. It was also observed that footprint was almost entirely due to the uneaten feed. Therefore, an efficient feeding management would reduce the unconsumed feed and would significantly improve the environmental compatibility. On the contrary mismanagement would produce a severe impact on the bottom sediments and benthic communities.

The definition of allowable change in an ECC study could be regarded as the most problematic issue due to the limited ability to predict the ecological and economic effects of environmental changes. The recovery assessment approach determines what is an acceptable impact or an undesirable perturbation *sensu* Tett et al. [8]. The recovery period of an area affected by organic matter enrichment depends on the temporal and spatial scale of hypoxia or anoxia. The longer the period of hypoxia the larger the amount of organic matter in the affected area that should be oxidized before macrofauna recolonisation could begin [26].

From the modelling results, aligning more than 12 production units should not be a recommended practice, as low oxygen levels could appear in the water column that might result in fish stress. When considering groups of 10 production units, the minimum distance between groups to overcome potential hypoxia would be of 550 m. Moreover, this distance is greater than footprint radio and would also avoid a synergic effect between facilities on the benthos.

Finally, the Mohid model adaptations that combined a NPZD model with the ability of zooplankton to consume directly organic matter were able to simulate the eutrophication resilience of the Mediterranean Sea waters. In addition, the implementation of the different organic matter pools related to the aquaculture production with lagrangian tracers resulted in a complete tool that would aid managers in terms of aquaculture production and coastal management.

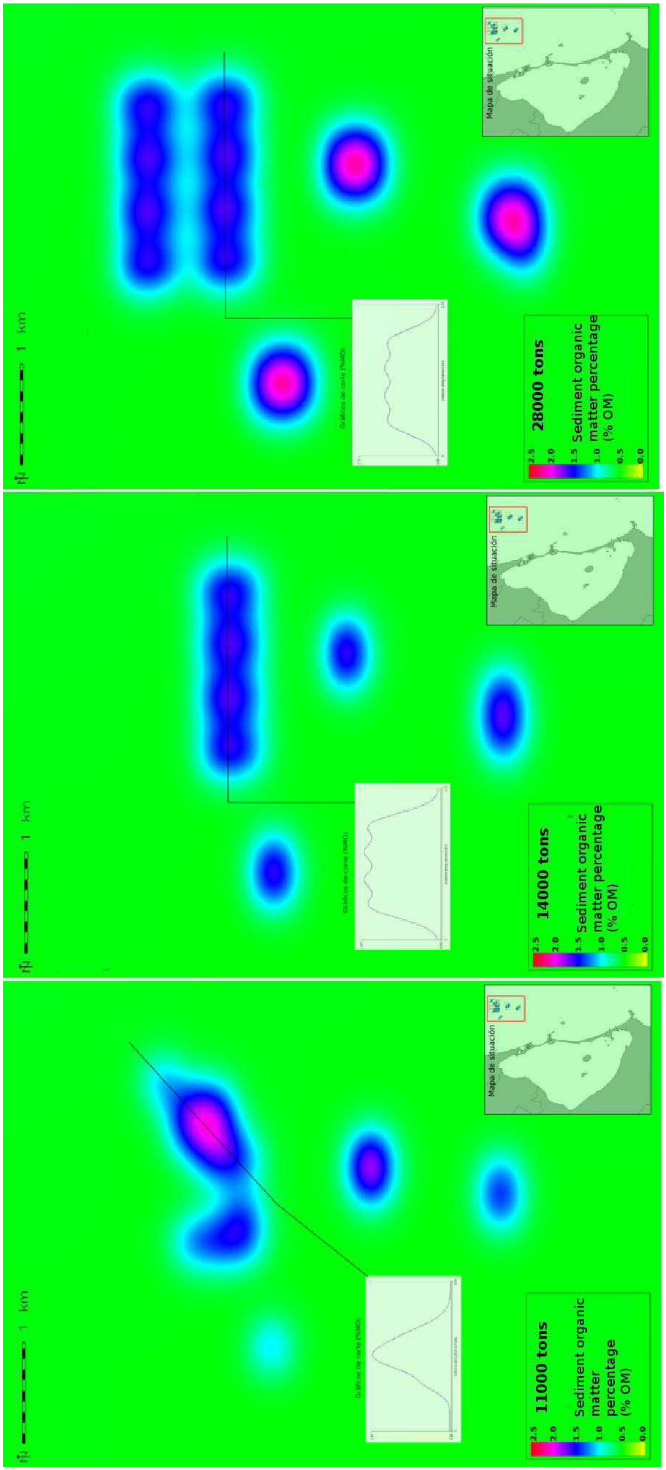

Figure 8. *TOrganic matter content in sediments for the simulated alternatives (I, II and III).*

ACKNOWLEDGEMENTS

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REFERENCES

1. IUCN, 2009. Guide for the Sustainable Development of Mediterranean Aquaculture 2. Aquaculture site selection and site management, IUCN, Gland, Switzerland and Malaga, Spain. 303 pp.
2. TAXON, 2007. Protocolo para la Realización de los Planes de Vigilancia Ambiental de las Instalaciones de Acuicultura Marina en la Región de Murcia. Servicio de Pesca y Acuicultura. Comunidad Autónoma de la Región de Murcia. 148 pp.
3. Gowen, R.J., Bradbury, N.B., Brown, J.R., 1989. The use of simple models in assessing two of the interactions between fish farming and marine environment. R. Billard, N., de Pauw, Aquaculture - a Technology in progress, European Aquaculture Society, Bredene Belgium, 1071-1080
4. Cromey, C.J., Nickell, T.D., Black, K.D., 2002. DEPOMOD—modelling the deposition and biological effects of waste solids from marine cage farms, Aquaculture, 214(1–4): 211-239.
5. Braunschweig, F., Martins, F., Leitão, P., Neves, R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus Estuary case. Ocean Dynamics, 53: 137–145.
6. Person-Le Ruyet, J., Chartois, H., Quemener, L., 1995. Comparative acute ammonia toxicity in marine fish and plasma ammonia response. Aquaculture, 136 (1-2): 181-194.
7. Lemarié, G., Dosdat, A., Covès, D., Dutto, G., Gasset, E., Person-Le Ruyet, J., 2004. Effect of chronic ammonia exposure on growth of European seabass (Dicentrarchus labrax) juveniles. Aquaculture, 229(1-4): 479-491.
8. Tett, P., Read, P., Fernandes, T., Huxham, M., Gilpin, L., Wilkinson, M., Kennington, K., Malcolm, S., Mills, D., Gowen, R., Service, M., 2004. Understanding of undesirable disturbance in the context of eutrophication, and development of UK assessment methodology for coastal and marine waters. Stage 1 project report: what is undesirable disturbance? Report for DEFRA March 2004.
9. Pearson, T., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanography and Marine Biology Annual Review, 16: 229-311.
10. Calderer, A. 2001., Influencia de la temperatura y salinidad sobre el crecimiento y consumo de oxígeno de dorada (Sparus aurata L.). PhD Thesis. Universidad de Barcelona.
11. Beveridge, M.C.M., 2004. Cage aquaculture. Malcolm C. M. Beveridge (Ed). Blackwell Publishing Ltd. 368 pp.
12. NIWA, 2000. An overview of factors affecting the carrying capacity of coastal embayments for mussel culture. NIWA Client Report: CHC00/69.
13. Bouza, N., Aboal, M., 2008. Checklist of phytoplankton on the South coast of Murcia (SE Spain, SW Mediterranean Sea). V. Evangelista, L. Barsanti, A.M. Frassanito, V. Passarelli, P. Gualtieri, Algal Toxins: nature, occurrence, effect and detection. The NATO Science for Peace and Security Programme, 179 -196.
14. MEDAR Group, 2002. MEDATLAS/2002 database. Mediterranean and Black Sea database of temperature salinity and bio-chemical parameters. Climatological Atlas. IFREMER Edition (4 Cdroms).
15. D'Ortenzio, F., D'Alcala, M.R., 2009. On the trophic regimes of the Mediterranean Sea: a satellite analysis. Biogeosciences, 6(2): 139-148.
16. Duarte, C.M., Agustí, S., 1998. The CO2 balance of unproductive aquatic ecosystem. Science, 281: 234-236.
17. Duarte, C.M., Agustí, S., Agawin, N.S.R., 2000b. Response of a Mediterranean phytoplankton community to increased nutrient inputs: a mesocosm experiment. Marine Ecology Progress Series, 195: 61–70.
18. Agustí, S., Duarte, C.M., Canfield, D.E., 1992. Self-regulation, bottom-up, and top-down control of phytoplankton communities: a reply to the comment by Kamenir. Limnology and Oceanography, 37: 683–687.

19. Lupatsch, I., 2004. Gilthead Seabream. Aqua Feeds: Formulation & Beyond, 1(1): 16-18.

20. Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., 2006. World Ocean Atlas 2005, Volume 4: Nutrients (phosphate, nitrate, silicate). S. Levitus, Washington D.C. (EEUU), U.S. Government Printing Office.

21. Sanz, J.L., Tello, O., Hermida, N., Fernández-Salas, I.M., González-Serrano, J.L., 2004. Características del estudio sistemático de la plataforma continental y talud superior españoles (proyecto ESPACE). Revista GEO-TEMAS, 6(2): 261-264.

22. Lyard, F., Lefevre, F., Letellier, T., Francis, O., 2006. Modelling the global ocean tides: modern insights from FES2004. Ocean Dynamics, 56: 394-415.

23. Frithsen, J.B., Oviatt, C.A., Keller, A.A., 1987. A comparison of ecosystem and single-species tests of sewage effluent toxicity: a mesocosm experiment data report. MERL Series, report No. 7. The University of Rhode Island, Kingston, Rhode Island, USA.

24. Kelly, J.R., Nixon, S.W. 1984. Experimental studies of the effect of organic deposition on the metabolism of a coastal marine bottom community. Marine Ecology Progress Series, 17: 157-169

25. Eleftheriou, A., Moore, D.C., Basford, D.J., Robertson, M.R., 1982. Underwater experiments on the effects of sewage sludge on a marine ecosystem. Netherlands Journal of Sea Research, 16: 465-473.

26. Díaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and behavioural responses of benthic macrofauna. Oceanography Marine Biology Annual Review, 33: 245-303.