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Assessment of coastal management options by means of multilayered ecosystem models

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A B S T R A C T

This paper presents a multilayered ecosystem modelling approach that combines the simulation of the biogeochemistry of a coastal ecosystem with the simulation of the main forcing functions, such as catchment loading and aquaculture activities. This approach was developed as a tool for sustainable management of coastal ecosystems. A key feature is to simulate management scenarios that account for changes in multiple uses and enable assessment of cumulative impacts of coastal activities. The model was applied to a coastal zone in China with large aquaculture production and multiple catchment uses, and where management efforts to improve water quality are under way. Development scenarios designed in conjunction with local managers and aquaculture producers include the reduction of fish cages and treatment of wastewater. Despite the reduction in nutrient loading simulated in three different scenarios, inorganic nutrient concentrations in the bay were predicted to exceed the thresholds for poor quality defined by Chinese seawater quality legislation. For all scenarios there is still a Moderate High to High nutrient loading from the catchment, so further reductions might be enacted, together with additional decreases in fish cage culture. The model predicts that overall, shellfish production decreases by 10%–28% using any of these development scenarios, principally because shellfish growth is being sustained by the substances to be reduced for improvement of water quality. The model outcomes indicate that this may be counteracted by zoning of shellfish aquaculture at the ecosystem level in order to optimize trade-offs between productivity and environmental effects. The present case study exemplifies the value of multilayered ecosystem modelling as a tool for Integrated Coastal Zone Management and for the adoption of ecosystem approaches for marine resource management. This modelling approach can be applied worldwide, and may be particularly useful for the application of coastal management regulation, for instance in the implementation of the European Marine Strategy Framework Directive.

1. Introduction

Coastal zones provide considerable benefits to society while at the same time human activities exert pressure on coastal ecosystems, therefore threatening those same benefits (Nobre, 2009). To promote the sustainable use of coastal zone resources an ecosystem approach is of considerable value, firstly in understanding the causal relationships between environmental and socio-economic systems, and the cumulative impacts of the range of activities developed in coastal ecosystems (Soto et al., 2008; Nobre and Ferreira, 2009), and secondly to manage coastal resources and biodiversity (Browman and Stergiou, 2005; Murawski et al., 2008). Marine Ecosystem-Based Management (EBM) is an emerging scientific consensus complementary to Integrated Coastal Zone Management (ICZM). EBM

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highlights the need to use the best available knowledge about the ecosystem in order to manage marine resources, with an emphasis on maintaining ecosystem service functions (Browman and Stergiou, 2005; Murawski, 2007; Murawski et al., 2008). In particular, improved planning and management of aquaculture production is highlighted as one of the sustainability issues related to coastal zone development and management that must urgently be addressed (GESAMP, 2001). Recently, several initiatives have occurred to support the development of an Ecosystem Approach to Aquaculture (EAA), which aims to integrate aquaculture within the wider ecosystem in order to promote the sustainability of the industry (Soto et al., 2008).

Ecosystem modelling is a powerful tool that can contribute the required scientific grounding for the adoption of such an Ecosystem-Based Management approach (Fulton et al., 2003; Greiner, 2004; Hardman-Mountford et al., 2005; Murawski, 2007). Specifically, modelling can be useful to: (1) provide insights about ecological interactions within the ecosystem (Raillard and Ménesguen, 1994; Plus et al., 2003; Dowd, 2005; Grant et al., 2008; Sohma et al., 2008; Dumbauld et al., 2009), (2) estimate the cumulative impacts of multiple activities operating on a given coastal area at an integrated catchment – marine ecosystem scale (Soto et al., 2008), and (3) evaluate the susceptibility of an ecosystem to pressures by means of scenario simulation (Hofmann et al., 2005; Nobre et al., 2005; Roebeling et al., 2005; Marinov et al., 2007; Ferreira et al., 2008a). James (2002), Fulton et al. (2003), and Moll and Radach (2003) have reviewed ecological models used in the simulation of the hydrodynamics and biogeochemistry of aquatic ecosystems. Such models vary widely according to their target application. For instance, aquaculture carrying capacity models can be developed at the farm scale (e.g., Ferreira et al., 2007, 2009; Cromey et al., 2009) or at the ecosystem scale (e.g., Dowd, 2005; Ferreira et al., 2008a). These models can focus on specific features of the environment such as seston biodeposition (Cromey et al., 2009; Weise et al., 2009), or can integrate the ecosystem biogeochemistry (Plus et al., 2003; Dowd, 2005; Grant et al., 2008; Ferreira et al., 2008a). Ecological models can also focus on how the environmental parameters affect the physiology of cultured species (e.g., Raillard and Ménesguen, 1994; Gangnery et al., 2004) or how aquaculture production affects the ecosystem as a whole (e.g., Grant et al., 2008; Weise et al., 2009). The role of models in evaluating the 'disturbances' caused by bivalve mariculture on coastal systems may be especially important in the USA where increasing regulations are in some cases being implemented on the basis of a rather strict interpretation of the precautionary principle, with a consequent restriction of aquaculture activities (Dumbauld et al., 2009). Concurrently, substantial efforts are also ongoing on the simulation of interactions between catchment and coast, for instance the work developed under the EuroCat ('European catchments, catchment changes and their impact on the coast') research project (Salomons and Turner, 2005). The work presented by Artioli et al. (2005), Hofmann et al. (2005) and Nikolaidis et al. (2009) exemplifies the existing modelling approaches including the interface between the biophysical and socio-economic models for the catchment and coastal systems.

Overall, if a model is to contribute to an Ecosystem-Based Management approach, it should integrate the range of key processes relevant to the questions asked, and thus allow simulation of the resulting cumulative impacts of human activities. For instance, to assist in the determination of ecological carrying capacity of aquaculture production, a model must include inputs from the multiple aquaculture farms situated in a given ecosystem and include simulation of other relevant activities, for example those within the catchment area that affect the coastal ecosystem such as agriculture and wastewater discharge and eventual treatment (Soto et al., 2008). Additionally, and particularly important for management, is the use of models for scenario simulation (Roebeling et al., 2005). This practice implies that management-relevant scenarios are developed to test changes in multiple uses or to explore impacts of global environmental changes (Hofmann et al., 2005; Nobre et al., 2005; Marinov et al., 2007; Ferreira et al., 2008a). This type of approach is crucial for EBM and requires close interaction with managers, decision-makers, and ecosystem and resource users (Ledoux et al., 2005; Nunneri and Hofmann, 2005). In addition, ecosystem stakeholders must be able to understand the information that models provide and also contribute information on the issues to be managed, so that model development addresses their particular needs. Ecological modelling was introduced as a management tool in the 1970's (Jørgensen and Bendoricchio, 2001); since then modelling tools have often proven useful in supporting the application and implementation of several legislative and management programmes worldwide, as exemplified in Table 1.

Ongoing research (Raick et al., 2006) is investigating trade-offs between (1) increasingly complex models that provide detailed simulations but require large datasets for model setup/validation (e.g., developed by Marinov et al., 2007) and generate outputs

Table 1
Examples of modelling tools used for the application of legislation and management programmes worldwide.

Legislation/management actions	Model application	Country/region
European Water Framework Directive (WFD, Directive, 2000/60/EC)	Hofmann et al. (2005), Artioli et al. (2005) and Volk et al. (2008)	European Union
CSIRO's Water for Healthy Country 'Floodplain renewal' program	'Landscape toolkit' developed for the management of the coastal strip adjacent to the Great Barrier Reef (Roebeling et al., 2005)	Australia
USA National Estuarine Eutrophication Assessment (NEEA) program	Eutrophication assessment model (Bricker et al., 2003). Also applied outside USA (Whitall et al., 2007; Borja et al., 2008).	USA, Europe and Asia
USA Clean Water Act (CWA).	Calculation of the total maximum daily load (TMDL) of a pollutant that a waterbody can receive and still safely meet water quality standards (EPA, 2008).	USA
Fisheries policy (management of the exploitation of aquatic renewable resources)	- Lobster fishery simulation to explore management options, regulations and the impact of environmental changes (Whalen et al., 2004) - Evolution of the Manila clam population in response to different management measures and to exceptional changes in environmental conditions (Bald et al., 2009).	Canada and France
Nuisance macroalgae blooms management	Combination of remote sensing data and current direction simulation to understand the origin of the world's largest green tide, recorded offshore in the Yellow Sea and along the coast of Qingdao (Liu et al., 2009).	China