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Towards an ecosystem approach to aquaculture: Assessment of sustainable shellfish cultivation at different scales of space, time and complexity

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ABSTRACT

The need for an ecosystem approach to aquaculture has led to the development of several aquaculture analysis tools in recent years, working at different scales of space (farm- to system-level), time (seasonal to annual and/or long-term analysis) and complexity (ease of use to complex process-based modelling). This work has tested the application of a range of complementary tools to the analysis of aquaculture practices and ecosystem impacts in Killary Harbour, Ireland. The selected tools included a system-scale, process based ecological model (EcoWin2000), a local-scale carrying capacity and environmental effects model (FARM) and a management-level eutrophication screening model (ASSETS). Both the system-scale and farm-scale models used ShellSIM to simulate individual shellfish growth. The tools were used to analyse the relationship between shellfish productivity and food sources, the impacts of changes to stocking densities of shellfish, and an overall assessment of the ecological status of Killary Harbour. EcoWin2000 was able to support a complex analysis, but required a significant amount of input data and effort for calibration and result analysis. FARM was able to provide similar (although less detailed) results at the shellfish farm scale with a smaller effort for parameterization and application, but was limited to testing scenarios with relatively moderate changes to present-day conditions. ASSETS provided simple, management-level results with a relatively low level of input data, although it is not appropriate for complex analysis. This paper illustrates the complementary nature of these tools, and how the unique capacities of each can be combined for integrated assessment of aquaculture in a coastal system. For Killary Harbour, the combined application of these tools revealed that: (i) the system's eutrophication status can be classified as Moderate Low, with a future trend of No Change; (ii) there is a large influence of ocean boundary conditions on shellfish food resources in the system; (iii) the maximum mussel production of the system is 4200 ton year^{-1}, but achieving this level would lead to lower harvest weights and longer growth cycles; and (iv) a scenario of lower stocking densities proposed for the system should lead to lower mussel productions, but could result in benefits such as higher mussel weight at harvest and/or shorter growth cycles.

1. Introduction

Global aquaculture currently stands at a reported production of about 52 million tons, with a valuation of over 61 billion euros (Food and Agriculture Organization, 2009). The relative increase in farmed production, compared to wild fisheries, has generated enthusiasm for the so-called blue revolution, a "new" paradigm for the supply of seafood products to world markets, holding the promise of food security (Sachs, 2007). Several authors (e.g. Costa-Pierce, 2010) have prescribed caution with respect to this vision of a marine panacea on the basis of various factors, including the risk that an ecosystem approach to aquaculture (EAA, e.g. Soto et al., 2008) may not accompany this predicted growth. This surge may largely be an "Asian Tiger" phenomenon, and a deregulated increase in aquaculture production may cause regional asymmetries and social conflicts, and pose a threat to food security as a whole.

In Europe, annual growth of aquaculture has declined to 1%, partly because of market factors, but also because the industry is subject to

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stringent regulation and sustainable development is a major consideration (e.g. Ferreira et al., 2008b). Recent environmental legislation, such as the European Union's Water Framework Directive (WFD; 2000/60/EC) and Marine Strategy Framework Directive (MSFD; 2008/56/EC) has implicitly promoted the three objectives of EAA, namely (i) human well-being; (ii) ecological well-being; and (iii) multisectorial integration.

There is a strong focus on ecological carrying capacity of aquaculture in marine systems (e.g. Goldburg and Naylor, 2005; McKindsey et al., 2006; Mirto et al., 2009; Sequeira et al., 2008), leading to the promotion of terms such as ecoaquaculture (Sequeira et al., 2008) and ecological aquaculture (Costa-Pierce, 2010). In Europe, the U.S., and Canada, the ecological and social pillars of carrying capacity (Inglis et al., 2000) are a clear focus for licensing, allied to the more traditional physical and production aspects (e.g. National Research Council, 2010).

Whereas fed marine aquaculture is relatively new to Europe (<50 years), organically extractive cultivation of shellfish has existed for many centuries, i.e. the "blue revolution" is really blue evolution. Various EU directives now regulate European shellfish culture, addressing e.g. water quality appropriate for cultivation (e.g. Directive 2006/13/EC — quality of shellfish waters), or the environmental effects of shellfish, such as eutrophication and organic biodeposition (WFD and MSFD).

Although shellfish aquaculture in Europe has a potential to expand further offshore (Kapetsky et al., 2010), particularly as appropriate cultivation structures develop, together with mixed use models associated e.g. with wind farms, inshore cultivation remains important in ecological, economic, and social terms.

The analysis and management of ecosystem integration and sustainability of inshore shellfish culture is nowadays supported by different tools, which may be applied at the system level or on a finer spatial scale, and can address a significant proportion of the issues that arise from usage conflicts among the various stakeholders of the coastal environment (Hovik and Stokke, 2007). In the EU, from a legislative point of view, with deadlines looming for both the WFD (2015) and MSFD (2020), detailed requirements promote the use of scientific assessments to determine compliance strategies, increasing demands from growers and managers for improved aquaculture management tools. Such tools vary in complexity, scale, and scope of application.

At one end of the scale are tools designed for low data requirements and ease of use (Borja et al., 2008), including ecological status evaluation methods, such as Assessment of Estuarine Trophic Status (ASSETS; Bricker et al., 2003), the OSPAR Comprehensive Procedure (OSPAR, 2005) or the Differential Drivers-Pressure-State-Impacts-Response (DDPSIR; Nobre, 2009). These tools are by definition highly aggregated, and can use both measured data and outputs of other types of models.

A number of tools exist for spatial analysis (Kapetsky et al., 2010; Nath et al., 2000), in some cases coupled with dynamic growth models (Kapetsky et al., 2010). In others, this type of Geographic Information System (GIS) takes into account legislation, point-source discharges, and other factors (Ervik et al., in preparation). At a finer spatial scale, tools addressing production and ecological sustainability are available (e.g. Ferreira et al., 2007b; Weise et al., 2009).

At the other end of the scale are more detailed research models, which resolve the circulation and boundary exchanges of water, dissolved, and particulate substances, together with internal processes (e.g. primary production, cycling of nutrients and organic matter) that interact with shellfish growth. Most of these models address aquaculture production, with a limited focus on ecological carrying capacity (McKindsey et al., 2006). Examples include box models for analysis of mussel carrying capacity (Filgueira and Grant, 2009), ecosystem models for food depletion (Grant et al., 2008), 3-D biogeochemical (Marinov et al., 2007), and ecological models (Ferreira et al., 2008b).

A recent trend has been the integration of multiple ecosystem evaluation methods to address management problems with different levels of complexity (Nobre and Ferreira, 2009). This integration includes complex biogeochemical multi-model approaches (Melaku Canu et al., 2010; Nobre et al., 2010), ecological–economic models (Nobre et al., 2009) or integration between simple and complex tools (Nobre et al., 2005). These approaches play different and often complementary roles in coastal system management, depending on the strengths of each assessment tool. Indeed, there is an outstanding requirement to better understand the relative roles that assessment tools with different levels of complexity can play in multi-method evaluation frameworks.

This paper aims to contribute to the EAA, and therefore to improved management of coastal systems where aquaculture occurs or is at the planning stage, by exemplifying the application of a range of complementary tools to analyse various aspects of blue mussel (*Mytilus edulis*) cultivation in Killary Harbour, Ireland. Three different levels of complexity are addressed, by means of:

1. A system-scale ecological model, EcoWin2000 (Ferreira et al., 2008b);
2. A local-scale carrying capacity and environmental effects model, FARM (Ferreira et al., 2009); and
3. A management level eutrophication screening model, ASSETS (Bricker et al., 2003), capable of qualifying system-scale trophic status.

Together, these tools address the four objectives of this work:

1. To provide an understanding of the role of boundary exchanges and internal processes in the production and environmental effects of shellfish cultivation in different parts of a system;
2. To determine local scale carrying capacity, economic potential, and the role of organically extractive aquaculture, including both positive and negative environmental impacts, as well as other externalities;
3. To evaluate eutrophication status, both for the current situation and in scenarios, supporting the determination of ecological status (*sensu* WFD);
4. To illustrate how combinations of different tools can be used to leverage the potential of each one and provide a robust platform for decision-support in implementing EAA.

2. Methods

2.1. Study site

Killary Harbour (Fig. 1) is a fjord-like inlet, 15 km long and 0.75 km wide, with a total area of 9.9 km^2, average depth of 15 m and an average volume of 4.5×10^9 m^3. It has a maximum depth of 45 m at the mouth, which opens out onto the Atlantic Ocean. Tidal range is 3.7 m with strongest currents at the narrow mouth of the inlet (50 and 30 cm s^{-1} at 1 and 10 m, respectively). The water column is stratified or partially mixed and a pronounced halocline can occur between 3 and 10 m during winter and summer, which can be broken by strong winds.

The average freshwater input to the system is 6.0 m^3 s^{-1}; around 90% of this input is contributed by the Bundorragha, Erriff and Bunowen rivers; streams account for the remainder. The mountainous catchment area is about 250 km^2 with high annual rainfall (2000 to 2800 mm year^{-1}). The population is very sparse: Leenaun is the main centre (150 people), located near the head of the estuary. Farming is extensive, with mountain pastures grazed by sheep, small numbers of cattle grazing lower slopes, and intensive production of grassland and hay. The watershed lies within a designated Special Area of Conservation. The majority of farmers are involved in the Rural Environmental Protection Scheme which brought about a 30% reduction in sheep numbers since 1998, with more cuts planned for the future, to reduce damage from overgrazing.

Rope culture of blue mussel (*M. edulis*) in the estuary began in the 1970s. The harbour was designated for aquaculture and mussel farming boundaries were set in 1984. Today's cultivated area is 157 ha, with an annual production of 1632 ton year^{-1} (fresh weight; data for 2006) and a productivity of 10.4 ton ha^{-1} year^{-1}. Mussels are grown on longlines from which 8 m long dropper ropes are suspended, and recent intensification of mussel cultivation has been blamed for poor growth and harvest (Bord Iascaigh Mhara, 2002). An option of decreasing