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Trade-offs between shellfish aquaculture and benthic biodiversity: A modelling approach for sustainable management

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Abstract

This paper presents an ecosystem modelling approach aimed at improving shellfish aquaculture management by explicitly considering natural benthic biodiversity. This methodology uses a combination of benthic field survey data, sediment and bathymetric mapping, physiological models and dynamic ecosystem modelling. The Wild species Integration for Shellfish Ecoaquaculture (WISE) approach helps to understand the baseline food requirements for maintaining natural benthic biodiversity of suspension-feeding organisms, thus informing managers on potential upper thresholds for shellfish aquaculture. WISE was tested in four coastal systems in Europe and China, including bays, estuaries and sea loughs with widely differing aquaculture activities. In the European systems, where the aquaculture industry is developing, species diversity and abundance are much higher and suspension-feeding wild species play an important role in the consumption of food resources. Densities of wild individuals were estimated to be 13 ind m^{-2} in Sanggou Bay (total: 2×10^9), 33 ind m^{-2} in Xiangshan Gang (total: 122×10^9), 95 ind m^{-2} in Carlingford Lough (total: 4.62×10^9) and 175 ind m^{-2} in Loch Creran (total: 2.62×10^9). Total clearance rates by wild populations were calculated as 5% of the total volume d^{-1} in Sanggou Bay (75×10^6 m^3 d^{-1}), 11% d^{-1} in Xiangshan Gang (434×10^6 m^3 d^{-1}), 40% d^{-1} in Loch Creran ($93 - 99\times10^6$ m^3 d^{-1}) and 45% d^{-1} in Carlingford Lough ($170–250\times10^6$ m^3 d^{-1}). In relative terms, wild populations play a more important role than cultivated shellfish in clearing suspended particles from the European systems due to the much lower aquaculture activity. 56% and 76% of total primary production in Loch Creran and Carlingford Lough, respectively, are consumed annually by wild organisms, while less than 50% is consumed in Chinese systems (45% in Sanggou Bay and 2.9% in Xiangshan Gang). Integration of the WISE approach within broader ecological modelling illustrates some of the trade-offs between commercial aquaculture and the conservation of biodiversity, showing that rates of and capacities for shellfish culture are reduced when both wild and cultured suspension-feeding species are considered in relation to the available seston. When food resources are partitioned between wild and cultivated species, there is a decrease in individual length and weight (9 to 22% reduction in shell length and 24 to 52% reduction in total fresh weight for the Pacific oyster; reductions of 6% in length and 20% in weight for blue mussel; reductions of 4% in length and 13% in individual weight for bivalves in Xiangshan Gang), resulting in a lower aquaculture production (e.g. for Pacific oyster, a reduction of 12.5% in Carlingford Lough, 34% in Loch Creran and of 9% for bivalves in Xiangshan Gang).

Keywords: Ecoaquaculture; Sustainable shellfish aquaculture; Biodiversity; Conservation; Wild species; Resource partitioning; Coastal systems; Ecological modeling; GIS; China; Europe

1. Introduction

The decline in fisheries worldwide (e.g. Naylor et al., 2000; Neori et al., 2004; Pauly et al., 1998; Pauly et al., 2002; Troell

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et al., 2003) has been accompanied by an increased commercial interest in aquaculture to meet the demand for fishery products, which is estimated to grow by 50 million tons by 2015 (FAO, 2004). World aquaculture production has been increasing at about 7.2% per year, with China being the major contributor (FAO, 2004). In that country alone, there are an estimated 42×10^6 ha deemed suitable for mariculture, and national targets have been set for a 15% production increase by 2010 and a 30% increase by 2020 (Zhu, pers. com.).

Shellfish aquaculture appears to be a particular growth area (e.g. Howlett and Rayner, 2004), taking advantage of the natural processing by filter-feeders of the base of the food-chain. The quality of farmed shellfish, which are both sessile and rely on naturally supplied particulate organic matter (POM), is not affected by the textural and dietary issues which can occur in cultivated finfish such as salmon and sea bass. Furthermore, shellfish culture is generally extensive by nature (although high density cultivation such as seen in the Po delta lagoons may exist), and therefore poses fewer environmental problems with respect to accumulated surplus food debris, localised benthic organic enrichment and oxygen depletion (McKindsey et al., 2006). In fact, it frequently plays a role in top-down control of the food web (e.g. Newell, 2004), and may have a significant effect in reducing the expression of eutrophication symptoms, as exemplified for Chesapeake Bay by Cerco and Noel (2007) and for Jiaozhou Bay in China by Xiao et al. (in press). Nevertheless, though to a far lesser extent than finfish, bivalve culture can also have undesirable effects on the environment (Miron et al., 2005). Shellfish are at a lower position in the trophic chain and community changes can affect various trophic levels (Cranford et al., 2003), and in particular may adversely impact natural biodiversity (e.g. Read and Fernandes, 2003).

Environmental modifications in shellfish-growing areas have been extensively documented (Raillard and Ménesguen, 1994; Christensen et al., 2003; Kurlansky, 2007), but center mainly on the impacts of over-exploitation and pollution on the cultivated species themselves. With the prospective expansion of shellfish aquaculture in Europe and America, there has been an important literature focus on carrying capacity (over 500 articles in the last five years: SCIRUS, 2007), and an effort to define terms (e.g. Inglis et al., 2000, Nunes et al., 2003) and refine methodologies to develop accurate assessments (Ferreira et al., 2007a; Gibbs, 2007). This is partly driven by emerging legislation, including the proposed U.S. Offshore Aquaculture Act (NOAA, 2006) and the E.U. Common Aquaculture Policy, currently under preparation.

The sustainable management of shellfish aquaculture must address some key concepts related to carrying capacity, including the harmonious co-existence of cultivated bivalves and naturally occurring (henceforth wild) species. The latter are important for many reasons, including preservation of biodiversity (e.g. Worm et al., 2006), role in ecosystem structure, and conservation aspects. Shellfish aquaculture may result in changes in benthic community composition (Crawford et al., 2003), through a range of mechanisms, such as excessive partitioning of food resources (Newell, 2004), competition for space (Gibbs, 2004) and increased sediment deposition (La Rosa et al., 2002). These concerns are reflected in legislative instruments such as E.U. Directive 92/43/EEC (Habitats) or the E.U. Biodiversity Strategy (1998a), and are in broad terms covered by the United Nations Convention on the Law of the Sea (UNCLOS).

The existing literature on interactions between cultivated shellfish and wild benthic species focuses mainly on direct deposition effects, organic enrichment of soft sediments and near-field modifications to community composition (Gibbs, 2007). Very little work exists at a broader scale, i.e. addressing ecosystem-scale effects (e.g. Mckindsey et al., 2006), and there are to our knowledge no models for prediction of shellfish carrying capacity which explicitly account for the role of wild species in partitioning the available food, and therefore allow for these organisms to be included in scenarios of development of commercial aquaculture.

This paper presents a modelling approach for the incorporation of benthic wild species in ecosystem models designed for evaluation of sustainable carrying capacity for bivalve aquaculture. Our approach, which is termed *Wild species Integration for Sustainable Ecoaquaculture* (WISE), has been developed with the following three objectives:

1. To determine baseline food requirements for maintaining benthic biodiversity in a natural system;
2. To improve accuracy in modelling carrying capacity for shellfish aquaculture by partitioning the food resource, i.e. phytoplankton and other particulate organic matter, between wild species and cultivated shellfish;
3. To establish upper thresholds to ensure the maintenance of wild populations when considering shellfish aquaculture development scenarios.

2. Methodology

2.1. General approach

The WISE approach aims for integrated sustainable management, and thus considers both the physical and biological features of a given ecosystem, and applicable legislation and uses.

The methodology is developed in three sequential stages: (i) Wild species distribution and selection; (ii) Resource partitioning assessment; and (iii) Integration in ecosystem models. These are described below, with reference to the conceptual model illustrated in Fig. 1. The focus of this paper is on naturally occurring species of benthic shellfish, which compete with cultivated animals by filtering the common resource pool of particulate organic matter. The approach presented is however applicable to filter-feeders in a general sense.

2.1.1. Wild species distribution and selection

Physical and biological features of an ecosystem, such as bathymetry, characteristic sediment types for different species, location of biotopes, and benthic abundance and density are analysed by means of seabed mapping via Acoustic Ground Discrimination Systems (AGDS), benthic grab data, descriptive surveys using Remote Operated Vehicles, video observations or diver surveys.