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Ecological Modelling 184 (2005) 163–174

ECOLOGICAL MODELLING

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A stochastic bioeconomic model for the management of clam farming

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Abstract

The Manila clam *Tapes philippinarum* is one of the most important commercial mollusc species in Europe. Intensive clam farming takes place in several coastal lagoons of the Northern Adriatic Sea, supporting local economy but raising the problem of the environmental sustainability of this activity. In this work, we propose a bioeconomic model that provides guidelines for an efficient management of intensive clam farming. Clam demography is described by a stochastic model of growth and survival, accounting for the effect of water temperature, seeding substratum and density dependence of vital rates. The model is calibrated on and applied to the case of Sacca di Goro, a lagoon located in the Po River Delta (Northern Italy). We consider two distinct management criteria: the optimisation of the marketable yield and the optimisation of monetary benefits, respectively. The use of a stochastic formulation allows us to reveal the existing trade-off between maximizing the median yield or profit and minimizing its variance. A Pareto analysis shows that seeding in spring or fall on sandy substrata and harvesting 18 months later provides the best compromise between these two contrasting objectives, maximizing profits while minimizing the associated uncertainty level. Finally, we show that seeding clams at high densities (more than 750 clams m^{-2} on muddy substrata and more than 1500 elsewhere) can have not only a potentially negative impact on the ecological sustainability of clam farming, but also a negative economic effect.

Keywords: Bivalve farming; Manila clam; *Tapes philippinarum*; Rearing policies; Bioeconomic models; Environmental stochasticity; Pareto analysis

1. Introduction

Effective management of mollusc farming is of crucial importance for both socioeconomic and ecological reasons. Intensive mollusc farming is indeed the basis of local economy in many coastal areas of Europe such as, for example, the lagoons of the Northern Adriatic Sea in Italy. Since its introduction in the early 1980s, the Manila clam *Tapes philippinarum* has become one of the most important commercial species in Italy together with the mussel *Mytilus galloprovincialis*. Today, Italy is the major European producer of clams, and the third mollusc producer after Spain and France (FAOSTAT, 2004). Recent work, however, has shown that high densities of filter-feeding bivalves can have important

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doi:10.1016/j.ecolmodel.2004.11.011

impacts on the trophic status of coastal ecosystems affecting oxygen and nutrient dynamics, altering the structure of the phytoplankton community and stimulating macroalgal growth (Prins et al., 1998; Sorokin et al., 1999; Smaal et al., 2001; Bartoli et al., 2001). The production of Manila clams in the Sacca di Goro lagoon (Po River Delta, Northern Adriatic Sea), one of the major areas of intensive clam rearing in Italy, grew up to 16,000 t at the beginning of the 1990s, but a decline in productivity did occur in recent years and the current production is about 10,000 t (Rossi and Paesanti, 1992; Rossi, 1996; Solidoro et al., 2000). This phenomenon has been mainly ascribed to dystrophic events caused by extensive macroalgal blooms. High clam densities, however, like those observed in some areas of Sacca di Goro (in some cases exceeding 2000 individuals m^{-2}), have been shown to have a detrimental effect on oxygen availability in the water column (Bartoli et al., 2001; Melià et al., 2003). In areas where clam fishing is not regulated, like the lagoon of Venice, further problems are caused by sediment resuspension due to extensive trawling, use of illegal fishing tools, and overfishing, while consumers' health is at risk because fishing may be performed in polluted zones (Pastres et al., 2001; Solidoro et al., 2003). Building reliable management models is fundamental to developing efficient and sustainable exploitation strategies for coastal ecosystems. Pastres et al. (2001) combined data about water pollution, bathymetry and trophism to build a suitability index for clam rearing in the lagoon of Venice. They also used a bioenergetic model (Solidoro et al., 2000) to estimate the productive potential of the different areas. However, their study was chiefly focused on the identification of the most suitable areas for rearing and did not analyse the bioeconomic aspects of the problem. Solidoro et al. (2003) developed a demographic model for the Manila clam and used it to evaluate the economic income associated with different fishing and rearing strategies. The deterministic formulation of the model, though, allowed the authors to provide only an estimate of the average performance of a given policy without information regarding the uncertainty of the forecasted benefits. When planning an effective exploitation of biological resources, this latter aspect is indeed of paramount importance. There is, in fact, a typical trade-off between maximizing the average productivity and minimizing its variability (see, e.g. the seminal work by Ricker, 1958, and the subsequent work by Gatto and Rinaldi, 1976; May et al., 1978 ; Aanes et al., 2002). In this paper, we perform a bioeconomic analysis of clam farming based on a stochastic demographic model. We describe growth and survival of Manila clams using the model proposed by Melià et al. (2004) and consider two distinct management criteria: the optimisation of the marketable yield and the optimisation of monetary benefits, respectively. The use of a stochastic formulation allows us to associate a risk level with the estimates of the objective functions and to point out the existing trade-off between maximizing yield or profit in the average and minimizing its variability. We finally carry out a Pareto analysis to identify the seeding and harvesting policies that provide the best compromise between these two contrasting objectives.

2. Model formulation

2.1. Demographic model

The demographic model used in this work to describe growth and survival of *T. philippinarum* was presented in detail elsewhere (Melià et al., 2004). Water temperature and clam density were identified as the main drivers of the demographic rates. Here, we describe only the major features of the model which encompasses body growth and natural mortality.

Body growth is described by a modified von Bertalanffy (1938) model accounting for seasonal fluctuations of the Brody growth constant driven by water temperature. The mean instantaneous variation in shell length L is described as

$$\frac{\mathrm{d}L}{\mathrm{d}t} = k_T T(t)(L_\infty - L(t)) \tag{1}$$

where L_∞ is the asymptotic mean size, $T(t)$ is the average temperature of the water column at time t, and k_T is a proportionality coefficient between the Brody growth constant and temperature. Temperature fluctuations are simulated using the sinusoidal curve proposed by Melià et al. (2003) for the Sacca di Goro lagoon:

$$T(t) = f\,\sin\left(\frac{2\pi}{365}(t + e)\right) + g \tag{2}$$

where time t is measured in days, with $t = 0$ corresponding to the first of January, and temperature is measured in °C, with $e = -114.74$ (phase), $f = 9.76$ °C (maximum