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A spatially explicit learning model of migratory fish and fishers for evaluating closed areas

Aristides Moustakas [a],[*], William Silvert [b], Apostolos Dimitromanolakis [c]

[a] *Ecology and Biodiversity Laboratory, Department of Environmental Engineering,*
Technical University of Crete, Polytechnioupolis, 73100 Chania, Crete, Greece
[b] *Instituto Nacional de Investigação Agrária e das Pescas IPIMAR,*
Departamento de Ambiente Aquático, Avenida de Brasília, s/n 1449-006 Lisboa, Portugal
[c] *Department of Computer Science, University of Toronto, 1105-100 Spadina Road, Toronto, Canada M5R 2T7*

Abstract

Fisheries models usually characterise the concentrations of fish and the distribution of the fishing fleet by spatial averages over large areas assuming homogeneous spatial characteristics. Many important management questions, such as those related to the spatial effects of closed areas, cannot be addressed by such models. This paper presents a model which describes the spatial movement of individual fish schools and the spatial response of individual fishing boats, and which can be applied on a much finer scale and thus can be used to analyse the scale-dependent development of the fishery. The motion of the fish is based on assumptions about time-dependent gradients in the relative attractiveness of nearby grid cells which motivate migrations based on feeding and spawning factors. The motion of fishing boats is modelled in a similar fashion, with the attractiveness of neighbouring cells based on historical catch records as a function of position and time of year, as well as whether current catch rates are high enough to justify staying in the same cell. Our model showed that marine reserves increase fish biomass but decrease fish catches. It is also indicated that marine reserves are of limited use when not combined with quotas of catches. Our findings also point that transfer rates of fish increase the benefits of marine reserves in terms of fish biomass but decrease fish catches.
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Keywords: Fish; Fishers; Closed area; Fleet dynamics; Marine reserves; Spatial behaviour

1. Introduction

Much of the difficulty in fisheries modelling and management arises from dealing with very different scales in time, space, and trophic depth (Gessner et al., 2004). Spatial scales are particularly difficult to

* Corresponding author. Present Address: Institute of Ecology, Friedrich Schiller University, Dornburger Str. 159, 07743 Jena, Germany. Tel.: +49 3641 949453; fax: +49 3641 949402.
E-mail address: aris.m@uni-jena.de (A. Moustakas).

address (Giller et al., 2004), since most fish species are very mobile, and while fishing fleets are also mobile their ability to locate fish aggregations is usually limited to those within a range of several hundred metres (there are some exceptions – surface-schooling fish like menhaden can be located with spotter airplanes). Stock assessments usually deal with the movement of fish by averaging the populations over large areas, typically several hundred square kilometres (e.g., NAFO map) and stock sizes are almost always calculated on an annual basis. These assessments are of limited value to fishers, particularly those who use fixed gear or who are restricted in the region they can fish because they use small boats or are subject to local regulatory restrictions. They also do not provide a suitable basis for assessment of localised management measures, such as marine protected areas (MPAs) and seasonal closures.

An alternate approach is to focus on the spatial distribution of the fish and fishers, and to develop models which focus on the factors affecting their motion, rather than trying to add transport mechanisms to models based on population dynamics and ecological interactions. One way to do this is by the use of cellular automata, which are designed specifically for the modelling of the dynamics of spatial distributions (Wolfram, 1983a; Ermentrout and Edelstein-Keshet, 1993). A cellular automaton is a grid-based discrete time model with rules describing how the occupancy of the grid cells changes from one time step to the next. Usually it is assumed that the contents of each cell depend only on the contents of it and adjoining cells during the previous time step, which provides a discrete representation of the continuous motion of objects (in this case fish and fishing boats) between positions represented by the cells (Wolfram, 1983b). However, the use of cellular automata in ecology can have trivial results when significant biological characteristics are omitted or misinterpreted (Ruxton and Saravia, 1998), so identifying the correct rules for iterating from on time step to the next is of critical importance.

The use of cellular automata is not the only way to address the modelling of spatial aspects of fisheries. One of the earliest approaches was that of Allen and McGlade (1986) who approached the fishery from the perspective of self-organising systems, while Hilborn and Walters (1987) treated the problem from an optimisation viewpoint. Considerable effort has gone into trying to understand the strategy of fishers (Gillis

et al., 1993) but generally not in terms of the interactive dynamics of the movement of fish stocks and the fishing fleet. It is generally accepted that cellular automata are a useful tool when dealing with uncertainty and complex ecological systems (Wu and David, 2002; Wiegand et al., 2004).

Several pelagic fish species migrate from feeding to spawning areas depending on seasonality (Beamish et al., 2005). Since the motion of fish and boats does not follow precise predictable rules, it is common to model it by a stochastic process (Kim, 2003). For fish this attraction depends on environmental factors such as water depth and temperature, and also includes variables to describe changes in preference for spawning sites, feeding areas, and attractive locations (Magnússon et al., 2005). Therefore, the attractiveness of an area for fish movement depends on seasonality taking into account the abovementioned parameters. The motion of the fleet is similar, but with an attraction potential based on the historical record of fish abundance (Gillis et al., 1993; Gillis et al., 1995). Thus, the attraction potential of an area for the fishing fleet is based on a past empirical knowledge of fish biomass records depending on seasonality.

Movement of fish has since long ago been a topic of interest in ecology (Bardach, 1958; Gerking, 1959; Gibson, 1967). Modelling tools for the movement of fish schools are given among others by Huth and Wissel (1992), Vabo and Nottestad (1997) and Stöcker (1999). Modelling fish movement using cellular automata is a well established technique (e.g., Pola, 1985; Stöcker, 1999). There are also studies modelling the learning behaviour of fishers (e.g., Xiao, 2004). However, there are no spatially-explicit learning models on the interaction between fish and fishers. In addition closed areas such as MPAs are becoming a popular measure for fish conservation (Horwood et al., 1998). There are several models evaluating the impacts of closed areas (e.g., Guénette and Pitcher, 1999; Lockwood et al., 2002) but these models are not spatially explicit and they assume homogeneous spatial properties. Furthermore, marine reserves are not always beneficial to fisheries management (Hilborn et al., 2004) and the spatial behaviour is important for the evaluation of closed areas (Smith and Wilen, 2003). It is unclear if closed areas generally increase fish catches (Horwood et al., 1998; Hilborn et al., 2004). Furthermore, it is reported that when fish transfer rates are high the benefits of marine reserves