Available online at www.sciencedirect.com
ScienceDirect
Fisheries Research 81 (2006) 9–14
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

A conceptual model of fish functional relationships in marine ecosystems and its application for fisheries stock assessment

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Received 5 February 2006; received in revised form 31 May 2006; accepted 9 June 2006

Abstract

This paper presents a conceptual model of the functional relationships of fish in their environment and describes how various factors and processes affect temporal and spatial dynamics of fish populations in marine ecosystems. The main objective of this model is to illustrate how spatial dynamics of fish, which occur on the organismal level, can be brought into a stock assessment framework, traditionally based on the population perspective. The conceptual model provides a holistic view on ecosystem relationships that determine abundance and spatial distribution of fish in marine ecosystems. It also designates several directions for further research efforts aiming to make quantitative predictions of fish distribution and to apply this knowledge for interpretation of survey data and estimation of population abundance.

Keywords: Fish population; Spatial dynamics; Conceptual model; Stock assessment

1. Introduction

With a rapidly growing world population and its concomitantly growing need for sources of protein, marine fisheries stock assessment is one of the most important scientific tasks facing the World, due to its role in ensuring the sustainability of marine resources for human consumption. Stock assessment uses various mathematical calculations and statistical techniques to make quantitative predictions of future scenarios of fish population dynamics under alternative management strategies and help managers choose the strategy that would balance harvest with sustainability.

Despite the recent progress and the refinement of fisheries stock assessment techniques within the last 20 years, current stock assessment methods still cannot predict the dynamics of fish populations accurately enough (National Research Council, 1998; Fréon and Misund, 1999; NMFS, 2001). One important reason why assessment methods do not perform well is that they do not account for the variation in fish spatial distribution due to changes in the fishes' environment, which includes ocean abiotic conditions, current patterns, topographical relief, etc.

Currently, variation in population dynamics due to changes in fish' environment is only accounted for in the error term with all other sources of extraneous variation, increasing uncertainty and decreasing the accuracy of the predictions of current models. The only attempts to consider fish movement for assessment purposes were related to modeling of population migrations (Quinn and Deriso, 1999; Hilborn and Waters, 2001). However, these movements are life history specific and, as such, temporally predictable. Most importantly, they make up only a small portion of the spectrum of fish spatial dynamics and distribution.

At the same time, behavioral response of fish populations to changes in their environments has been detected many times for both marine and freshwater ecosystems (Ottersen et al., 1998; Abookire et al., 2000; Guisan and Zimmermann, 2000; Swain et al., 2000; Mariani, 2001; Ciannelli et al., 2002; Orlowski, 2003; Slotte et al., 2004; McClatchie and Coombs, 2005). Fish are able to detect environmental characteristics of their habitat and consequently react to their variations by horizontal or vertical displacement. It means that environmental variations can cause fish populations to move into or out of the sites covered by research surveys, which might create fluctuations in catch rates and produce erroneous trends in the estimates of population abundance. Thus, without understanding of behavior and spatial distribution of fish caused by environmental variability we cannot correctly interpret fisheries catch data, and the adequacy

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0165-7836/$ – see front matter
doi:10.1016/j.fishres.2006.06.004

of stock assessment and related management advice is open to considerable doubt.

Fréon and Misund (1999), trying to explain why fish behavior is not fully taken into account by assessment techniques, pointed out that historically these two disciplines have been developing relatively independently from each other and research teams that include both fisheries biologists and animal behaviorists still remain scarce. Besides, fisheries biologists and animal behaviorists traditionally focus their research efforts on different scales. Behavioral biologists work on a small, primarily organismal scale that involves limited number of individuals, while stock assessors operate on larger scale of fish populations and communities.

It is clear that a reliable mathematical mechanism is needed to bridge together organismal and population perspectives to predict fish population distribution and integrate this knowledge into stock assessment methods. A mathematical model is the central part of such a mechanism that describes spatio-temporal dynamics using mathematical equations, algorithms and computer programs to predict the abundance and distribution of fish. However, the foundational step on the way to the development of a mathematical model is the development of a conceptual model (Jørgensen, 1986, 2002; Jørgensen and Bendoricchio, 2001). The conceptual model graphically represents the processes and relationships of fish populations in ecosystem and answers the questions of what components and processes are essential for the spatio-temporal dynamics of fish, why and how we can take them into account. The conceptual model, therefore, inevitably precedes the development of a mathematical model.

We developed a conceptual model of fish functional relationships in the marine environment that includes factors and processes on both organismal and population levels that affect the abundance and distribution of fish. Our model allowed us to outline what we need to know to correctly interpret fisheries data and improve accuracy of quantitative predictions of fish population dynamics. This paper is devoted to the explanation of our conceptual model. In the paper we also discuss the possible direction for further quantitative modeling that would allow numeric predictions of distribution of fish populations and the ways to incorporate this knowledge into stock assessment methods.

2. Description of the conceptual model

An animal habitat is a complex of physical and biotic factors that describe the area where animals live. We divided all factors that affect fish population in their environment into five groups, which include abiotic, biotic trophic, biotic interactive, eco-physiological and anthropogenic factors. First, we will describe these groups in turn and then show how they determine fish density within fish population spatial habitat.

2.1. Groups of factors affecting fish

The most ecologically significant abiotic factors for marine fish include temperature, salinity, water current, lighting, and bottom relief. For demersal species fundamental habitat selection is based on the bottom relief, which includes sea bed shape, depth, and substrate type. More dynamic abiotic factors, such as temperature, salinity, etc., may influence marine fish populations in several ways. First, they may directly affect fish abundance when the values of one or several abiotic factors exceed fish tolerance ranges. Second, abiotic factors, in particular, temperature, influence fish metabolic rates and hence, define the amount of food necessary to support their metabolic activity. Finally, abiotic factors affect the abundance and distribution of resources and thus, determine the amount of food available for fish.

Biotic trophic factors primarily refer to resource availability. The term *resource* in this case aggregates the various types of prey, including phyto- and zooplankton, benthic organisms, and a variety of fish, which are represented respectively as resource 1, resource 2, resource 3, and resource 4 in the model. The exact list of resource types varies depending on which fish species we investigate. Biotic interactive factors are primarily represented by competition, predation and cannibalism. They also include the presence of the organisms, who feed on eggs of its own species (these organisms are called homoprotophages), and organisms, who feed on eggs of another species (these individuals are called heteroprotophages).

Eco-physiological factors are represented by natural mortality and stochastic elimination. In our model the term *natural mortality* refers to “background” mortality from natural causes, such as genetic and physiological disorders, when environmental fluctuations do not exceed the fish’s tolerance range. There are times, however, when fluctuations in abiotic factors (temperature, salinity, etc.) exceed the organisms’ tolerance range, causing a massive number of fish to migrate or die. These severe fluctuations are, as a rule, unpredictable, and as such, stochastic. The term *stochastic elimination* represents a decrease in the number of fish induced by the severe fluctuations in abiotic environment.

Finally, anthropogenic factors primarily refer to fishing mortality. However, if we consider coastal waters especially near highly urbanized areas, this group also might include pollution with toxic chemicals and nutrients (Chouksey et al., 2004; Laws et al., 1999; Moore et al., 2002; Scheren et al., 2002).

2.2. Functional relationships of fish in their habitat

The factors of different groups listed above characterize the area of habitat where animals can exist. Now let us look at the functional connections among these factors and build the conceptual model. The diagram of our conceptual model is shown in Fig. 1. Our model includes two main submodels: the factors and mechanisms that define fish abundance $N(t)$ and logical links that determine fish spatial distribution $\Delta N(x,y,z)$. We will describe these two submodels in turn and then will bring them together to complete our conceptual model.

2.2.1. Population abundance submodel

The number of organisms in a population at time t, first of all, depends on the initial number N_0, which is the number of fish at