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The trophic-level based model: A theoretical approach of fishing effects on marine ecosystems

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Abstract

We propose the trophic-level based model as a new approach to analyse the functioning of marine ecosystems in both ecological and fisheries contexts. The model considers a virtual ecosystem where all the animal biomass is distributed along a continuum of trophic level classes. Biomass moves from one class to the upper ones according to predation and ontogenic processes. From a given secondary production occurring at trophic level 2, the ecosystem biomass distribution can therefore be expressed as the result of the biomass flow passing through the ecosystem, from low to upper trophic levels. The model is based on two main equations. One is regarding biomass flow, which decreases according to fishing and natural losses occurring during transfers. The other expresses the speed of the flow per trophic level, assuming that high metabolism rates induce fast transfers at the lower trophic levels. Additionally, various hypotheses of ecosystem functioning are considered, dealing with the extent of top-down controls, the intensity of feedback effects on secondary production through biomass recycling and the occurrence of a biomass inaccessible to fisheries.

Depending on which trophic levels are targeted, various scenarios are simulated. Results highlight the impact of increasing fishing efforts on the ecosystem, in term of total biomass, biomass distribution and mean trophic level. We notably show that high fishing pressure and low trophic level of first catch may lead to severe biomass depletions, even if no overfishing is generally observed. Transfer efficiencies as well as flow kinetics appear as key characteristics of the ecosystems functioning, determining its response to fishing pressure. Feedback effects on secondary production amplify the fishing effects. Conversely, the top-down control may be a major feature of the ecosystem resistance to fishing. It implies that any catch may have effects for all trophic levels and can induce cascade effects in the ecosystem.

More generally, we show that the trophic-level based model, built from a small number of very simple and rather unquestionable assumptions, leads to a relevant representation of ecosystem impacts of fishing. It might be regarded as a theoretical basis contributing to our understanding of such impacts. We finally discuss on the use of the model in real cases and we address its usefulness to build a general theory on marine ecosystem functioning.

Keywords: Ecosystem modelling; Fishing impact; Trophic level; Biomass flow; Transfer efficiency; Kinetics of transfer; Top-down control

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1. Introduction

Fisheries management is nowadays still largely based on single species approaches, using models of population dynamic-developed since the 1950s. Stock assessment procedures are thus applied to each of the main targeted species and particularly intend to generate stock-specific annual advices and management recommendations like total allowable catches (TAC). Nevertheless, over the last decade improving ecosystem approach to fisheries has progressively been recognised as a necessity (Garcia, 2005) and we assist to the development of a wide range of models dealing with fishing effects at ecosystem scale. These new approaches should be considered more as complementary than alternatives to the single species ones. Indeed, ecosystem-based fisheries management is not meant to replace stock-assessments, which could be considered as tactical, but to provide a strategic context to it and criteria to choose TAC's (Christensen and Pauly, 2004).

In this context, a general consensus has emerged in the community of fisheries scientists that studying trophodynamics is a major concern to improve our understanding of marine ecosystems functioning (Pitcher and Cochrane, 2002; Cury et al., 2003). Since a few years, many ecosystem case studies have been analysed, generally using models that express trophic flows between the various groups present in the ecosystem. The most popular model and software that relies on the allocation of biomass in discrete groups is the mass-balanced Ecopath model (Polovina, 1984; Christensen and Pauly, 1992) and its dynamic extension Ecosim (Walters et al., 1997). Each group merges all species characterized by similar preys and predators and is considered as a functional group in the ecosystem. Such models appear as useful tools to investigate the ecosystem functioning and to analyse the past and present effects of fishing. Nevertheless, they do not provide a general theory on ecosystem impact of fisheries. Probably due to their high number of parameters, they also appear until now as poor tools of forecasts.

We propose here the trophic-level based model as a theoretical representation of ecosystem functioning and impact of fishing. This model can be regarded as a new step in the trophodynamic approach; it does not consider species any more but is directly based on trophic levels. The trophic level may be considered as the metric, which expresses the trophic process itself. It is the result of what is eaten and represents a state variable characterising each unit of biomass present in an ecosystem. Thus, trophic levels can be used in order to analyse and model transfers in the food web, due to predation which implies discrete transfers of biomass from each prey to its predator, as well as to ontogenic processes characterized by continuous changes according to growth.

The trophic-level based model considers all the animal biomass of the ecosystem, distributed along a continuum of trophic level values split into fractional classes. Biomass moves from one class to the upper ones according to biomass flow equations, depending on natural processes and fishing.

Considering here a virtual ecosystem under steady state, theoretical simulations were conducted in order to analyse consequences of fishing on catches and ecosystem biomass, per trophic level or at the whole ecosystem scale. The model is firstly presented. Various hypotheses of ecosystem functioning are considered, dealing with: the extent of top-down controls, the intensity of feedback effects on secondary production and the occurrence of a biomass inaccessible to fishing. Simulations are then conducted with increasing fishing efforts and various scenarios in term of trophic levels targeted. We show the effects of the considered ecological hypothesis on yield, biomass and trophic levels trends.

We finally discuss the use of the trophic-level based model in real cases and we address its usefulness to analyse ecosystem effects of fishing and to build a general theory on marine ecosystem functioning.

2. Method

2.1. Biomass equations

The trophic level concept was firstly introduced by Lindeman (1942) to characterise the position of organisms within the food webs: 1 for primary producers and detritus, 2 for secondary producers, 3 for their predators, etc. Odum and Heald (1975) and Adams et al. (1983) defined fractional trophic levels for mixed regimes; thus, trophic levels of animals appear continuously distributed in the ecosystem.

Conventionally, the trophic-level based model is structured by trophic classes of $\Delta\tau = 0.1$ range step,