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New trophic indicators and target values for an ecosystem-based management of fisheries

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ABSTRACT

In the present study, we tested five trophic indicators and we demonstrated their usefulness to assess the environmental status of marine ecosystems and to implement an ecosystem approach to fisheries management (EAFM). The tested indicators include the slope of the biomass spectrum, the mean trophic level (MTL), the marine trophic index (MTI) and two newly developed indicators, the high trophic level indicator (HTI) and the apex predator indicator (API). Indicators are compared between current state and potential reference situations, using as case studies: the Celtic Sea/Bay of Biscay, North Sea and English Channel ecosystems. Trophic spectra are obtained from Ecopath models while reference situations are estimated, simulating with EcoTroph and Ecosim different fishing pressures including three candidate scenarios for an EAFM. Inter-ecosystems assessments are done using Ecopath models, simulations outputs and scientific surveys data to assess the current states of the studied ecosystems, contrast the reference situations and analyze the responses of all indicators. Sensitivity analyses are also conducted on the main simulation parameters to test the robustness of the chosen indicators. Ecosystems specific targets for EAFM are proposed for the five trophic indicators estimated from whole-ecosystem models, while in the Celtic Sea/Bay of Biscay ecosystem targets are proposed for the MTL (=3.85) and HTI (48%) estimated from standard bottom-trawl surveys. The HTI is proposed to be relevant for survey data and the API is recommended using whole-ecosystem models. We conclude that HTI and API show trends in ecosystems health better than MTI.

1. Introduction

Among the different anthropic pressures, the most impacting on the structure and functioning of marine ecosystems is overexploitation (Dayton et al., 1995; Jackson et al., 2001; Ma et al., 2013; Worm et al., 2006). Its persistence is known to have consequences on individuals, populations and entire communities (Shin et al., 2005). Generally, long-lived and large species, which are the predators in the system, are the most impacted due to their intrinsically slow biological turnover (Pauly et al., 1998; Gascuel et al., 2008). Thus, increasing fishing pressures result in the size and mean trophic level of exploited fish assemblage gradually declining, as does the mean trophic level of catches. Such change in fish assemblage and in the catch, known as 'fishing down the marine food web' process (Pauly et al., 1998), has been observed in many ecosystem worldwide (see www.fishingdown.org). In Europe, a decrease in the mean trophic level of landings has notably been observed in the Bay of Biscay (Guenette and Gascuel, 2012), the Celtic Sea (Pinnegar et al., 2002) or the North Sea (Heath, 2005; Jennings et al., 2002). More generally, Gascuel et al. (2015) observed a decrease in the mean trophic level within all European seas, from the North Sea to the Iberian coast, not only for landings but also for survey data.

In Europe, political authorities adopted in 2009, the Marine Strategy Framework Directive with the aim to achieve a 'Good Environmental Status' (GES) of marine ecosystems by 2020. This directive reinforces the emergent need for simple indicators, which has recently became a major concern in marine ecology and fisheries (Greenstreet and Rogers, 2006; Jennings and Dulvy, 2005; Rice and Rochet, 2005; Rochet et al., 2005). In particular, part of

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the good environmental status of marine ecosystems, as defined by the European directive, refers to food web (D4) and implies to define valid indicators of food web health. Besides the mean trophic level, other indicators based on changes in biomass distribution between different trophic levels could be used to meet the directive requirements. This proposal emerges from the evidence that repercussions of overexploitation occur on the shape of biomass trophic spectra (Gascuel et al., 2005), even if their evolution and resilience against fishing pressure just begin to be investigated (Branch et al., 2010; Rombouts et al., 2013; Shannon et al., 2014). In the present paper, we propose new trophic indicators and demonstrate their usefulness.

A good indicator must be concrete, have a theoretical basis, be easily understandable, inexpensive, accurate, available over a long period of time, sensitive and quickly responsive and specific to a type of pressure (Rice and Rochet, 2005). Usually, absolute values of indicators have no meaning and observed values must be compared to reference states, especially looking to a less-exploited state of the ecosystem when available (Ainsworth et al., 2002; Lotze and Worm, 2009; Mackinson, 2001; McClenachan et al., 2012) or by generating it by simulation (Jennings and Blanchard, 2004; Ravard et al., 2014).

Here, we explored reference states using simulations which are supposed to predict the effects of an ecosystem approach to fisheries management (EAFM). Two scenarios assumed to represent an EAFM, were simulated, one derived from Froese et al. (in press) and the other from Worm et al. (2009). In both cases, scenarios can be simulated and related trophic indicators calculated using ecosystem models such as Ecopath with Ecosim approach (Polovina, 1984; Christensen and Pauly, 1992; Walters et al., 1997) and the more recently developed EcoTroph model based on the concept that an ecosystem can be represented by its biomass distribution across trophic levels, the biomass trophic spectrum (Gascuel et al., 2005; Gascuel and Pauly, 2009).

Thus, the present study aims at testing five trophic indicators, including two new candidates, and at exploring the ability of tropho-dynamic models to define targets related to an EAFM. (1) Based on the Celtic Sea/Bay of Biscay case study and using EcoTroph, we assessed the sensitivity of each indicators to an increasing fishing pressure. (2) Using EcoTroph we simulated fisheries scenarios assumed to represent an EAFM in various European seas, including the North Sea, the Celtic Sea and the Bay of Biscay, and we quantified the related target values for each indicator. (3) Based on Ecosim simulations, we propose target values for indicators derived from bottom trawl surveys and we compared theses values with trends observed over the last 20 years. We also performed sensitivity analyses on a selection of parameters of the models to test the robustness of chosen indicators, which would represent an innovative task toward GES.

2. Materials and methods

2.1. Indicators

Five trophic indicators are tested in the simulations.

- **Slope**: the slope of size spectra is well-known to be a marine ecosystem state indicator, as it becomes steeper with increasing fishing pressure (Rice and Gislason, 1996; Bianchi et al., 2000). However it was never tested in trophic spectra. In our study, it is calculated by a linear regression of log (biomass) function of the trophic level, beginning at the trophic level from 2.5 representing the higher biomass to avoid the unaffected part of the ecosystem. This indicator is not calculated in survey data, where a large proportion of the species is missing, especially for low trophic levels.
- **Mean Trophic Level (MTL)**: this indicator is proposed to reflect the effect of fishing on the food web (Jiming, 1982; Pauly et al., 1998). It is calculated by

$$MTL = \sum \frac{B_{TL} * TL}{B} \quad (1)$$

  where B_{TL} is the biomass at the trophic level TL ($TL \geq 2$) and B the total biomass of consumers. It is expected that its value should decrease with an increasing fishing pressure.
- **Marine Trophic Index (MTI)**: it reflects the trophic structure of the upper part of the food web (Pauly and Watson, 2005). It is calculated as MTL of species whose trophic level is higher than a predefined threshold. The chosen trophic level threshold is 3.25, excluding the planktivores whose high biomass tends to vary widely mainly in response to environmental factors.
- **High Trophic Indicator (HTI)**: this indicator has been developed for this study represents the percentage of consumers with a trophic level equal or higher than 4 in the ecosystems, which is a threshold for top predators, excluding small and intermediate pelagics (Essington et al., 2006; Shannon et al., 2014). It is expected that its value should decrease with the depletion of large individuals caused by an increasing fishing pressure.
- **Apex Predator Indicator (API)**: this indicator has also been developed for this study and is calculated as HTI, except that it represents the percentage of top or apex predators (i.e. trophic level ≥ 4) on the total of predators excluding planktivores (i.e. trophic level ≤ 3.25). The values of this ratio are expected to decrease with the depletion of large individuals caused by an increasing fishing pressure and be less sensitive to annual biomass fluctuations compared to HTI.

2.2. Pre-existing models and scientific surveys

The study focuses on the Celtic/Biscay ecosystem and complementarily on the North Sea and the English Channel (Fig. 1). For every area a pre-existing model was selected:

- The Celtic/Biscay 2012 model is based on the 1980 model built by Guenette and Gascuel (2009) and updated by Bentorcha et al. (in press). It was originally developed to assess the fishing impact on this ecosystem. An Ecosim model was fitted on time series of landings and fishing mortality (F) between 1980 and 2012. The model considers 38 trophic groups including 31 exploited groups.
- The Bay of Biscay continental shelf food web model of Lassalle et al. (2011, 2012) was originally developed for the structure and functioning understanding of this ecosystem, with emphasize on the ecological roles played by top predators and small pelagics. The model considers 32 trophic groups including 11 exploited groups and represents a typical year between 1994 and 2005.
- The North Sea model of Mackinson and Daskalov (2007) was built as a tool for ecosystem-based management. Its two principal aims are the quantitative description of the ecological and spatial structure of species assemblages in this ecosystem and to calibrate the dynamic responses of the modeled system by comparison with observed historical changes. It includes an Ecosim model and an Ecospace model. The model considers 68 trophic groups including 48 exploited groups and represents the ecosystem for the year 1991.
- The Western English Channel model of Araújo et al. (2008) was built to describe the properties and the trophic interactions in the ecosystem and to explore the effects of changes in phytoplankton production and fisheries. The model considers 52 trophic groups including 40 exploited groups and represents the ecosystem for the year 1994.