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Modelling the effects of fishing on the North Sea fish community size composition

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ABSTRACT

Ecosystem-based management of the North Sea demersal fish community uses the large fish indicator (LFI), defined as the proportion by weight of fish caught in the International Bottom Trawl Survey (IBTS) exceeding a length of 40 cm. Current values of the LFI are ∼0.15, but the European Union (EU) Marine Strategy Framework Directive (MSFD) requires a value of 0.3 be reached by 2020. An LFI calculated from an eight-species subset correlated closely with the full community LFI, thereby permitting an exploration of the effects of various fishing scenarios on projected values of the LFI using an extension of a previously published multi-species length-structured model that included these key species. The model replicated historical changes in biomass and size composition of individual species, and generated an LFI that was significantly correlated with observations. A community-wide reduction in fishing mortality of ∼60% from 2008 values was necessary to meet the LFI target, driven mainly by changes in cod and saithe. A 70% reduction in cod fishing mortality alone, or a 75% reduction in otter trawl effort, was also sufficient to achieve the target. Reductions in fishing mortality necessary to achieve maximum sustainable harvesting rates are projected to result in the LFI over-shooting its target.

1. Introduction

Many studies of exploited fish communities have demonstrated shifts towards smaller sized fish, related to increased fishing (Daan et al., 2005; Shin et al., 2005; Greenstreet and Rogers, 2006; Heath and Speirs, 2012), whilst an increase in the mean size of fish inside marine reserves is one of the most frequently observed responses following the cessation of fishing (Molloy et al., 2009). Consequently, the large fish indicator (LFI), defined as the proportion by weight of demersal fish >40 cm sampled during the quarter 1 International Bottom Trawl Survey (Q1 IBTS) (Greenstreet et al., 2011), has been adopted as an OSPAR Ecological Quality Objective (EcoQO) for the North Sea fish community (Heslenfeld and Enserink, 2008) and is the principal status assessment tool for implementing an ecosystem approach to fisheries management in Europe. The LFI has also been adopted as an indicator to support implementation of the Marine Strategy Framework Directive (MSFD), and is identified in the 2010 decision document as an indicator to monitor change in the proportion of top predators in fish components of marine food webs (European Commission, 2010). It may also fulfil the function of indicator 1.7.1, monitoring change in the relative abundance of ecosystem components, in this instance large and small fish (Modica et al., 2014).

The simplicity of the LFI belies complex processes that can influence its value. As a ratio indicator, changes towards low values can be caused by increased small fish abundance as well as by the depletion of large fish (Daan et al., 2005). Predator–prey interactions may affect the LFI, for example an increase in small fish abundance might arise from release of predation pressure, as larger piscivorous fish are removed (Christensen et al., 2003; Myers and Worm, 2003; Frank et al., 2005; Heithaus et al., 2008). In addition, the community of fish comprises species of widely varying maximum sizes, so shifts in community composition towards species with lower maximum size (e.g. in response to warming temperatures) could also cause LFI values to decline (Shephard et al., 2012; Beare et al., 2004; Simpson et al., 2011). So, use of the LFI in assessing ecosystem status and achieving particular goals for the state of the system requires a clear understanding of what has driven changes in the LFI in the past in order to predict its response in the future.

In the early 1980s the North Sea LFI had a value of ≈0.3, before declining to <0.1 in the early 2000s, followed by some recovery

Abbreviations: LFI, large fish indicator; IBTS, international bottom trawl survey; EU, European Union; MFSD, marine strategy framework directive; OSPAR, Oslo-Paris convention for the protection of the marine environment of the North-East Atlantic; EcoQO, ecological quality objective; PDMM, population dynamical matching model; FCSRM, fish community size-resolved model; ICES, International Council for the Exploration of the Seas; TSB, total stock biomass.

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in subsequent years (Fung et al., 2012; Greenstreet et al., 2012a). Greenstreet et al. (2011) conducted a statistical analysis of the North Sea LFI time series and, concluded that there was a 12–18 year lag in the relationship between changing demersal fish harvesting rates and the indicator response. Subsequent studies in different marine regions have demonstrated similar lagged relationships between fishing mortality and the LFI (Shephard et al., 2011). A number of size-structured models of fish communities show the anticipated inverse relationship between fishing mortality and indices of fish size (Hall et al., 2006; Pope et al., 2006; Blanchard et al., 2009; Rochet et al., 2011; Blanchard et al., 2014; Thorpe et al., 2015).

In understanding how the LFI has responded to historical changes in fishing pressure, and how it might respond to future management decisions, size-structured models are clearly important tools. However, the complexity of the factors affecting the LFI, including multispecies predator–prey interactions, has meant that attempts at modelling it have thus far been fairly few. Shephard et al. (2012) studied changes in the LFI in the Celtic Sea using two different modelling approaches. The first was based on the Population-Dynamical Matching Model developed by Rossberg et al. (2008), which uses a quasi-evolutionary process and allometric scalings to generate size-structured communities of composed of species of varying body size. The second used the Fish Community Size-Resolved Model (FCSRM) of model of Hartvig et al. (2011) that involves coupled size-spectra to represent the size distributions of groups of species with similar maturation sizes. The models are contrasting in that the PDMM produces changes in the LFI only through shifts in relative species abundance, while the FCSRM can do so as a result of changes in the population length distributions of groups of species. It was concluded that the changes in the Celtic Sea LFI arose mainly through changes in species abundance. Fung et al. (2013) also used the PDMM model configured for the Northeast Atlantic and predicted multi-decadal recovery times in response to reductions in community fishing pressure. Most recently, Blanchard et al. (2014) used a variant of the FCSRM where individual size-spectra represented 12 individual North Sea species rather than species groups and found, by contrast, that a rapid recovery in the LFI could occur when the fishing mortality on the various species was moved to maximum sustainable yield (MSY) levels.

Here, we apply an alternative discrete-time multispecies length-structured model for the North Sea fish community developed by Speirs et al. (2010) to model the observed changes in the LFI, and then use it to explore what may happen in the future under alternative scenarios of fishing fleet activity and recruitment patterns of key species. One of the features of the model is that predator–prey interactions are specified in terms of body length ratios applicable across all species, thereby reducing the need for complex dietary parameterisation. The model also includes the key commercially exploited pelagic and invertebrate species in the North Sea, enabling the trade-offs required to restore the demersal LFI to a given state to be explored. As with Blanchard et al. (2014) individual species are explicitly represented, but the Speirs et al. (2010) model differs substantially in numerical implementation as well as a number of other key respects, including that we model individual length rather than weight, and that we represent reproduction as species-specific seasonal function of the spawning stock rather than having recruitment as an annual external driver. Since both the revised Common Fisheries Policy and the MSFD require fisheries to operate at MSY, we address the question of whether achieving this is sufficient to reach the LFI targets for North Sea fish. In contrast to earlier modelling work, we also consider the extent to which the LFI target might be achieved by changes in effort of different fishing fleets rather than changing overall fishing mortality, or species-specific mortalities.

2. Methods

2.1. The data

The North Sea First Quarter (Q1) International Bottom Trawl Survey (IBTS) is an annual survey with wide spatial coverage. Fish caught are identified to species, and numbers at length, as well as age and sexual maturity data from subsamples of selected species, are recorded (ICES, 2010). The data are publicly available from the ICES DATRAS database portal (http://datras.ices.dk). Individual fish weights are obtained from standard cubic-power weight-at-length relationships (Greenstreet et al., 2012b), which when applied to the survey data allowed the calculation of the LFI.

2.2. The model

We used the Speirs et al. (2010) discrete-time length-structured model of the North Sea fish community. The model describes a food web composed of a set of key predator and prey species together with a small number of more crudely represented alternative food sources. For the explicitly represented species the number, $n_{i,j,t}$, of individuals of species i in length class j at time t is updated over time step Δt according to

$$n_{i,j,t+\Delta t} = \begin{cases} (1-p_i)\sigma_{i,j,t}n_{i,j,t} + h_{i,t} & j=0 \\ (1-p_i)\sigma_{i,j,t}n_{i,j,t} + p_i\sigma_{i,j-1,t}n_{i,j-1,t} & j>1 \end{cases}$$

where $0<p_i<1$ is a constant fraction of individuals progressing from one length class to the next over the interval $t \to t+\Delta t$, and $\sigma_{i,j,t}$ and $h_{i,t}$ are, respectively, the corresponding survivorship and hatchlings to the first length class. The length of individuals of length class j is given by

$$L_{i,j} = L_{\infty,i} - \left(L_{\infty,i} - L_{0,i}\right)\exp\left(-j \times \Delta q_i\right)$$

where $L_{0,i}$ is the length of the smallest length class, $L_{\infty,i}$ is the asymptotic length of species i, and Δq_i is a constant. In order to model growth up to a maximum length $L_{\max,i}$ (necessarily less than $L_{\infty,i}$) using $j_{\max,i}$ length classes we set

$$\Delta q_i = -\ln\left(\frac{L_{\infty,i} - L_{\max,i}}{L_{\infty,i} - L_{0,i}}\right)/j_{\max,i}$$

As shown in Speirs et al. (2010), in our model the mean length, $\hat{L}_{i,t}$, of a cohort of individuals with length $L_{0,i}$ at $t=0$ will increase with growth rate γ_i according to a von Bertalanffy function

$$\hat{L}_{i,t} = L_{\infty,i} - \left(L_{\infty,i} - L_{0,i}\right)e^{-\gamma_i t}$$

provided that $p_i = \gamma_i \Delta t/\Delta q_i$ and $p_i \in (0, 1)$. So, if the parameters $L_{0,i}$, $L_{\infty,i}$, and γ_i are known from observations we can chose any $j_{\max,i}$ (and hence Δq_i) and Δt that satisfy these requirements and get the required von Bertalanffy growth. Although the choice does not impact on the mean cohort length, it does control the variability around that mean. Increasing Δq_i or decreasing Δt will have the effect of increasing the variability in length of a cohort. Biomass features in the calculation of the survival and recruitment terms, described below, so we assume that weight and length are related by $w_{i,j} = a_i L_j^{b_i}$, with a_i and b_i constants.

The recruitment term, $h_{i,t}$, is the number of eggs hatched from a distinct egg class, $n_{e,i,t}$. We assume that the proportion of sexually mature individuals producing eggs increases with length according to a cumulative normal distribution. So, the proportion of mature adults, $m_{i,j}$, in length class j is given by

$$m_{i,j} = \Phi\left((L_{i,j} - L_{m,i})/s_{m,i}\right)$$