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Modelling recovery of Celtic Sea demersal fish community size-structure

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ABSTRACT

The Large Fish Indicator (LFI) is a size-based indicator of fish community state. The indicator describes the proportion by biomass of a fish community represented by fish larger than some size threshold. From an observed peak value of 0.49 in 1990, the Celtic Sea LFI declined until about 2000 and then fluctuated around 0.10 throughout the 2000s. This decline in the LFI reflected a period of diminishing 'large' fish biomass, probably related to high levels of size selective fishing. During the study period, fishing mortality was maintained at consistently high values. Average biomass of 'small' fish fluctuated across the whole time series, showing a weak positive trend in recent years. Inter-annual variation in the LFI was increasingly driven by fluctuation in small fish biomass as large fish biomass declined. Simulations using a size-based ecosystem model suggested that recovery in Celtic Sea fish community size-structure (LFI) could demand at least 20% reductions in fishing pressure and occur on decadal timescales.

1. Introduction

The Large Fish Indicator (LFI) is a univariate indicator of demersal fish community 'state' (Cury and Christensen, 2005; Greenstreet et al., 2011). This indicator describes the proportion (by weight) of the fish community that is larger than some pre-defined length threshold, i.e., ('large' fish biomass)/(total fish biomass). Thus, the LFI expresses a well-understood direct effect of fishing – loss of large individuals and large species that results in curtailment of community size-structure (e.g., Haedrich and Barnes, 1997; Shin et al., 2005; Shephard et al., 2012). However, the metric also integrates a longer-term indirect effect of fishing, i.e., increasing biomass of small fish contingent on reduced predation pressure associated with removal of large piscivores (Greenstreet et al., 2011; Shephard et al., 2011). The LFI has been adopted by OSPAR as a 'fish community' indicator (Heslenfeld and Enserink, 2008) and identified in the European Union's Marine Strategy Framework Directive (MSFD) as a 'food web' indicator.

The current study calculates LFI for two temporally overlapping fisheries surveys to describe the 'state' of the Celtic Sea demersal fish community from 1986 until 2011. This builds on the work of Shephard et al. (2011) whose single-survey LFI time series concluded in 2004. The Celtic Sea is an excellent location for such an analysis since good fisheries survey programmes were already established quite early in the fisheries development phase (Pinnegar et al., 2002). This means that data are available to calculate values of ecosystem indicators for the period before long-term intensive exploitation of the fish community, and also up to the present when many of the commercial species in the region are 'seriously depleted' (ICES, 2010a,b). In order to interpret observed trends in the LFI and to make useful management predictions, both empirical and modeling analyses are presented. Changes in the empirical indicator (1986–2011) are considered in relation to changes in 'large' and 'small' fish biomass and in fishing mortality. A size-based community model is then used to evaluate fishing scenarios that might move this heavily exploited fish community towards the MSFD target of 'Good Environmental Status' (GES) by 2020.

2. Methods

2.1. Empirical analyses

Fisheries-independent survey data and fishing mortality estimates from stock assessment models were used. Two survey time series were analysed:– the (no longer active) first quarter (Q1) UK West Coast Ground Fish Survey (WCGFS) and the fourth quarter

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(Q4) Irish Ground Fish Survey (IGFS). Both surveys were designed in accordance with the standard International Bottom Trawl Survey (IBTS) protocol and cover overlapping areas of the Celtic Sea (ICES area VIIg). The UK Centre for Environment, Fisheries and Aquaculture Science (Cefas) operated the WCGFS using a Portuguese high headline trawl with a 20 mm codend liner. This survey took place in March each year, with effort varying around $n = 30–60$ hauls per year in the study area. The first 2 years of the WCGFS had inadequate sampling effort and/or spatial coverage, and were thus excluded leaving valid survey data for 1986–2004. The Irish Marine Institute conducts the IGFS survey annually in October/November using a Grande Ouverture Verticale (GOV) trawl with a 20 mm codend liner. In a given year, trawl samples are collected at around $n = 60$ sites randomly selected from a pool of around $n = 100$ fixed sampling stations in the area. The IGFS commenced in 1997 using the RV Celtic Voyager but since 2003 has employed the RV Celtic Explorer. To avoid inconsistency introduced by changing survey vessel, we use IGFS data only from 2003 to 2011.

All fish in survey catches are identified to species. For the current study, catch numbers at length (L) were converted to weight (W) at length using weight–length relationships ($W = \alpha L^{\beta}$), where the α and β parameters were derived from survey data when available (only main commercial species are weighed in the survey) or from FishBase (http://www.fishbase.org). For the WCGFS, catch weight at length of each species and length class in each trawl sample was converted to a biomass density by dividing the observed catch by the area trawled, where area trawled is wingspread × distance towed. For the IGFS, catch weight at length of each species and length class was converted to a rate (biomass sampled per unit time) based on individual trawl duration. It should be noted that biomass of small fish is typically much greater in the Q4 IGFS than in the Q1 WCGFS, as the former survey encounters large numbers of small summer-recruited fish prior to winter mortality.

The established LFI protocol was followed (Greenstreet et al., 2011) to produce overlapping survey LFI series based on the same species complex and 'large' fish threshold (50 cm) as described by Shephard et al. (2011). ICES statistical rectangles sampled in fewer than half of all years of the WCGFS were excluded to minimise the potential for bias associated with variation in sampling effort or spatial variation in fish community composition. The IGFS has a much larger survey footprint than the Celtic Sea component of the WCGFS and in the two overlapping years (2003 and 2004) the two surveys only sampled around 10–14 ICES rectangles in common. The initial intent of the current paper was to use data from only the overlapping rectangles in order to produce a combined LFI based on the same underlying fish community. However, it was decided that this overlapping area was too small to be of management value and included too few data for robust analyses. As such, the same WCGFS data were used as in Shephard et al. (2011) and a partially overlapping, larger component of the IGFS data was selected to correspond. The selected IGFS area comprised all trawl samples located between longitude 5.00–9.00°W and latitude 50.00–52.00°N.

The observed maximum values of the WCGFS LFI (approximately 0.42–0.49 in the late 1980s) were taken to represent values for this metric during an earlier period in the Celtic Sea fisheries exploitation history when fish stocks were generally in better condition. These values may be considered to describe GES in this community. The LFI responds to changes in biomass of both 'large' and 'small' fish and it is important to understand the relative influence of these groups. Hence, mean annual biomass of each of large and small groups was plotted for the study period of each survey.

Fishing pressure in the Celtic Sea was considered in terms of the harvesting rate H, which we define as the rate at which a population's total biomass decreases because of removals by fishing. In the model community used below, entire populations (including all age groups) of fish species are modelled, so the use of H is more appropriate than F, because, unlike F, H gives the fishing mortality for the whole population. Use of H in the current paper for both empirical and modelling analyses allows a direct comparison. Harvesting rates were calculated from time series of empirically derived catch and total stock biomass estimates for the Celtic Sea (1986–2008) from ICES reports (ICES, 2006, 2007, 2008, 2009, 2010a). For each year over the period 1986–2008, a mean H value, $\bar{H}$, was calculated as the biomass-weighted mean H for eight main fish stocks assessed in the Celtic Sea [anglerfish, blue whiting, cod, haddock, hake, megrim, monkfish (*Lophius budegassa*) and whiting], although there were some missing years for anglerfish (2006–2008), blue whiting (2002–2004, 2007–2008), cod (2008), haddock (1986–1992), megrim (2006–2008) and monkfish (2006–2008) because of missing catch and/or total stock biomass data. For each species, for each year where data was available, H was calculated by computing the proportion (catch)/(total stock biomass) and converting this proportion into a rate in units of year^{-1}. This conversion was required because the model used below operates in continuous time. Annual harvesting rate (H) by species showed a close linear relationship with F (Fig. 1). The two observed LFI series were qualitatively interpreted in terms of temporal changes in large and small fish biomass and annual mean harvesting rate $\bar{H}$.

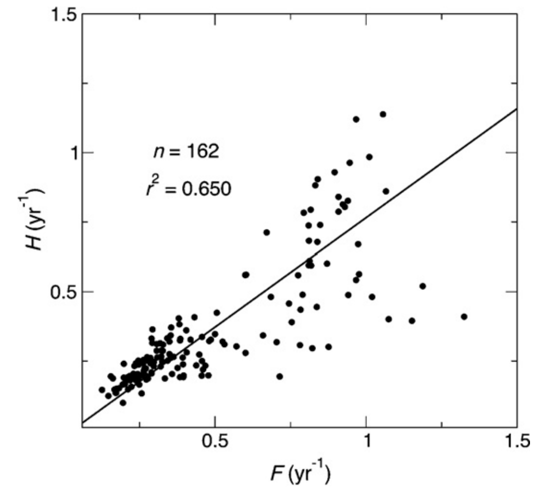

Fig. 1. Correlation between annual harvesting rates (H) and fishing mortality rate (F) for eight assessed fish species in the Celtic Sea, for the years 1986–2008. The slope of the regression line is 0.786.

2.2. Modelling

The ecological mechanisms underlying changes in the LFI are complicated. Greenstreet et al. (2011) suggested that the slow response of the North Sea LFI to reductions in fishing pressure could be due to the time it takes to reverse increases in biomass of small fish individuals that have arisen from predation release. Mechanisms underlying this maintenance of increases in small fish individuals are uncertain, but could include depensation effects, whereby increases in small fish species result in increased predation and/or competition with the juveniles of larger species, thus preventing or delaying their growth into large individuals (Walters and Kitchell, 2001; Fauchald, 2010; Rossberg, 2012; Minto and Worm, 2012). Shephard et al. (2012) showed that changes in the Celtic Sea LFI during 1986–2004 were mainly due to changes in relative species abundances, rather than changes in intraspecific size-structures. The dominance of species composition in changing community size-structure implies that recovery of the LFI may depend on corresponding recovery of large species.