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Differential impacts of exploitation rate and juvenile exploitation on NE Atlantic fish stock dynamics over the past half century

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ABSTRACT

Exploitation rate, as measured by average fishing mortality, has been a major focus of fisheries management in the past half century in the NE Atlantic and its temporal development and negative impact on stock status are well-documented. This is not the case for juvenile exploitation, i.e. the proportional fishing mortality of juveniles, despite the expected benefits from allowing fish to spawn before capture. In this study, we describe the aggregate (cross-stock) temporal development of fishing mortality, juvenile exploitation and stock status for three ecologically distinct groups of ICES stocks (demersal roundfish, pelagic and flatfish stocks) and separately for cod stocks and NE Arctic (Barents Sea) stocks. Both the long- and short-term effects of the variation in fishing mortality and juvenile exploitation on the temporal development of stock status were explored within all five groups. The long-term aggregate temporal trends were represented for each group by calculating the average values of fishing mortality, juvenile exploitation and stock status over all stocks by year. On aggregate, time periods with high fishing mortalities, in conjunction with high juvenile exploitation, are associated with rapid declines in stock status. Stocks are better able to withstand higher fishing mortalities when juvenile exploitation is low. The short-term effects of fishing mortality and juvenile exploitation on aggregate stock status were investigated using multiple linear regressions. Significant negative effects of recent fishing mortality on stock status were found for all groups of stocks examined, whereas the effects of recent juvenile exploitation were mostly non-significant. Overall, the results indicate that when ICES stocks are considered on aggregate, exploitation rate is the main driver of stock status trends through time.

1. Introduction

Fisheries exploitation is widely recognised as one of the main forces driving the dynamics of both low and high trophic level fish stocks (Christensen et al., 2003; Myers and Worm, 2003; Smith et al., 2011). Fisheries science identifies two distinct aspects of such exploitation: exploitation rate (fishing intensity) and exploitation pattern (fishing selection). For stocks having analytical assessments, exploitation rate is usually quantified by fishing mortality (F) (ICES, 2008) and corresponds to the proportion of the population or biomass of a fish stock that is removed per year (FAO, 2010). The precautionary approach in fisheries in Europe, introduced in 1997, has led to the adoption of reference points for F and spawning stock biomass (B) (ICES, 2008) and the main focus of fisheries management in the NE Atlantic and elsewhere has been the regulation of F to ensure a target B is achieved (Froese et al., 2008; ICES, 2008). Exploitation pattern is defined as the distribution of fishing mortality over the different age/size components of a fish population (FAO, 2010) and depends on the selectivity of the gears used in a fishery and on the extent to which particular age/size classes can be selectively targeted. Exploitation pattern is broadly indicative of the proportional exploitation of juveniles because size in fish is linked to their maturity stage. A relevant metric of the proportional exploitation of juveniles (juvenile exploitation index – JEI) that results from a given exploitation pattern is the fishing mortality of immature fish divided by that of mature fish ($JEI = F_{imm}/F_{mat}$; Vasilakopoulos et al., 2011).

Protection of juveniles has been traditionally considered to play an important role in fisheries management and the use of fishing gears which retain large fish in the catch while allowing juveniles to escape has been expected to promote sustainability (Armstrong et al., 1990). This "spawn-at-least-once" principle presumes that there is a significant correlation between the size of the spawning stock and the subsequent recruitment (Myers and Barrowman, 1996; Myers and Mertz, 1998). Allowing fish to survive long enough to spawn is assumed to prevent recruitment overfishing (Myers and Mertz, 1998; Halliday and Pinhorn, 2002). In addition, protection of the small-sized immature fish reduces the potential for growth

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overfishing (Beverton and Holt, 1957; Froese et al., 2008). The efficacy of the "spawn-at-least-once" principle has been challenged by studies focusing on the uncertainty of both stock–recruitment relationships (Gilbert, 1997) and yield-per-recruit models (Halliday and Pinhorn, 2002). It has also been suggested that protecting other demographic components of fish populations (e.g. big, old females; Caddy and Seijo, 2002; Palakovich Carr and Kaufman, 2009) or fishing different age/size classes more evenly (Zhou et al., 2010; Garcia et al., 2012; Law et al., 2012) would be more effective in achieving sustainability. To test the efficacy of protecting juveniles, Vasilakopoulos et al. (2011) analysed data for 38 ICES stocks, where *F* and *JEI* (then named *ER* and *EP* respectively) were averaged over a standardised time-period, to show that both *F* and *JEI* have independent, negative effects on stock status, providing empirical evidence for the benefits from protecting juveniles. That study also showed that values of $F > 0.63$ and $JEI > 0.50$ are associated with a higher probability of individual stock status falling below precautionary limits.

In their study of the effects of *F* and *JEI* on stock status, Vasilakopoulos et al. (2011) used stock-specific values of *F* and *JEI* averaged over time. Switching to an aggregate (cross-stock) scale by performing a meta-analysis of annual values of *F* and *JEI* averaged over many stocks is an approach to resolve how aggregate values of *F* and *JEI* have developed over an extended time-scale and how variation in *F* and *JEI* has affected the dynamics of fish stocks on this broader spatial and biological scale. Such meta-analyses are often utilised to explore generic features of the temporal development of fish stocks in response to fishing over broad spatial and temporal scales because they make underlying general trends and patterns easier to detect (Myers, 2001; Sparholt et al., 2007). Garcia and De Leiva Moreno (2005) performed a meta-analysis to investigate the aggregate temporal trends of *F* and stock status of 14 ICES stocks in the period 1970 – 2003. Froese and Proelss (2010) conducted a similar analysis of 54 ICES stocks for the period 1970 – 2007 to investigate the effect of international management agreements on the aggregate development of *F* and stock status and to explore the expected aggregate development of stocks in the future. Sparholt et al. (2007) also undertook a meta-analysis of 38 stocks grouped as demersal and pelagic to calculate the aggregate temporal trends of *F*, stock status, recruitment and catch over a longer time-period (1946 – 2003). That study aimed to investigate the effect of changes in overall management on the aggregate trends and to identify the *F* associated with high sustainable yields on a meta-scale.

To complement previous studies that focused on the aggregate temporal development of *F* and stock status (Garcia and De Leiva Moreno, 2005; Sparholt et al., 2007; Froese and Proelss, 2010), here we undertake a comparable analysis including the aggregate temporal trends of *JEI* as well. Building on the study of Vasilakopoulos et al. (2011), we investigate the long-term changes in *F*, *JEI* and stock status of NE Atlantic fish stocks over the past half century when cross-stock data are considered on aggregate. For this, average values over all stocks of *F*, *JEI* and stock status were calculated by year for three ecologically distinct groups of ICES stocks (demersal roundfish, pelagic fishes and flatfish). We also examined the variation of aggregate temporal trends in two separate groups of ICES stocks that represent extremes of fishing mortality and juvenile exploitation respectively: cod stocks and NE Arctic (Barents Sea) stocks. The observed *F* and *JEI* levels were compared to the pre-defined benchmark values associated with individual stock status having higher probability to fall below precautionary limits (Vasilakopoulos et al., 2011). The short-term effects of changes in aggregate *F* and *JEI* on stock status were identified at five time lags. Thus, we were able to assess the roles of *F* and *JEI* in shaping stock status in the long- and short-term, when ICES stocks are considered on an aggregate scale.

2. Materials and methods

Time-series data for *B* and *F* of 38 stocks up to 2008 (2007 in the case of Celtic Sea cod) were taken from ICES assessment reports published in 2008 and 2009. For each time-series the estimates for the most recent two years (one year in the case of Celtic Sea cod) were rejected due to their lower precision (Sparholt et al., 2007); therefore the final year of all time-series was 2006 (Table 1). The stocks included in this analysis met the following criteria: (a) age-structured maturity, abundance and *F* estimates were available to calculate proportional exploitation of juveniles and (b) precautionary biomass limits (B_{pa}) were reported which allowed the definition of stock status. The stocks were then grouped according to their type as demersal roundfish (D), pelagic fishes (P) and flatfish (F) (Table 1).

For all 38 stocks, stock status in year *t* (SS_t) was defined as the value of B_t expressed as a proportion of the precautionary reference point, B_{pa} ($SS_t = B_t/B_{pa}$). A $SS_t \geq 1$ indicates stocks within safe biological limits while $SS_t < 1$ indicates overfished stock status. Exploitation rate in year *t* was expressed by F_t (year^{-1}), i.e. the average fishing mortality of the age classes primarily targeted by the fisheries (ICES, 2008). Proportional exploitation of immature fish in year *t* (JEI_t) was estimated for every stock as the relative fishing mortality of immature to that of mature fish ($JEI_t = F_{imm,t}/F_{mat,t}$) in age classes ≥1 (Vasilakopoulos et al., 2011). In the cases of stocks where the youngest age class provided in the assessment was >1, missing abundances of younger age classes were reconstructed using the available natural mortality values given in the assessment reports (Table 1). *JEI* is essentially an index that quantifies the effect of fishing on the future reproductive potential of the stock and also a crude proxy of size selection; the higher the value of *JEI* the fewer juveniles are allowed to enter the spawning stock. *JEI* has been also shown to be uncorrelated with *F* (Vasilakopoulos et al., 2011).

To illustrate the long-term aggregate temporal development of F_t, JEI_t and SS_t, average values over all stocks by year were calculated separately for demersal roundfish (18 stocks), pelagic (9 stocks) and flatfish (11 stocks) species. Flatfish were examined separately from the demersal roundfish due to the distinct differences in their ecology. For example, juvenile flatfish are less exposed to fisheries because they dwell in shallow nurseries (Ryer et al., 2010). Average annual values of F_t, JEI_t and SS_t, were also calculated for two separate groups including all cod stocks (7 stocks) and the NE Arctic (Barents Sea) stocks (3 stocks – cod, haddock and saithe). These groups allow for investigating the effects of *F* and *JEI* at their most extreme levels, as the cod stocks had the highest values of *F* among the stocks examined, while the NE Arctic stocks exhibited the lowest *JEI* values. Thus, for each of the five groups of stocks we created new time-series of average values representing the aggregate temporal trends of $\bar{F}_t$, $\overline{JEI}_t$ and $\overline{SS}_t$ (Sparholt et al., 2007). This analysis of temporal trends allowed for the description of low-frequency variation (i.e. overall trend) in $\bar{F}_t$, $\overline{JEI}_t$ and $\overline{SS}_t$ over a long time-scale and for the comparison of the levels of $\bar{F}_t$, $\overline{JEI}_t$ with the benchmark values proposed by Vasilakopoulos et al. (2011).

In order to investigate whether the $\overline{SS}_t$ development is impacted by short-term, high-frequency fluctuations of $\bar{F}_t$ and $\overline{JEI}_t$, $\overline{SS}_t$ was modelled as a function of $\bar{F}_t$ and $\overline{JEI}_t$ at five consecutive time lags (1) for the five different groups of stocks and was analysed by the use of multiple linear regression.

$$\overline{SS}_t = f(\bar{F}_{t-1}, \bar{F}_{t-2}, \bar{F}_{t-3}, \bar{F}_{t-4}, \bar{F}_{t-5}, \overline{JEL}_{t-1}, \overline{JEL}_{t-2}, \overline{JEL}_{t-3}, \overline{JEL}_{t-4}, \overline{JEL}_{t-5}) \quad (1)$$

To reduce the disproportionate effect that the longest time-series could have in the analysis, the time-series used in the analysis for every group of stocks commenced in the year when $\overline{SS}_t$, $\bar{F}_t$ and $\overline{JEI}_t$ could be calculated by averaging the values of at least two stocks