Fishing down the deep

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Abstract

Global landings of demersal marine fishes are demonstrated to have shifted to deeper water species over the last 50 years. Our analysis suggests deep-water fish stocks may be at serious risk of depletion, as their life histories render them highly vulnerable to overfishing with little resilience to over-exploitation. Deep-sea fisheries are exploiting the last refuges for commercial fish species and should not be seen as a replacement for declining resources in shallower waters. Instead, deep-water habitats are new candidates for conservation.

Keywords deep-sea, deep-water fisheries, fisheries crisis, global trends

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Introduction

A global crisis in marine fisheries was regarded with scepticism by many fisheries scientists as recently as 10 years ago. Today, however, few dispute worrying trends [Pitcher and Pauly 1998; Pitcher 2001; Pauly *et al.* 2002; Christensen *et al.* 2003; Hilborn *et al.* 2003; Pauly and Maclean 2003; Food and Agriculture Organization (FAO) 2004]. Historical data from marine ecosystems clearly suggest that overfishing has had, for thousands of years, a major impact on target species and have fundamentally altered marine ecosystems (Jackson *et al.* 2001; Pitcher 2001), including coral reefs (Pandolfi *et al.* 2003). A dramatic depletion of large predators (Baum *et al.* 2003; Christensen *et al.* 2003; Myers and Worm 2003) has triggered fisheries to target species of lower trophic levels in a process called 'fishing down marine food webs' (Pauly *et al.* 1998a). More recently, fisheries exploitation has spread from coastal areas to the open ocean and a general decline in fish biomass has been reported (Baum *et al.* 2003; Christensen *et al.* 2003; Myers and Worm 2003): as a consequence, many marine species are of serious conservation concern (Casey and Myers 1998; Spotila *et al.* 2000; Baum *et al.* 2003; Sadovy and Cheung 2003). Not surprisingly, there has been a decline in global fisheries catches since the late 1980s (Watson and Pauly 2001; Zeller and Pauly 2005) at an approximate rate of 0.4 million tonnes per year. Nevertheless, a global increase of fishing effort and catching power has continued (Gréboval 2003).

With the decline of shallow coastal waters resources, increasing demand, and new technology, fisheries are evidently expanding offshore (e.g. Christensen *et al.* 2003; Myers and Worm 2003; Pauly *et al.* 2003) and into deeper waters (Koslow *et al.* 2000; Garibaldi and Limongelli 2003; FAO 2004; Gianni 2004). The expansion into offshore areas has been well documented, (for example, fisheries targeting oceanic tuna, billfishes and their relatives covered the world ocean by the early 1980s; Myers and Worm 2003), but the extension into deeper waters is less well analysed. While many local examples of fisheries expansion into deeper waters have been reported (e.g. some European, Soviet, USA, Canada, New Zealand and Australian fishing fleets: see references in Hopper 1995; Moore 1999; Koslow *et al.* 2000; Roberts 2002), we lack a global quantitative analysis.

Deep-water fish resources are generally considered to have high longevity, slow growth, late maturity, and low fecundity. Thus, they have been considered more vulnerable to exploitation than most species exploited on the continental shelf, upper continental slope or in open ocean pelagic ecosystems (Merrett and Haedrich 1997; Koslow *et al.* 2000). Deep-water stocks can be rapidly depleted and recovery can be very slow, although this will not apply to a few deep-water species with life history traits comparable to shallow water species (Large *et al.* 2003).

Whereas previous studies on global trends of fisheries have focused on catch or biomass changes over time (e.g. Christensen *et al.* 2003; Myers and Worm 2003), in this paper we have analysed changes in the mean depth of fishing to test if the predicted expansion into deeper-waters can be detected in global landings datasets. We also tested for the predicted higher vulnerability of deep-water fisheries resources, using longevity as the main proxy for vulnerability.

Methods

We used three publicly available databases; official landings statistics from the FAO from 1950 to 2001, which are based on reports submitted annually by FAO member states; FishBase (http://www.fishbase.org), an information system with key data on the biology of fishes (Froese and Pauly 2004); and the Sea Around Us Project database (SAUP: http://www.seaaroundus.org), which contains estimated maps of global fisheries catches from 1950 to the present. The SAUP database includes data from the FAO, International Council for the Exploration of the Seas (ICES), Northwest Atlantic Fisheries Organization (NAFO), and other sources (Watson *et al.* 2004) and was used to compile catch data for high seas areas.

In this study, depth range is defined as the extremes of the depths reported for juveniles and adults (but not larvae), while common depth is the range where adults are most often found, and is more precisely defined as the range within which approximately 95% of the biomass of a species occurs (Froese and Pauly 2004). For those taxa not reported to species level, the average for the genus or family was calculated using the species most likely to be present at that locality.

FishBase was used to estimate the average depth of occurrence for most of the 775 different species or groups of marine fishes included in the FAO landings statistics, and to gather data on their longevity. Average depth of occurrence for taxa identified at species level in the landings statistics was estimated as the mean of the common depth range or as one-third of the total depth range. In the latter case, we assume fish to have a lognormal distribution with depth, whose peak in abundance is at one-third of their range (Alverson *et al.* 1964; Pauly and Chua 1988). We have tested this assumption using FishBase data on full depth ranges and common depth ranges for 136 fish species; the only species with both ranges in the database. The average peak abundance was 0.302 of the full depth range (95% confidence interval; 0.28–0.33): this value is not significantly different from a one-third assumption (*t*-test: $P > 0.01$).

By combining mean depths and catch series, time series of the mean depth of the catch of marine bottom fishes (excluding pelagic) and for all marine fishes were estimated for the world and for different groupings of FAO statistical areas (ocean basis). The mean depth of the fisheries catch by year and ocean basis was estimated as the average depth of occurrence of the species (or group caught), weighted by the logarithm of their catch.

Visual inspection of different datasets suggested an inflection point such that a single regression line would not suffice. We therefore fitted simple linear biphase regression models, using the algorithm described in Hintze (1998). We then compared biphase regression models to other simpler and more complex models. For this, we have fitted simple linear regression models as well as quadratic, cubic and fourth order models to the data. If the simpler model fits better (has a smaller sum-of-squares) than the more complex model (more parameters), then no statistical analysis was preformed and the simpler model was accepted. As this rarely occurred, we used the likelihood ratio test (Hilborn and Mangel 1997) to compare the goodness-of-fit of two models, where the more complex equation fits better than the simple equation. For most of the cases (seven of 10) biphase regression models fitted the data significantly better than any other tested model (Table 1). Thus, biphase regression models were preferred. The only cases where biphase regression models were not preferred were for the time-series data of mean depth of the fisheries catch for Antarctica and the whole world where quadratic models fitted the data significantly better.

Additionally, we estimated a time series of the mean longevity of fish in the world catch by combining data on fish longevity from FishBase with fish landings from FAO. The mean longevity of landings for each year and FAO area was estimated as the mean of the longevity of each species or group, weighted by the logarithm of their catch. The mean fish longevity of the catch was also estimated as a function of depth of fish occurrence. As this has to be carried out in a yearly basis, we used year 2001 in FAO dataset.

Results

Global trends

Our results (Fig. 1a) show that, for bottom marine fishes, the overall trend over the past 50 years has been a 42 m increase in the mean depth of the catch, from around 103 m in the early 1950s to 145 m in 2001. The biphase linear regression fitting the data (overall $r^2 = 0.94$) suggests two periods with different trends: a period of slow increase in the mean depth of fishing from 1950 to 1978 with a slope of about 2 m decade^{-1}, followed by a period of marked increase in the mean depth of fishing at a rate of about 13 m decade^{-1} (Table 2). If we include pelagic fishes in the analysis (Fig. 1a), the increase in mean depth of the catch is lower but still considerable, with two distinguishable periods (overall $r^2 = 0.93$). In both cases, the early plateau and the estimated break point can be attributed to either a real increase in the fishing deeper trend, or to a lack of taxonomic resolution in the FAO landing statistics before the 1970s. Application of our method to catches from high seas areas only (i.e. beyond countries' EEZ's) showed a more dramatic decline in the mean depth of fishing, at a rate of 22 m decade^{-1} for bottom fishes only and 9.0 m decade^{-1} when considering pelagic fishes.

In general, fishing began to operate deeper from the late 1960s. Since the taxonomic resolution in the FAO landing statistics improved after the 1970s, this increase in depth could be caused by, (i) a proportional decrease in the catches of shallow water species (resulting from collapse of coastal resources); (ii) a proportional increase in the landings of deep-water species (from the expansion of fisheries into deep water); or (iii) both. Figure 1b helps elucidate this by showing that, at a global level, the increase in the mean depth of fishing has been caused by an increase in landings of deep-water species such as the orange roughy (*Hoplostethus atlanticus*, Trachichthyidae), grenadiers (Macrouridae), alfonsinos (*Beryx* spp., Berycidae) and several deepwater sharks. The steepest rates of depth increase match the development of most of the deepwater fisheries around the world (Hopper 1995; Merrett and Haedrich 1997; Moore 1999; Koslow *et al.* 2000; Roberts 2002; Garibaldi and Limongelli 2003).

Similar trends of increased mean depth of fishing were observed for all oceans, with rates ranging