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Fishing down the deep

Telmo Morato[1, 2], *Reg Watson*[2], *Tony J. Pitcher*[2] *& Daniel Pauly*[2]

[1]Departamento de Oceanografia e Pescas, Universidade dos Açores, PT 9901-862, Horta, Portugal; [2]Fisheries Centre, AERL Building, 2202 Main Mall, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada

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

Correspondence:
Telmo Morato, Fisheries Centre, AERL, 2202 Main Mall, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada
Tel: +1 604 822 1636
Fax: +1 604 822 8934
E-mail: t.morato@fisheries.ubc.ca

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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

Table 1 Summary of the likelihood ratio test (Hilborn and Mangel 1997) used to compare the goodness-of-fit of different models where the more complex equation fits better than the simple equation. The more complex model was accepted of $P < 0.01$.

Ocean basis	Model	*n*	d.f.	SS	Comparisons	Ratio (*F*-value)	*P*-value	Best fit
N. Atlantic	Linear	2	50	2378.2				
	Quadratic	3	49	777.6	L/Q	100.86	>0.001	Quadratic
	Linear-linear	4	48	351.7	Q/LL	58.12	>0.001	Linear-linear
	Cubic	4	48	429.5	LL/C			
	Fourth	5	47	334.1	LL/F	2.48	0.122	Linear-linear
C. Atlantic	Linear	2	50	184.5				
	Quadratic	3	49	148.8	L/Q	11.76	0.001	Quadratic
	Linear-linear	4	48	129.0	Q/LL	7.35	0.009	Linear-linear
	Cubic	4	48	130.1	LL/C			
	Fourth	5	47	126.1	LL/F	1.10	0.300	Linear-linear
S. Atlantic	Linear	2	50	2928.9				
	Quadratic	3	49	2002.3	L/Q	22.67	>0.001	Quadratic
	Linear-linear	4	48	1270.6	Q/LL	27.64	>0.001	Linear-linear
	Cubic	4	48	1125.9	LL/C			
	Fourth	5	47	1105.1	LL/F	7.04	0.011	Linear-linear
N. Pacific	Linear	2	50	1501.5				
	Quadratic	3	49	1258.0	L/Q	9.48	0.003	Quadratic
	Linear-linear	4	48	876.9	Q/LL	20.86	>0.001	Linear-linear
	Cubic	4	48	800.1	LL/C			Cubic
	Fourth	5	47	791.6	LL/F	5.07	0.029	Linear-linear
C. Pacific	Linear	2	50	1287.7				
	Quadratic	3	49	672.6	L/Q	44.81	>0.001	Quadratic
	Linear-linear	4	48	426.7	Q/LL	27.67	>0.001	Linear-linear
	Cubic	4	48	476.7	LL/C			
	Fourth	5	47	381.3	LL/F	5.59	0.022	Linear-linear
S. Pacific	Linear	2	50	13764.4				
	Quadratic	3	49	6441.9	L/Q	37.51	>0.001	Quadratic
	Linear-linear	4	48	3645.6	Q/LL	24.54	>0.001	Linear-linear
	Cubic	4	48	4576.5	LL/C			
	Fourth	5	47	4568.7	LL/F			
Indian Ocean	Linear	2	50	3135.4				
	Quadratic	3	49	1124.9	L/Q	87.57	>0.001	Quadratic
	Linear-linear	4	48	946.8	Q/LL	9.03	0.004	Linear-linear
	Cubic	4	48	921.2	LL/C			
	Fourth	5	47	823.0	C/F	7.07	0.011	Linear-linear
Antarctic	Linear	2	34	48560.6				
	Quadratic	3	33	37051.8	L/Q	10.25	0.003	Quadratic
	Linear-linear	4	32	32769.0	Q/LL	4.18	0.049	Quadratic
	Cubic	4	32	36762.0	LL/C			
	Fourth	5	31	36415.9	LL/F			

Where *n* is the number of parameters estimated in each model; d.f., degrees of freedom; SS, the sum-of-squares. L stands for Linear models, Q for quadratic, LL for the biphase linear-linear models, C for cubic models and F for fourth order models.

from 1 m decade^{-1} deeper for the North Pacific to 180 m decade^{-1} for Antarctic fisheries (Table 2).

Atlantic Ocean

In the Atlantic Ocean, the mean depth of the catch has increased steadily over the last decades at a rate of 32, 5 and 15 m decade^{-1} for the North, Central and South Atlantic, respectively. In the North Atlantic (Fig. 2a), the simplest biphase linear regression that fit the data suggests two periods with different trends: a period with a small rate of fishing deeper from 1950 to 1989 (±1.8 SE), with a slope of 5.5 m decade^{-1}, followed by a period of marked increase in fishing deeper at a rate of 32.1 m decade^{-1}.

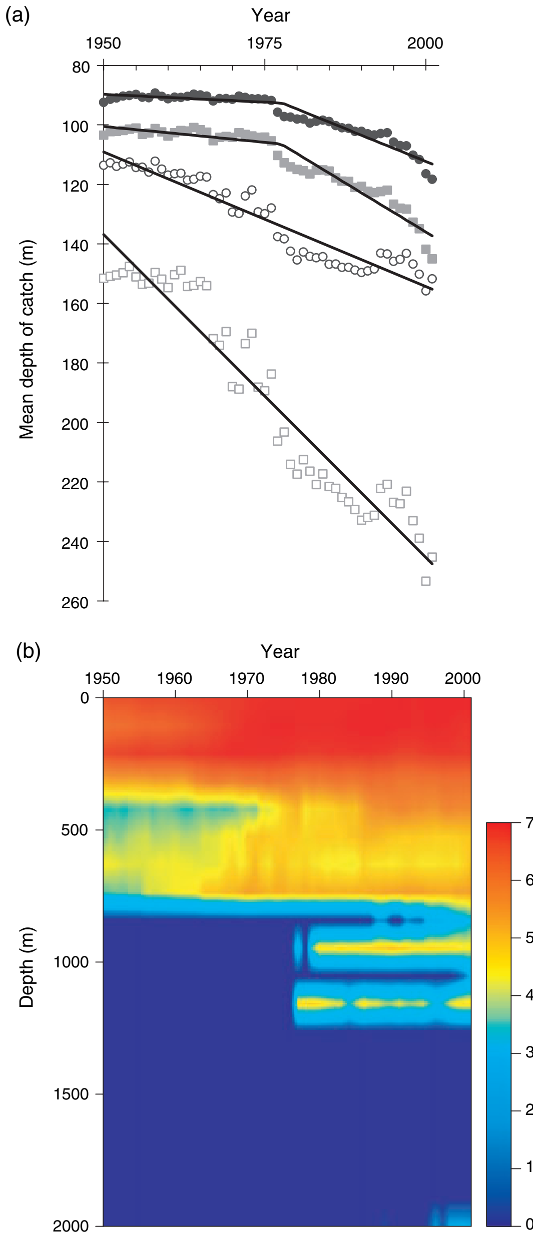

Figure 1 (a) Global trend of mean depth of world marine fisheries catches from 1950 to 2001 for all marine fishes including pelagics (dark grey dots) and for bottom marine fishes only (light grey squares). Open symbols are estimates for high seas areas only (beyond countries EEZs). Trend lines are fitted using the piecewise-polynomial model linear-linear (Hintze 1998) or simple linear regression. (b) Time series of world marine bottom fisheries catches by depth strata. Catch in tonnes are $\log_{10}$ transformed.

The first period corresponds to the relative increase in the reported landings of some deepwater species (Fig. 3a) such as the roundnose grenadier (*Coryphaenoides rupestris*, Macrouridae), alfonsinos, ling (*Molva molva*, Lotidae), blue ling (*M. dypterygia*, Lotidae), and tusk (*Brosme brosme*, Lotidae). The steepest increase observed for the second period, after 1989, matches the development of most of the deepwater fisheries in the North Atlantic (Hopper 1995; Merrett and Haedrich 1997; Moore 1999; Koslow *et al.* 2000; Gianni, 2004). In Fig. 3a we can clearly see some new deepwater species, with an average depth of about 1000 m, being reported for the first time after 1989. These were orange roughy, bulls-eye (*Epigonus telescopus*, Epigonidae), and deepwater sharks (*Centroscymnus coelolepis*, Dalatiidae; *Dalatias licha*, Dalatiidae; *Centrophorus squamosus*, Centrophoridae; *Deania calcea*, Centrophoridae).

Similar trends are apparent throughout the time series for the Central (Fig. 2b) and South Atlantic (Fig. 2c), although in the Central Atlantic fishing operates in more shallow waters (Fig. 3b). In the South Atlantic (Fig. 2c), the mean depth of fishing time series suggests two periods with different depth of fishing trends: a period of fluctuating mean depth of fishing from 1950 to 1966 (±1.9 SE), with a slope of −3.0 m decade^{-1}, followed by a period of marked increase in the mean depth of fishing at a rate of 15.2 m decade^{-1}. In the South Atlantic basis, some deepwater fisheries have developed since the 1970s on the Patagonian shelf, Western South Atlantic (Catarci 2004), and on the deeper continental shelf and slope of the Eastern South Atlantic (Boyer *et al.* 2001). The highest rate of fishing deeper corresponds with increased landings of species with average depths at about 400, 700 and 1100 m (Fig. 3c).

Pacific Ocean

The Pacific Ocean shows somewhat contrasting trends. The North Pacific (Fig. 2d) has a steep increase in the mean depth of fishing (20 m decade^{-1}) for the period from 1950 to 1959 (±1.4 SE), but no significant change after that. Large-scale deepwater fisheries have a long history in the North Pacific Ocean with some of the targeted species been fished since the early 1900s (Moore 1999). There are also established deepwater fisheries for dover sole (*Microstomus pacificus*, Pleuronectidae), thornyheads (*Sebastolobus* spp., Sebastidae), other rockfishes (*Sebastes* spp., Sebastidae), pelagic armorhead (*Pseudopentaceros wheeleri*, Pentacerotidae) and alfonsinos. The lack of a clear

Table 2 Rate of increasing depth of fishing per decade before and after the breaking point (BP) estimated using a two phase model (linear-linear) as described in Hintze (1998). Coefficient of determination (r^2) for regressions also presented.

	Linear-linear two model				
	Slope (m decade^{-1})	BP		Slope (m decade^{-1})	
	BP – 1950	Year	SE	BP-2001	r^2
All fish	1.06	1978	2.0	8.80	0.93
Demersal fish	2.13	1978	2.0	13.17	0.94
Atlantic, North	5.49	1989	1.8	32.05	0.97
Central	8.36	1985	5.6	5.05	0.98
South	–3.05	1966	1.9	15.17	0.92
Pacific, North	20.03	1959	1.4	0.58	0.59
Central	–1.80	1992	6.0	21.76	0.67
South	–7.64	1968	1.3	35.55	0.95
Indian Ocean	–0.09	1986	2.4	22.54	0.83
Antarctica	99.84	1985	4.6	180.13	0.96

trend in the mean depth of fishing in the North Pacific may be attributed to the time scale used in the analysis, because most of the deepwater fisheries started before 1950s or early 1960s (Moore 1999; Koslow *et al.* 2000). Nevertheless, Fig. 3d clearly shows the start of fisheries of some deep-water species, observed in the early 1960s and the late 1970s.

The overall trend for Central Pacific Ocean (Fig. 2e) is not clear. Until early 1990s the mean depth of the catch got shallower. This trend may be explained by three alternative hypothesis: (i) a problem with the official landings statistics mainly due to assigning catches to broad categories; (ii) a proportional increase in shallow water fish landings greater than for deeper water species; and (iii) a real lack of fisheries expansion into deeper waters. The last is not likely to be true, because it is clear from Fig. 3b that in early 1970s some deeper water fish species like sablefish were being reported in the official landing statistics. After 1992 (±6.0 SE) the mean depth of fishing in the central Pacific increased at a rate of 21.8 m decade^{-1}, with the increase in importance of some deeper water fish species (Fig. 3e), such as the dover sole.

In the South Pacific (Fig. 2f) the mean depth of fishing has increased rapidly since 1968, at a rate of 36 m decade^{-1}, coinciding with the start of orange roughy and other deepwater fisheries around New Zealand and Australia (Koslow *et al.* 2000). Figure 3f clearly shows that some deepwater species with average depths of fishing at about 400, 700 and 900 m start being reported during the 1970s.

Indian Ocean

The Indian Ocean (Fig. 2g) shows no clear trend until 1986, but a steep increase in depth afterwards, at a rate of 22 m decade^{-1}. The second period matches the appearance of deepwater species, such as the silver gemfish, *Rexea solandri*, orange roughy and Patagonian toothfish (*Dissostichus eleginoides*, Nototheniidae) in landing statistics (Fig. 3g).

Antarctic

Finfish fisheries in Antarctica began only during the mid 1960s (Kock 1992). This region (Fig. 2h) exhibits the most dramatic increase in mean depth of the catch, from about 100 m in the mid 1960s to 600 m in 2001, a rate of more than 100 m decade^{-1}. The observed trend in Antarctica clearly reflects the collapse and the implementation of fisheries restrictions for some shallower water fishes (Fig. 3h) such as marble rockcod (*Notothenia rossii*, Nototheniidae) and other Nototheniidae species in the late 1980s (CCAMLR 2004). It also reflects the increase landings of the deepwater Patagonian toothfish during late 1980s (Kock 1992; Constable *et al.* 2000).

Mean longevity of the catch

The mean longevity of the catch (Fig. 4a) has increased during the past 50 years, but most dramatically since the early 1990s. Mean longevity

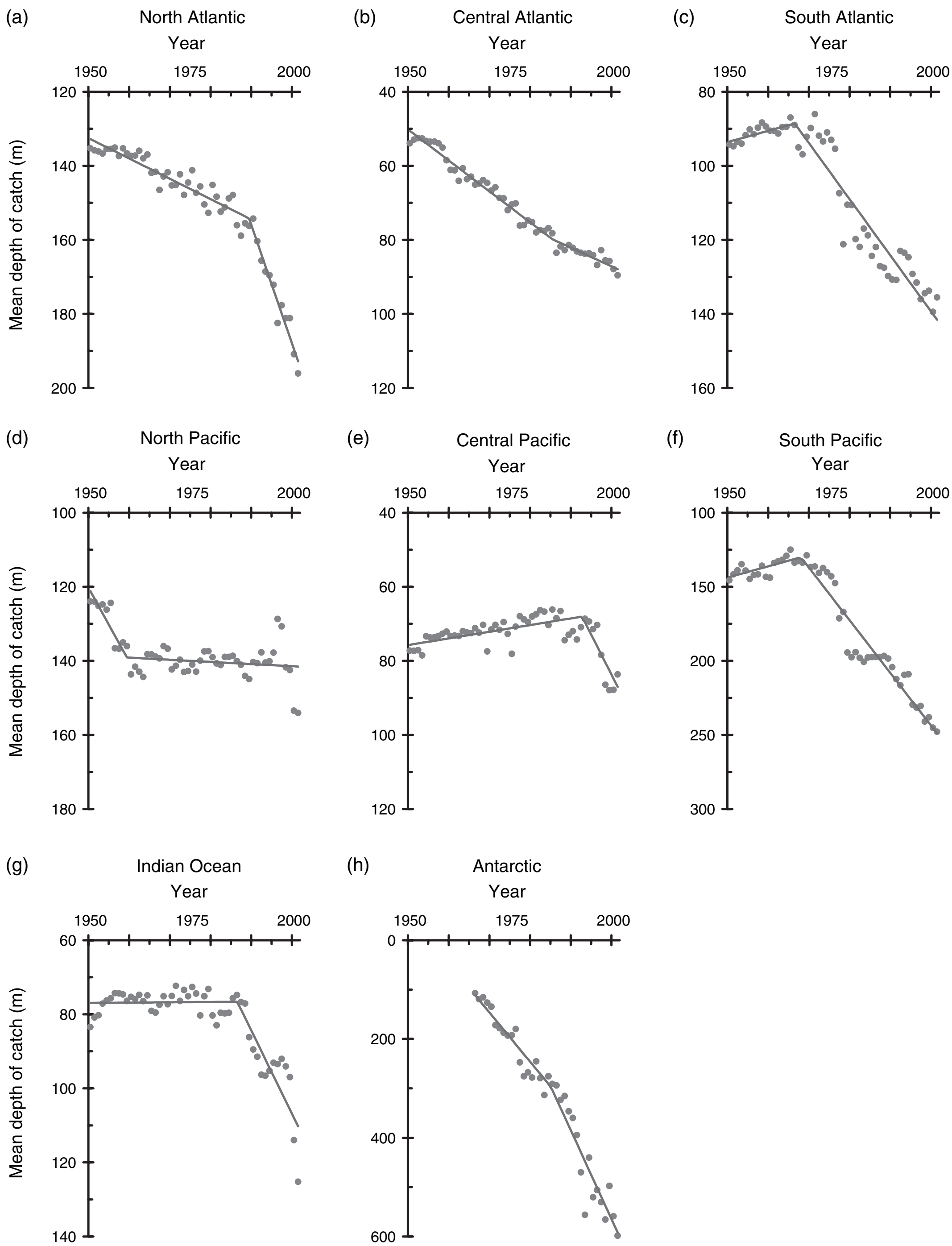

Figure 2 Trend of mean depth of marine bottom fisheries catches for: (a) North Atlantic; (b) Central Atlantic; (c) South Atlantic; (d) North Pacific; (e) Central Pacific; (f) South Pacific; (g) the Indian Ocean; and (h) Antarctic. Trend lines are fitted using the piecewise-polynomial model linear-linear (Hintze 1998).

of the catch by depth (Fig. 4b) in landings from shallow waters has a lower mean longevity (about 15 years) when compared to intermediate (about 40 years) or deeper waters (over 100 years). Hence, fishing deeper means fishing for increasingly longer-lived and thus more vulnerable species.

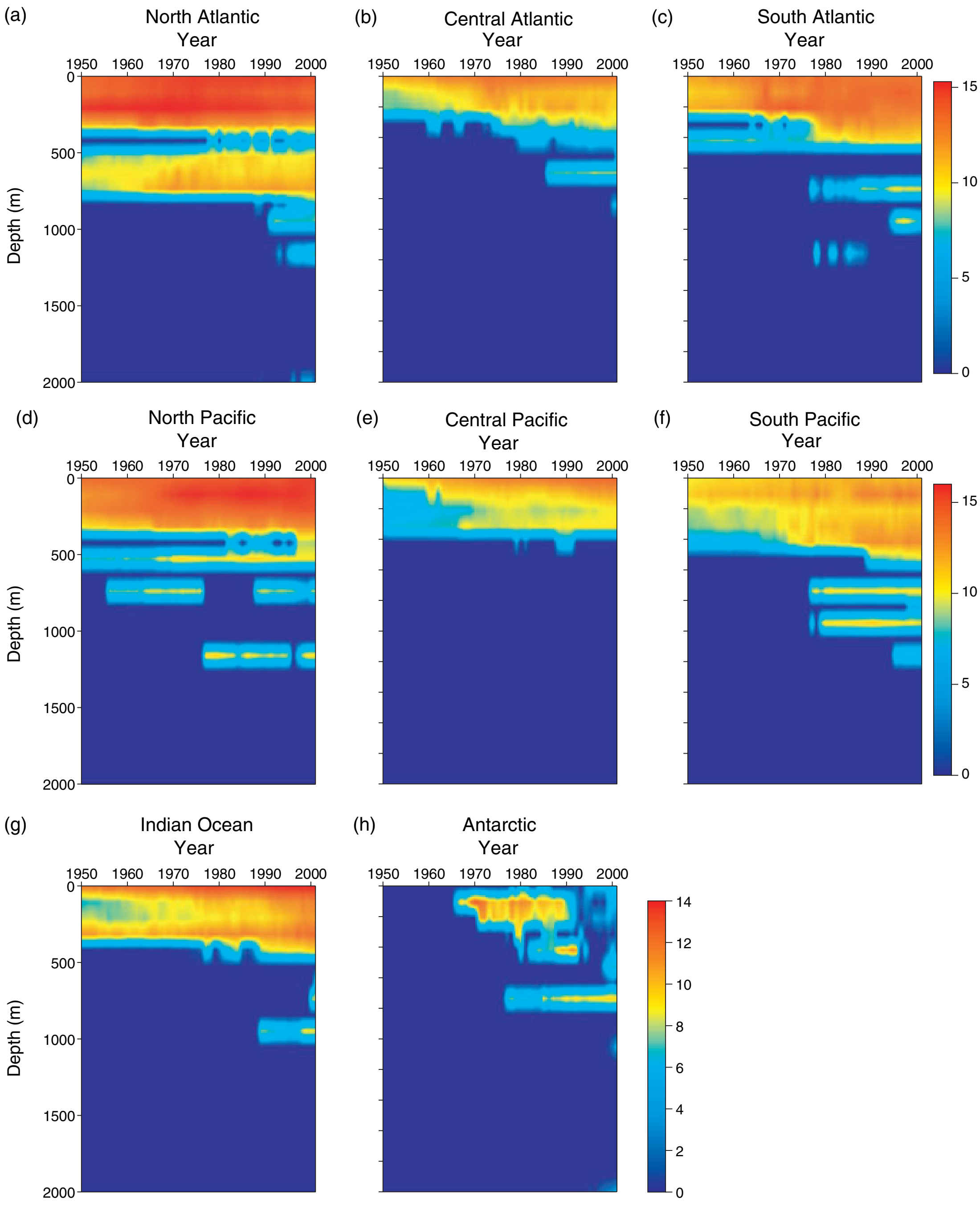

Figure 3 Time series of marine bottom fisheries catches by depth strata for: (a) North Atlantic; (b) Central Atlantic; (c) South Atlantic; (d) North Pacific; (e) Central Pacific; (f) South Pacific; (g) the Indian Ocean; and (h) Antarctic. Catch in tonnes are $\log_e$ transformed.

Discussion

We have shown that global landings of fishes have shifted in the last 50 years from shallow to deeper water species, and also that, as a likely consequence, the mean longevity of the fish species caught has increased dramatically. This trend is a serious concern because species with larger body

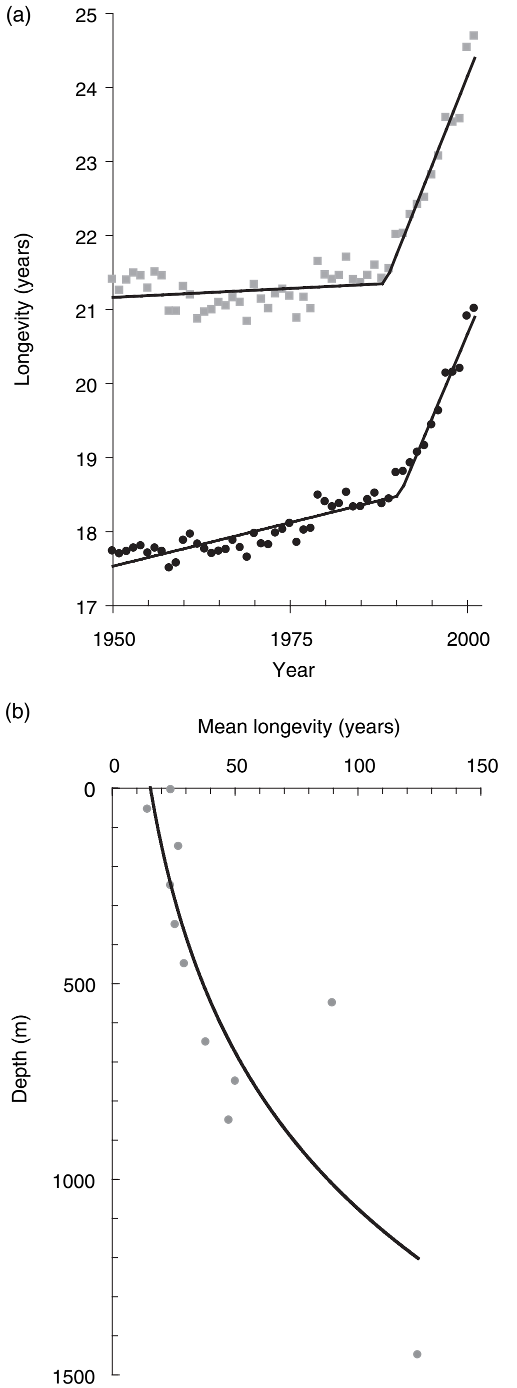

Figure 4 (a) Global trend of mean fish longevity of the catches for all marine fishes including pelagics (dark grey dots), and for bottom marine fishes only (light grey squares). (b) Global trend of mean longevity of the 2001 world bottom marine fisheries catch by depth. Line is the least squares fit through points by using a logarithmic equation ($r^2 = 0.75$). Mean age at maturity shows a similar pattern.

size, longer life span, later sexual maturity, and slow growth are more vulnerable to overfishing and extirpation (Jennings *et al.* 1998; Dulvy *et al.* 2003, 2004; Cheung *et al.* 2005). Deep-water fishes are thus highly vulnerable to overfishing and potentially have little resilience to over-exploitation (Koslow *et al.* 2000; Clark 2001; Morato *et al.* in press). Moreover, deep waters act as the last refuge for some coastal stocks with an extensive vertical distribution where no fishing was occurring some decades ago (Caddy 1993). With a fisheries expansion to deeper waters those refuges will no longer operate.

There is a recent tendency in fisheries development to argue for a diversification of target fish species, mainly through the exploitation of 'underutilized' deepwater species (see Moore 1999). In fact we are already seeing the well-documented declines observed for shallow water fish stocks repeated in deepwater stocks (see Roberts 2002 for some examples). Because of their life-history characteristics (Merrett and Haedrich 1997; Morato *et al.* in press) this phenomenon will be much faster with a smaller likelihood of recovery after collapse. Hence, deep-sea fisheries cannot be seen as a replacement for declining shallow-water resources; instead, deep-water habitats should be considered as the new candidates for conservation.

Our work is based on the FAO catch statistics and on the reported average depth range of fish from FishBase. The reliability the FAO catch statistics is of some concern (for more details see FAO 2002; Pauly *et al.* 2002; Watson *et al.* 2004) and the lack of taxonomic resolution can be a problem when drawing general conclusions at a global scale (Watson *et al.* 2004). However, we have demonstrated global and regional trends towards fishing deeper in the oceans in spite of a large portion of the world's landings being assigned to broad categories. This is especially true for newly developed or undocumented fisheries as is the case of many deep-water demersal fisheries. As an example, the dropline fishery around the Madeira Islands for the deepwater black scabbardfish (*Aphanopus carbo*, Trichiuridae) is known to have operated since the early 19th century (Martins and Ferreira 1995), but the first official record of landings of this species is in 1986. As in this case, landing statistics may include a great proportion of deepwater species in broader categories, and because many deep-sea fishes are not very well known, the likelihood of having them aggregated in broader categories is higher when compared to well-known shallow coastal bottom fishes. Assigning catches to broad categories is often the case in tropical developing countries with strongly multispecies fisheries (Pauly *et al.* 1998b) and we did, in fact, find trends in the tropics less evident. In both cases we believe that, if better taxonomic resolution were to be available, the effect would be stronger because more deepwater fish species would be taken into account.

We used the average depth range of fish distribution as an indicator of fishing depths because fisheries will mainly operate at depths where higher abundances of target species occur. Although this is probably not true for non-target species and by-catch, we do not think it unduly affected the analysis because: (i) the proportion of non-target landings is smaller and thus will not have a significant effect on the general trends; or, (ii) by-catch species are not generally reported in FAO statistics.

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References

Alverson, D.L., Pruter, A.T. and Ronholt, L.L. (1964) *A Study of Demersal Fishes and Fisheries of the Northeastern Pacific Ocean*. H. R. MacMillan Lectures in Fisheries, Institute of Fisheries, University of British Columbia, 190 pp.

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J. and Doherty, P.A. (2003) Collapse and conservation of shark populations in the Northwest Atlantic. *Science* **299**, 389–392.

Boyer, D.C., Kirchner, C.H., McAllister, M.K., Staby, A. and Staalesen, B.I. (2001) The orange roughy fishery of Namibia: Lessons to be learned about managing a developing fishery. *South African Journal of Marine Science* **23**, 205–221.

Caddy, J.F. (1993) Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in Fisheries Science* **1**, 57–95.

Casey, J.M. and Myers, R.A. (1998) Near extinction of a large, widely distributed fish. *Science* **281**, 690–692.

Catarci, C. (2004) *World Markets and Industry of Selected Commercially Exploited Aquatic Species with an International Conservation Profile*. FAO Fisheries Circular 990, 186 pp.

CCAMLR (2004) *Schedule of Conservation Measures in Force 2004/05*. CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources), Hobart, 162 pp.

Cheung, W.W.L., Pitcher, T.J. and Pauly, D. (2005) A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biological Conservation* **124**, 97–111.

Christensen, V., Guénette, S., Heymans, J.J., Walters, C.J., Watson, R., Zeller, D. and Pauly, D. (2003) Hundred-year decline of North Atlantic predatory fishes. *Fish and Fisheries* **4**, 1–24.

Clark, M. (2001) Are deepwater fisheries sustainable? The example of orange roughy (*Hoplostethus atlanticus*) in New Zealand. *Fisheries Research* **51**, 123–135.

Constable, A.J., de le Mare, W.K., Agnew, D.J., Everson, I. and Miller, D. (2000) Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES Journal of Marine Science* **57**, 778–791.

Dulvy, N.K., Sadovy, Y. and Reynolds, J.D. (2003) Extinction vulnerability in marine populations. *Fish and Fisheries* **4**, 25–64.

Dulvy, N.K., Ellis, J.R., Goodwin, N.B., Grant, A., Reynolds, J.D. and Jennings, S. (2004) Methods of assessing extinction risk in marine fishes. *Fish and Fisheries* **5**, 255–276.

Food and Agriculture Organization (FAO) (2004) *The State of World Fisheries and Aquaculture*. FAO Fisheries Department, Rome, 153 pp.

FAO (2002) *The State of World Fisheries and Aquaculture*. FAO Fisheries Department, Rome, 150 pp.

Froese, R. and Pauly, D. (eds) (2004) *FishBase*. World Wide Web electronic publication http://www.fishbase.org, version 16 February 2004.

Garibaldi, L. and Limongelli, L. (2003) *Trends in Oceanic Captures and Clustering of Large Marine Ecosystems: Two Studies Based on the FAO Capture Database*. FAO Fisheries Technical Paper No. 435, Rome, 71 pp.

Gianni, M. (2004) *High Seas Bottom Trawl Fisheries and Their Impacts on the Biodiversity of Vulnerable Deep-Sea Ecosystems*. IUCN, Gland, Switzerland, 90 pp.

Gréboval, D. (2003) The measurement and monitoring of fishing capacity: introduction and major considerations. In: *Measuring Capacity in Fisheries* (eds S. Pascoe and D. Gréboval), FAO Fisheries Technical Paper 445, Rome, pp. 113–119.

Hilborn, R. and Mangel, M. (1997) *The Ecological Detective: Confronting Models with Data*. Monographs in Population Biology 28, Princeton University Press, Princeton.

Hilborn, R., Branch, T.A., Ernst, B., Magnusson, A., Minte-Vera, C.V., Scheuerel, M.D. and Valero, J.L. (2003) State of the world's fisheries. *Annual Review of Environment and Resources* **28**, 15.01–15.40.

Hintze, J.L. (1998) *User's Guide. NCSS 2000 Statistical System for Windows*. Number Cruncher Statistical Systems, Kaysville, Utah.

Hopper, A.G. (ed) (1995) *Deep-Water Fisheries of the North Atlantic Oceanic Slope*. Kluwer Academic Press, Dordrecht.

Jackson, J.B.C., Kirby, M.X., Berger, W.H. et al. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**, 629–638.

Jennings, S., Reynolds, J.D. and Mills, S.C. (1998) Life history correlates of responses to fisheries exploitation. *Proceedings of the Royal Society of London: Biological Science* **265**, 333–339.

Kock, K.-H. (1992) *Antarctic Fish and Fisheries*. Cambridge University Press, Cambridge, U.K.

Koslow, J.A., Boehlert, G.W., Gordon, J.D.M., Haedrich, R.L., Lorance, P. and Parin, N. (2000) Continental slope and deep-sea fisheries: implications for a fragile ecosystem. *ICES Journal of Marine Science* **57**, 548–557.

Large, P.A., Hammer, C., Bergstad, O.A., Gordon, J.D.M. and Lorance, P. (2003) Deep-water fisheries of the northeast Atlantic: II. Assessment and management approaches. *Journal of Northwest Atlantic Fishery Science* **31**, 151–163. http://journal.nafo.int/archive22–33/J31/session3/large.pdf.

Martins, R. and Ferreira, C. (1995) Line fishing for Black Scabbardfish (*Aphanopus carbo* Lowe, 1839) and other deep water species in the eastern mid-Atlantic to the north of Madeira. In: *Deep-Water Fisheries of the North Atlantic Oceanic Slope* (ed. A.G. Hooper), Kluwer Academic Publishers, Dordrecht, pp. 323–335.

Merrett, N.R. and Haedrich, R.L. (1997) *Deep-Sea Demersal Fish and Fisheries*. Chapman & Hall, London.

Moore, J.A. (1999) Deep-sea finfish fisheries: lessons from history. *Fisheries* **24**, 16–21.

Morato, T., Cheung, W.L. and Pitcher, T.J. (in press) Vulnerability of seamount fish to fishing: fuzzy analysis of life history attributes. *Journal of Fish Biology* **??**, ??.

Myers, R.A. and Worm, B. (2003) Rapid worldwide depletion of predatory fish communities. *Nature* **423**, 280–283.

Pandolfi, J.M., Bradbury, R.H., Sala, E. et al. (2003) Global trajectories of the long-term decline of coral reef ecosystems. *Science* **301**, 955–958.

Pauly, D. and Chua, T.E. (1988) The overfishing of marine resources: socioeconomic background in Southeast Asia. *AMBIO: a Journal of the Human Environment* **17**, 200–206.

Pauly, D. and Maclean, J. (2003) *In a Perfect Ocean: Fisheries and Ecosystems in the North Atlantic*. Island Press, Washington, D.C.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. and Torres, F. Jr (1998a) Fishing down marine food webs. *Science* **279**, 860–863.

Pauly, D., Froese, R. and Christensen, V. (1998b) Response to Caddy *et al*. How pervasive is ''fishing down marine food webs?''. *Science* **282**, 1384–1386.

Pauly, D., Christensen, V., Guénette, S. et al. (2002) Towards sustainability in world fisheries. *Nature* **418**, 689–695.

Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P. and Watson, R. (2003) The future for fisheries. *Science* **303**, 1359–1361.

Pitcher, T.J. (2001) Fisheries managed to rebuild ecosystems: reconstructing the past to salvage the future. *Ecological Applications* **11**, 601–617.

Pitcher, T.J. and Pauly, D. (1998) Rebuilding ecosystems, not sustainability, as the proper goal of fishery management. In: *Reinventing Fisheries Management* (eds T.J. Pitcher, P.J.B. Hart and D. Pauly), Fish and Fisheries Series 23, Kluwer Academic Press, Netherlands, pp. 311–329.

Roberts, C.M. (2002) Deep impact: the rising toll of fishing in the deep sea. *Trends in Ecology and Evolution* **17**, 242–245.

Sadovy, Y. and Cheung, W.L. (2003) Near extinction of a high fecund fish: the one that nearly got away. *Fish and Fisheries* **4**, 86–99.

Spotila, J.R., Reina, R.D., Steyermark, A.C., Plotkin, P.T. and Paladino, F.V. (2000) Pacific leatherback turtles face extinction. *Nature* **405**, 529–530.

Watson, R. and Pauly, D. (2001) Systematic distortion in world fisheries catch trends. *Nature* **414**, 534–536.

Watson, R., Kitchingman, A., Gelchu, A. and Pauly, D. (2004) Mapping global fisheries: sharpening our focus. *Fish and Fisheries* **5**, 168–177.

Zeller, D. and Pauly, D. (2005) Good news, bad news: global fisheries discards are declining, but so are total catches. *Fish and Fisheries* **6**, 156.