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Chapter 4
FISHING DOWN MARINE FOOD WEBS: AN UPDATE

Daniel Pauly
Fisheries Centre, University of British Columbia, 2204 Main Mall, Vancouver, B.C. Canada V6T 1Z4.

Maria Lourdes D. Palomares
Marine Biologist, International Center for Living Aquatic Resources Management (ICLARM), MC P.O. Box 2631, Makati 0718, Philippines.

ABSTRACT

One of the major ecosystem impacts of fishing is the selective extirpation of large, long-lived fishes and their replacement in the ecosystem and in fisheries catches by small, short-lived fishes and invertebrates. As large fish tend to be top-predators, feeding on smaller fishes while smaller fish and invertebrates feed on plankton and/or detritus, this process, recently shown to be operating globally, has been called "fishing down marine food webs."

Here, the demonstration is made that two potential sources of bias identified by critiques of the approach used to demonstrate this process in fact contribute to partly mask it; thus explicit consideration of these sources of bias shows the process to be stronger than initially thought. Some applications are briefly discussed.

INTRODUCTION

It is obvious that fishing must impact on the ecosystem within which the species are embedded that are targeted by fisheries. It is less obvious — though increasingly well demonstrated — that fisheries also impact the species they do not target, the by-catch, whether that by-catch is subsequently discarded or not (Alverson et al. 1994).

Even less obvious — at least to many fisheries managers is that fisheries also impact species they do not catch, either through habitat alterations (see Norse, this volume) or through appropriation of biological production (Pauly and Christensen 1995).

In fact, many of those who grant that fisheries may have such direct impact in specific cases suggest that the occurrence of such impact needs, in other specific cases, to be demonstrated before mitigating measures are taken. This implies that the burden of proof still is, in the case of any given fishery, upon those who argue that such indirect effects do occur. This attitude may have been justified until a few years ago — at least as far as species changes due to fishing are concerned — given that the change of species composition to be expected from fishing appeared to be largely unpredictable, and/or, mainly influenced by environmental conditions (Daan 1980; Skud 1982).

Thus, for example, the so-called "gadoid outburst," which occurred in the North Sea in the early 1960s, not only remained unexplained to date (in spite of valiant efforts by Cushing 1982), but also colored the perception of an entire generation of European scientists as to the unpredictable nature of species changes in marine ecosystems. Another case is the disappearance of sturgeons from most of their range. Thus, Silliman (1831) writes:

> Sturgeons were in great abundance [in the Hudson River] half a century ago. I saw forty-eight lie on the shore two years ago, at one time, (the shortest five feet, the longest nine feet), which were caught in the space of three hours; Mr. Adam told me, that this would have been considered but an ordinary case, even thirty years ago, and that they had been diminishing yearly, for more than fifty years.

It is all too easy to ignore such reports, and this is mainly done by labeling them as "anecdotes" (Pauly 1995). However, upon examination of a large number of cases, and when going sufficiently-back in time, a clear pattern does emerge: it is mainly large fish, that is, the top predators that disappear, leading to catches consisting predominantly of small fishes and of invertebrates, both groups originating from the lower part of food webs.

FOOD WEBS AND TROPHIC LEVELS

Food webs can be defined in terms of "trophic levels" (TL):

- algae, at the bottom of the food web have a TL of 1;
- herbivorous zooplankton, which feeds on microscopic algae, have a TL of 2;
- large zooplankton or small fishes that feed on herbivorous zooplankton have a TL of 3; etc. (Lindeman 1942; Odum and Heald 1975).

Large fishes (cod, tuna, groupers, etc.), usually have TL s between 3.5 and 4.5, because their food tends to be a mixture of low- and high-TL organisms. Thus, fisheries, when removing large fish tend to reduce the mean TL of the fish remaining in an ecosystem, which eventually leads to lower mean TLs in the catches extracted from that ecosystem (Pauly et al. 1998a).

The widespread nature of this process was demonstrated by combining existing global databases:

- the global database of fisheries catches created and maintained by the Food and Agriculture Organization of the United Nations (FAO), covering the years 1950 to 1997; and
- a global database of the TL estimates, derived from diet composition records in FishBase, the global information system on fishes (Froese and Pauly 1998 and see www.fishbase.org) and/or from food web models analyzed with the Ecopath software (Christensen and Pauly 1992, see www.ecopath.org), and of which a subset were shown to be very close to estimates using stable isotope analyses (Kline and Pauly 1998).

Fishing Down Marine Food Webs: Demonstration

From these databases, the mean TL in the catch — and hence in a straightforward manner in the ecosystem — of any area of the world can be computed. Pauly et al. (1998a), using this approach, were able to show declining trends of TL in many parts of the world, and for the world fisheries as a whole, a process they called "fishing down marine food webs." [They showed this

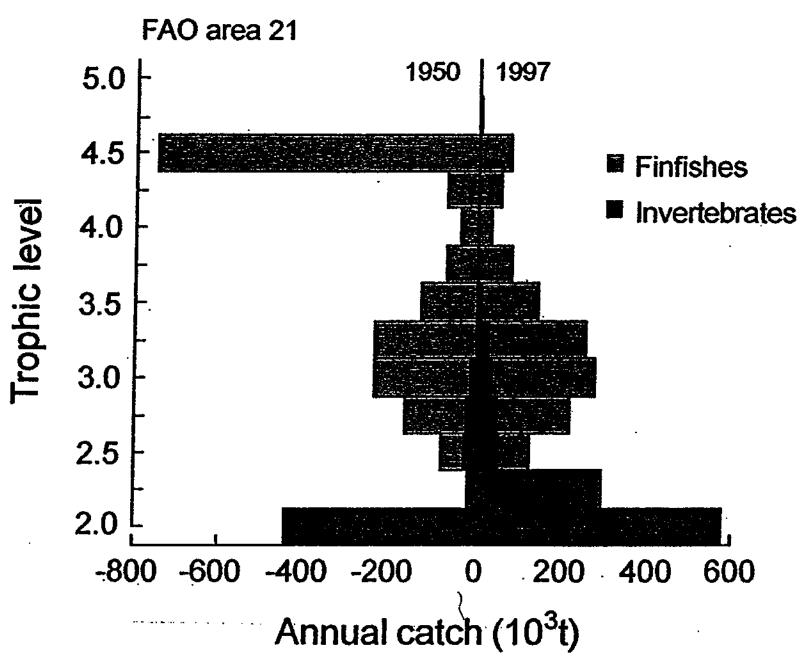

Figure 1. "Catch pyramids" for the Northwestern Atlantic (FAO Statistical Area 21), showing the TLs from which fisheries catches were taken in 1950 (left; mean TL = 3.79) and 1997 (right; mean TL = 3.28). Note collapse of high-TL species (i.e., mainly cod off Eastern Canada and USA) and their partial replacement by low-TL species, especially invertebrates.

process to also occur in freshwater fisheries, but did not follow up on this, as the FAO fisheries statistics include a sizeable amount of cultured fish.] Figures 1 and 2 illustrate this process for two areas with major concentration of fisheries scientists and managers. Figure 1 is a contrast between TLs in 1950 and 1997 in the Northwest Atlantic fisheries, i.e., of the East coast of the USA and Canada. Figure 2 documents "fishing down marine food webs" for the Northeastern Atlantic area, i.e., the waters around western and northern Europe, where detailed statistics and the absence of a single stock dominating all others (as did cod in the Northwestern Atlantic, or the anchoveta off Peru) shows this process in its clearest form. Thus, we shall limit most of our subsequent discussion to this case.

Trends such as that in Figure 2 are important because they are not based on a single fishery, from a single area, nor do they pertain to a single species, however widespread. Rather, Figure 2 summarizes thousands of data points representing catches per year, per species (groups) combined with species-specific estimates of TLs themselves based on hundreds of food habit studies. Thus, the quantitative trend that can be estimated from Figure 2, of 0.04 TL per decade is worrisome in spite of the slowness of the decline it implies, as it

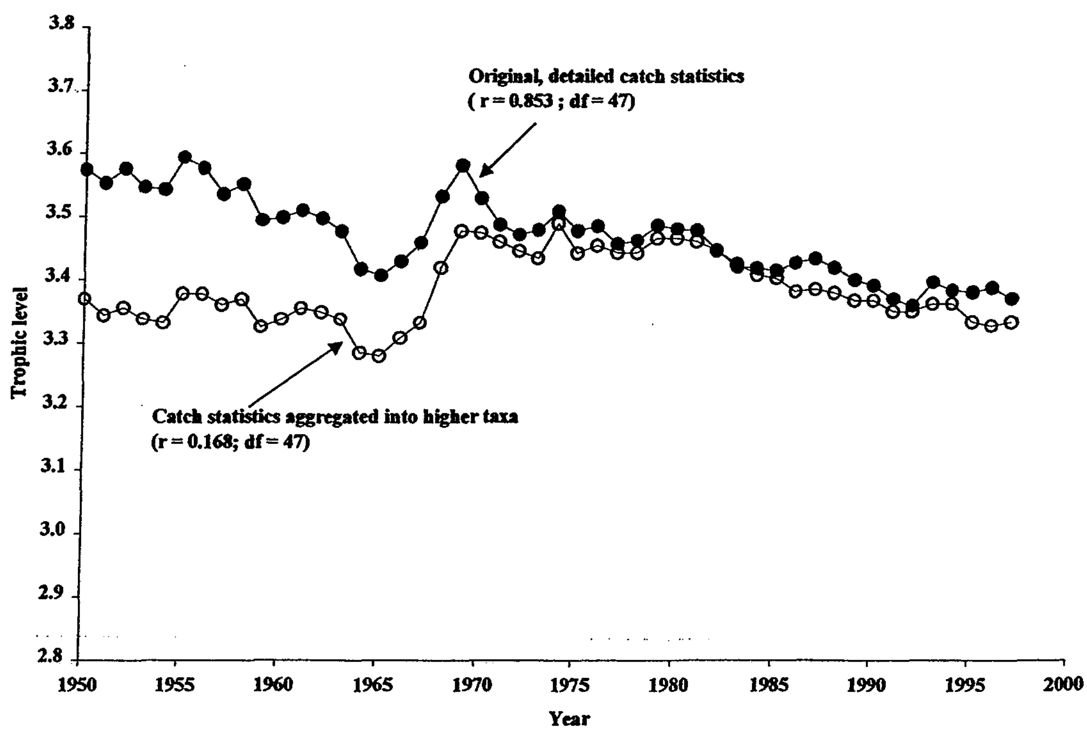

Figure 2. The full dots are time series of mean TL in the Northeastern Atlantic (FAO Area 27), illustrating a nearly pure form of fishing down marine levels. Calculated trend corresponds to 0.04 TL per decade but is an underestimate of the true trend (see text). The open dots represent the mean TL that would be obtained, were one to regroup the species, genera and families used for fisheries statistics in FAO Area 27 with larger taxa. Note absence of trend for these open dots.

indicates that the fisheries in question are unsustainable, despite what single-species assessments might say. This was well understood by journalists who upon publication of the article in which this and similar trends were presented (Pauly et al. 1998a) confronted the public with headlines such as: "Fishing Down the Food Chain is Catch 22" (*The New York Times*); "Global Collapse of Fishery Feared" (*The Vancouver Sun*), "The Rape of the Sea" (*New Scientist*), etc.

A Challenge and the Response

Thus, it was surprising that a number of FAO staff (Caddy et al. 1998) should object to our interpretation of the FAO data set, which, they suggested, is not good enough to support this kind of analysis. While they concede that "fishing down marine food webs" does happen throughout the world, they suggested this process cannot be demonstrated based on FAO catch data, because:

- the FAO catch time series are generally over-aggregated i.e., they do not include sufficient details at species level; and
- the TLs of fish change with fish growth, and this invalidates analyses based on the assumption that TLs are conservative properties of species.

Brief, preliminary responses were given to these and two other, related points in Pauly et al. (1998b). Here, we refute the claims in (1) and especially (2), leading to a re-evaluation of our previous estimate of 0.1 TL per decade as a global measure of "fishing down marine food webs."

The open dots of Figure 1 illustrate what happens if the relatively detailed FAO data for the Northeastern Atlantic are aggregated (prior to TL analysis) into extremely broad groupings ("pelagic fishes," "bottom fishes," "bony fishes," etc.) such as commonly done in low latitude areas (Table 1). As might be seen, such over-aggregation results in completely masking the "fishing down marine food web" effect.

Therefore, the effect of over-aggregation of statistical data is not to somehow generate a downward trend of TL when there is none, but on the contrary, to mask this effect when it occurs. Thus, given that there is independent evidence for "fishing down marine food web" effects (e.g., Christensen 1999) in low-latitude areas, where no TL trend appears when the overaggregated FAO data are analyzed, we can safely conclude, given Table 1, that the global estimate of 0.1 TL per decade is an underestimate.

Considering TL changes within species also leads to a similar conclusion. Figure 3 shows the relationship between TLs and size that can be established, for: (i) fishes that become piscivorous when adult; and (ii) fish that are zooplanktivorous as adults, or which feed on small detritivorous benthic organisms.

Table 1. Percentage of catches reported by FAO at different aggregation levels in the late 1980s, by FAO statistical areas arranged from North to South.

Latitude	FAO area (no.)	Species	Genus	Family	Higher taxa
High north	North West Atlantic (21)	88.1	8.4	0.2	3.3
	North East Atlantic (27)	83.3	10.1	3.5	3.1
	North East Pacific (67)	88.0	2.9	3.7	5.4
	North West Pacific (61)	68.6	4.9	5.0	21.5
	Mediterranean and Black Sea (37)	67.6	6.0	11.4	15.0
(Sub) Tropical	Central West Atlantic (31)	71.7	5.7	7.0	15.7
	Central East Atlantic (34)	62.8	15.5	9.5	12.2
Tropical	Central East Pacific (77)	70.2	6.9	9.7	13.2
	Central West Pacific (71)	9.9	22.2	4.8	63.0
(Sub) Tropical	Western Indian Ocean (51)	26.3	6.4	20.6	46.7
	Eastern Indian Ocean (57)	17.6	23.5	13.8	45.0
	Southern West Atlantic (41)	56.9	9.6	17.7	15.7
	Eastern West Atlantic (47)	72.1	22.3	2.0	3.7
	South East Pacific (87)	96.1	1.3	0.9	1.8
	South West Pacific (81)	72.6	6.5	12.2	8.8
Low South	Antarctic (48, 58, 88)	99.4	0.0	0.2	0.4

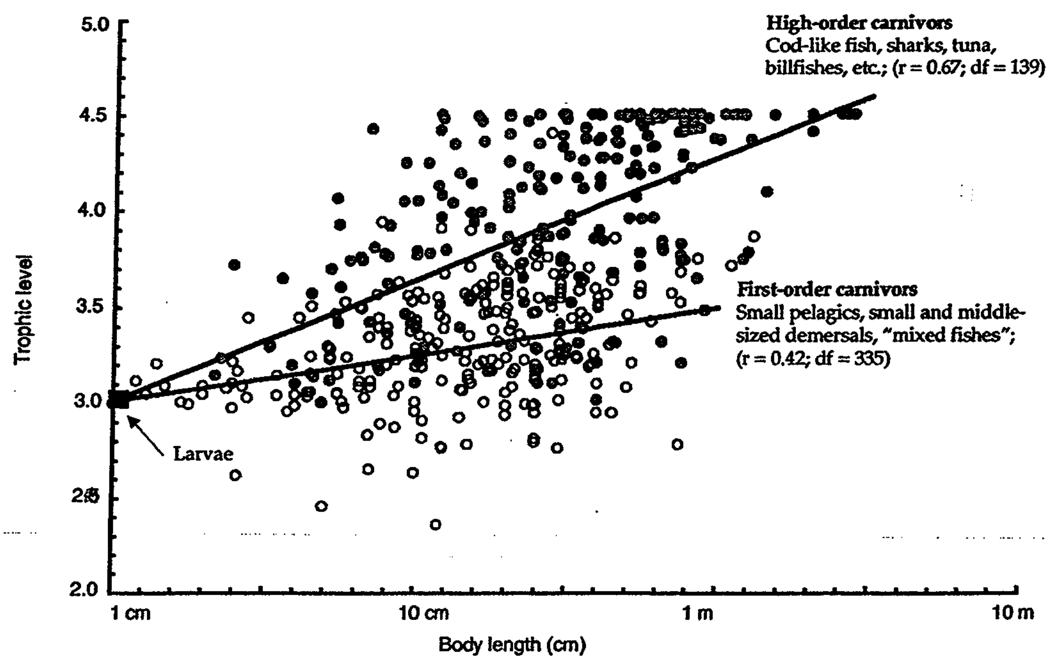

Figure 3. Relationship between TL and body length in the two groups (high-order carnivores and first-order carnivores) of fish contributing to the overwhelming bulk of fisheries catches in the Northeastern Atlantic. Based on data in FishBase (Froese and Pauly 1998).

Figure 4 shows the relationship between mean size (in % of maximum size, L_{max}) in fisheries catches and exploitation rate (E = fraction of fish killed by fishing gear over all deaths), as a function of the ratio of natural mortality to growth rate (M/K), and of length at first capture (L'), based on the Beverton and Holt theory of fishing (Beverton and Holt 1957; Pauly and Soriano 1986).

Unsurprisingly, mean size decreases with E, that is, with fishing mortality and thus with fishing effort as well. Combining Figures 3 and 4 leads to a nomogram which can be used to estimate the decline of TL *within species* that is due to increasing levels of exploitation. Applying this nomogram to evaluate the bias in trends such as in Figure 2 requires assumptions not only about present levels of E, but also about the transition from early levels of exploitation to the present, and about approximate values of L'. With World War II having largely closed important European fisheries (Beverton and Holt 1957), and destroyed much fishing capacity, overall fishing effort after the war was very small relative to the present, and fishing mortality was low relative to the biomass that had rebuilt during the war (Kurlansky 1997). Hence we shall assume E = 0.1 in 1950.

As for the present value, we can assume that E = 0.5, that is, that fishing mortality is about equal to the natural mortality in all stocks. This is a conservative assumption as fishing effort is known to be well above optimum in much of FAO Area 21, and E = 0.5 overestimates optimal fishing mortality, if anything (Beddington and Cooke 1981). Figure 5 shows the trend of TLs that

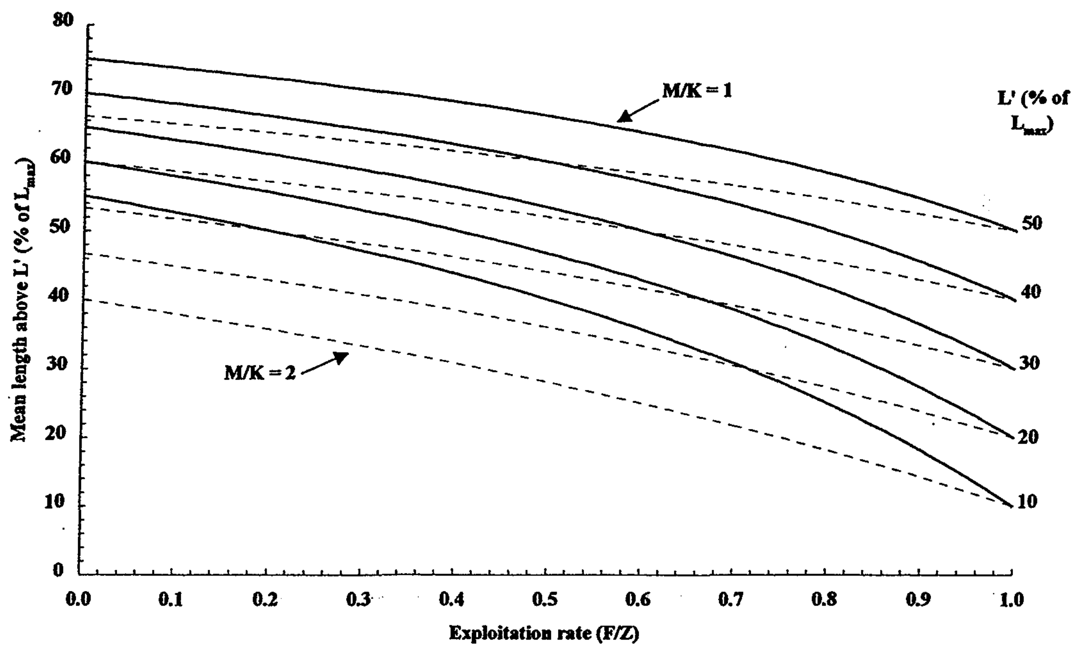

Figure 4. Decline of equilibrium mean length in fisheries catches (in % of maximum length) due to increase in exploitation rate (E) for two values of the ratio of natural mortality to growth rates (M/K) and ranges of size at first capture (L'), derived from

$$\bar{L} = \left[L_{max} + \left(\frac{(M/K)}{1-E} \cdot L'\right)\right] \Big/ \left[\frac{(M/K)}{1-E} + 1\right]$$ (Pauly & Soriano 1986; based on Beverton & Holt 1957).

results from combining Figure 4 with the data used to generate the original trend in Figure 2. As might be seen, the decline in TL that results from the reduction of mean size due to fishing, *increases* the rate of TL decline here by about 15%.

CONCLUSION

The main conclusion is that "fishing down marine food webs" appears to be a robust phenomenon, stronger and more widespread than originally thought. Its main implication is that, from an ecosystem view, most marine fisheries as presently operated are not sustainable, whatever meaning is given to this increasingly vacuous term (Frazier 1997). A long-term projection of the trend represented by "fishing down marine food webs" would imply the disappearance of large fish from marine ecosystems and increasingly the emergence of food webs dominated by invertebrates, including jellyfish. Indeed, there is scattered and anecdotal but increasingly worryisome evidence of jellyfish having recently become abundant on depleted fishing grounds. An example reported recently by the press (*National Post,* Canada, July 6, 1999) states that "jellyfish invade France" and that "Last month, fishermen refused to go to sea and demanded government compensation for the jellyfish invasion, which started in May. They say they are catching nothing but jellyfish."

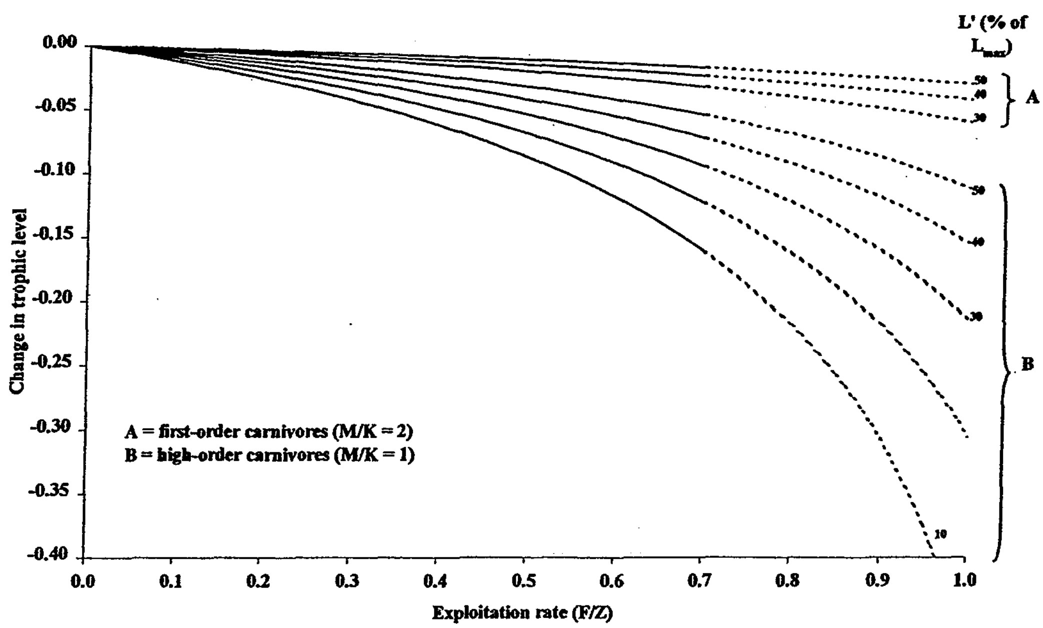

Figure 5. Nomogram representing the decline of TL due to an increase of exploitation rate, for two values of M/K and different lengths at first capture (L'), for first- and higher-order carnivores. The lines are dotted past E = 0.7, as such high values of E tend to be rare, optimum exploitation usually occurring when E = 0.5 (Beddington and Cooke 1981; Pauly and Soriano 1986).

Reversing the trend toward "fishing down marine food webs" trend will imply, globally, a massive change of the way fisheries are run. Technological "fixes," such as mariculture cannot become (given present feed technology and market conditions) a *net* source of marine fish products, as far more fish is consumed (in form of fish meal and oil) by fish in sea cages than is produced in these same sea cages (Tacon 1998). Thus, expecting aquaculture to somehow protect endangered wild fish is similar to expecting the poultry industry to protect avian biodiversity (and ignoring that aquaculture routinely does the equivalent of feeding chickens with imported, ground up songbirds).

Rather, large marine protected areas will have to be established for the most sensitive of the large marine fish species. Moreover, fishing effort will have to be drastically reduced in the remaining fished areas.

We are aware that such drastic actions (though required, as well, to reduce the massive environmental damage caused by bottom trawling – see Norse, this Volume) are presently impossible to implement. Thus, we will see more of "fishing down marine food webs."

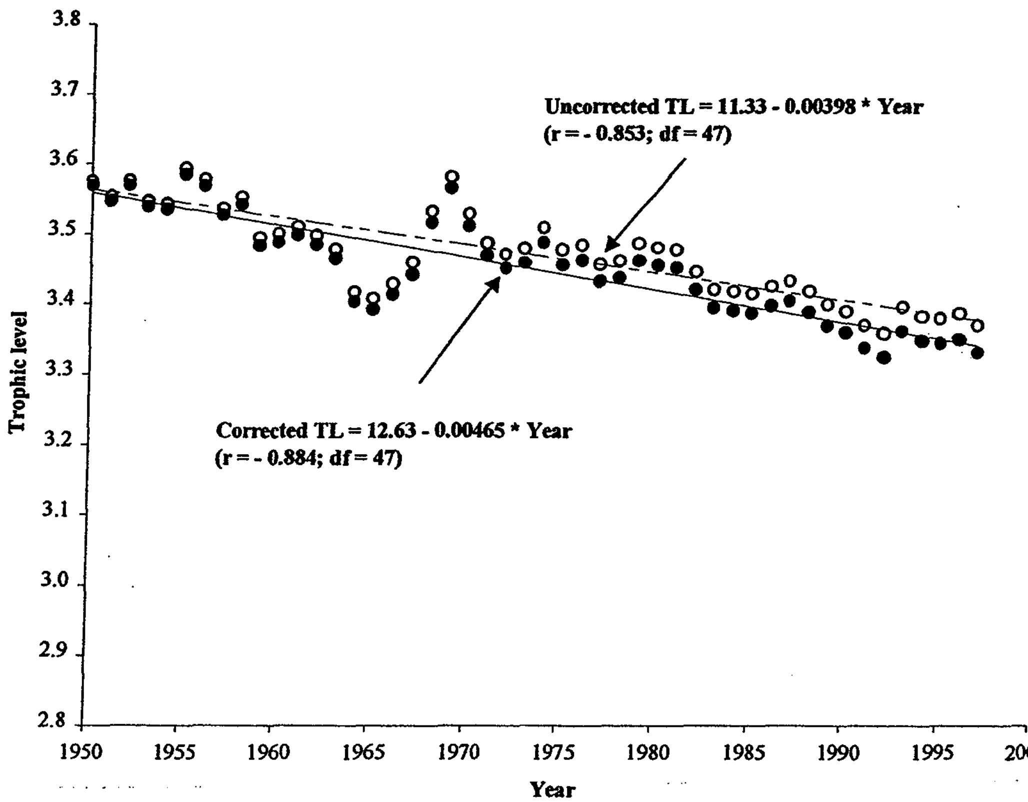

Figure 6. Trends of TL in the Northeastern Atlantic. Open dots: original values (see Figure 2). Filled dots: values corrected for the effect of declining size (and hence TL) within species, as implied by Figure 4. Further assumptions are $E_{1950} = 0.1$; $E_{1997} = 0.5$ and $L' = 40\%$ of L_{max} and M/K=2 for first-order carnivores and $L' = 20\%$ of L_{max} and M/K=1 for higher-order carnivores.Note increased downward slope from full (-0.00398) to open dots (0.00465), representing an increase of about 15%.

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