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Food security implications of global marine catch losses due to overfishing

U. Thara Srinivasan · William W. L. Cheung · Reg Watson · U. Rashid Sumaila

Abstract Excess fishing capacity and the growth in global demand for fishery products have made overfishing ubiquitous in the world's oceans. Here we describe the potential catch losses due to unsustainable fishing in all countries' exclusive economic zones (EEZs) and on the high seas over 1950–2004. To do so, we relied upon catch and price statistics from the *Sea Around Us* Project as well as an empirical relationship we derived from species stock assessments by the U.S. National Oceanic and Atmospheric Administration. In 2000 alone, estimated global catch losses amounted to 7–36% of the actual tonnage landed that year, resulting in a landed value loss of between \$6.4 and 36 billion (in 2004 constant US\$). From 1950–2004, 36–53% of commercial species in 55–66% of EEZs may have been overfished. Referring to a species-level database of intrinsic vulnerability (V) based on life-history traits, it appears that susceptible species were depleted quickly and serially, with the average V of potential catch losses declining at a similar rate to that of actual landings.

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The three continental regions to incur greatest losses by mass were Europe, North America, and Asia—forming a geographic progression in time. But low-income and small island nations, heavily dependent on marine resources for protein, were impacted most profoundly. Our analysis shows that without the inexorable march of overfishing, ~20 million people worldwide could have averted undernourishment in 2000. For the same year, total catch in the waters of low-income food deficit nations might have been up to 17% greater than the tonnage actually landed there. The situation may be worst for Africa, which in our analysis registered losses of about 9–49% of its actual catches by mass in year 2000, thus seriously threatening progress towards the UN Millennium Development Goals.

Keywords Catch loss · Food security · Undernourishment · Landed values

JEL Classification Q22 · D57

1 Introduction

Overfishing, the taking of more biomass from a marine population than the biomass can replace, plagues many of the world's fisheries (Grainger and Garcia 1996; Pauly et al. 1998; Froese and Kesner-Reyes 2002; MA 2005). Indeed, it has been recognized as the foremost force in the global degradation of coastal ecosystems (Jackson et al. 2001; MA 2005). In a recent study, the World Bank and the United Nations' Food and Agriculture Organization estimated that excess fishing may cost the world roughly $50 billion a year in *net* economic losses—value the world could potentially recoup by scaling back fishing efforts, and allowing rebuilding of depleted marine resources so that sustainably higher catches can be obtained in the future at higher population levels (World Bank & FAO 2009). In the case of the U.S., Sumaila and Suatoni (2006) showed that the net present value (NPV) of 17 stocks that have implemented rebuilding plans is estimated to be three times higher than the NPV of the same stocks if they are not rebuilt, but continue to be fished at current levels. By failing to safeguard the world's ocean ecosystems, humankind is losing not only revenue from fisheries but also long-relied upon sources of nourishment and employment. Through overexploitation of targeted species and the disruption of food webs (Pauly et al. 1998; Jackson et al. 2001; Pauly et al. 2002), we are losing biodiversity and injuring marine ecosystem services (MA 2005; Worm et al. 2006). In the twentieth century, fishing has driven several marine species to local extinction (Dulvy et al. 2003; MA 2005), and many marine fish on the IUCN's Red List of Threatened Species (http://www.iucnredlist.org/) are jeopardized by overfishing (Dulvy et al. 2003), yet certain marine species well known to be endangered by commerce are not yet covered under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (CITES 2010; FAO 2010).

The period from the latter half of the twentieth century to the present is probably the most crucial stage in humankind's fishing history (Grainger and Garcia 1996; Pauly et al. 2002; Myers and Worm 2003; MA 2005; Lotze et al. 2006; Worm et al. 2006). By 1950, species groups worldwide were already exhibiting significant declines in abundance (Myers and Worm 2003; Lotze et al. 2006). Applying a prehistoric baseline to 12 coastal and estuarine ecosystems, Lotze et al. (2006) estimated that by 1950, the relative abundance of bottom-dwelling fish had fallen by ~40%, compared to a ~25% loss for pelagic species, and ~80% for oysters. Due to massive exploitation of a virgin stock, catches of the American cupped oyster (*Crassostrea virginica*), for instance, plunged from ~600,000 tonnes from the Chesapeake Bay in 1884 (Jackson et al. 2001) to ~230,000 tonnes from the whole Northeast U.S. continental shelf in 1950 (www.seaaroundus.org). In the latter marine area, the onset of industrial fishing around 1950 reduced landings of the species by more than a factor of ten by 2000, an all-too-common pattern wherever post-World War II technology has been applied to catch fish (Pauly et al. 2002; Myers and Worm 2003).

Different classes of species bear different susceptibilities to overfishing. Demersal fish, which dwell in deeper water than pelagic ones, and are comparatively larger, longer-lived, and late to mature, are intrinsically more vulnerable to exploitation (Pauly et al. 1998; Jennings et al. 1999; Denney et al. 2002; Sadovy and Cheung 2003; Pauly et al. 2005). These, as well as large migratory fish that form dense schools, make up the "table fish" commonly known to consumers in the developed world: cod, tuna, and halibut, for example (Pauly et al. 2005; Garcia 2009). The collapse of Atlantic cod is an oft-cited caution to overfishing. Historically, the Northwest Atlantic supported vast stocks, which, despite massive reductions in fishing pressure and moratoria in some fisheries (MA 2005) but continued high pressure in others (Hilborn and Litzinger 2009), have yet to recover; fishing currently targets cod's former prey (Myers and Worm 2003; MA 2005). Similarly, fishing has decimated populations of tuna in the Atlantic and Pacific Oceans, partly due to the high prices these long-lived creatures, up to 800 kg in weight and 4.6 m in length (www.fishbase.org), attract in high-income markets (MA 2005; Black 2007). In general, the smaller pelagic species, which grow more rapidly and are exceedingly responsive to environmental fluctuations, are consumed directly or converted into fishmeal or fish oil. These lower-trophic-level fish can withstand heavier exploitation, to a point—unrelenting pressure drove both Peruvian anchovy (*Engraulis ringens*) and North Sea herring (*Clupea harengus harengus*) to crash in the 1970s (Bjørndal 1988; Pauly et al. 2002; MA 2005). In many cases of swift collapse, including those of Peruvian anchovy and Canadian cod, overexploitation served to magnify the intrinsic vulnerability of species to natural variation in ecosystem pressures, such as unfavorable climate conditions and increased predation (Pauly et al. 2002; Hilborn and Litzinger 2009).

Much energy has been spent estimating the maximum sustainable catch that could be wrested from the world's oceans (Pauly 1996)—100 million tonnes, perhaps (Gulland 1971), which we have yet, if ever, to reach with reported landings (www.seaaroundus.org), but may have surpassed if artisanal, discarded, and illegal, unregulated and unreported (IUU) catches were included. Considerably less effort has been devoted to quantifying the debt the world has accumulated due to overfishing. By species and by continent or country, what are the potential losses incurred by unsustainable fishing? Grainger (1999) arrived at an estimate by subtracting then-current catches from time-smoothed peak landings for 16 marine areas. The resulting loss was considerable: $8–16 billion, or ~9–18% of actual gross revenues (landed values) in the study year.

To create a global picture of overfishing with sufficient detail at the country-level, it is not possible to rely solely on scientific stock assessments, which are focused mostly in developed-country waters and are thus relatively sparse with respect to species and geographic coverage (Grainger and Garcia 1996). Instead, we analyzed a set of stock assessments, deriving an empirical relationship between predicted maximum sustainable yield (MSY) and the maximum catch recorded, which we then applied to catch time series from the *Sea Around Us* Project (SAUP) database (www.seaaroundus.org) for 1,066 species of fishes and invertebrates caught in 301 exclusive economic zones (EEZs) and the high seas over 1950–2004.[1]

Of course, there are many reasons besides depletion why a species' reported landings in an EEZ might decline, including changes in fishing effort in view of market forces or quotas; changes in species distribution across EEZ boundaries; and natural cyclical fluctuations in populations due to climate forcing or other reasons (Grainger and Garcia 1996; Klyashtorin 2001; de Mutsert et al. 2008). Moreover, reported catch represents only one aspect of real fishing mortality. IUU catch, discarded bycatch, and "ghost" catch caused by fisheries' discarded or lost gear also contribute significantly (Alverson et al. 1994; Kelleher 2005; Pramod et al. 2008; Agnew et al. 2009).

Fishing effort has been variable as well. Although by 2001, the number of new large vessels being built may have fallen back to 1950s levels (Garcia and Grainger 2005), the fishing power of individual vessels has continued to rise due to technological advances. According to one study, from 1970 to 1989, global fishing effort increased by 332%, while a global abundance index declined by 62% (Garcia and Newton 1997). Since the mid-1980s, despite the likelihood of sustained growth in real fishing effort (MA 2005), reported global catch has been on a plateau (www.seaaroundus.org) and real catch may have stagnated as well (Kelleher 2005; Agnew et al. 2009). If a similar situation exists for individual stocks, more recent catch reductions may signal steeper declines in underlying abundance than such patterns seen previously. In any case, without systematic global databases of either species biomass or fishing effort, patterns in reported catches remain our best indicator of stock health across the board, with "declining catches…an indication of declining stocks" (Froese et al. 2009). Comparing trends in biomass from stock assessments with catches for three focal regions, Worm et al. (2009) showed that for demersal species, the biomass patterns of overall stability or severe decline were also reflected in catch trends.

In this study, we aimed to: (i) determine when species-EEZ combinations may have begun to be overfished over 1950–2004; (ii) determine MSY levels[2] for these species-EEZ pairs; and (iii) put our results in the context of food security by comparing the losses of food-deficit countries to their levels of undernourishment. This third objective conforms with recent literature on poverty alleviation and pro-poor fisheries management in developing countries (Béné et al. 2010).

[1] The spatial allocation method applied by the SAUP to FAO data has performed well in independent tests, for example by Gascuel et al. (2007) for Mauritania.

[2] Estimating maximum economic yield (MEY) instead is not possible given the current unavailability of biomass, fishing, and cost data at the EEZ-level worldwide. Besides, recent work suggests that the difference between MEY and MSY may not be great in practice (Sumaila and Hannesson in press).

To achieve these objectives, we first analyzed catch time-series from the SAUP database for patterns of peak-and-decline. Next, we devised a general MSY formula by analyzing a set of published stock assessments and deriving a relationship between the assessment MSYs and the average maximum catches recorded for those stocks. This enabled the calculation of potential catch losses by mass, which we converted to dollar terms using SAUP's country-level price data.

2 Methods

2.1 Identification of overfished species-EEZ pairs

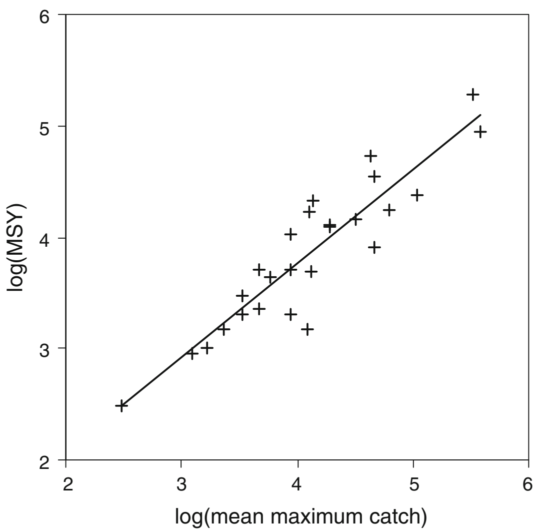
Starting with catch time series obtained from the SAUP database (www.seaaroundus.org), we first smoothed the data using 5-year running means where possible and 3-year means for the second and penultimate years in each series, leaving the first and last years of catch data as-is. Next, we analyzed the smoothed catch time series in order to identify when overfishing of species-EEZs pairs may have begun according to three different criteria based on normalized catch. For each species-EEZ pair, catch volumes were normalized by the maximum catch recorded for the series, with a series considered for analysis only if data existed for at least 10 years following the year for which the maximum catch was recorded. According to our lower-bound criteria intended to reduce the risk of false alarm, a species-EEZ stock was flagged as overfished if, subsequent to the year of maximum catch, its normalized catch $\underline{C}$ fell to ≤ 0.25 for either a consecutive succession of at least 10-year or 15-year in total by the year 2004 (Srinivasan et al. 2008). For the mid-level and upper bound criteria, thresholds of $\underline{C} = 0.50$ and 0.75, were used, respectively, with the latter setting meant as precautionary (i.e. reducing the risk of overlooking the onset of overfishing). The mid-level setting was based on the criterion of Froese and Kesner-Reyes (2002), by which a species was arbitrarily classified as overfished if its global catch fell below 50% of its maximum value (when catch declined below 10%, a species stock was considered collapsed). A sample calculation for Atlantic bluefin tuna (*Thunnus thynnus*) in US waters is given in Supplementary Material.

2.2 Computing catch losses due to overfishing

In theory, the maximum sustainable yield (MSY) of a fish stock is the highest average catch that can be removed at a continuous rate from the resource while still preserving its complete sustainability (Hilborn and Walters 1992). For each species-EEZ pair deemed to have been overfished over 1950–2004, we estimated MSY levels based on an empirical relationship we developed from species stock assessments and catch time series from the U.S. National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center (NEFSC 2010). For 26 stocks covering 19 species in 6 geographical areas off the northeast coast of the United States[3], we compared

[3] Stock assessments by the NEFSC undergo peer review by the Northeast Regional Stock Assessment Workshop process or the Transboundary Resources Assessment Committee (TRAC) (NEFSC 2010).

Fig. 1 Empirical relationship between stock-assessment-based MSY levels and maximum reported catch, using data from the U.S. National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center. The linear regression is as follows: $\log y = 0.8458 \cdot \log x + 0.3777$ (N=26, $R^2 = 0.84$, $p<0.001$)



the stock-assessment MSY with the maximum landings observed over 1940–2004, first smoothing the catch time series using 5-year running means as before. As the distribution of MSY levels appears to follow exponential distribution, we log-transformed both MSY and maximum catch, revealing a robust relationship between the two variables (Fig. 1). We then applied this linear regression to predict MSY from maximum catch for each species-EEZ stock classified as overfished over our study period. To calculate lower and upper bound MSY levels, we used the 50% prediction interval of the regression, choosing 50% rather than 90% or higher in order to avoid unrealistically large variation in the ratio of MSY-to-maximum catch predicted by the empirical power-law relationship. As a conservative measure, we capped the upper-bound MSY prediction for each stock by the maximum catch level observed; this was only a concern for low-volume stocks.

Potential catch losses L (tonnes) were then tallied for each overfished species-EEZ pair i for all years t subsequent to the year of maximum catch in which the estimated MSY was greater than the recorded catch C_t. Let L_{it}, the loss in catch of species-EEZ pair i in year t, be defined by the equation:

$$L_{it} = MSY - C_{it}. \tag{1}$$

The sum of catch loss in year t is then given by:

$$L_t = \sum_i L_{it}. \tag{2}$$

Finally, the total catch loss over the period from 1950 to 2004 is given by the expression:

$$L_{1950-2004} = \sum_{\substack{t > t_{\max catch} \\ t = t_{MSY} > c_t}} L_{it}. \tag{3}$$

See Supplementary Material for a sample calculation of lost catch for Atlantic bluefin tuna in US waters.

To provide a picture of the potential gross revenues lost due to overfishing, we obtained price information from the SAUP database (www.seaaroundus.org, Sumaila et al. 2007) and applied it to the estimated global catch losses for the year 2000.

In order to discern trends in the potential catch losses with respect to species' intrinsic susceptibility to fishing pressure, we employed a vulnerability index (Cheung et al. 2005) available from FishBase (www.fishbase.org). This indicator has been validated for fish species against the IUCN's threatened species list as well as population trends of North Sea demersal fish and exploited species in the northern South China Sea (Cheung et al. 2005). It integrates several key life history and ecological characteristics of marine organisms: maximum length, age at first maturity, the von Bertalanffy growth rate parameter K, natural mortality rate, maximum age, fecundity, geographic range, and strength of spatial behavior (representing a species' aggregation in feeding, spawning, migration, etc.). The resulting index V ranges from 1 to 100, with 100 as the most vulnerable. V values were available for all fish species tagged here as overfished. For 72 of 99 invertebrate species not in the database, we used genus-level values, applying the mean V for all invertebrates in the database (15 ± 0.19 SE) to the remaining species. Considering both actual and lost catches over the period, we assessed trends in the mean catch-weighted V, separating results for demersal and pelagic species.

2.3 Comparing to undernourishment levels

Catch losses (year 2000) were compared to country-level statistics on the prevalence of undernourishment (2003–2005) from the FAO's Statistics Division (http://www.fao.org/faostat/foodsecurity/index_en.htm). In addition, we converted the estimated year 2000 catch losses into potential food energy, assuming an energy content of ~120 kcal per 100 g of marine landings. Dividing the lost food energy by the FAO's 2003–2005 estimates of the dietary deficits (kcal/person-day) of undernourished populations by country allowed us to estimate the number of people in each food-deficit country for whom sustainable fishing might have alleviated hunger. Assuming marine landings to be 15–20% protein by weight (FAO 2005), we also compared the potential protein losses to FAO country data on actual protein consumption (g/person-day).

3 Results and discussion

3.1 Overfished species-EEZ pairs

Starting with catch time-series data for a total of 11,804 species-EEZ stocks, we estimated 16–31% of stocks were overfished over 1950–2004, corresponding to 388–563 species across 167–200 EEZs, or 36–53% of commercial species in 55–66% of EEZs.

Similarly, the FAO estimated that 28% of stock groups were overexploited, depleted or recovering from depletion by 2007 (FAO 2009). Froese and Kesner-Reyes (2002) put 50% of exploited species as overfished, collapsed or closed by 1999—also within our range.

Over 1950–2004, the mean V of all species tagged as overfished by the mid-level setting ($V = 43 \pm 0.95\,\mathrm{SE}$) and that of all species covered in the catch dataset ($44 \pm 0.68\,\mathrm{SE}$) were similar (two-tailed Student's heteroscedastic t test, $p = 0.63$), meaning species at all points of the intrinsic vulnerability spectrum were overfished, though not equally by volume or evenly over time as we will see in Fig. 3. Of the 44 species in the SAUP database that were also listed in the IUCN Red List of Threatened Species (http://www.iucnredlist.org/) as vulnerable, endangered, or critically endangered, 18 were tagged as overfished under the mid-level criteria (e.g. Atlantic cod (*Gadus morhua*), basking shark (*Cetorhinus maximus*), bigeye tuna (*Thunnus obesus*), common whitefish (*Coregonus lavaretus*), *etc.*). Species widely recognized as overfished (Pauly et al. 2002; Baum et al. 2003; Myers and Worm 2003) were classified as overfished under all three of our criteria, including swordfish, several types of shark, cod, tuna, and marlin. Of the ten species that contributed most to global landings by quantity in 2006 (FAO 2009), nine appeared on our mid-level list, indicative of the intense fishing pressure on these species. That five are deepwater fish and four are small pelagics, however, underscores the breadth of the problem.

Certainly, our empirical approach to MSYs is at best indicative, as we applied a relationship derived from the well-established fisheries off the Northeastern U.S. to all fisheries at different development stages, ranging from undeveloped to collapsed. Indeed the ratio of catch to underlying biomass must range widely across the board. Nevertheless, to minimize the over-attribution of variable fishing effort and natural fluctuations to overfishing, we required the presence of depressed catch for an extended period following the year of maximum catch, avoiding de Mutsert and co-workers' criticism (de Mutsert et al. 2008) of the use of a yearly collapse criterion by Worm et al. (2006). For example, while overfishing contributed to the 1971–1972 crash of Peruvian anchovy (Pauly et al. 2002), the El Niño oscillation was also significant. Since catches remained depressed for more than a decade following the 1970 peak in Peru's EEZ, all three of our overfishing criteria were fulfilled. In Chilean waters, however, where overexploitation probably also contributed to lowered catches over 1972-1985, landings went on to peak in 1994, so that this species-EEZ pair was not classified as overfished by our methodology. Of course, with SAUP "stocks" defined with respect to EEZs, shifts of interbreeding populations across borders due to climatic or other factors are inevitable.

Given the broad scale of our assessment, we did not make case-by-case corrections for particular reductions in fishing effort due to the adoption of quotas or disturbances such as war (e.g. Sierra Leone, Liberia). Notably, distant-water landings as a percentage of overall marine catches dropped after 1970 for a confluence of reasons (e.g. adoption of EEZs, rising oil prices, declining Alaska pollock), and plummeted in the 1990s with the break-up of the former USSR and scale-back of its subsidized fleet (Grainger and Garcia 1996). The latter event, along with the adoption of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) mitigated fishing pressure on Antarctic stocks, for example, but striking declines of numerous species had already occurred by then (www.seaaroundus.org, Grainger and Garcia 1996; MA 2005; CCAMLR 2009).

3.2 Global catch losses due to overfishing

Turning now to catch and gross revenue losses derived using our estimated MSYs, that is, catches and values foregone by fishing beyond sustainable levels, Fig. 2a depicts the evolution of the losses for the three overfishing designations and the MSY regression. Using the mid-level scenario (50% overfishing criteria and MSYs from the regression), global losses grew ~0.25 million tonnes/yr after 1967 ($R^2 = 0.95$). Froese and coworkers observed a qualitatively similar rise in the percentage of collapsed stocks from 1970 onward (Froese and Kesner-Reyes 2002; Froese et al. 2009). The FAO (2009), on the other hand, estimated the share of 523 world fish stocks that was overexploited or worse more than tripled over 1974–1992, but has stabilized over the last 10–15 years.[4]

Estimated losses for the year 2000 alone—between \$6.4–36 billion in 2004 constant dollars, corresponding to 6–35% of the landed value reported for that year—are comparable to the \$8–16 billion range arrived at by Grainger (1999) using a much more aggregated approach. Ironically, our loss figures are of the same order of magnitude as the global subsidies that support excess fishing capacity annually, estimated in this issue at \$25–29 billion (Sumaila et al. in press) or previously at \$20–50 billion, the latter figure similar to annual global revenue (Christy 1997; MA 2005). By 1950, our baseline year due to data availability, the coastal waters of Northern countries, in particular, were already showing symptoms of serial overfishing (Jackson et al. 2001; Pauly et al. 2005). Thus, the losses reported here represent only the recent history, albeit a crucial period.

Applied to the large number of stocks in the SAUP database, our simple empirical approach for setting MSYs is likely to reveal robust trends. To some degree, the over- and underestimates in such large empirical datasets cancel each other (Pauly 1996). Of course, our estimates are intended indicatively rather than literally, as some stock declines may be irreversible and the extent to which environmental variation played a part is unknown. The serial depletion of stocks and changing composition of global catches (Pauly et al. 2005) means that lower-trophic-level species have experienced some release from predation and competition, allowing them to increase in abundance (Myers and Worm 2003). Because of this compensation, we must be careful in adding actual catches to those potentially lost to unsustainable fishing. Nonetheless, our approach is conservative. The MSY levels used here could not exceed actual landings, as can occur with theoretical approaches. Hence, our MSYs were likely underestimates for unexploited and still-developing fisheries, but as we focused on stocks with clear peak-and-decline patterns, this was not a main concern. Ideally with a global database of fishing effort, we could use catch rates as an index of biomass. With detailed trends

[4] It is difficult to gauge the effect of unreported landings such as discards and IUU catches on our final estimates of catch losses, as both factors may be neither constant nor correlated with reported catch over time.

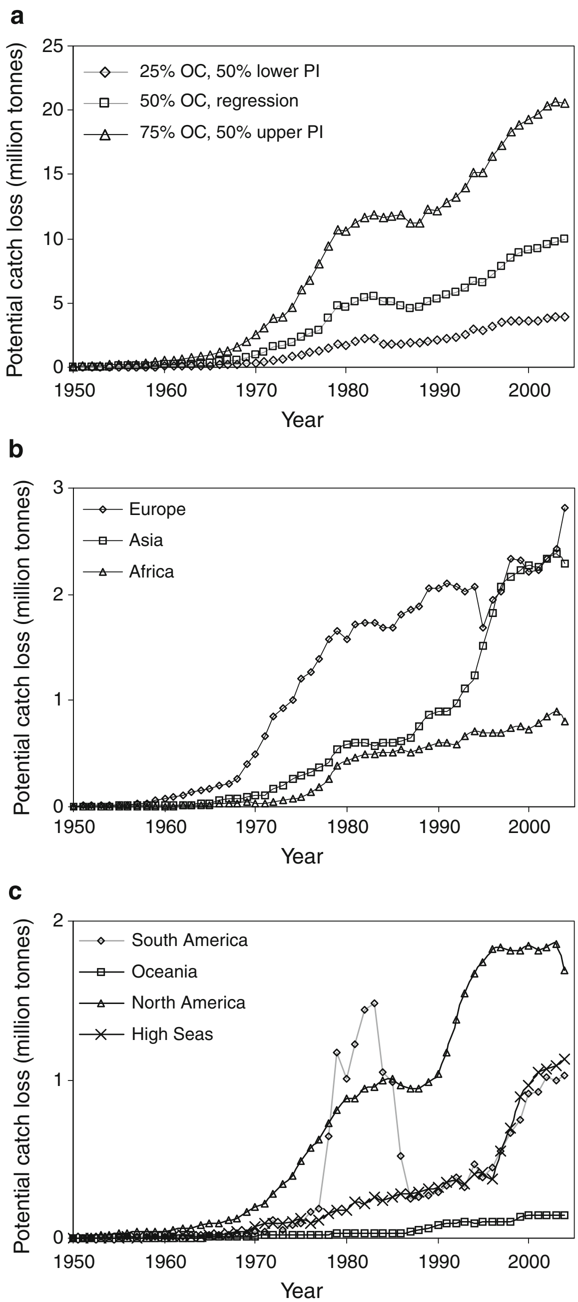


Fig. 2 **a** Potential catch losses by mass using the 25% overfishing criteria (OC) and 50% lower prediction interval (PI) of the MSY regression, the 50% OC and MSY regression, and 75% OC and 50% upper PI. **b, c** Catch loss estimates by mass for the six continental regions plus the high seas using the mid-level scenario (50% OC and MSY regression)

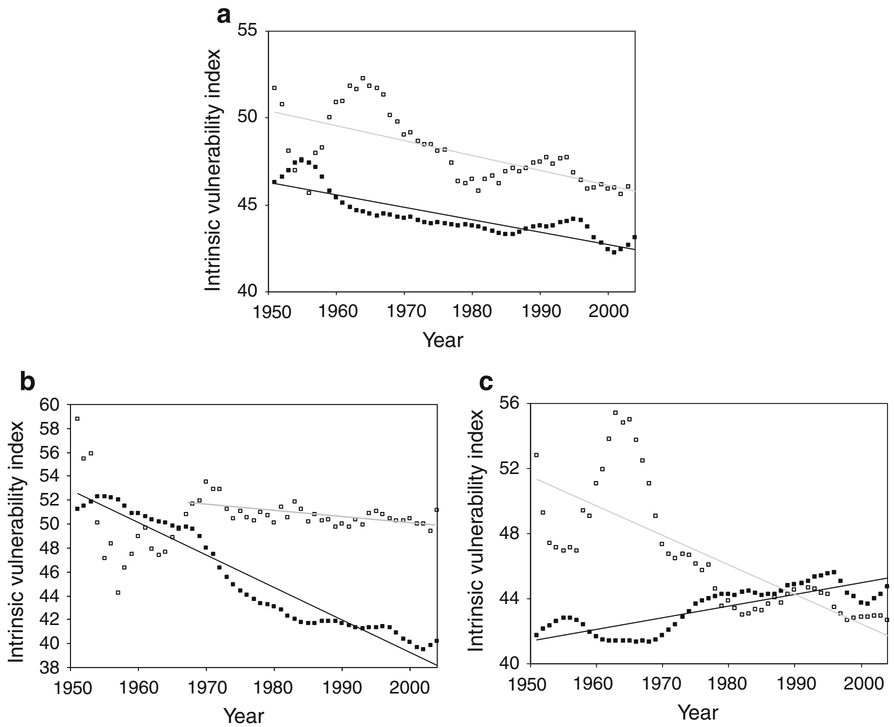


Fig. 3 Mean catch-weighted vulnerability index *V* over 1951–2004 for actual landings (*filled square, black line*) compared to mid-level scenario predictions of potential catch losses (*open square, gray line*) for **a** all species-EEZ pairs (actual catch: $y = -0.071x + 190$, $R^2 = 0.73$; catch losses: $y = -0.099x + 240$, $R^2 = 0.46$), **b** demersal species (actual catch: $y = -0.27x + 580$, $R^2 = 0.93$; catch losses, 1967–2000 only: $y = -0.048x + 150$, $R^2 = 0.36$), and **c** pelagic species (actual catch: $y = 0.071x - 96$, $R^2 = 0.66$; catch losses: $y = -0.18x + 400$, $R^2 = 0.58$). All p values < 0.001

in effort unknown, however, catch remains our best, although imperfect, indicator of stock levels—underestimating stock levels when effort is increasing but accurate when effort is constant. Gross overestimation is not likely as cases of drastic effort reduction on a large scale in the absence of a declining stock are very rare (Froese et al. 2009).

Considering actual landings reported at the species level for all fish and invertebrates, the global catch-weighted mean vulnerability, *V*, declined over 1950–2004[5] (Fig. 3a). For the potential catch losses, gauged here using the mid-level scenario, we found a similarly-sloped decline starting at a higher *V* (Fig. 3a). Results for demersal species (Fig. 3b) show a steeper reduction starting at higher mean *V* for actual landings, with a steady decline for catch losses after the late 1960s. In contrast, reported landings show that pelagic species of higher vulnerability (e.g. tuna, swordfish) have been exploited increasingly, with the dip between 1960–1970 due to the large volume of anchovy caught ($V = 39$) followed by fishery collapses through the 1980s. The pattern in the catch losses (Fig. 3c) is roughly the reverse: higher vulnerability values until

[5] As reported by Cheung et al. (2007) for fish species only.

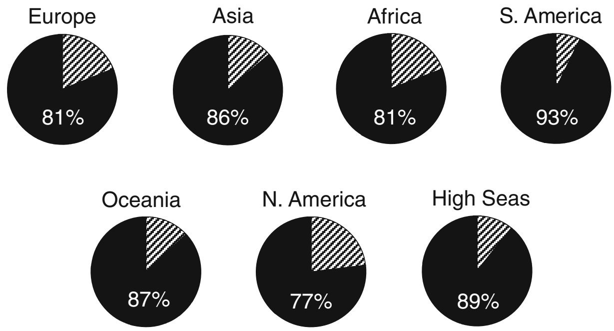


Fig. 4 Estimated catch loss (striped wedge) as a fraction of potential total catch (tonnes) for the year 2000 by region using the mid-level scenario of catch losses. For each region, the actual reported catch as a percentage of the potential total catch is indicated

1970, then stabilization at lower values until 2004, caused by the dominance of lost anchovy.

3.3 Catch losses by continent

Estimates of global lost tonnage separated into six continental regions and the high seas are shown in Fig. 2c, d. The mid-level scenario was used here and in the remainder of the analysis. Summing over the whole time period, the regions suffered losses from highest to lowest as follows: Europe, North America, Asia, South America, Africa, High Seas, and Oceania.

Given that European fisheries were already well-developed by 1950 (Grainger and Garcia 1996), it is not surprising that Europe was the first continental region to register significant losses, beginning in the late 1960s. For North America, losses have been climbing relatively steadily from 1970 to the mid-1990s, stabilizing recently perhaps due to better management (Beddington et al. 2007; Pitcher et al. 2009) but also because of rising imports, increasingly from Asia (FAO 2009). Asian losses, in turn, accelerated over the 1990s, reflecting the cumulative effect of dramatically increased fishing effort in the region over 1970–1990. While the rest of the world fleet appeared to stabilize from 1976 to 2000, the number of Asian fishing vessels more than doubled (MA 2005; FAO 2008). South America's losses, peaking in the late 1970s to the mid-1980s, were dominated by the dramatic crash of its anchovy fisheries, also apparent in the global pattern (Fig. 2a). For Africa, distant-water fleets played a major role in the steady increase in catch losses from the mid-1970s onwards (Alder and Sumaila 2004, MA 2005). In contrast, Oceania as a whole did not accumulate large debts to overfishing, although we estimated serious losses for several Pacific island states.

Figure 4 illustrates how each region's losses by weight compare to its actual landings for the year 2000. In these relative terms and considering a single year, North America lost the most tonnage to overexploitation, with Africa second, followed by Europe, Asia, Oceania, the high seas, and South America as last. Thus, the gradually-increasing trajectory for Africa in Fig. 2c belies the severe impact to the continent in relative terms.

3.4 Comparison to undernourishment levels

Table 1 lists country-level catch losses using the mid-level MSYs alongside FAO undernourishment levels for the 41 countries with both: (i) potential catch losses as a percentage of their actual catches in the year 2000, and (ii) undernourishment levels greater than 5%. For the 43 LIFDCs in our analysis, 26 of which are in Africa, catch losses by mass averaged $75 \pm 26\,(\mathrm{SE})$ % of the actual tonnage landed in each of their EEZs in 2000. Many island nations, where fish has long been a cultural staple, also suffered unduly. Devastating losses, 770 times the actual catches in 2000, have befallen Palau, whose citizens' diets are most dependent on fish (92 kg/year)[6]. Worldwide, had losses to overfishing been averted, perhaps 20 million people—12 million in China, Peru, Ecuador, Brazil, and Angola—may have averted malnutrition in 2000. For the same year, Namibia's citizens lost roughly the equivalent of the marine protein they actually consumed on average (FAO 2008).

Nonetheless, many of the top 40 exporters of marine products (FAO 2008)[7] are low-income countries with undernourishment levels >10%: Bangladesh (27%), Senegal (26%), India (21%), Panama (17%), Thailand (17%), Indonesia (17%), Philippines (16%), Ecuador (15%), and Viet Nam (14%). With ever greater emphasis on exports to mostly developed markets, many of these countries have made sacrifices regarding the availability of domestic supplies and the quality of imports (UNEP 2002; Alder and Sumaila 2004; Atta-Mills et al. 2004). The rise in imports by developing countries, consisting mostly of low-cost small pelagics, partly mitigates the risk to food security. Still, in 2006 developing countries accounted for 38% of imports by quantity (20% by value), with an increasing share of these imports destined for processing and re-export to developed countries. Of the top ten importers that year, China was the only non-high-income country (FAO 2009).

4 Conclusions

With roughly half of commercial marine species in half of the EEZs potentially overfished over the past half-century and losses mounting since the late 1960s, this study underscores the vital need to reduce fishing levels worldwide. A familiar pattern has repeated itself, world over: the rapid depletion of stocks coinciding with the onset of industrial exploitation (MA 2005). Over the study period, pressure on marine resources intensified sharply, nearly quintupling global landings while sweeping southward. China is now the largest producer and exporter of fish and fishery products (FAO 2009), and the food-deficit countries of Thailand and Viet Nam rank third and eighth in exports (FAO 2009). World fisheries are caught in a high-volume cycle: exports to rich countries (and China) fund lower-value imports to developing countries for consumption and processing purposes, the latter increasingly for re-export to the

[6] The outlook is likewise grim for the LIFDC Kiribati, where consumption is at 76 kg/yr, but the bulk of whose losses we did not count due to the recent decline in landings, mostly foreign.

[7] Export of marine products includes fish and fishery products as well as the processing of imports for re-export and aquaculture products.

Table 1 Undernourishment levels (source: FAO) compared to potential catch losses estimated using the mid-level overfishing criteria and MSY levels

Country	Prevalence (%) of undernourishment in total population, 2003–2005	Potential catch loss (tonnes) as % of actual tons caught, 2000	Percentage (%) dietary protein derived from seafood, 2003–2005
Democratic Rep. of Congo	76	320	7
Sierra Leone	47	9.0	16
Angola	46	120	9
Liberia	40	200	–
Mozambique	38	9.9	–
Togo	37	12	–
Tanzania	35	16	–
Djibouti	32	200	–
Kenya	32	7.9	–
Dem. People's Rep. of Korea	32	45	–
Guinea-Bissau	32	200	2
Gambia	30	15	14
Cambodia	26	45	14
Senegal	26	5.9	15
Pakistan	23	15	–
Rep. of the Congo	22	12	12
Grenada	22	450	16
Nicaragua	22	8.0	–
Sri Lanka	21	22	12
Dominican Rep.	21	10	5
Myanmar	19	6.2	9
Benin	19	22	5
Namibia	19	83	6
Guinea	17	24	7
Thailand	17	190	16
Guatemala	16	220	–
Philippines	16	10	18
Cape Verde	15	22	9
Ecuador	15	100	4
Gaza Strip[a]	15	55	–
Côte d'lvoire	14	8.7	9
Viet Nam	14	69	9
Georgia	13	180	–
Honduras	12	144	–
Venezuela	12	7.9	8
Colombia	10	7	–

Table 1 Continued

Country	Prevalence (%) of undernourishment in total population, 2003–2005	Potential catch loss (tonnes) as % of actual tons caught, 2000	Percentage (%) dietary protein derived from seafood, 2003–2005
El Salvador	10	46	2
Trinidad and Tobago	10	140	7
Mauritania	8	6	7
Brazil	6	26	–
China[a]	9	7	9

Note ([a]) that the catch loss value for the Gaza Strip is given alongside the undernourishment value for the Occupied Palestinian Territory. Similarly, the catch loss for mainland China is presented with the undernourishment value for China as a whole

developed world (FAO 2009). Yet with rising demand forecasted (FAO 2009), the coming century holds no clear refuge for global marine stocks. On the contrary, the ecosystem variation and shifts accompanying climate change will further stress stocks already weakened by overfishing (Dulvy and Allison 2009).

Many factors contributed to the estimated losses, including subsidies and overcapacity; rising demand and increasing access to global markets; poor monitoring and IUU fishing; and bycatch. Curbing fishing effort will allow vulnerable stocks to rebuild, wherever possible. Catch losses aside, the world could recoup $50 billion in profits annually from fishing through effort reduction alone (World Bank & FAO 2009). Pitcher et al. (2009) recommended making mandatory the voluntary FAO Code of Conduct for Responsible Fisheries published in 1995. They wrote, “The time has come for a new international legal instrument”— a call amply supported by our study. However, the costs of rebuilding are likely to be substantial. In a study of three North Atlantic fisheries, Arnason et al. (2000) found management costs to range from 3–25% of total gross revenues. Thus, the costs of implementing sustainable paths and the prospects for cost recovery by the fisheries sector must be discussed explicitly and receive greater attention. Trade-offs between socioeconomic and conservation goals impact the benefits and costs of management in both the short and long terms, with near-term unemployment a key obstacle to longer-term ecological and economic gains (Cheung and Sumaila 2008).

Increased fishing pressure and the expansion of fishing areas have masked losses to overfishing. Local losses are also hidden from end consumers by the huge trade flow in fishery products. Apparently, Chinese vessels operating illegally in West African waters carry EU hygiene permits, enabling exports to European seafood markets (EJF 2009). The true burden of catch losses, however, falls upon the world’s poorest, the subsistence and artisanal fishers who are losing access to an important source of cheap protein (MA 2005). To turn the tide, we need many remedies, implemented at once (Pauly 2009). Fisheries management must be strengthened by establishing or reestablishing requirements such as catch quotas and no-take zones; by improving monitoring capabilities using targeted aid to developing countries; by giving fishing communities incentives for good stewardship; and by providing sound, precautionary scientific analysis. As consumers we demand “the wrong kinds of fish and too many of them," while shifting preferences to smaller, less vulnerable species could benefit human health as well as that of fisheries (Dewailly and Rouja 2009). During the collapse of Atlantic cod, recommendations from stock assessments proved dangerously optimistic (Walters and Maguire 1996). Now, we cannot wait for detailed guidance from stock-by-stock assessments in order to change course, especially given the importance of fish as a source of animal protein in many undernourished countries of the world.

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