Global fishery development patterns are driven by profit but not trophic level

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Successful ocean management needs to consider not only fishing impacts but drivers of harvest. Consolidating post-1950 global catch and economic data, we assess which attributes of fisheries are good indicators for fishery development. Surprisingly, year of development and economic value are not correlated with fishery trophic levels. Instead, patterns emerge of profit-driven fishing for attributes related to costs and revenues. Post-1950 fisheries initially developed on shallow ranging species with large catch, high price, and big body size, and then expanded to less desirable species. Revenues expected from developed fisheries declined 95% from 1951 to 1999, and few high catch or valuable fishing opportunities remain. These results highlight the importance of economic attributes of species as leading indicators for harvest-related impacts in ocean ecosystems.

economic value | ecosystem management | food webs | global fisheries | indicators

A widely discussed interpretation of global fisheries development is that humans have preferentially fished high trophic level species, as evidenced by declining mean trophic level of catch since 1950. Under the "fishing down" explanation for this pattern (1), stocks high in food webs have been serially depleted through industrialized fishing. Essington et al. (2) propose instead that "fishing through" occurs by serially expanding into lower trophic level groups, while maintaining harvest high in food webs. Although the consequences of declining mean trophic level of catch are not fully understood, nonrandom harvest on food webs can lead to large ecosystem changes including trophic cascades (3, 4) or productivity shifts (5). Thus, mean trophic level of catch has been adopted as an indicator for the ecological impacts of fishing (6).

For successful fisheries management, it will be necessary to move beyond the symptoms of fishing and to take into account drivers of harvest pressure that result in potentially significant ecosystem change. One step in this direction is to incorporate leading indicators for current and future impacts of fishing into management. What motivates fishermen? Modern industrialized fishing is a business activity, and harvest decisions are made to attain profits: revenues net of fishing costs. We expect that good indicators for fishing pressure are related to economic costs and benefits. One explanation suggested for the evolution of global fisheries development and declining mean trophic level of catch is that organisms high in food webs are more valuable, making them preferentially targeted by commercial harvesters (2). If this hypothesis was correct, trophic level could be a leading indicator for fishing pressure under profit-driven harvest.

Using global data on catch (ref. 7; www.seaaroundus.org), ex-vessel price (8), and life history characteristics (9), we examine whether higher trophic level organisms are more valuable. We find that trophic level has little relation to economic opportunity or the pattern of commercial fishery development since 1950; however, the progression of fishing development demonstrates a clear pattern of profit-driven harvest, highlighting the importance of taxa attributes related to economic forces as leading indicators of fishing activity.

Results

We find no support for the hypothesis that globally fishing down or fishing through occurs because taxa higher in food webs are more valuable. Linear regression (Fig. 1 and Table S1) shows no statistically significant relationship between trophic level and indices of ex-vessel price or annual gross revenues (referred to as "revenues" from here on). On the contrary, if we divide fisheries into three groups, we find that the lowest trophic level assemblage containing shellfish and invertebrates has the highest mean price index, 25% higher than the assemblage containing top predators, and 45% higher than an intermediate group containing most pelagic taxa (one-way ANOVA, $P < 0.01$; Table S2). This result is more extreme when comparing trophic level groups in relation to the revenue index: The lowest trophic level assemblage has average annual revenues 39% higher than the top trophic level group and 99% higher than the intermediate group (one-way ANOVA, $P = 0.03$; Table S2). This pattern is not surprising given the high price of low trophic level taxa, such as shrimps and abalones, and the increase in stock biomass available for harvest when moving down food webs (10, 11). Our data show a disconnect between trophic level and economic drivers of fishing impacts, where at any given trophic level, a wide range of prices and revenues exist (Fig. 1).

Economic theory holds that producers make decisions based on profits (12, 13). We examined the global catch record in light of taxa attributes more directly related to revenue- and cost-side drivers of harvest and found patterns consistent with profit-driven fishery development. Taxa with higher potential profit are targeted first, followed by progressively less economically attractive alternatives.

In the absence of reliable fishing costs information, the depth at which fished taxa live provides a proxy for the costs of fishing, where presumably harvest of deeper organisms entails higher travel costs and fishing technology investment. When weighted by catch, the average depth range of fished taxa has increased 35% over the catch record, suggesting a preference for fishing lower cost taxa first, then moving to increasingly deeper ranging, costlier taxa (Fig. 2*A*). Catch density plots (Fig. 2*A Lower*) show that this trend is the result of expansion into deeper ranging taxa later in the catch record, i.e., a fishing through effect. These results are corroborated by depth trend analyses by using regional scale data (14) and hold across different metrics for taxa depth ranges (*Sensitivity Analyses* in *SI Materials and Methods*).

As indicators of per-unit profitability, we examined price and two metrics for size of fished organisms: maximum observed length and weight of each taxon. The assumed relationship be-

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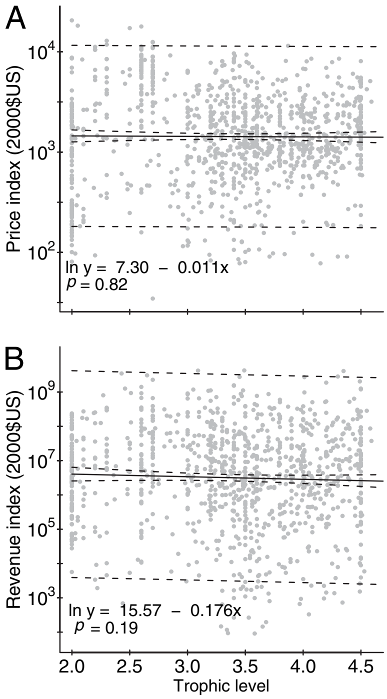

Fig. 1. Linear regression of trophic level against log transformed price index (*A*) and revenue index (*B*) for 1,040 taxa (dots). Regression lines are in black, inner and outer dashed lines correspond to 95% confidence and prediction bands, respectively. The *P* values for slope estimates account for heteroskedasticity. Plotted taxa represent 87% of total global catch 1950–2004.

tween size and economic desirability, where larger size is more profitable, is motivated by processing considerations. Smaller organisms tend to yield less finished product per unit biomass (Fig. S2) and may require higher capital and labor inputs to process large volumes of low-value final product. Additionally, larger organisms allow for a wider range of higher valued final products, such as fillets (*Organism Size and Profitability* in *SI Materials and Methods*). We find similar patterns of moving from better to lesser opportunities for these size proxies for economic desirability. Catch-weighted mean length and weight metrics declined by 25% and 45%, respectively (Fig. 2 *B* and *C*), as a result of expansion into smaller-sized taxa through time, and not the serial depletion of larger taxa. There is no clear time pattern in the catch-weighted mean price in global landings although, again, we see evidence of fishing through expansion of catches at lower prices (Fig. 2*D*). Weighted average metrics can be dominated by large-catch taxa; however, these trends are robust to the exclusion of high biomass pelagic stocks, such as anchovies and pilchards (*Sensitivity Analyses* in *SI Materials and Methods*).

The time pattern of decisions to develop ocean resources reveals preferences for taxa attributes and further emphasizes the role of revenue and cost drivers behind global fishing impacts. We constructed a global development chronology since 1950 by considering a fishery to be developed in the year in which annual harvest first reached 25% of the maximum observed annual harvest and then examined how the year of development was related to trophic level, revenue, and cost attributes of fished taxa.

No obvious preference based on trophic level is apparent in the time pattern of developments, which shows no trend in fishing sequentially down food webs, but of developing across all trophic levels (Fig. 3*A*); however, the data highlight the impor-

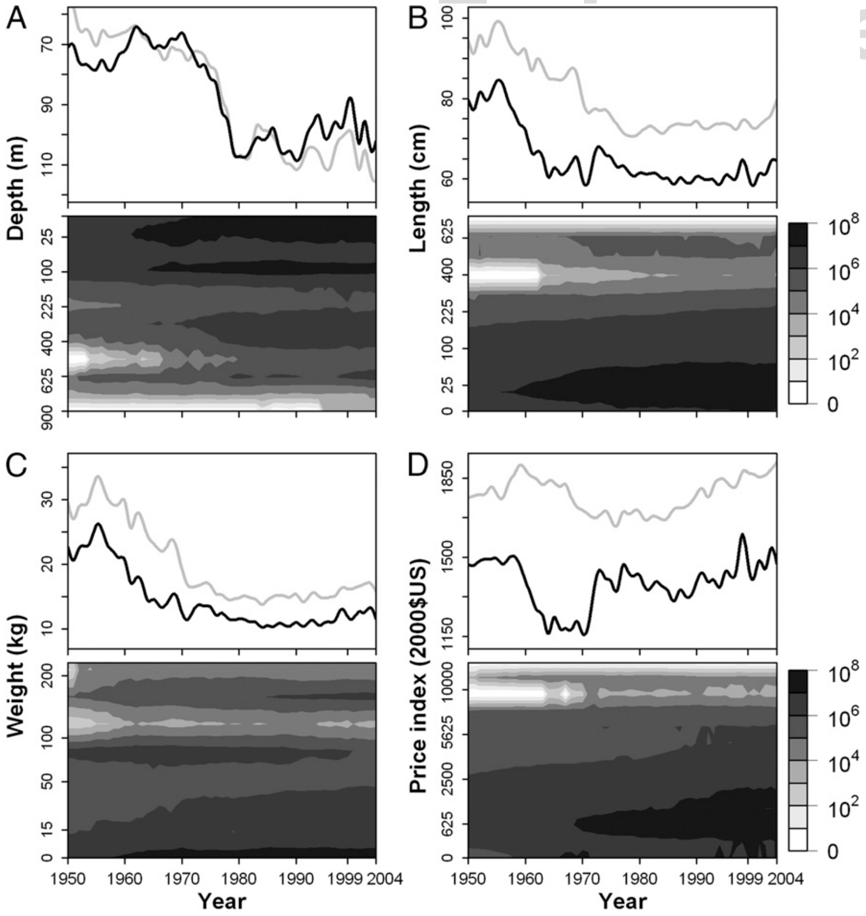

Fig. 2. Catch-weighted trends 1950–2004 for geometric mean of depth range (*A*), maximum observed taxon length (*B*) and weight (*C*, finfish only), and price index (*D*). Upper graphs are catch-weighted means with large-catch pelagic stocks either included (black lines) or excluded (gray lines). Lower images are total annual catch (tons) over time, including large-catch pelagics. The *y* axis is square-root transformed in the lower graphs. Data coverage as percentage of total global catch including pelagic stocks 1950–2004: price index = 87%, depth = 89%, length = 89%, and weight = 65%.

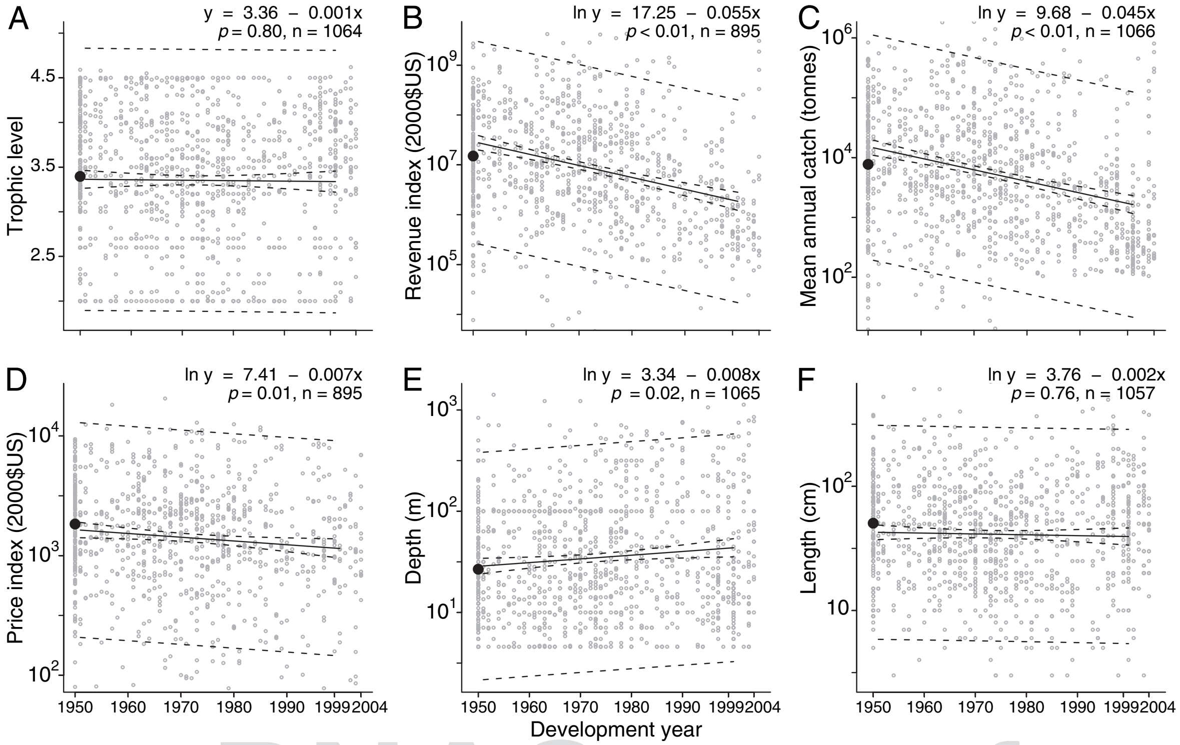

Fig. 3. Chronology of global fishery development by trophic level (*A*), revenue index (*B*), mean annual catch (*C*), price index (*D*), geometric mean of depth range (*E*), and length (*F*). Gray circles indicate the development year for each taxon, excluding fisheries developed after 1974 with mean annual catch <100 tons. Regression lines are in black, inner and outer dashed lines correspond to 95% confidence and prediction bands, respectively. The *P* values for slope estimates account for heteroskedasticity. Nonparametric permutation testing found significant differences ($P \leq 0.05$) between the 1950 (large black dot) and 1951–1999 group means for all plots except trophic level ($P = 0.56$).

tance of economic attributes of fished stocks. The most striking observation is that high-revenue fisheries developed before low-revenue fisheries. The trend estimated in Fig. 3*B* corresponds to a 95% drop in the revenue index from 1951 to 1999. This downward move is primarily driven by the catch component of revenue (Fig. 3*C*; *Sensitivity Analyses* in *SI Materials and Methods*), although price also plays a role, with evidence of developing from higher to lower priced taxa over time (Fig. 3*D*). Consistent with a preference to develop lower cost resources first, fisheries for shallower ranging taxa developed initially (Fig. 3*E*) and taxa already developed in 1950 were significantly larger in size than taxa developed later in the catch record, although the time trend for taxa developed from 1951 to 1999 was not statistically significant (Fig. 3*F*). Comparisons of group means of fisheries considered developed in 1950 (Fig. 3, black circles) against those developed later were consistent with the estimated time trends for all other tested metrics, indicating that similar drivers for fishery development may have been present at the start of the catch record.

These data show that economic forces drive early development of the largest biomass, highest revenue fisheries. Given that there is a limited supply of potential fisheries, this pattern has implications for future growth in wild capture fisheries. The rate of new fishery development has remained stable at approximately 15–20 per year (Fig. 4*A*), with some indication of a higher rate around 1970 (15), yet, under our definition of development, high value opportunities are all but gone. Fisheries already developed by 1980 contribute 90% (and those developed by 1990, 97%) of the expected annual catch (Fig. 4*B*) and revenue (Fig. 4*C*) for all fisheries contained in the catch record. Fisheries developed after 1980 have yielded small catches and low revenues.

Discussion

Our results highlight the importance of considering metrics for economic opportunity as leading indicators of harvest-related impacts. Modern industrial fishing is a business venture. Over the last half-century, the best economic opportunities have been taken advantage of first, i.e., those with the lowest cost and highest potential revenues. At present, remaining new fishery development opportunities appear to be low biomass and low revenue. We take a post-1950 and global approach here, acknowledging that some taxa were already heavily impacted before the start of the catch record (e.g., ref. 16). Local-scale and historical studies show similar development patterns in ocean ecosystems, where economic forces drive fishing impacts, including expansion into harder to access waters (17, 18) and sequential resource use along transportation cost gradients (19–21).

Ecosystem-level fishing effects are important to understand given the scale of industrialized fishing with annual global wild harvests of ≈90 million tons (22), even before accounting for illegal and unreported landings (23). Management and interpretation of ocean ecosystems could be improved, however, by rebalancing the focus on lagging indicators for fishing impacts to include leading indicators related to the drivers behind harvest pressure. For example, the data show trophic level is unrelated to the time pattern of commercial fishery developments since 1950, whereas taxa with attributes associated with high profit potential, including high catch biomass or shallow depth range, have been preferentially affected.

In moving toward ecosystem-based fisheries management, taxa attributes related to economic opportunity will be important for understanding which species are susceptible to new fishery development or expansion of existing harvest when costs and benefits are altered, for example through government subsidies (24) or increases in biomass from competitive release (25). One applica-

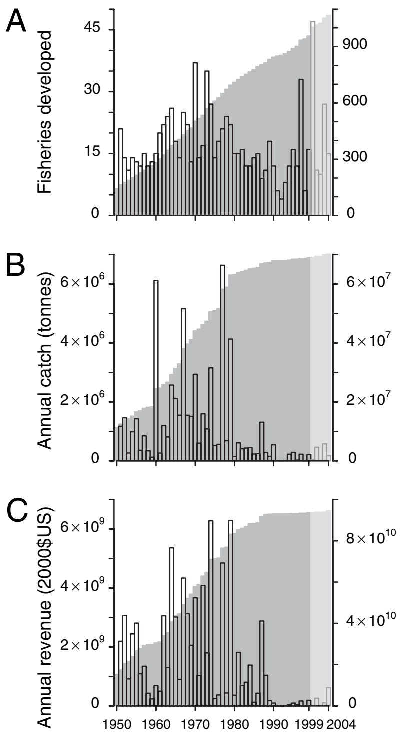

Fig. 4. Developed fishing opportunities. Outlined bars (left *y* axis) are number of fisheries developed in each year (*A*) and the combined expected annual catch (*B*) and revenue (*C*) of all fisheries developed in a respective year, excluding 1950. Expected catch and revenues are measured as the mean annual catch or revenue after year of development. Shaded areas (right *y* axis) are cumulative totals achieved by each respective year; 1950 summarizes developments before the start of the catch record. Light gray bars and shaded areas after 1999 indicate years where fisheries are potentially still developing their full catch or revenue production (*Materials and Methods*).

tion suggested by our results is to include scenarios of preferential fishing on large bodied, shallow ranging, high priced, and high catch biomass taxa to simulate realistic progressions of fishery development in ecosystem modeling. Furthermore, attributes of fished stocks related to profits are of direct interest to fishermen. Incorporating information on such attributes into the management process may help engage the harvest sector and provide metrics to evaluate the success of socioeconomic goals of fisheries management: sustained stock levels and sustained livelihoods for harvesters.

Materials and Methods

Data. Data were consolidated from three publicly available databases. Global landings 1950–2004 are from the Sea Around Us Project (ref. 7; www.seaaroundus.org). Landings time series are recorded by geographic region and are of varying taxonomic resolution including species-specific records and aggregate groups such as "squids." We define a fishery to be a time series of landings records for each taxon aggregated across regions, resulting in 1,316 global fisheries after excluding the aggregate "pelagic fishes" group for which there are no reliable morphological or price data available and which makes up ≈10% of global landings from 1950 to 2004.

Species morphological characteristics and trophic levels are from FishBase (9) and the Sea Around Us Project (www.seaaroundus.org). Trophic level, length, and depth information are available for both finfish and invertebrates; weight information was available only for finfish taxa.

Price data are from the Fisheries Economics Research Unit (FERU) ex-vessel price database (8). The FERU database represents the most comprehensive source of price data available; however, it is incomplete. An interpolation algorithm is used to fill data gaps, where raw data records are used to populate price records for closely related organisms based on taxonomy. Each price record is assessed an interpolation penalty within the database, ranging from a score of 0 for raw information to 37 for the most heavily interpolated records. Aiming for a balance between data quality and global coverage, we used a data filter to only accept records with a penalty score <20. We conducted sensitivity analysis by using a more conservative data filter and found no changes in our conclusions (*SI Materials and Methods*, Table S1, and Table S2).

We construct two measures of the economic value of a fishery: an ex-vessel price index and an annual ex-vessel gross revenues index, referred to as the "revenue index". The price index is the mean price over a taxon's discounted price time series in 2000$US (discounted and converted to US$ by FERU price database analysts). In some cases, more than one price time series for a taxon is available; for example, when there are directed fisheries for a taxon in multiple regions. To maximize information content, we average across all available price records discounted to 2000$US over time and space to construct the price index. By averaging over space, we implicitly assume a common global price index for a taxon. This assumption is not unreasonable at a global scale considering the speed at which seafood opportunities develop across locations once an opportunity has been identified and the existence of open globalized markets for fish products (19, 26). By averaging over time, the price index does not account for own- or cross-price supply and demand dynamics; however, we tested the stability of the real price time series by conducting univariate regression for time trends (Fig. S3). Price trends are generally small, where 90% of price series have an estimated trend of <2.5% price change per year, and we find no evidence of systematic distribution of trends across taxa (*Sensitivity Analyses* in *SI Materials and Methods*). As such, we take the price index as a measure of "intrinsic" per unit value of a fishery that is comparable across taxa.

The revenue index is the price index for a taxon multiplied by its mean annual catch after the year in which harvest first reaches 25% of maximum annual harvest, corresponding to our development algorithm outlined below. This metric provides a measure of gross revenues available in a fishery in an average year.

We use the geometric mean of a taxon's naturally occurring depth range as a proxy for the costs of fishing (Fig. 2*A* and 3*E*). Size metrics for profitability based upon processing considerations in Fig. 2 are the maximum observed length and weight of a specimen from a taxon (for further discussion see *Organism Size and Economic Opportunity* in *SI Materials and Methods*).

Primary Analyses. Linear regression and ANOVA were conducted on natural log transformed data except in cases where trophic level was the response variable. Statistical inference was conducted by using White SEs, which correct for generic forms of heteroskedasticity (27). Groups for ANOVA tests of means coincide roughly to shellfish and invertebrates, trophic level interval [1,2.7], top predators (3.9,5], and a mid group including most pelagic species (2.7,3.9] (Table S2 and Table S3).

We report changes in catch-weighted metrics (Fig. 2) as the percentage change from the mean of the first five years to the mean of the last five years of the time series.

A chronology of global development patterns was constructed by using the Sea Around Us Project catch database (www.seaaroundus.org). A fishery was considered developed in the year where annual catch first reached 25% of its maximum observed annual catch. Mean annual catch (used in Figs. 1*B*, 3 *B* and *C*, and 4 *B* and *C*) is calculated after a fishery is considered developed.

The development algorithm could potentially introduce several biases. First, all taxa with 1950 catch >25% of the maximum catch, e.g., those with a maximum catch in 1950, are considered developed in that year. As such, the 1950 group represents a summary of the historical development pattern before the catch record begins. Second, fisheries considered developed in the last few years of the catch record may not have had adequate time to reach their full potential mean annual catch or revenue. To avoid these biases, linear regression (Fig. 3) was conducted only on fisheries considered developed over the period 1951–1999. A nonparametric permutation routine (*SI Materials and Methods*) was used to test for differences between the 1950 and 1951–1999 group means for reported fishery attributes. Finally, we exclude any fisheries that were considered developed after 1975 with mean annual catch <100 tons to avoid inclusion of small fisheries, which appear in the catch record because of increases in FAO reporting resolution in later decades, but which had been fished earlier under aggregate taxa headings.

We tested the robustness of our results with a range of sensitivity analyses presented in the *SI Materials and Methods*: examination of the relationship between price and catch time trends and taxa attributes, examination of the relationship between trophic level and value indices across time, and using different price data quality filters, removal of large biomass pelagic stocks from catch-weighted metrics, use of alternative depth range metrics, examination of the robustness of the declining revenue development trend to price data error, examination of development patterns within trophic level assemblages, and use of an alternative definition of mean annual catch.

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1. Pauly D, Christensen V, V, Dalsgaard J, Froese R, Torres F, Jr (1998) Fishing down marine food webs. *Science* 279:860–863.
2. Essington TE, Beaudreau AH, Wiedenmann J (2006) Fishing through marine food webs. *Proc Natl Acad Sci USA* 103:3171–3175.
3. Baum JK, Worm B (2009) Cascading top-down effects of changing oceanic predator abundances. *J Anim Ecol* 78:699–714.
4. Daskalov GM (2002) Overfishing drives a trophic cascade in the Black Sea. *Mar Ecol Prog Ser* 225:53–63.
5. Fogarty MJ, Murawski SA (1998) Large-scale disturbance and the structure of marine systems: Fishery impacts on Georges Bank. *Ecol Appl* 8:S6–S22.
6. Pauly D, Watson R (2005) Background and interpretation of the 'Marine Trophic Index' as a measure of biodiversity. *Philos Trans R Soc Lond B Biol Sci* 360:415–423.
7. Watson R, Kitchingman A, Gelchu A, Pauly D (2004) Mapping global fisheries: Sharpening our focus. *Fish Fisheries* 5:168–177.
8. Sumaila UR, Marsden AD, Watson R, Pauly D (2007) A global ex-vessel fish price database: Construction and applications. *J Bioecon* 9:39–51.
9. Froese R, Pauly D, eds (2009) *FishBase*. Version October 2009. Available at www.fishbase.org. Accessed March 10, 2010.
10. Ryther JH (1969) Photosynthesis and fish production in the sea. *Science* 166:72–76.
11. Elton C (1927) *Animal Ecology* (MacMillan, New York).
12. Brown GM (2000) Renewable natural resource management and use without markets. *J Econ Lit* 38:875–914.
13. Clark CW (1976) *Mathematical Bioeconomics* (Wiley, New York).
14. Morato T, Watson R, Pitcher TJ, Pauly D (2006) Fishing down the deep. *Fish Fish* 7:24–34.
15. Froese R, Stern-Pirilot A, Kesner-Reyes K (2009) Out of new stocks in 2020: A comment on "Not all fisheries will be collapsed in 2048.". *Mar Policy* 33:180–181.
16. Rosenberg AA, et al. (2005) The history of ocean resources: Modeling cod biomass using historical records. *Front Ecol Environ* 3:84–90.
17. Erlandson JM, Rick TC, Braje TJ (2009) Fishing up the food web? 12,000 years of maritime subsistence and adaptive adjustments on California's Channel Islands. *Pac Sci* 63:711–724.
18. Lotze HK (2007) Rise and fall of fishing and marine resource use in the Wadden Sea, southern North Sea. *Fish Res* 87:208–218.
19. Berkes F, et al. (2006) Ecology. Globalization, roving bandits, and marine resources. *Science* 311:1557–1558.
20. Kirby MX (2004) Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. *Proc Natl Acad Sci USA* 101:13096–13099.
21. Orensanz JML, Armstrong J, Armstrong D, Hilborn R (1998) Crustacean resources are vulnerable to serial depletion—the multifaceted decline of crab and shrimp fisheries in the greater Gulf of Alaska. *Rev Fish Biol Fish* 8:117–176.
22. FAO (2009) *The State of the World's Fisheries and Aquaculture 2008* (FAO, Rome).
23. Agnew DJ, et al. (2009) Estimating the worldwide extent of illegal fishing. *PLoS ONE* 4:e4570.
24. Sharp R, Sumaila UR (2009) Quantification of U.S. marine fisheries subsidies. *N Am J Fish Manage* 29:18–32.
25. Schrank WE (2005) The Newfoundland fishery: Ten years after the moratorium. *Mar Policy* 25:407–420.
26. Deutsch L, et al. (2007) Feeding aquaculture growth through globalization: Exploitation of marine ecosystems for fishmeal. *Glob Environ Change* 17:238–249.
27. White H (1980) A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica* 48:817–838.