Patterns and ecosystem impacts of global invertebrate fisheries expansion

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Introduction

Over the last 50-100 years, exploitation has depleted many traditional finfish fisheries globally (e.g. Pauly et al. 2002; Myers and Worm 2003; Christensen et al. 2003; Frank et al. 2005; Myers and Worm 2005). In tandem with these declines has been a large-scale expansion of low trophic-level invertebrate fisheries. This trend has been observed through increasing catch (e.g. Pauly et al. 2002; FAO 2007), increasing value of catch (FAO 2007), spatial expansion of selected fisheries (e.g. Berkes et al. 2006), and a declining trophic level of the overall fisheries catch (Pauly et al. 1998; 2001). In 2006, shrimp was the most valuable fishery at 16.5% of global fisheries value compared to 10% for all groundfish combined (FAO 2007). Apart from these overall trends, a comprehensive picture of species- and region-specific trends and drivers is lacking.

Jamieson (1993) suggested that invertebrate fisheries may not be as resistant to overexploitation as once thought. My previous work has pointed to gaps in knowledge of population parameters such as growth rate, biomass, and geographic range in developing invertebrate fisheries on the East Coast of Canada that may impair their longterm viability (Anderson et al. 2008). Some invertebrate populations have already experienced severe declines (e.g. Tegner et al. 1996) and patterns of serial depletion have been suggested for some invertebrate fisheries such as crabs and shrimps (Orensanz et al. 1998), oysters (Kirby 2004), and chitons and sea urchins (Salomon et al. 2007) on regional scales and for sea urchins (Berkes et al. 2006) and sea cucumbers (Therkildsen and Petersen 2006) on a global scale. Thus, despite globally increasing total invertebrate catches, the underlying patterns of individual species may look less optimistic.

A variety of forces have been suggested as drivers of these increases and declines of fisheries, for example, changing market value (Botsford et al. 2004), local social and economic pressures (Roy 1996; Hamilton et al. 2004), as well as population increases caused by release from predation (Worm and Myers 2003; Myers et al. 2007). It is unclear whether a single factor or combination of factors are the most important drivers.

Many invertebrate species serve important roles in the marine ecosystem (discussed in Section 1.4). The ecosystem impacts of removing low-trophic level species and of the gear often used in these fisheries remains to be assessed on a global scale.

In this thesis I aim to address the above mentioned fisheries, population, and ecosystem impacts of invertebrate fisheries as well as their potential drivers.

Objectives

A global overview of recent trends in invertebrate fisheries has yet to be completed; the first half of this work aims to address this gap. Further, despite the identification of serial depletion patterns in some regions within certain taxonomic groups, their existence and common drivers on a global scale have not been formally tested. In this thesis, I propose to analyze global fisheries catch and value records to:

1. Describe the global expansion of invertebrate fisheries over time and space as a whole and by taxonomic groups, functional groups, and gear types.

2. Formally identify the common drivers of these patterns and their potential consequences such as serial depletion.

1 Global expansion of invertebrate fisheries

A global trend of increasing total invertebrate catch was noted by Pauly et al. (2002). Specific taxa in certain regions, and in some cases globally, have been reviewed, yet a broad overview of trends in global invertebrate fisheries has yet to be compiled. The following represent the main large-scale reviews of the invertebrate taxa. Within molluscs, the largest invertebrate fisheries by catch, cephalopod fisheries, were reviewed in some regions in Fisheries Research Vol. 78, Issue 1 (Foreword by Payne et al. 2006). Caddy (1989*a*) reviewed research and management trends in wild bivalve fisheries. Leiva and Castilla (2001) provided a review of gastropod fisheries, although much research focus has been directed towards abalone fisheries, which have experienced severe declines in numerous locations (e.g. Tegner et al. 1996; Hobday et al. 2001). Caddy (1989*b*) provided a general overview of global crustacean fisheries. In the Bering Sea, patterns of serial depletion in crustacean fisheries have been reviewed by Orensanz et al. (1998). Echinoderms as a group were reviewed by Conand and Sloan (1989). An overview of global sea urchin fisheries was conducted by Andrew et al. (2002); sea cucumbers by Conand and Byrne (1993) and later Therkildsen and Petersen (2006). These reviews indicate that invertebrate fisheries are far from immune to declines and some species may be prone to serial depletion. Notably, a recent global overview of these fisheries is lacking, and it is here that I direct the first half of my thesis.

The Sea Around Us Project (SAUP) (2008*a*) has compiled the most accurate and complete global database of fisheries landings based on catch reported to the Fisheries and Agriculture Organization (FAO) since 1950. SAUP processes the data through a series of filters such as adjusting the Chinese catch (Watson and Pauly 2001), disaggregating species, and adding missing records (Sea Around Us 2008*b*). I propose to use the catch as reported caught by countries. This is largely similar to the FAO data (R. Watson, pers. communication) and reduces the introduction of bias associated with the SAUP spatially aggregated data (see Close et al. 2006). Additionally, Sumaila et al. (2005) have developed a database of ex-vessel prices (the price a fisher is estimated to have received for their catch). While the quality is improving, some data remains interpolated from assumed relationships with catch based on minimal points of known price (Sumaila et al. 2005) and its inclusion in this thesis remains uncertain. Although with limitations, the SAUP data represent the best available global fisheries statistics and facilitate the discovery of novel patterns. I have chosen wherever possible to introduce as little bias as possible by using the catch reported caught by countries and aggregating the data into groups. Much of this thesis will involve careful decision-making given the limitations of the data and the manipulation of large datasets – tasks which present non-trivial challenges.

In this section I will attempt a broad overview of the development of invertebrate fisheries globally and the potential impacts from the perspective of functional group and habitat loss.

1.1 Global catch and diversity of catch: the overall picture

To provide an overall description of the catch and diversity of catch in invertebrate fisheries, I propose to address the following 4 questions:

(1) *Overall and by taxonomic groups, at what rate is global invertebrate catch increasing*? I will investigate the total invertebrate catch over time and divided by taxonomic groups (e.g. crabs, squids, and sea urchins; herein referred to as "taxa") and larger groupings (crustaceans, cephalopods, bivalves and gastropods, and echinoderms) (see Figure 1A for one example). I will identify how the rate of change of catch has evolved over time as well as compare trends across taxonomic groups.

(2) *To what extent is increased reporting to FAO responsible for the trends observed in these and further analyses and to what extent are there more countries fishing invertebrates*? I will examine how the number of countries reporting catch of invertebrates is changing compared to the number of countries reporting any fisheries catch (Figure 1B). The number of countries reporting any catch will account for the increasing number of countries participating in the FAO reporting process. The degree to which the disparity in reporting of invertebrate and finfish catch is an artifact of increased reporting precision will be partially addressed below through regional ground truthing.

(3) *To what extent are those countries that are fishing invertebrates fishing them harder*? I will plot the mean and median of invertebrate catch for those countries reporting catch and evaluate this trend over time. I thus far calculated 95% confidence intervals for the mean trend based on a log-normal distribution (Figure 1C).

(4) *To what extent is the diversity of invertebrate species fished increasing*? Local examples (e.g. Lotze 2004) indicate the number of species fished is increasing and these trends may extend globally. Such expansion should be expected as traditional fisheries are depleted (Pauly et al. 1998). Initially, I counted the number of species/taxa reported as fished per country. I will investigate the importance of a variety of catch cut-offs before a species is considered fished as well as compare the mean and median trends. Given the log-normal distribution of the count data by year, I calculated 95% confidence intervals (Figure 1D). I will verify these trends for a select group of disparate regions to assess to what degree this trend is the result of increased reporting precision to FAO. I propose to check selected taxa in Canada[1], the United States[2], and Australia[3], where detailed regional

[1] `http://www.dfo-mpo.gc.ca/csas/`
[2] `http://www.nmfs.noaa.gov/`
[3] `http://www.afma.gov.au/research/reports/`

records are available.

1.2 The number of countries fishing invertebrates: the spatial expansion

To what extent is there spatial expansion of invertebrate fisheries? As a proxy to the spatial expansion of invertebrates fisheries, I will examine the number of countries reporting catch of various taxa. This trend is confounded by 2 main factors: (1) increased reporting of catch to FAO, and (2) changes to the definition of countries over time (territories becoming new countries) (R. Watson, pers. communication). To partially account for the 1^{st} issue, I will scale the trend to the number of countries reporting any fisheries catch (fish or invertebrate) each year (see Figure 1B). It will be important to assess the sensitivity of these results to the chosen catch cut-off used to determine when a country is considered to have fished a species. I have thus far examined the trend with cut-offs of 0t, 0.5t, and 5t, and although the absolute numbers change, the relative trends remain similar. Preliminary results are shown in Figure 2. To account for the 2^{nd} issue, I propose to re-aggregate the data by the original country definitions where possible. For example, Guinea-Bissau began reporting catch in 1976 but likely reported catch as Portuguese before their official independence in 1974. I would remove this "artificial" inflation of reporting by re-aggregating Guinea-Bissau and Portugal.

1.3 Trends within taxa: the underlying patterns

What are the underlying patterns to the overall increasing catch trends? Berkes et al. (2006) identified that the underlying patterns in catch by region may not reflect the overall catch trends when analyzing global-market driven fisheries.

One method of addressing this question would be to determine the percentage of undeveloped, developing, fully exploited, overfished, and collapsed or closed fisheries following the methodology of Froese and Kesner-Reyes (2002), which is based on the actual catch relative to the maximum catch observed. As an initial approach, and to avoid making assumptions about the state of a fishery based only on percentage of maximum catch, I began by examining the relative frequency of the first difference of catch by taxa over time. First, I removed fisheries with less than 5 years of consecutive data to eliminate minor fisheries. I then log-transformed and smoothed the catch trends with a 5 year running mean to stabilize the variance. I calculated the 1^{st} difference of catch for each country each year and plotted the relative frequency each year of these values by colour. I log-transformed the colour-spectrum to better distinguish the majority of frequency values which were in the lower half of the spectrum. See Figure 3 for an example with sea cucumber.

1.4 Functional groups: the food-web changes

Many invertebrate species play key roles in their marine ecosystems (Dayton et al. 2002). Some maintain water quality (e.g. Lawrence 1975), others provide habitat, and most serve as food for higher trophic levels. Perhaps most alarming is that invertebrate fisheries in a given area may expand into a suite of functional groups simultaneously thereby having a greater impact on ecosystem function (Shackell and Frank 2007).

What are the trends in invertebrate fishery catch by functional group? I propose to aggregate the catch trends by the functional groups: carnivores, herbivores, scavengers, filter feeders, and detritivores. I may also separately consider habitat-providing species groups such as mussel banks, oyster reefs, and sponge beds. Given food-web dynamics described in the literature, I will consider the potential food-web changes induced by increasing invertebrate catches (Lotze and Milewski 2004; Heath 2005; Shackell and Frank 2007).

1.5 Gear: the habitat impact

The method of fishing can have a substantial influence on the impact to marine habitat (reviewed by Kaiser et al. 2006). In particular, bottom trawling and dredging may induce longterm changes to benthic biodiversity with the recovery of some biogenic structures measured in years if not decades (Collie et al. 2000; Kaiser et al. 2006). Other species tend to be fished by diving – a highly selective practice that may, however, eliminate the natural refuges that are avoided by trawlers. Raking, although unlikely to induce the long-term habitat impacts associated with trawling, can induce habitat alteration that persists beyond 1 year (Kaiser et al. 2001). Traps and pots can entangle marine mammals (Johnson et al. 2005) and are a substantial threat to the survival of some whale populations (e.g. Kraus et al. 2005).

What are the trends in invertebrate fishery gear type? I will evaluate the trends in gear use as well as categorize these trends by ecosystem impact. Given that 7 gear types were responsible for the majority of catch and species fished, I began by plotting the total catch and number of species fished by these gear types, grouping the remaining minor gear types into "others" (Figure 4). Next, I propose to create gear type categories according to potential ecosystem impact: bottom impact (e.g. bottom trawls, dredges, raking devices), traps/pots, by hand (diving, by hand), and the less common line and net methods. While generating an overview of the potential impacts, such an approach will incorporate the 12 minor gear categories. I will interpret these trends via a review of the literature on the subject (e.g. those cited in this section).

2 Common drivers and consequences

Following the preceding descriptive analysis of catch trends, I will address the following questions:

1. *What are the common drivers of invertebrate fisheries catch?* (Section 2.1)
2. *To what degree might these drivers be causing detectable patterns of serial depletion?* (Section 2.2)

2.1 Identifying the common drivers

A number of drivers of fisheries in general, and invertebrate fisheries in particular, have been suggested. The price a fisher expects to obtain for their catch, the ex-vessel price, may be most obvious (Sumaila et al. 2005). Such prices result from a combination of other economic drivers such as the strength of the economy or the decline of local catch in the main importing nation. Botsford et al. (2004) noted the relationship between the Japanese Yen-US dollar ratio and global sea urchin catch (see Figure 5 for a similar analysis with sea cucumber I conducted[4]). Berkes et al. (2006) suggested the decline of the dominant Japanese sea urchin fishery in conjunction with increasing globalization may be fuelling rising demand for exports of sea urchins globally.

Other influences from outside a fishery can influence the fishing effort for a given invertebrate. The loss of employment in traditional fisheries may drive an increase in effort in newer, often invertebrate fisheries. For example, the decline of the groundfishery on the East Coast of Canada left many unemployed fishers, many of whom have since moved into lucrative crustacean fisheries (Hamilton et al. 2004). Changes in the availability or efficiency of gear may also influence fishery catch trends (Arreguín-Sánchez 1996; Marchal et al. 2007).

Finally, changes in invertebrate catch can be a result of changes in invertebrate abundance. These may be the result of causes besides the fishery such as changes to ocean temperature (Anderson and Piatt 1999; Hare and Mantua 2000), changes to habitat (Jennings et al. 2001), or changes in food web dynamics such as predator release or suppression (Worm and Myers 2003; Myers et al. 2007), or due to the fishery itself.

Given the variety and complexity of the relationships between the covariates and the catch trends observed, additive models and Generalized additive models (GAMs) (Hastie and Tibshirani 1990) may be the most appropriate methodology to apply. GAMs provide a framework for combining the properties of Generalized linear models (GLMs) with additive models where both parametric and non-parametric terms can be included, allowing for a better fit to non-standard relationships (Hastie and Tibshirani 1990; Wood 2006). The *mgcv* package (Wood 2006) in R (R Development Core Team 2008) provides the additional

[4]Yen-USD data from the Bank of Japan. Accessible at:
`http://www.boj.or.jp/en/type/stat/dlong/fin_stat/rate/cdab0780.csv`

benefit of objectively choosing a degree of smoothing. The relative importance of the covariates and the shape of their influence could be determined by the importance of the model terms.

I propose to assess the relative role of the following variables through the use of GAMs:

Driver	Variable measure
Time	Year
Loss of traditional fisheries employment	First difference of local finfish catch
Changing value of species	Ex-vessel fishing price
Decline of fishery in driving country	Rate of change of driving fishery
Transportation costs	Distance between most populated cities
Health of driver's economy	United States dollar/driver's currency

I hypothesize that some of these variable affect global catch patterns (e.g. rate of change of the driving fishery) while others affect local catch patterns (e.g. loss of traditional fisheries employment). This facet of the data will need to be addressed to build a general model.

I propose to divide these fisheries into groups that I expect have similar market drivers, catch trends, and life-history traits. I propose these groups comprise (1) sea cucumbers and sea urchins; (2) gastropods and bivalves; (3) crabs, lobsters, shrimps and prawns; and (4) octopuses, cuttlefishes, and squids. While I hypothesize that fisheries for sea cucumber, sea urchin, octopus, cuttlefish, and squid are driven by Asian markets; crab, lobster, and shrimp fisheries may have more disparate drivers.

2.2 Testing for patterns of serial depletion

Serial depletion may occur by species or by geographic location. By species, it may occur on a small scale, moving from high to less desirable species within the same taxa (e.g. the recent fishing of the North Atlantic sea cucumber *Cucumaria frondosa* – a less desirable species of sea cucumber in Japan), or it may occur on a large scale, moving from high to less desirable taxa (e.g. cod to sea cucumbers). By location, serial depletion may occur on a small scale, with boats moving farther from their port to fish, or on a large scale, with countries importing from increasingly distant locations with a rising cost of transportation. The proposed dataset lacks the species and geographic precision necessary to address small scale serial depletion. Further, detecting large scale species serial depletion based solely on invertebrate species given the brief available time-series may be problematic. The proposed dataset best lends itself to identifying patterns of serial depletion on a large geographic scale.

I propose the following research questions: (1) *Is there a spatial pattern to the initiation or peak of catch within any taxa*? (2) *If so, across what taxa do we see similar patterns*?

(3) *Is there a typical trajectory to the catch trends within and/or between any taxa*?

First, I will assess catch trends by country (e.g. Figure 6) in conjunction with regional stock assessments and global fisheries reviews (see Section 1 Paragraph 1) to determine where the decline of a major fishery may be driving the development of other fisheries. Where I observe these trends, I will test for patterns in the countries' geographic location and the initiation and/or peak of catch using additive models and/or GAMs. I will account for, where possible, the covariates identified in Section 2.1 such as ex-vessel price and local finfish decline. Where possible, I will compare the results within the groups described in Section 2.1.

I foresee the following challenges and potential solutions:

1. *Catch trends may vary substantially between countries and taxa and not be universally expressible through linear models and GLMs.* Instead, I propose to apply additive models and GAMs as described above. If a pattern is evident, catch trends across countries could be analyzed using a single model by lagging the data according to the distance-catch relationship. Alternatively, the smooth terms could be combined as random effects through a Generalized additive mixed model approach (GAMMs) (Lin and Zhang 1999; Wood 2006). By combining the trends within and between taxa I could define the similarity of the trends and what a typical catch trajectory resembles. If covariates could be satisfactorily included for a taxa, and in consultation with the literature, I could suggest to what degree these trends may be the result of changes to abundance.

2. *The scales of catch differ substantially within and between some taxa.* For example, the peak in sea cucumber catch in Japan is 3-fold greater than the peak in any other country. I propose the following possible solutions: (1) model these trends separately, (2) model the rate of change, (3) log-transform the catch data, and/or (4) scale the data to a uniform mean and variance.

3. *In many time-series, zero-inflation prior to the onset of fishing presents a statistical challenge.* Possible solutions include (1) assuming the response follows a quasi-poisson family distribution, (2) assuming a gaussian family distribution of the log(catch + 1), and/or (3) when modelling the typical trajectory, shortening the time-series to exclude the zeros.

4. *The calculation of the distance between countries is problematic given the presence of land, water, multiple cities of export, and multiple cities of import.* Since many invertebrate species are flown to foreign markets (e.g. DFO 2000; Berkes et al. 2006). I propose the great-circle distance be used as a proxy to flight distance. Further, to simplify the approach, I propose to consider the most populated cities. These cities are likely the location of highest consumption and in many cases a stopover

or departure point for export flights. Within the importing country, I propose the distance from the major city to the farthest coast as a proxy for the farthest distance the catch would have been transported before foreign sources became desirable.

5. *The propagation of uncertainty from the initial distance-lag model through the analysis presents challenges.* One solution may be a sensitivity analysis (Saltelli et al. 2000); another may be a state-space approach (J. Flemming, pers. communication).

6. *The ex-vessel price data, has partly been interpolated.* Where interpolated, the exvessel price data may be inappropriate to answer the proposed questions. I propose to exclude these interpolated trends. Where interpolated data is pervasive for certain taxa this co-variate may be excluded.

Preliminary results for an analysis of the peaks of sea cucumber catch based on distance between major cities and Tokyo are shown in Figure 7. Here, a linear model was built based on distance from Japan and the year that catch peaked (Figure 7A) and this model was used to lag the catch trajectories to have a uniform calculated year of maximum catch. An additive model was then fit through the Japanese and other countries' lagged catch trajectories (Figure 7B). This approximates the typical catch trajectory according to the distance-lagged model and demonstrates the difference in scale between the Japanese fishery and the ensuing other fisheries. When summed, these ensuing fisheries have maintained a generally increasing global catch since 1969 (Figure 5) when the Japanese catch began to decline (Figure 6). Further, an analysis of the p-values for the parametric country factors could be used to assess the relative influence of each country to the trend.

Proposal conclusions

In comparison to the substantial declines we have already experienced with many finfish fisheries (e.g. Pauly et al. 2002; Myers and Worm 2003; 2005), there remains time to prevent similar trends in invertebrate fisheries. There are indications that invertebrate fisheries are not immune to declines. The results of this thesis may have broadscale management implications by providing an awareness of the potential driving forces, the often rapid expansion, and the potential for rapid decline of invertebrate fisheries. This thesis will flag fisheries on a global scale that may be particularly susceptible to large scale market drivers thereby potentially expanding faster than management can respond. While it is important to assess regional invertebrate catch trends in detail, when the driving forces are global in nature, a broad overview affords an important additional perspective.

References

Anderson, P. and J. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Mar. Ecol. Prog. Ser., **189**:117–123.

Anderson, S., H. Lotze, and N. Shackell. 2008. Evaluating the knowledge base for expanding low-trophic level fisheries in Alantic Canada. Can. J. Fish. Aquat. Sci. In Review.

Andrew, N. L., Y. Agatsuma, E. Ballesteros, E. Bazhin, E. P. Creaser, D. K. A. Barnes, L. Botsford, A. Bradbury, A. Campbell, J. D. Dixon, S. Einarsson, P. K. Gerring, K. Hebert, M. Hunter, S. B. Hur, C. Johnson, M. A. Juinio-Menez, P. Kalvass, R. Miller, C. A. Moreno, J. S. Palleiro, D. Rivas, S. M. L. Robinson, S. C. Schroeter, R. S. Steneck, R. L. Vadas, D. Woodby, and Z. Xiaoqi. 2002. Status and management of world sea urchin fisheries. Oceanogr. Mar. Biol. Annu. Rev., **40**:343–425.

Arreguín-Sánchez, F. 1996. Catchability: A key parameter for fish stock assessment. Rev. Fish. Biol. Fish., **6**:221–242.

Berkes, F., T. P. Hughes, R. S. Steneck, J. A. Wilson, D. R. Bellwood, B. Crona, C. Folke, L. H. Gunderson, H. M. Leslie, J. Norberg, M. Nyström, P. Olsson, H. Osterblom, M. Scheffer, and B. Worm. 2006. Globalization, roving bandits, and marine resources. Science, **311**:1557–1558.

Botsford, L., A. Campbell, and R. Miller. 2004. Biological reference points in the management of North American sea urchin fisheries. Can. J. Fish. Aquat. Sci, **61**:1325–1337.

Caddy, J. 1989*a*. Recent developments in research and management for wild stocks of bivalves and gastropods. In J. Caddy, editor, Marine Invertebrate Fisheries: Their Assessment and Management, pages 665–700. John Wiley and Sons, New York, NY.

Caddy, J. 1989*b*. Overview of crustacean fisheries: Assessments and population dynamics. In J. Caddy, editor, Marine Invertebrate Fisheries: Their Assessment and Management, pages 3–12. John Wiley and Sons, New York, NY.

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

Close, C., W. Cheung, S. Hodgson, V. Lam, R. Watson, and D. Pauly. 2006. Distribution ranges of commercial fishes and invertebrates. Fishes in databases and ecosystems. Proceedings of the 2006 FishBase Symposium. Edited by Maria Lourdes D. Palomares, Konstantinos I. Stergiou and Daniel Pauly, **14**:27–37.

Collie, J. S., S. Hall, M. Kaiser, and I. Poiner. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. J. Anim. Ecol., **69**:785–795.

Conand, C. and M. Byrne. 1993. A review of recent developments in the world sea cucumber fisheries. US Natl. Mar. Fish. Serv. Mar. Fish. Rev., **55**:1–13.

Conand, C. and N. Sloan. 1989. World fisheries for echinoderms. In J. Caddy, editor, Marine Invertebrate Fisheries: Their Assessment and Management, pages 647–663. John Wiley and Sons, New York, NY.

Dayton, P., S. Thrush, and F. Coleman. 2002. Ecological effects of fishing in marine ecosystems of the United States. Pew Oceans Commission, Arlington, VA.

DFO. 2000. Nova scotia green sea urchins. DFO Science Stock Status Report C3-48(2000).

FAO. 2007. The state of world fisheries and aquaculture 2006. Technical report, Food and Agriculture Organization of the United Nations, Rome.

Frank, K. T., B. Petrie, J. S. Choi, and W. C. Leggett. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science, **308**:1621–1623.

Froese, R. and K. Kesner-Reyes. 2002. Impact of fishing on the abundance of marine species. ICES Council Meeting Report CM 2002/L:12, International Council for the Exploration of the Sea (ICES), Copenhagen, Denmark, 2002.

Hamilton, L., R. Haedrich, and C. Duncan. 2004. Above and below the water: Social/ecological transformation in northwest Newfoundland. Popul. Env., **25**:195–215.

Hare, S. and N. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progr. Oceanogr., **47**:103–145.

Hastie, T. J. and R. J. Tibshirani. 1990. Generalized Additive Models. Chapman and Hall, New York.

Heath, M. 2005. Changes in the structure and function of the North Sea fish foodweb, 1973-2000, and the impacts of fishing and climate. ICES J. Mar. Sci., **62**:847–868.

Hobday, A., M. Tegner, and P. Haaker. 2001. Over-exploitation of a broadcast spawning marine invertebrate: Decline of the white abalone. Rev. Fish. Biol. Fish., **10**:493–514.

Jamieson, G. 1993. Marine invertebrate conservation: Evaluation of fisheries over-exploitation concerns. Am. Zool., **33**:551–567.

Jennings, S., J. Pinnegar, N. Polunin, and K. Warr. 2001. Impacts of trawling disturbance on the trophic structure of benthic invertebrate communities. Mar. Ecol. Prog. Ser., **213**:127–142.

Johnson, A., G. Salvador, J. Kenney, J. Robbins, S. Landry, and P. Clapham. 2005. Fishing gear involved in entanglements of right and humpback whales. Mar. Mam. Sci., **21**:635–645.

Kaiser, M., G. Broad, and S. Hall. 2001. Disturbance of intertidal soft-sediment benthic communities by cockle hand raking. J. Sea. Res., **45**:119–130.

Kaiser, M., K. Clarke, H. Hinz, M. Austen, P. Somerfield, and I. Karakassis. 2006. Global analysis of response and recovery of benthic biota to fishing. Mar. Ecol. Prog. Ser., **311**:1–14.

Kirby, M. 2004. Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. Proc. Natl. Acad. Sci. USA, **101**:13096–13099.

Kraus, S., M. Brown, H. Caswell, C. Clark, M. Fujiwara, P. Hamilton, R. Kenney, A. Knowlton, S. Landry, C. Mayo, W. McLellan, M. Moore, D. Nowacek, D. Pabst, A. Read, and R. Rolland. 2005. North Atlantic right whales in crisis. Science, **309**:561–562.

Lawrence, J. 1975. On the relationships between marine plants and sea urchins. Oceanogr. Mar. Biol. Annu. Rev., **13**:213–286.

Leiva, G. and J. Castilla. 2001. A review of the world marine gastropod fishery: evolution of catches, management and the Chilean experience. Rev. Fish. Biol. Fish., **11**:283–300.

Lin, X. and D. Zhang. 1999. Inference in generalized additive mixed models by using smoothing splines. J. Roy. Stat. Soc. B, **61**:381–400.

Lotze, H. 2004. Repetitive history of resource depletion and mismanagement: the need for a shift in perspective. in: H. I. Browman, K. I. Stergiou, editors. Perspectives on ecosystem-based approaches to the management of marine resources. Mar. Ecol. Prog. Ser., **274**:282–285.

Lotze, H. and I. Milewski. 2004. Two centuries of multiple human impacts and successive changes in a North Atlantic food web. Ecol. Appl., **14**:1428–1447.

Marchal, P., B. Andersen, B. Caillart, O. Eigaard, O. Guyader, H. Hovgaard, A. Iriondo, F. L. Fur, J. Sacchi, and M. Santurtun. 2007. Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. ICES J. Mar. Sci., **64**:192–209.

Myers, R. A., J. K. Baum, T. D. Shepherd, S. P. Powers, and C. H. Peterson. 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science, **315**:1846–1850.

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

Myers, R. A. and B. Worm. 2005. Extinction, survival or recovery of large predatory fishes. Phil. Trans. Roy. Soc. Lond. B., **360**:13–20.

Orensanz, J., J. Armstrong, D. Armstrong, and R. Hilborn. 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.

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

Pauly, D., V. Christensen, S. Guenette, T. J. Pitcher, U. R. Sumaila, C. Walters, R. Watson, and D. Zeller. 2002. Towards sustainability in world fisheries. Nature, **418**:689–695.

Pauly, D., M. Palomares, R. Froese, P. Sa-a, M. Vakily, D. Preikshot, and S. Wallace. 2001. Fishing down Canadian aquatic food webs. Can. J. Fish. Aquat. Sci, **58**:51–62.

Payne, A., D. Agnew, and G. Pierce. 2006. Trends and assessment of cephalopod fisheries - foreword. Fish. Res., **78**:1–3.

R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.

Roy, N. 1996. The Atlantic Canada resource management catastrophe: What went wrong and what can we learn from it? Can. J. Econ., **29**:S139–S144.

Salomon, A. K., N. M. Tanape, and H. P. Huntington. 2007. Serial depletion of marine invertebrates leads to the decline of a strongly interacting grazer. Ecol. Appl., **17**:1752–1770.

Saltelli, A., K. Chan, and E. M. Scott. 2000. Sensitivity Analysis. Wiley, West Sussex, England.

Sea Around Us. 2008*a*. A global database on marine fisheries and ecosystems. http://seaaroundus.org. Fisheries Centre, University of British Columbia, Vancouver

(British Columbia, Canada).

Sea Around Us. 2008*b*. Description of SAUP global fisheries mapping data versions. http://www.seaaroundus.org/doc/saup_manual.htm. Fisheries Centre, University of British Columbia, Vancouver (British Columbia, Canada).

Shackell, N. L. and K. T. Frank. 2007. Compensation in exploited marine fish communities on the Scotian Shelf, Canada. Mar. Ecol. Prog. Ser., **336**:235–247.

Sumaila, U., A. D. Marsden, R. Watson, and D. Pauly. 2005. Global ex-vessel fish price database: Construction, spatial, and temporal applications. Technical Report Working paper #2005-01, Fisheries Center: The University of Britich Columbia.

Tegner, M., L. Basch, and P. Dayton. 1996. Near extinction of an exploited marine invertebrate. Trends Ecol. Evol., **11**:278–280.

Therkildsen, N. and C. Petersen. 2006. A review of the emerging fishery for the sea cucumber *Cucumaria frondosa*: Biology, policy, and future prospects. SPC Beche-de-mer Information Bulletin, **23**:16–25.

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

Wood, S. N. 2006. Generalized Additive Models: An Introduction with R. Chapman and Hall, New York.

Worm, B. and R. A. Myers. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology, **84**:162–173.

Figures

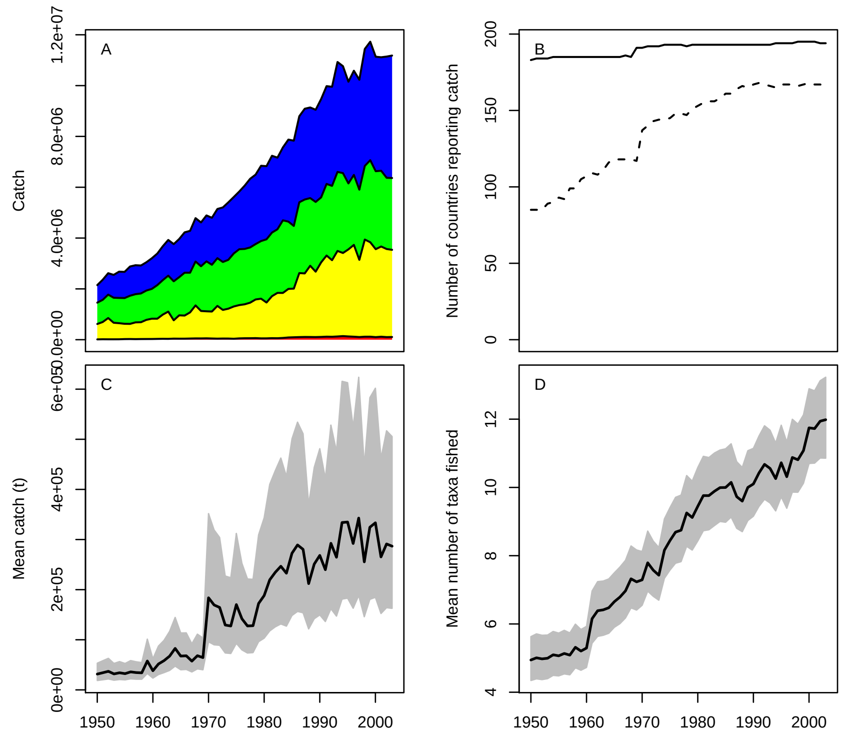

Figure 1: (A) Global catch for crustaceans (blue), gastropods and bivalves (green), cephalopods (yellow), and echinoderms (red). (B) Total number of countries reporting catch of any species (fish or invertebrate) (solid line), and number of countries reporting catch of invertebrate species (dashed line). (C) Mean and log-normal distributed 95% confidence interval of invertebrate catch per country. (D) Mean and 95% confidence interval of the number of invertebrate species reported fished per country.

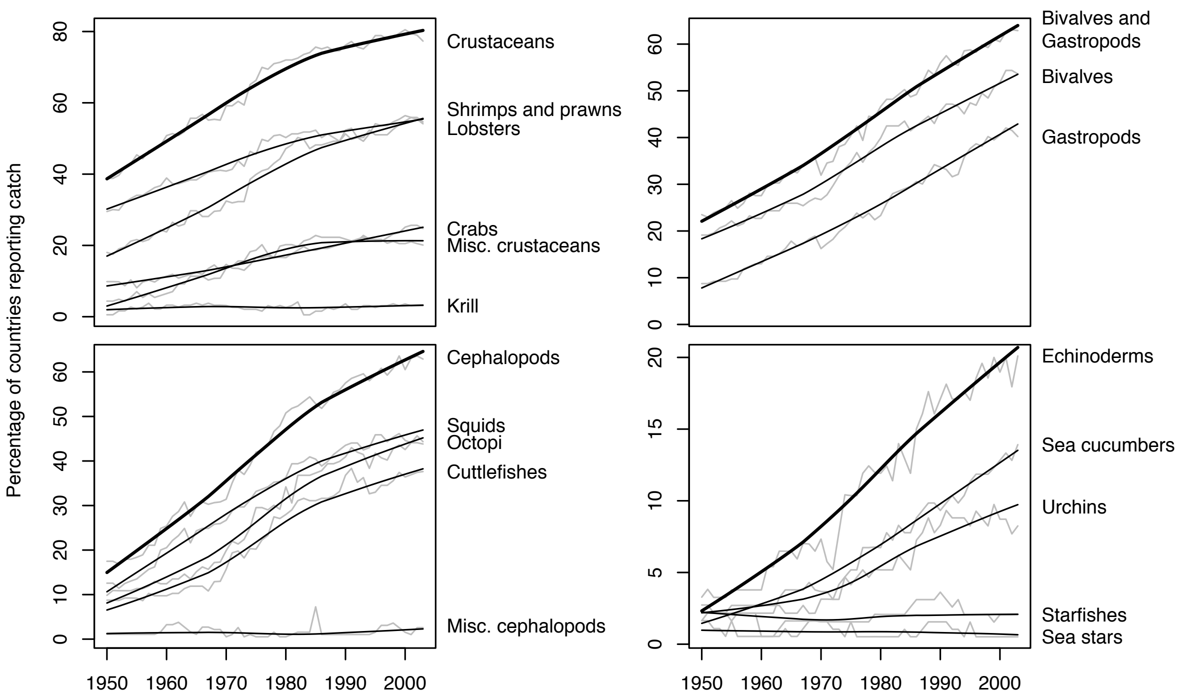

Figure 2: Percentage of those countries that reported catch of any species (finfish or invertebrate) who reported at least 0.5t of catch of a species from each invertebrate taxa. Light grey line represents original data; thick black line represents loess curve (smoothing span = 2/3). Note the different scales on the vertical axes. Upper darker line on each plot represents total for each grouping.

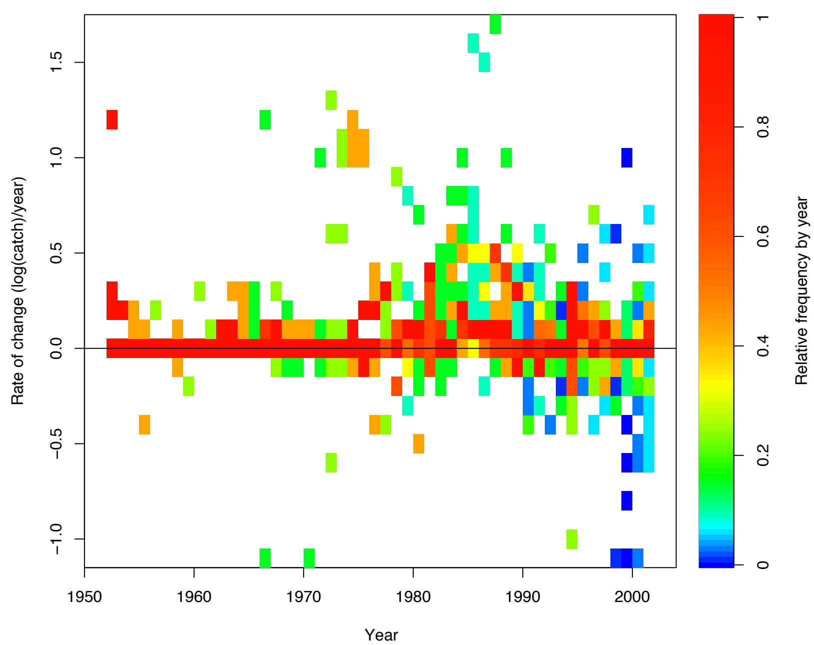

Figure 3: Relative frequency of first difference in log of catch trends for global sea cucumber fisheries. Frequency is relative to each year and the catch trends were smoothed with a 5 year running mean. Fisheries with less than 5 years of data were excluded. White areas represent an absence of data at these rates of change.

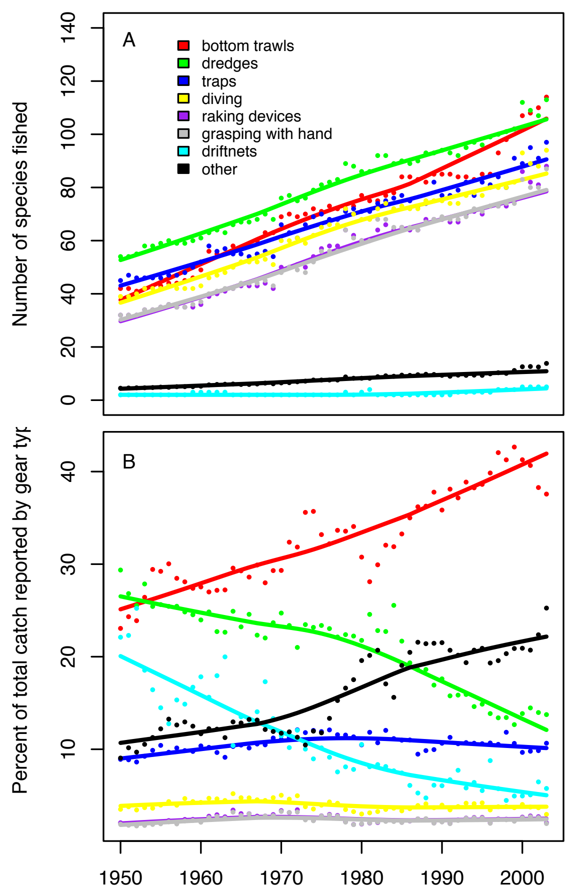

Figure 4: (A) Number of invertebrate species fished by various gear types. "Other" category represents mean number of species fished by the 12 gear types not shown. (B) Percent of total invertebrate catch reported for various gear types. "Other" category represents total percent of catch for the 12 gear types not shown. Dots represent original data; lines represent loess curves (smoothing span = 2/3). Other category includes: without gear, tongs, lines, squid hooks, mid-water trawls, purse seines, ring nets, gillnets, bagnets, hand dredges, pots, and box like traps.

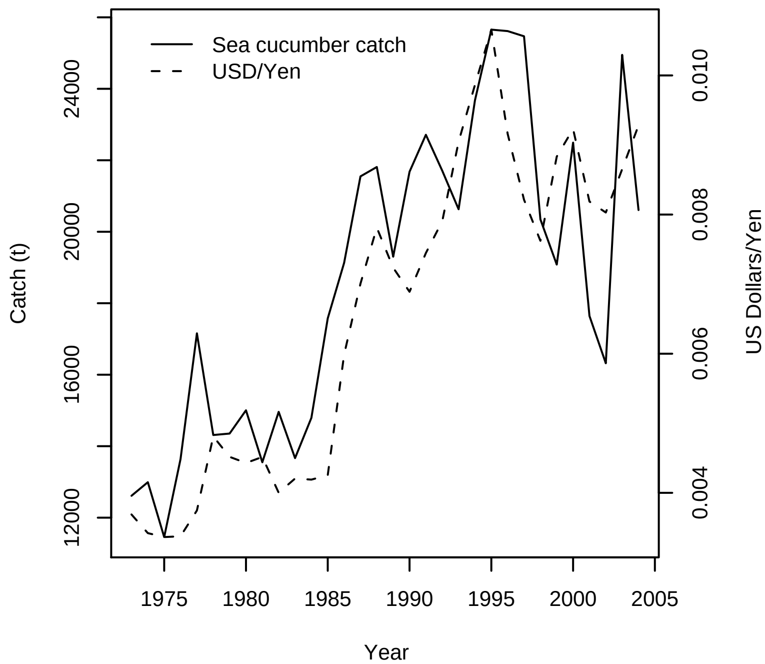

Figure 5: Global sea cucumber catch and the US Dollar-Japanese Yen ratio between 1973 and 2004 (correlation: r = 0.867, not adjusted for autocorrelation). Prior to 1973 the Yen-Dollar ratio was fixed and is not shown.

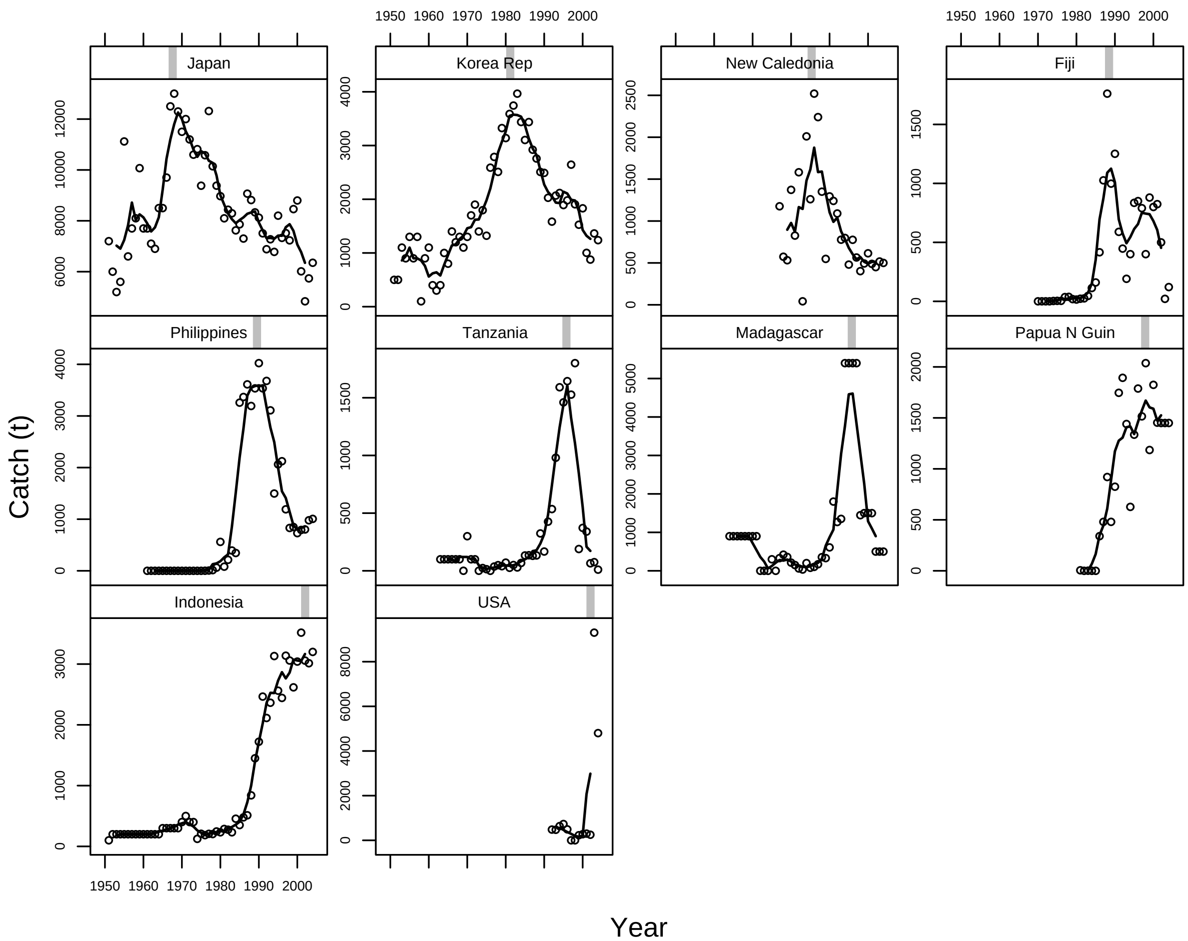

Figure 6: Sea cucumber catch for the 10 countries with the greatest combined catch from 1950-2004. Countries are ordered in ascending order by year of maximum catch (shown as grey bar in title regions) as obtained from a 5 year moving average (solid line). Data prior to first year of reported catch (zero tons) not shown. Note the different y-axis scales.

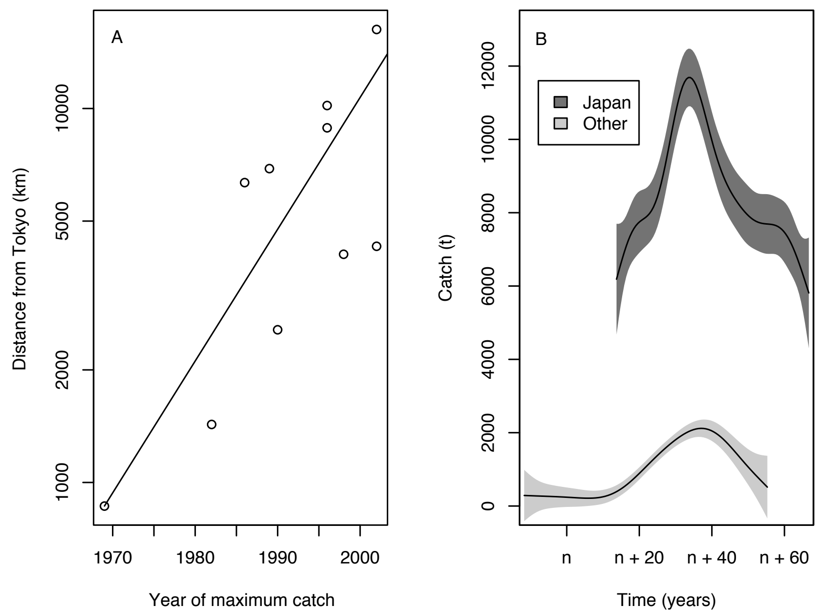

Figure 7: (A) Great-circle distance from the largest city in Japan (Tokyo) and the largest city in each of the 9 countries with the greatest total catch vs. the year of maximum catch for each country as calculated from a 5 year running mean (r=0.778, p=0.008). Points represent individual countries and the line represents the least-square linear regression fit. Note the log scale on the vertical axis. (B) General trajectory and standard error of Japanese catch (dark grey) and the 9 other countries (light grey) as calculated from additive models (1) and (2). The catch of the "other" countries was lagged according to (A) as shown by equation (3) to have a uniform calculated year of maximum catch. The horizontal axis units are in relative years since the absolute years no longer have meaning.

$$\mathbb{E}[CatchJapan_i] = f_1(Year_i) + \epsilon_i,\ \epsilon \sim Gaussian \tag{1}$$

$$\mathbb{E}[CatchOther_i] = f_1(LaggedYear_i) + \beta_0 + \beta_1 Country + \epsilon_i,\ \epsilon \sim Gaussian \tag{2}$$

$$Year_{max} = 12.32(log(D_{Tokyo}) - log(D_{Japan})) + Year_{MaxJapan}, \tag{3}$$

where $Year_{max}$ is the year of maximum catch for a given country, D_{Tokyo} is the distance from Tokyo to the largest city of a given country, D_{Japan} is the distance from Tokyo to the farthest Japanese coast (865 km), and $Year_{MaxJapan}$ is the year of maximum catch in Japan (1969).