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Global marine yield halved as fishing intensity redoubles

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Abstract

There is widespread concern and debate about the state of global marine resources and the ecosystems supporting them, notably global fisheries, as catches now generally stagnate or decline. Many fisheries are not assessed by standard stock assessment methods including many in the world's most biodiverse areas. Though simpler methods using widely available catch data are available, these are often discounted largely because data on fishing effort that contributed to the changes in catches are mostly not considered. We analyse spatial and temporal patterns of global fishing effort and its relationship with catch to assess the status of the world's fisheries. The study reveals that fleets now fish all of the world's oceans and have increased in power by an average of 10-fold (25-fold for Asia) since the 1950s. Significantly, for the equivalent fishing power expended, landings from global fisheries are now half what they were a half-century ago, indicating profound changes to supporting marine environments. This study provides another dimension to understand the global status of fisheries.

Keywords Fishing effort, fishing intensity, spatial expansion, yield

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Introduction

With the possible exception of human-induced climate changes underway (Cheung *et al.* 2009; Sumaila *et al.* 2011), fishing is likely to be the greatest anthropogenic impact on the world's marine ecosystems; therefore, we are compelled by concerns wider than our own future food supplies to closely monitor and understand consequential changes. While some argue that the decline in global fish landings (Grainger and Garcia 1996; Watson and Pauly 2001; FAO 2009) is being largely reversed or even engineered by prudent management (Garcia and Grainger 2005; Hilborn 2007; Worm *et al.* 2009; Branch *et al.* 2011), others maintain that fisheries demand a significant share of ocean production and that overexploitation has undermined the productivity of fisheries and the ecosystems into which they are embedded (Pauly and Christensen 1995; Jackson *et al.* 2001; Chassot *et al.* 2010). Consensus is difficult because most countries lack the resources to complete conventional assessments, leading to potential bias. Attempts to obtain a generalized picture using the only source of global data – trends in commercial landings – although criticized (Branch *et al.* 2011), have been vindicated (Froese *et al.* 2012, Kleisner *et al.* 2012).

The response of fisheries resources to exploitation allows an insight not only into the state of these fisheries but also into ocean health in general. Comprehensive data on fishing intensity (Watson *et al.* 2004; Anticamara *et al.* 2011) will greatly assist in the interpretation of widely available landings data.

Methods

Data sources

Fishing effort data for the period 1950–2006 were obtained from the United Nations Food and Agriculture Organization, the European Union, global tuna commissions, and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Data from these diverse and disparate sources were brought together in standardized units based on engine power (watts) and fishing days (Anticamara *et al.* 2011).

Anticamara *et al.* (2011) reported on the state of global fishing effort statistics. They found many weaknesses such as years with no reported effort for some countries, and indeed no effort statistics at all for some countries. They proposed methods to fill these gaps. They did not, however, attempt specifically to estimate fishing effort by global tuna fleets or those fleets fishing in the Antarctic. The former are very extensive and use powerful, widely ranging fishing vessels. The latter have good statistics but fish far from ports in very sensitive marine habits. As such, the Anticamara study did not attempt to summarize all global fishing effort. Unlike the current study, they did not attempt the difficult task of mapping fishing effort but left it by reporting country. Fishing effort statistics, unlike global fisheries catch statistics, are not provided by reporting areas, so initially nothing is known about where the fleets fished. This had to be deduced from what is known about catch. Global catch has been mapped (Watson *et al.* 2004) but to do the same for fishing effort was more difficult because of the poor data quality generally. This was to allow for the interaction between fishing effort and other spatial marine data to be investigated. These include, for example, interactions with sensitive marine habitats and with populations of marine mammals and seabirds. Mapping fishing effort also allowed us to use previously mapped fisheries catch data to examine important trends in fisheries yields.

All fishing effort used in this study was in the public domain when sourced. Primary sources were United Nations Food and Agriculture Organization (FAO) and European Union (EU). From these, we removed all identifiable tuna fisheries effort data to avoid overlap with other sources (we refer to what remained as 'port-based' effort). To this, we added tuna fisheries effort data from the Secretariat of the Pacific Community (SPC), International Commission for the Conservation of Atlantic Tunas (ICCAT), Inter-American Tropical Tuna Commission (IATTC), Indian Ocean Tuna Commission (IOTC) and FAO's Atlas of Tuna and Billfish (ATB), while being careful to avoid overlaps. For the fisheries of the Antarctic, the source was CCAMLR. Basically, the port-based fishing effort data compiled by Anticamara *et al.* (2011) were augmented by data from tuna data sources and CCAMLR (both describing widely ranging fleets where ports have less significance to the mapping process) (Fig. 1). These sources were accessed online during 2009.

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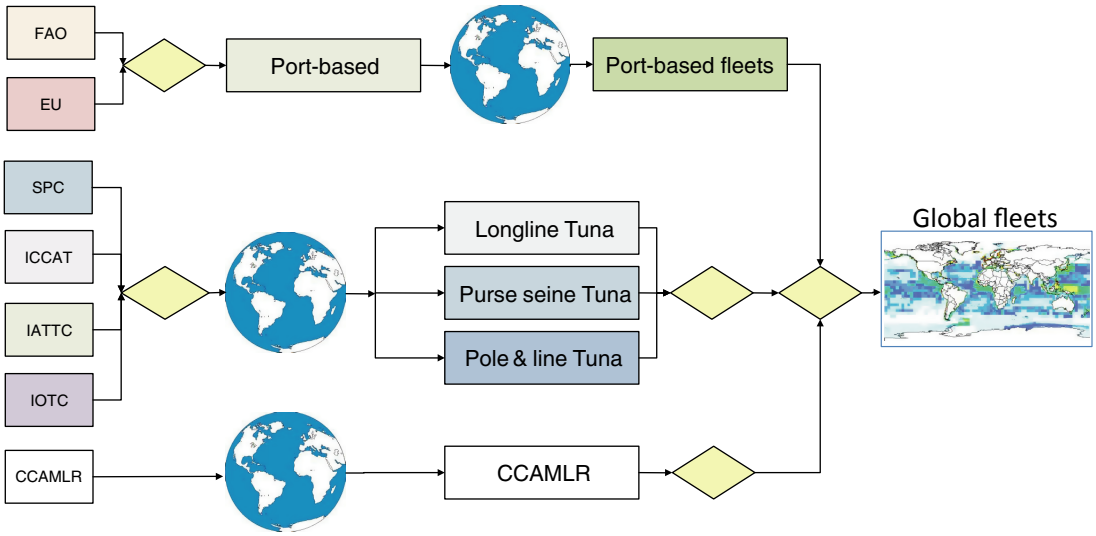

Figure 1 Flowchart to show assembly of global effort database. Data sources appear on the left. For the port-based effort, these are FAO and EU; for tuna fisheries, these are Secretariat of the Pacific Community, International Commission for the Conservation of Atlantic Tunas, Inter-American Tropical Tuna Commission, and for the fisheries of the Antarctic Commission for the Conservation of Antarctic Marine Living Resources. Diamond symbols indicate data were harmonized (units converted) and merged. Globe symbols represent mapping using rule-based methods that were customized for the effort type. Resulting database components appear to the right of globe symbols, and these in turn were merged to produce the global effort database.

Standardization of nominal global effort

The standardization procedures used were as described in Anticamara *et al.* (2011). In addition, it was necessary to standardize effort data from tuna data sources to continuous power use by the principal fishing vessels in watts. Reporting of fishing effort for tuna fleets traditionally uses units of hooks, net sets or fishing days (or combinations), whereas effort data for other fleets are often in vessel numbers or their associated dimensions or power rating. We choose to convert all measures to a continuous (as if the fleet fished all year) power rating based on the main engine expressed in watts.

Most fishing effort data have deficiencies, some major. Initially, these had to be addressed individually for each data set used. The data sets from EU and FAO presented challenges in the conversion of units and in the interpolation and extrapolation of missing data. The latter consisted not only in missing years when no data were reported by a fishing country, but also in data for some countries missing altogether. Missing periods in the time-series data were extrapolated and interpolated while data from missing countries were represented by surrogates following a classification analysis of all available data. In this analysis, countries were clustered according to their landings of marine taxa associated with types of fishing gears (Watson *et al.* 2006a,b) to identify which surrogates best fitted a county's fishing pattern and intensity. This was required for only a small proportion of the total global fishing effort.

Some tuna data sources and data from CCAMLR included spatial information which FAO and EU sources did not include. Once overlapping reports from tuna fleets were removed, the latter sources for non-tuna effort were considered to be largely reports of fishing effort associated with fishing ports. Some sources of tuna data had only relatively coarse spatial references (e.g. by 5-degree blocks) while others such as purse seine data often included exact longitudes and latitudes. The decision to release the details of where spatial effort was expended, or even which country was fishing, varied and depended partially on what data were collected by agencies, but mostly on the policies of these agencies and commissions. Some data are deemed confidential and are not available. Data from these agencies are, however, reported to the FAO, and we used their ATB which reports data on large spatial grids, to extrapolate spatial distributions where required. Furthermore, when the identity of the fishing country associated with the effort was not released (as with SPC tuna data),

we used the mapped catch data from the Sea Around Us project (Watson *et al.* 2005, 2006a,b) to infer the breakdown of effort by fishing country. The Sea Around Us data were also used to clarify likely fishing gear types associated with reported fishing effort so that it was possible to associate all fishing effort to a broad gear type.

Mapping fishing effort

The mapping of non-tuna-related data from FAO and EU into spatial cells of 30-min longitude and latitude proceeded in two steps. The first was to associate the fishing effort to ports, and the second was to model the distribution of fishing effort from each of those ports. The Sea Around Us project (Watson *et al.* 2005, 2006a,b) had prepared maps of reported landings broken down by country fishing, taxa and associated fishing gear for the period 1950–2006. These maps integrate what is known about the distribution of the reported taxa, the access of countries to the coastal Exclusive Economic Zones of other countries and other factors. It was therefore possible to calculate the likely landings taken from all spatial cells accessible by fishing fleets operating around each potential port in the world. The ratio of these was used to prorate fishing effort between ports for each fleet (defined by country and broad fishing gear type) for each year.

Then, a 'gravity-model' (Gelchu and Pauly 2007) was used to determine how much of the fishing effort was associated with each spatial cell in accessible proximity to each port. This recursive model optimized for benefit/costs using the catch value (in $US) known to be taken by country and gear type based on mapped catch (Sumaila *et al.* 2007), and the cost of reaching that cell from each port, taken to be related to the fuel intensity associated with that type of fishing by a given county, the distance to that cell and considering competitive fishing by other vessels and fleets.

Each type of fishing effort was initially mapped in the fishing effort units usually associated with it. For the longline tuna data, these were '1000 hook-days', for purse seine and pole and line tuna data these were 'days fishing'. With the FAO and EU data, it was possible to calculate kilowatt fishing days based on vessel power and assumptions about the number of days vessels were fishing on average. For the other data sets, this was possible only after additional research into associated fishing vessel sizes, engine power and fishing patterns. After these data were mapped to spatial cells (which change size with latitude), the units were expressed as watts (expended annually) per square kilometre of ocean area (Fig. 2).

Effective fishing effort

Fishing effort reported by agencies and used in our analysis is not initially adjusted for annual efficiency changes. Changes in fishing efficiency can be estimated, and fishing effort can be standardized in terms of its effective power (termed effective effort). Here, we have used a conservative annual increase in efficiency of 2.42% based on a prior meta-analysis of published efficiency increases (Pauly and Palomares 2010) and standardized all effort values to the year 2000.

Catch per unit of effort (CPUE) analysis

To examine CPUE without bias (Walters 2003), it was necessary to compare the independently developed global catch database (Watson *et al.* 2004) with fishing effort records, using generalized additive and linear models (Wood 2006) to control for distance from shore, fishing gear, latitude and longitude following a range of interpolation and extrapolation procedures (Data S1).

The extensive database that was developed over a 3-year period and covered all reported global fishing from 1950 to 2006, comprising billions of data records. Using database information on the country of origin of the fishing fleet (regardless of location or port used), it was possible to map for any year or for decadal averages the distribution of fishing effort from each continent.

Results and discussion

Changes in effort intensity and spatial distribution

We find that global fishing intensity has been growing continuously since 1950 (when conventional data collection started). Correcting for very modest increases in efficiency (Pauly and Palomares 2010), the intensity of fishing effort has grown 10-fold for all countries on average during this period (Fig. 3a), but with great variability between regions (Fig. 3b). The largest increase by continent was Asia, which increased its effective fishing effort by 25-fold since 1950. In contrast,

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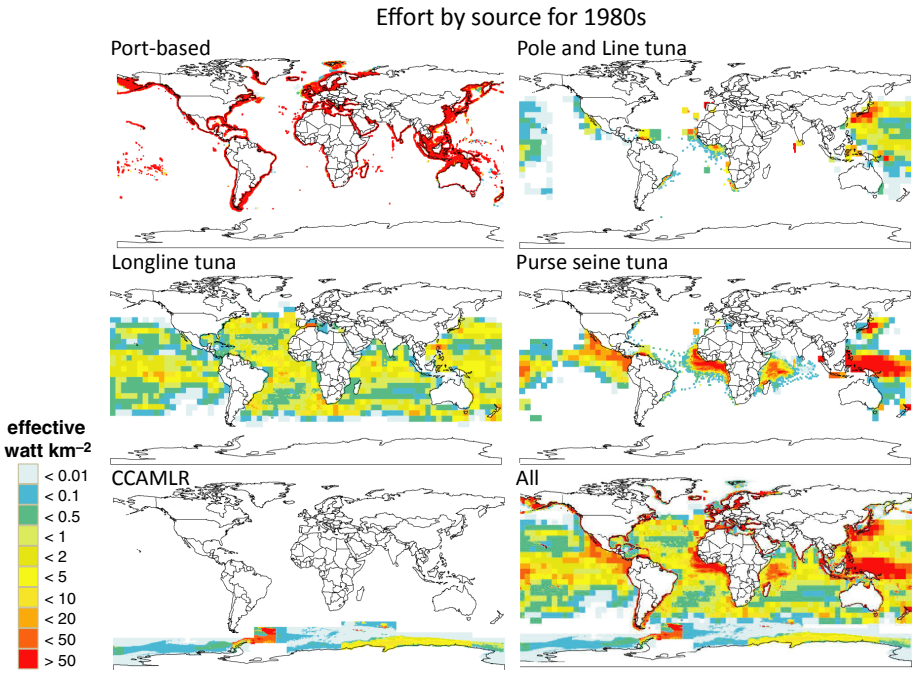

Figure 2 Mapped effective fishing effort for each of the major database components (see Fig. 1 for details) for the 1980s.

catch per unit of fishing effort (CPUE), an important proxy of resource abundance, decreased during this period (Fig. 3c). While effort has increased since the 1950s, and fisheries had expanded their reach over the global oceans (Figs 3a and 4), catches, which strongly increased from the 1950s to the mid-1980s, started to stagnate, and then slowly declined in the late 1980s, in spite of the continuing increase and expansion of effort in the last two decades. Despite new technologies, the high value of seafood and the global nature of the industry, we seem unable to increase global landings or even halt the slow decline. Inherent limitations of the resource would seem to be the most likely explanation (Chassot *et al.* 2010).

The trajectory of the relative CPUE in Fig. 3c is of concern as it implies a continual decline in resource abundance. More fishing effort measured in the power of fishing vessels is not returning a commensurate increase in landings. Extrapolation would be dangerous, however, as even with industry subsidies and high seafood prices a continued decline in returns is likely not sustainable.

Change in CPUE

The reduction in CPUE shown in Fig. 3c indicates that it is very likely that biomass supporting global fisheries has been substantially reduced in the last few decades. We believe that CPUE was maintained in many areas of the world until the mid-1990s through a continued expansion of global fisheries into newer areas (Fig. 4) as older ones were depleted. This pattern of spatial expansion of fisheries corroborates with those reported by Swartz *et al.* (2010). It is not possible to know whether the reduction in CPUE is directly proportional to biomass reduction. This is because there are many varying fisheries involved, and it is widely accepted that CPUE may not represent biomass in all fisheries well, especially when stocks aggregate. We do believe, however, that there has been a real and substantial reduction in biomass. For some fisheries, this may only represent a reduction to B_{MSY} levels. This is a reduction to approximately half of the unfished biomass levels, generally accepted as the maximum sustainable yield, often first attributed to Gulland's handbook (1969). It is, however, very important to note here that many global fisheries were already below their initial unfished biomass levels when our time series began in the 1950s. Certainly many fisheries including those in the North Sea had seen intense fishing for several decades by that time. Therefore, the reduction to about half the biomass implied by the CPUE decrease could easily repre-

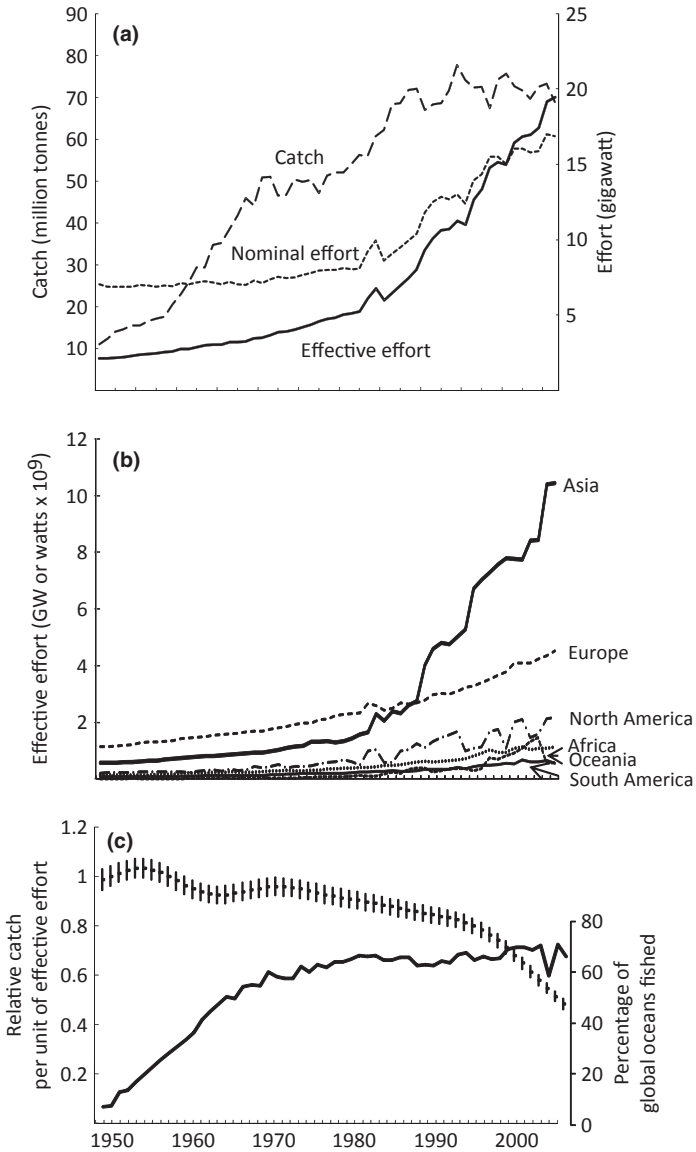

Figure 3 Trends in global fisheries from 1950 to 2006 as indicated by (a) total catch (landings) and effort, (b) fishing effort by continent of fleet and (c) catch per unit of effort (with error bars) and per cent of global oceans fished by area (solid black line). Global fisheries catch is based on the Sea Around Us project data (Watson *et al.* 2004). Concurrent global fisheries effort in gigawatts annually is expressed in both nominal and effective [standardized to the year 2000 to correct for increasing efficiencies (Pauly and Palomares 2010)]. Relative global catch per unit of effective effort is estimated from a general additive model (bars are 95% confidence limits) (see Supporting information).

sent reductions >50% of the initial biomass levels for many fisheries. It is also now widely accepted that while biomass of the most productive stocks fished may be reduced to half and reach some maximum sustainable yield, it will nevertheless cause less productive species and stocks to either be eliminated or reduced below their respective MSY (Larkin 1977). Gulland (1969) stated that the obtainment of MSY (i.e. reductions of biomass to half their unfished state) should not be the object of management except in exceptional circumstances.

Fisheries landings have been mapped with some confidence showing where the catches were taken (Watson *et al.* 2004), however, we present here the first attempts to map global fisheries effort. As Anti-

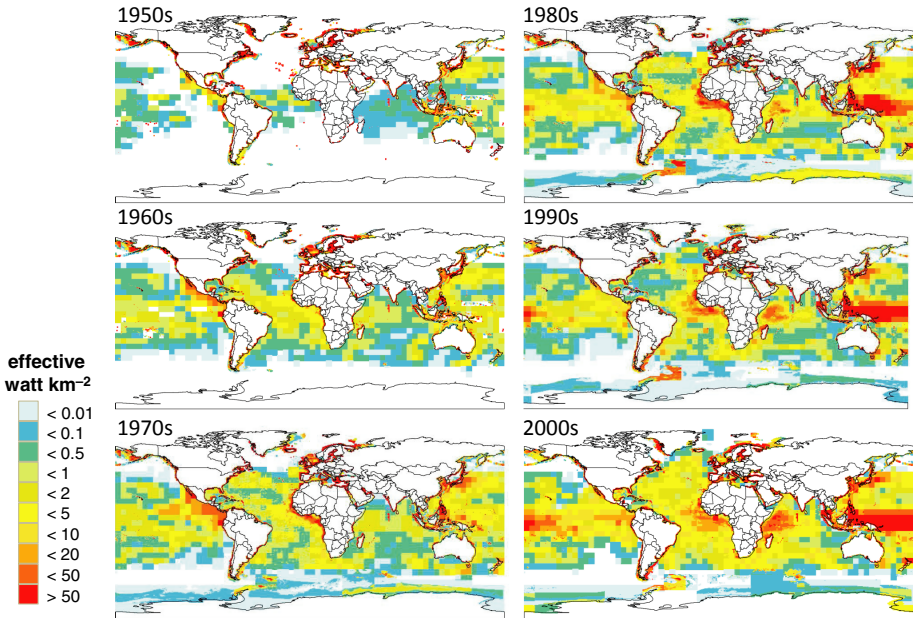

Figure 4 Decadal averages for global mapped fishing effort. The panel labelled 2000s is an average inclusive of 2000–2006. The legend is graded from low effort intensities effort (pale blue) to high (red) in watts year^{-1} km^{-2} of ocean.

camara *et al.* (2011) pointed out, the current quality of fisheries effort data is much poorer than that of catch data, and the quality is also quite variable. For example, in Fig. 3b, we can see fluctuations in the effort of North American fishing fleets that are associated largely with those vessels using tuna purse seine gear. Post-1994 there were three fishing effort reductions that may be partially attributable to reporting problems with the agencies involved. It is possible, however, that changes in fishing arrangements in the coastal waters of tropical countries may also have contributed. We believe that effort reporting is mostly to blame as the catch of 'tuna-like' fishes from this region was relatively constant. There may be similar reasons for the decline in fishing effort by the fleets from Oceania. This trend was reversed in 2006 when our time-series data end. Fishing access arrangements are important for wide-ranging fleets such as those chasing tuna with purse seine gear. National exclusive access claims to coastal seas mean that the richest resources are normally only available through negotiation. A reduction in the access arrangements of foreign fleets may explain the slight dip in the per cent of global oceans fished in Fig. 3c but is hard to verify this as frequently such arrangements are confidential.

Fishing fleets have not just increased their intensity since the 1950s, but they have also expanded their reach, deploying fishing gear over an increasingly large part of the world's oceans (Swartz *et al.* 2010). This is particularly well demonstrated by mapping fishing effort by Asian and European fleets (Fig. 5). It is likely, however, that there have been even greater increases in the fishing effort of developed countries in some coastal waters than our figures here reveal. After the mid-1970s, Exclusive Economic Zones (EEZ) were being declared globally. This restricted access and forced fleets from developed countries to negotiate access arrangements with developing countries. At times, however, though they might be brokered by governments, these arrangements were treated more as confidential business transactions. When reviewing global catch data, it sometimes appears as if foreign fishing has abruptly ceased, but on closer inspection, it can be seen that visiting fleets have simply adopted the 'flag' of the resource provider. Vessel 'reflagging' does much to conceal the full extent of fishing by foreign fleets in some countries (Agnew *et al.* 2009). This means that vessels that appear to be from NW Africa, for example, may actually be operated by fishing companies based in European or Asian countries, which would effectively mask some of their increasing fishing effort in this region. At the end of 2006, it was reported that there were approximately 400 fishing vessels operating under

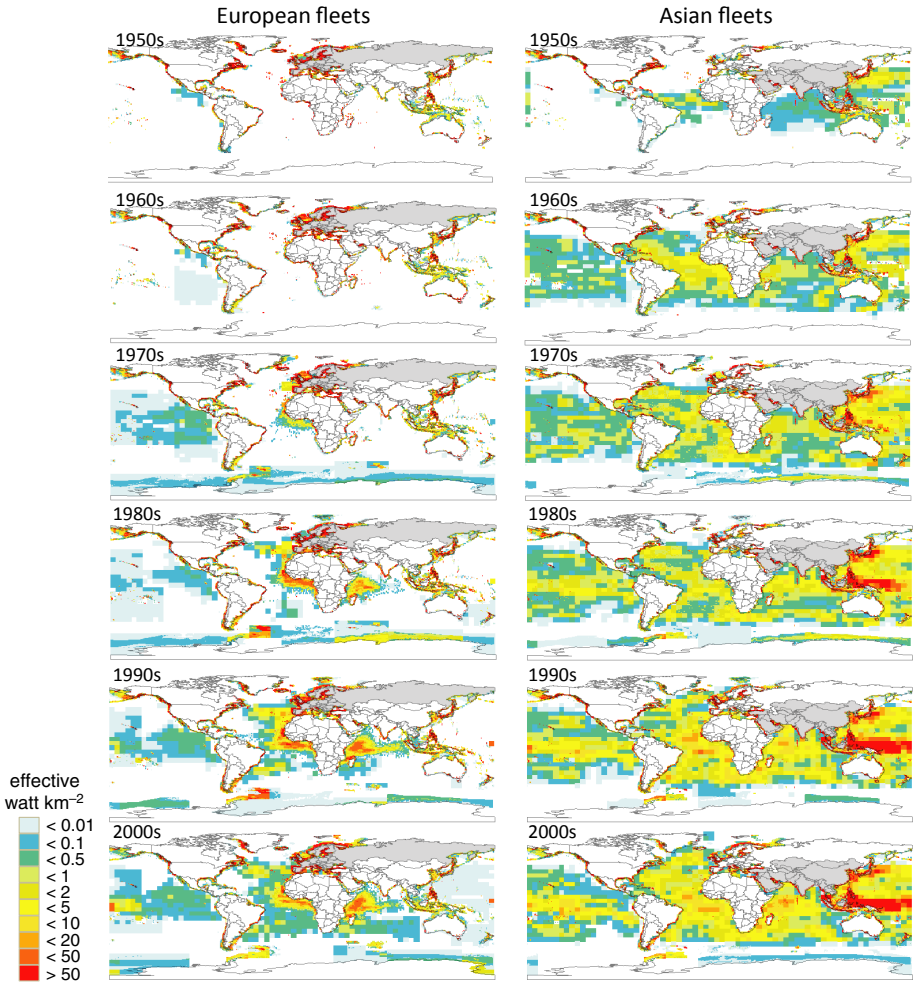

Figure 5 Decadal averages for global mapped fishing effort from European and Asian fleets. The 2000s is an average inclusive of 2000–2006. The legend is graded from low effort intensities effort (pale blue) to high (red) in watts year^{-1} km^{-2} of ocean.

mixed companies established in third-world countries with a European partner (European Union http://www.cfp-reformwatch.eu/pdf/013.pdf), and the practice is widespread.

We also used a GAM analysis for each geographic region (FAO statistical area) to reveal their CPUE trends (Fig. 6). In general, the majority of the 18 regions had an overall reduction in CPUE in recent years following some maximum in the 1970s or 1980s, though individual patterns differ somewhat. In the Northeast Atlantic, overall CPUE increased from the 1950s to 1990s then declined rapidly. There was no clear trend of CPUE in the Northwest Atlantic. In Western Central Atlantic and Southwest Atlantic, CPUE decreased to around 40–50% of the 1950s level. On the eastern side of the Atlantic, no consistent CPUE trend was found in the eastern central area, while a steady decline in CPUE from the 1950s to 20% of the historical level in the 2000s was found in the south-western region. In the northeast Pacific, the CPUE trend was mainly dominated by the rapid expansion of the trawl catches, largely contributed by the Alaskan Pollock fisheries. In the northwest Pacific, CPUE declined rapidly from the 1950s to the 1970s, followed by a large increase until the late 1990s. CPUE has decreased rapidly since then. In the Indo-Pacific region, CPUE increased steadily until the 1980s and then decreased. CPUE in the Eastern Central Pacific decreased from the 1970s, while those in southeast Pacific increased. Decrease in CPUE was consistent in both the eastern and western Indian Ocean.

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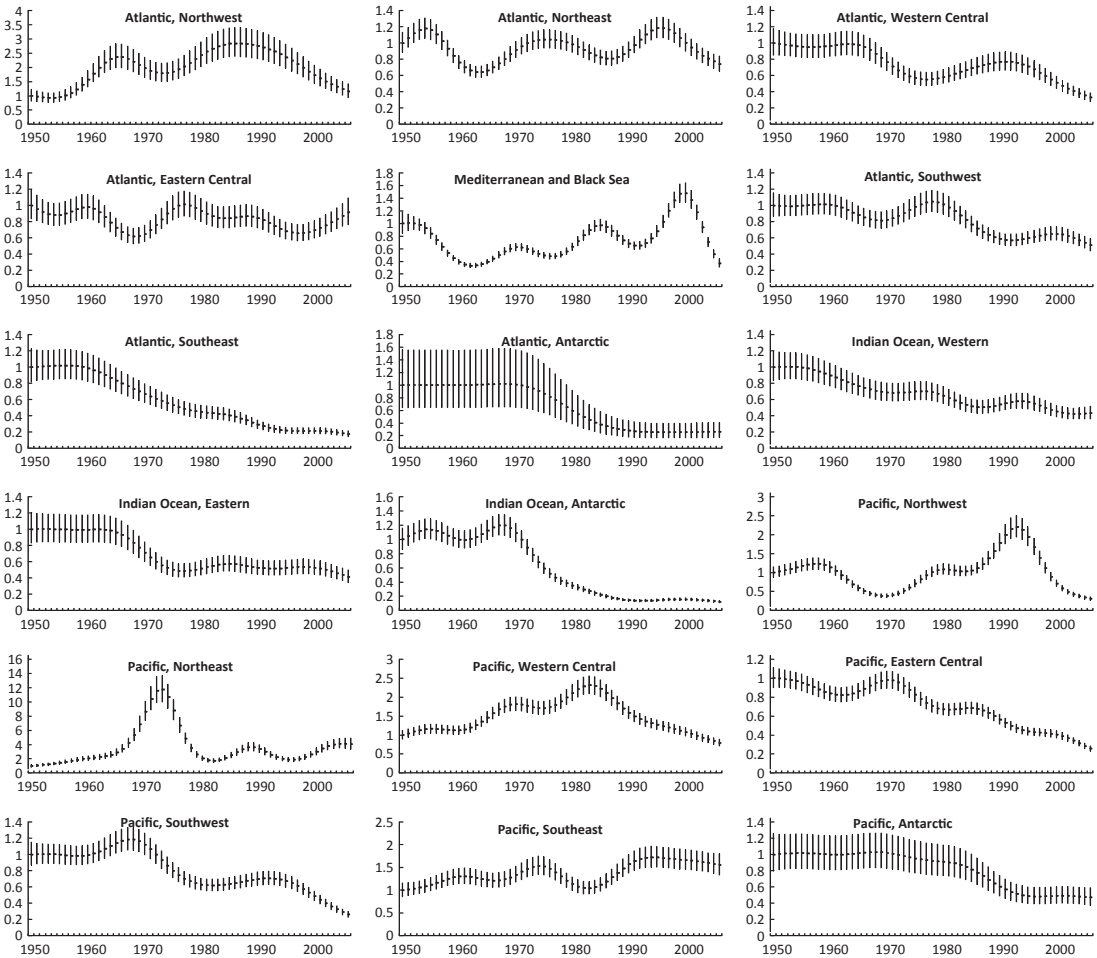

Figure 6 Relative catch per unit of effective effort for each FAO statistical reporting area based on a generalized additive model. The *x*-axis is the fishing year (1950 until 2006), and the *y*-axis is the relative catch per unit effort (scaling varies).

How can fishing continue to intensify and expand its range despite falling yields for the effort and money invested? The main reason the expansion has continued is that most fishing fleets are supported by huge government subsidies which allow them to operate when they would otherwise have been reduced years ago (Sumaila *et al.* 2010). Sumaila *et al.* (2010) estimated this globally at US$ 18.5 billion for developing countries and US$ 8.8 billion for developed countries. This is especially true for fuel, which is one of the biggest costs to fishing (Tyedmers *et al.* 2005; Sumaila *et al.* 2008), and more so as falling catches force fleets to range further and further from ports.

Human population pressures and global warming will exert huge impacts on our marine environments, their important biodiversity and resources (Pauly *et al.* 2005; Worm *et al.* 2006, 2009; Halpern *et al.* 2008). Taking action to curb our demands to sustainable levels, especially on the high seas, has never been so important. Whatever climate change brings, it will create difficulties for some regions even while improving productivity in others (Cheung *et al.* 2010), but we must increase our vigilance. Finding ways to monitor all global fisheries, even for those countries unable to afford the newer, more intensive methods, is long overdue.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Methods.

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