FISH and FISHERIES

Global fishing capacity and fishing effort from 1950 to 2012

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Abstract

Global marine wild-capture landings have remained relatively stable for >20 years; however, there is a lack of credible fishing capacity and effort information required to assess the sustainability and efficiency of the global fleet. As such, we estimated global fishing capacity and effort from 1950 to 2012 using a relatively comprehensive database developed by the FAO, supplemented by other data sources. Using random sampling techniques, we estimated the uncertainty surrounding many of our estimates enabling the identification of deficiencies and limitations. Global fishing capacity and effort increased rapidly from the late 1970s through to around 2010 before stabilizing. The Asian fleet is more than an order of magnitude larger than any other region in both capacity and effort, and continues to increase. Most other regions have stabilized, and there have been considerable declines in Europe and, to a lesser extent, in North America. Developed nations, as a whole, have decreased in both measures in the recent years and are responsible for the stabilization of the global trend. Developing and undeveloped countries are still increasing with the former having the largest fleet and showing the greatest relative increase with the socioeconomic impacts of reversing these trends likely to be high. The efficiency of the global fleet, in terms of watt days of fishing effort per tonnage of wild marine catch, is now less than in 1950 despite the considerable technological advances, and expansion throughout the world's oceans, that has occurred during this period of time.

Keywords Fisheries management, fishing efficiency, fishing energy use, fishing power

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Introduction

Global marine wild-capture fish landings have remained relatively stable at 75 to 85 million tonnes since the early 1990s (FAO 2012, 2014); however, reconstruction of the total catch (including discards) indicates a steady decline since 1996 (Pauly and Zeller 2016). The proportion of stocks assessed as overfished globally has increased from 10% in 1974 to 28.8% in 2011 (FAO 2014). As such, current global landings may be unsustainable, and their observed stability is potentially the result of increased fishing effort, the transfer of effort to previously under exploited stocks or misreporting (Watson and Pauly 2001; Watson *et al.* 2013; FAO 2014).

Global fishing capacity (the quantity of fishing vessels participating in fisheries) was estimated to be double that required to catch global landings, which costs the global economy an estimated US $51 billion (80% CI of $37 billion and $67 billion) in 2004 alone (Arnason *et al.* 2009). At present, however, there is a lack of quantitative information regarding the fishing capacity and fishing effort (the amount of fishing) that take the global marine wild catch. Although regional bodies such as the European Union (EU) and various international tuna commissions gather significant data, the only organization that attempts to gather the information required to estimate this globally is the FAO. Their efforts are hampered by a lack of reporting by many countries (Anticamara *et al.* 2011; Watson *et al.* 2013), which stems in part from social complexities associated with fisheries management (Holt 2009). Landings data tend to be more complete, and FAO presents a global breakdown of landings biennially along with select fishing capacity information [see FAO (2014) for most recent edition].

Reducing fishing capacity and associated fishing effort were flagged as one of the key actions required to ensure the sustainability of global wild-capture fisheries (FAO 2014) and to ensure the greatest economic yield (Arnason *et al.* 2009; Ye *et al.* 2013), which is critical if these resources are to play a significant role in nourishing the worlds' growing population.

Fishing capacity and fishing effort can be measured in a myriad of different ways. Published accounts include the following: the number of vessels taking part in a fishery (Dunn *et al.* 2010; Rodríguez-Quiroz *et al.* 2010); the quantity of gear used (e.g. the number of hooks, length of gillnet, the number of traps) (Miller 1990; Walker *et al.* 2005); the duration of fishing (e.g. time spent trawling) (Greenstreet *et al.* 1999; Jennings *et al.* 1999); the product of the tonnage or length of vessels taking part in a fishery (Dunn *et al.* 2010; Stewart *et al.* 2010), or the amount of power [horsepower (HP) or kilowatts (KW)] expended while fishing (Philippart 1998; Villasante 2010; Anticamara *et al.* 2011). A detailed review of the various measures of fishing capacity is available in Kirkley and Squires (1999). Most of these measures vary considerably, and it is not possible to combine them in a meaningful fashion to describe the trends of mixed fleets (e.g. at a country, regional or global level). To be comprehensive, any measure should capture fishing operations ranging from those operated by hand, through those operated via sailing vessels, and extend through to giant pelagic purse seiners. This means using measures other than the number of hooks, or net lengths or other measures that cannot be translated across this spectrum (Anticamara *et al.* 2011). Further, most of these methods are only able to quantify nominal fishing effort, which does not take into account technological advances, or the skill of the skipper and crew, potentially masking increases in effective fishing effort.

Only one study has attempted to quantify fishing effort on a global scale, which was achieved by estimating fleet capacity, measured in (KW rating of the main vessel engine) KW, multiplied by the number of days that vessels fish, thus providing a measure of KW days of fishing effort

(Anticamara *et al.* 2011). This approach has gained support recently: the FAO reports the fishing capacity of selected countries in KW (FAO 2014), and in an attempt to spatially restrict fishing effort to facilitate the recovery of Atlantic cod (*Gadus morhua,* Gadidae), countries within the European Union (EU) are assigned set numbers of KW days spatially (EU 2008, 2013). In addition, this technique allows fuel consumption and greenhouse gas production to be easily estimated, which enable the indirect impacts of fisheries to be assessed (Pauly *et al.* 2003; Tyedmers *et al.* 2005).

Anticamara *et al.* (2011) were, however, hampered by a lack of data in the recent years (ending in 1995 for most countries) and were therefore required to forecast greatly to estimate trends up until 2010. Since then, FAO has developed a more comprehensive database of the vessel numbers from most countries current to 2012. Using these superior data, along with other sources, this study presents the major improvements to Anticamara *et al.* (2011) using bootstrapping techniques to estimate uncertainty, thereby enabling identification of factors responsible for introducing uncertainty. The findings suggest that there was a large increase in both fishing capacity and effort throughout the 1990s and 2000s, trends unable to be identified by Anticamara *et al.* (2011), and that global fleets are far larger than is required to take the global catch. This study can therefore provide guidance in the future direction of monitoring and managing the capacity and effort of global fishing fleets.

Methods

A more thorough description of the methods is provided in the supplementary information. All statistical analyses were undertaken using R (R Core Team 2014).

Data availability

Three FAO data sets were utilized (detailed below), each providing various annual country levels of information on the numbers of fishing vessels in various length, or gross registered tonnage (GRT), and at times gear type categories from 1950 to 2012. Data were also obtained from the European Union (EU) 'EUROPA' vessel registrar database (http://ec.europa.eu/fisheries/fleet/) that includes detailed information on individual vessels, including length, gross tonnage, engine power, fishing gear, and the date of commission. Additionally, within the EUROPA database, there was detailed information on fleet dynamics (http://datacollection.jrc.ec.europa.eu/), specifically the number of days fished by various fleets annually from 2008 to 2011.

Data processing

To identify whether vessel power varied with fishing gear and through time within each gross tonnage (GT) class, we performed a series of Kruskal–Wallis tests for each length and GT category of the EU data set. In almost all cases, power varied through time and between fishing gears (detailed in supplementary information), and therefore, wherever possible, all interpolation of fishing power for the FAO data, using EU data, was undertaken using vessels from the same year and with the same gear type. All fishing gear categorizations were made following the International Standard Statistical Classification of Fishing Gear System (FAO, 1990).

The early data (1950–1967) contain the annual total GRT of the fishing fleet of a selection of countries by fishing gear. Firstly, GRT was converted to GT using the linear relationship developed by Cross (2001). We then used linear models derived from the EU data set to estimate the fishing capacity, in watts, of a fleet with a given GT.

The second two FAO data sets contain the number of vessels in various GT, or length, classes, and the EU data were used to estimate the fishing capacity, in watts, of each. To this end, a form of 'hotdeck' imputation (Andridge and Little 2010) was used whereby suitable donor vessels (i.e. from the same year and with the same gear) were extracted from the EU fleet, and a random sample of the power of an equivalent number of vessels was taken 1000 times (i.e. bootstrapped) to create a distribution of possible capacity estimates. A Shapiro–Wilk test was used to determine whether the bootstrapped results were normally distributed: if normally distributed, the mean was retrieved, and if non-normally distributed, the median was used. From the bootstrapped data, 5 and 95% confidence intervals were then obtained. Where gear and/or length and/or GT were not provided, the donor vessels were retrieved using whatever level of information was available.

To impute a country's capacity for missing years within the time frame in which data were reported, generalized additive models (GAM) of the annual fishing capacity trend through time were created using the 'mgcv' R package. The capacity value for the missing year was retrieved from the GAM, and 5 and 95% confidence intervals were retrieved from the model.

When a country's data did not extend to 2012, or historically back to 1950, forecasting and backcasting were undertaken as required using autoregressive integrated moving average (ARIMA) models. These were created using the 'autoARIMA' function from the forecast package in R, and confidence intervals were retrieved from the models.

For countries that report marine landings to FAO but for which no fishing fleet data exist, we identified a surrogate country through a cluster analysis based on a Bray–Curtis dissimilarity matrix of their reported landings (Watson *et al.* 2004). Once the best possible surrogate was identified (i.e. the country with the least dissimilarity), the capacity and effort of the surrogate were weighted relative to the difference in the annual tonnage of their landings to represent the country in question.

Finally, when insufficient data were available to enable ARIMA modelling of early and late data, the last available value was carried forward, or backward, to complete the data set as required.

Calculation of fishing effort

The number of days fished (i.e. days when fishing gear was deployed) was estimated by back-calculating the mean number of days fished by individual vessels within the aggregated EU fleet data. This provided mean annual fishing days for >1200 combinations of vessel length, gear type and year combinations from 2008 to 2011. Kruskal–Wallis tests were then used to determine whether the number of days fished annually varies with vessel length class or fishing gear. Where significant differences existed, multiple pairwise Mann–Whitney *U*-tests were performed to explore *post hoc* differences with *P*-values corrected for multiple pairwise comparison (Benjamini and Yekutieli 2001).

Based on the above methodology, appropriate linear models were fitted to the data numerically, enabling fishing days to be estimated for vessel length classes that were not reported in the EU effort data (the EU effort data were reported by four broad length classes, whereas the FAO data are reported by a wide variety of classes). To create the numeric linear model, the mean (when normally distributed) or median (when non-normally distributed) length of vessels from the EU fleet database within each length class of the EU effort data set was used.

These numeric linear models were fitted to the length and GT categories by estimating the median length of vessels within each category (previous analyses have shown that these data were non-normally distributed). Fishing effort (nominal) was then calculated as the product of the fishing capacity of each category (in watts) and the number of days fished, as estimated by the above linear models.

When no fishing gear or length/GT data were present in the FAO data sets, the number of days fished was estimated by bootstrapping the entire EU effort data set and the mean/median used as previously.

Annual fishing efficiency (tonnes of wild-caught marine organisms per watt days of fishing effort) was calculated for the global fleet, and a local regression was used to model the trend using the default behaviour of the 'loess' function in R.

Incorporation of uncertainty into fishing capacity and fishing effort estimations

When aggregating the fishing capacity of each country and when aggregating the global, regional and socioeconomic developmental status (following Anon, 2014) capacity, it was possible to estimate the uncertainty that was introduced. This was achieved by bootstrapping the earlier created capacity and effort distributions 1000 times, while data were being aggregated at the country, global, regional and developmental status levels. The median and confidence interval were retrieved using the methods detailed above.

Where bootstrapped data did not already exist (i.e. when GAM, ARIMA or surrogates were used), confidence intervals (or % dissimilarity for surrogates) were used to generate a normal distribution of 1000 possible values. These data were then incorporated with the aggregation of bootstrapped data. It was not possible to obtain any realistic estimate of the uncertainty involved in carrying the last value forward and back, and in these instances, it was necessary to also carry forward and back the confidence intervals with the estimate and use these as above.

As fishing effort was calculated at the vessel length/GT and fishing gear level, it was not possible to propagate the uncertainty surrounding fishing effort through to the global, regional or developmental status levels. If we had taken a more simplistic approach and converted fishing capacity to effort at the aggregated level, it would have been possible to do so; however, this would have introduced error to the process as fishing effort is complex and dependent on a variety of operational parameters (detailed in the results). As such, fishing effort estimates were bootstrapped as per capacity and only incorporate the degree of uncertainty generated during capacity estimation.

Assumptions

The analyses herein required several assumptions: (i) most notably, it must be assumed that the vessel specifications of the EU fishing fleet are representative of the global fishing fleet (at least the non-subsistence sector); (ii) vessels that were active post 1989 are representative of the fleet since the time they were commissioned; (iii) these vessels have not undergone major changes at fleet level in their operational characteristics (i.e. engine replacements or major engineering enhancements); (iv) that they were fishing vessels throughout the entire period in which they have been operational; (v) that the fishing activity of the EU fleet is representative of global fishing fleets; (vi) that the fishing activity of the EU fleet from 2008 to 2011 is representative of fishing activity throughout the entire time series; (vii) the data reported by each country are accurate; and (viii) there has not been any data manipulation (e.g. imputation, extrapolation) prior to us receiving it.

Results

Fishing capacity

The capacity of the global fishing fleet was relatively stable until the 1970s before increasing consistently up until 2010 (Fig. 1). From 2010 to 2012, the trend stabilized or even began to decline slightly. However, an increasing reliance on forecasting since the late 1990s (see supplementary information) has resulted in greater uncertainty during these later years. The trend fluctuates throughout the 1990s even though this was the period for which the FAO data set was most complete and, as a result, had the least uncertainty surrounding the estimates. This may be due to a change in reporting during this time period (i.e. GT to length category), but this was also a period of time in which the largest fishery in the world collapsed (Atlantic cod fishery) and widespread fisheries management reforms were occurring. Nevertheless, this noise does not alter the increasing trend during this period of time.

The fishing capacity of the Asian fleet is an order of magnitude greater than any other region (Fig. 2), and the large increase in this region during the mid-1990s was responsible for the rapid increase in the global trend described above. The fishing capacity of Europe, Africa, North America and South America are similar, with Oceania being considerable less. Fishing capacity increased

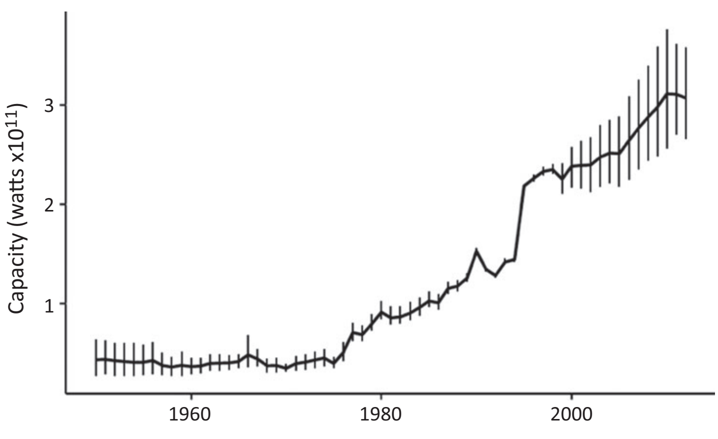

Figure 1 Global fishing capacity from 1950 to 2012. Error bars represent 95% confidence intervals.

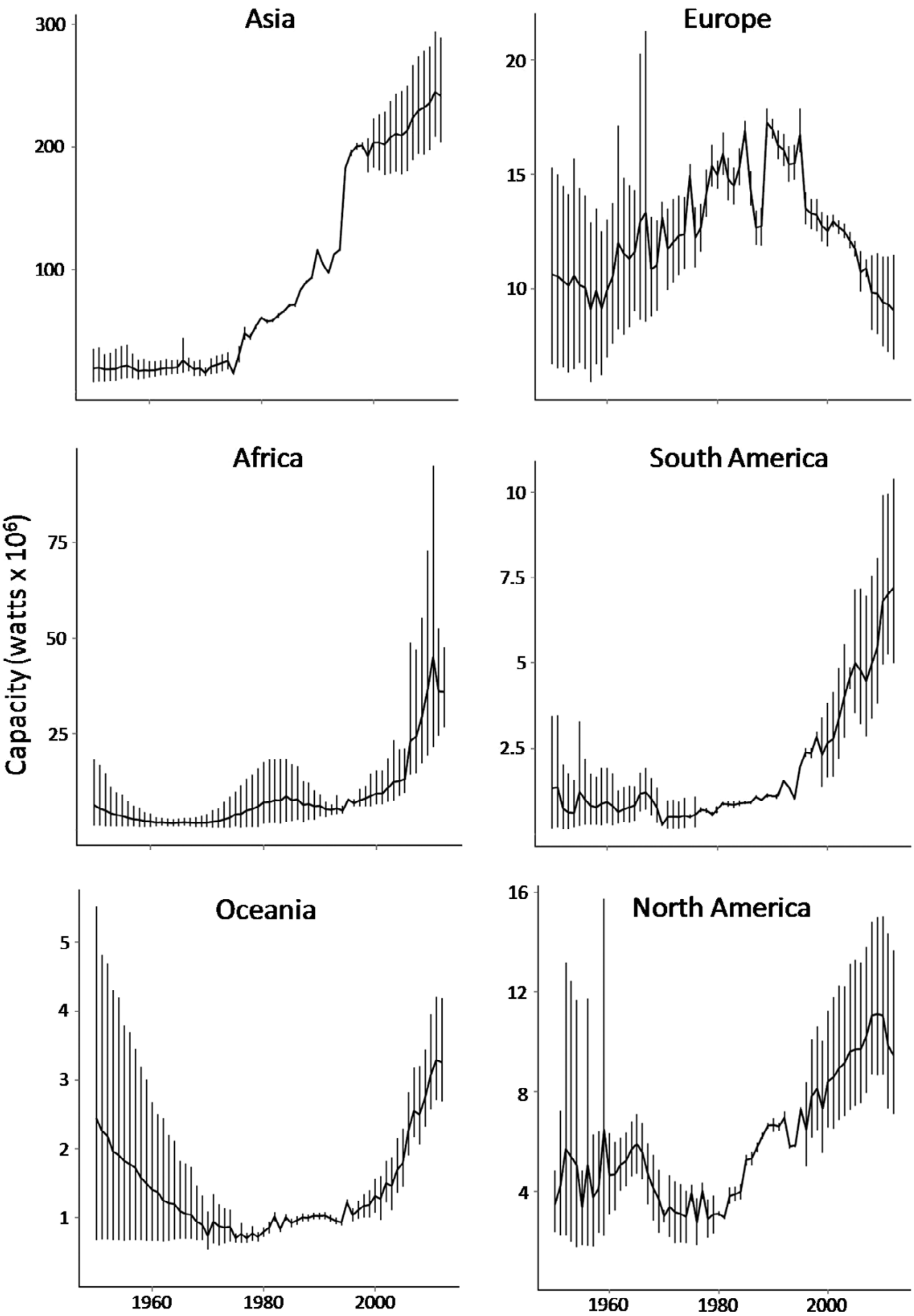

Figure 2 Regional fishing capacity from 1950 to 2012. Error bars represent 95% confidence intervals.

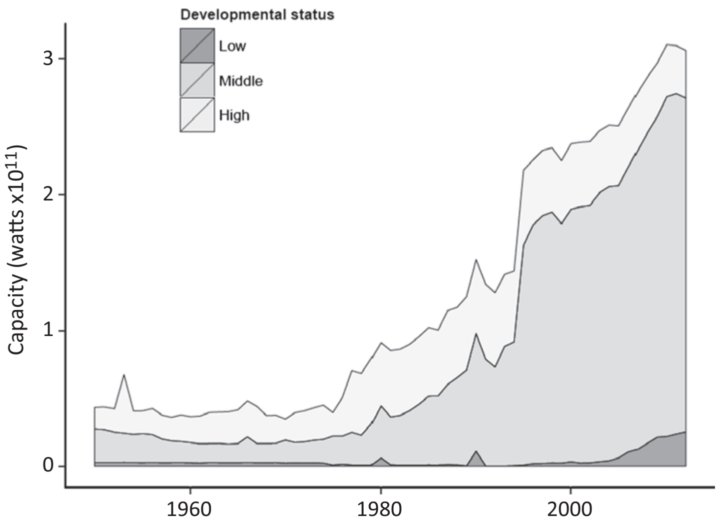

Figure 3 Fishing capacity of highly developed (high), developing (middle) and non-developed (low) countries from 1950 to 2012.

throughout the time series in North America, Asia, South America and Africa, but not in Europe or Oceania. Most regions show a stabilizing trend in the last few years of the time series, and the European fleet has declined to around 1960 levels after reaching a maximum around 1990. Oceania increased from 1980 onwards, but showed a decreasing trend from 1950 to 1970. During this period, data were poor for this region, and capacity estimation relied heavily on ARIMA modelling, and an increasing trend from 1975 to 1970 meant that backcasting continued this increasing trend back to earlier years. As a result, there is considerable uncertainty surrounding this period of time, and we do not consider this result reliable. Fishing capacity of the Oceania fleet during this time period is more likely to have been similar to 1970 levels.

The trend in fishing capacity was heavily dependent on national developmental status with developing nations having the largest fleets and showing the greatest relative increase (Fig. 3). In the last few years, however, there is some indication that the trend has stabilized and begun to decline. The fishing capacity of developed nations increased, but at a lower rate, until around 2000, after which it began to decline. The fishing capacity of undeveloped nations was low until around the mid-2000s, since there has been a relatively rapid increase, without any slowing tendency, and is approaching the level of developed nations, but remains small compared to developing nations.

Table 1 Kruskal–Wallis tests of variation comparing the mean number of days that vessels fish annually within each length category and fishing gear.

Variable	χ^2	*df*	*P*
Length category	282.51	4	<0.001
Fishing gear	162.26	6	<0.001

Table 2 Critical α-value of post hoc pairwise Mann–Whitney *U*-tests of variation in the number of days fished annually with vessel length category.

	<12	12–18	18–24	24–40
12–18	<0.001	–	–	–
18–24	<0.001	<0.001	–	–
24–40	<0.001	<0.001	0.016	–
>40	<0.001	<0.001	0.057	1.000

Conversion of fishing capacity to effort

The number of days fished was highly variable, and Kruskal–Wallis tests indicated that there was significant variation due to both fishing gear and vessel length (Table 1). Most pairwise comparisons of length category were significantly different (Table 2), and the number of days fished increased consistently with vessel size category (see supplementary information). Few multiple pairwise

Table 3 Critical α-value of post hoc pairwise Mann–Whitney *U*-tests of variation in the number of days fished annually with fishing gear category.

	Dredgers	Gear unknown	Gillnet	Hook	Pot/trap	Purse seine
Gear unknown	0.051	–	–	–	–	–
Gillnet	1.000	0.062	–	–	–	–
Hook	0.870	0.953	0.870	–	–	–
Pot/trap	0.056	<0.001	0.051	0.004	–	–
Purse seine	1.000	0.870	1.000	1.000	0.010	–
Trawl	<0.001	<0.001	<0.001	<0.001	0.487	<0.001

Table 4 Kolmogorov–Smirnov test of whether vessels in the EU fleet registry are normally distributed within each length category of the EU fishing effort database. The median length of each length category is provided as in each case the test indicated a non-normal distribution, and this was used in the linear model for conversion of capacity to effort.

Length category	D-statistic	*P*	Median length (m)
0–12 m	0.9971	<0.001	6.48
12–18 m	1.00	<0.001	14.25
18–24 m	1.00	<0.001	20.60
24–40 m	1.00	<0.001	27.50
>40 m	1.00	<0.001	48.60

comparisons of fishing gear were different (Table 3): notably, the number of days fished by trawlers and pot/trap vessels tended to be greater than the other categories. There were few significant differences between the other vessel types, and where they existed, they were only slightly different (Table 3). Therefore, to avoid introducing bias by over-dividing the available data, we created three linear models describing the number of days fished annually and vessel size: one for trawlers and pot/trap vessels, another for the remaining gear categories and a third with all fishing gears for use when there was no information on fishing gear (see supplementary information). The final estimate of annual days fished was generated by bootstrapping (when there was no gear or size information in the FAO data) was 93.4 (95% CI: 88.8, 97.4).

Kolmogorov–Smirnov tests indicated that the data within each length category of the effort data set were non-normally distributed (Table 4); thus, we estimated the median length of vessels within each length class. This enabled the creation of the numeric linear models (Table 5) required to apply fishing days to the broad range of categories present in the FAO data and to each vessel individually within the EU data set.

The number of days fished annually for each length/GT estimated by linear models ranged from 64.5 to 334.3, although there was a reasonable degree of uncertainty surrounding these models with pseudo-R^2 of 0.1 to 0.2 as a result of the high variation within each category.

Global nominal fishing effort

Global nominal fishing effort increased throughout the time series and more than tripled from 1950 to 2012 (Fig. 4). Interestingly, the downturn

Table 5 Linear models of the relationship between vessel length and the number of days fished annually for trawl and pot/trap fishing methods combined and all other fishing gear categories combined.

Category	*n*	$\bar{R}^2$	Coefficient	Estimate	St. error	*t* value	*P*
Trawl and pot/trap	512	0.179	Intercept	80.649	4.625	17.440	<0.001
			Length	2.012	0.190	10.610	<0.001
Other fishing gears	726	0.102	Intercept	54.603	3.674	14.862	<0.001
			Length	2.004	0.219	9.151	<0.001
All fishing gears	1238	0.184	Intercept	59.500	2.856	20.830	<0.001
			Length	2.360	0.141	16.76	<0.001

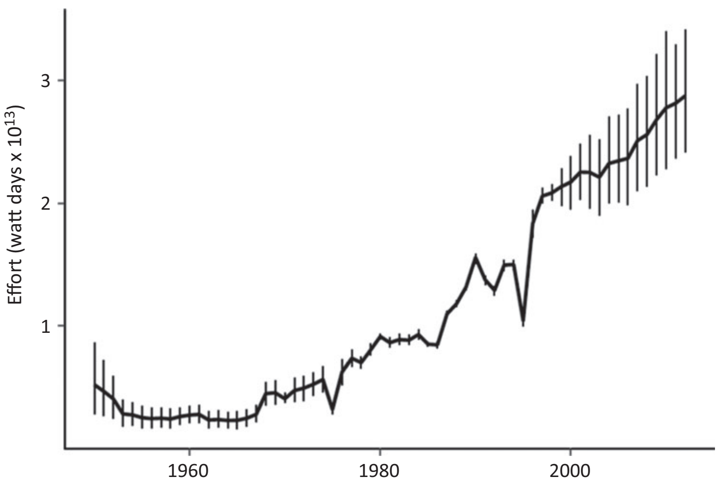

Figure 4 Global fishing effort from 1950 to 2012. Error bars represent 95% confidence intervals.

observed in fishing capacity in later years was not observed in fishing effort, presumably because vessel size has increased and larger vessels tend to fish more frequently. Although there was considerable data noise during the mid-1990s, this did not mask the overall increasing trend throughout the time series. This noise was generated by the Asian fleet (Fig. 5), which dominated global fishing effort at greater than ten times that of any other single region, and nearly four times greater than the combined effort of all other regions in 2012.

Other than Europe, all regions displayed an increase in fishing effort throughout the time series with the rate of increase being greater from the 1970s onwards in most regions (Fig. 5). Fishing effort peaked in Europe in 1990 and then declined to levels similar to those in the 1960s, but has shown a small increase over the last five years. Fishing effort in North America and Africa has shown a decreasing trend in the last few years, whereas Oceania, Asia and South America continue to show increasing trends.

Like fishing capacity, the trends in fishing effort were strongly related to national developmental status with the largest fleets and greatest relative increase throughout the time, occurring in developing nations (Fig. 6). Significantly, the fishing effort of developed nations has been in decline since maximum levels in the 1980s and 1990s. Fishing effort of undeveloped nations has increased slightly, but remains a very small component globally. Interestingly, the increase in the fishing capacity of undeveloped nations observed in Fig. 3 was not as obvious in fishing effort, probably because the increase in capacity is likely to be comprised of mostly smaller vessels that fish less days, on average, than do larger vessels.

Catch efficiency (tonnes of wild-caught marine landings per watt days of fishing effort) grew rapidly throughout the 1950s and 1960s, presumably as a result of technological development and expansion into previously underutilized fisheries (Fig. 7). There has been a considerable decrease in the catch efficiency of the global fishing fleet since the 1970s, and it is now lower than in 1950.

Discussion

Global fishing capacity and nominal fishing effort

Global fishing capacity and nominal fishing effort continue to rise, particularly that of Asia and developing nations. This is a disturbing trend considering global marine wild-capture fish landings have remained relatively stable at 75 to 85 million tonnes since the early 1990s (FAO 2012, 2014). During this period of time, we estimate that fishing capacity and effort have almost doubled, suggesting a considerable reduction in the overall efficiency of the global fishing fleet. Fishing efficiency, in terms of tonnes of wild-caught marine landings per watt day of fishing effort, is now less than it was in 1950, despite considerable technological advancement and expansion throughout the world's oceans. While this measure cannot be interpreted as is traditional catch per unit effort, catch rate has also declined throughout much of the world since 1950 (Watson *et al.* 2013). Due

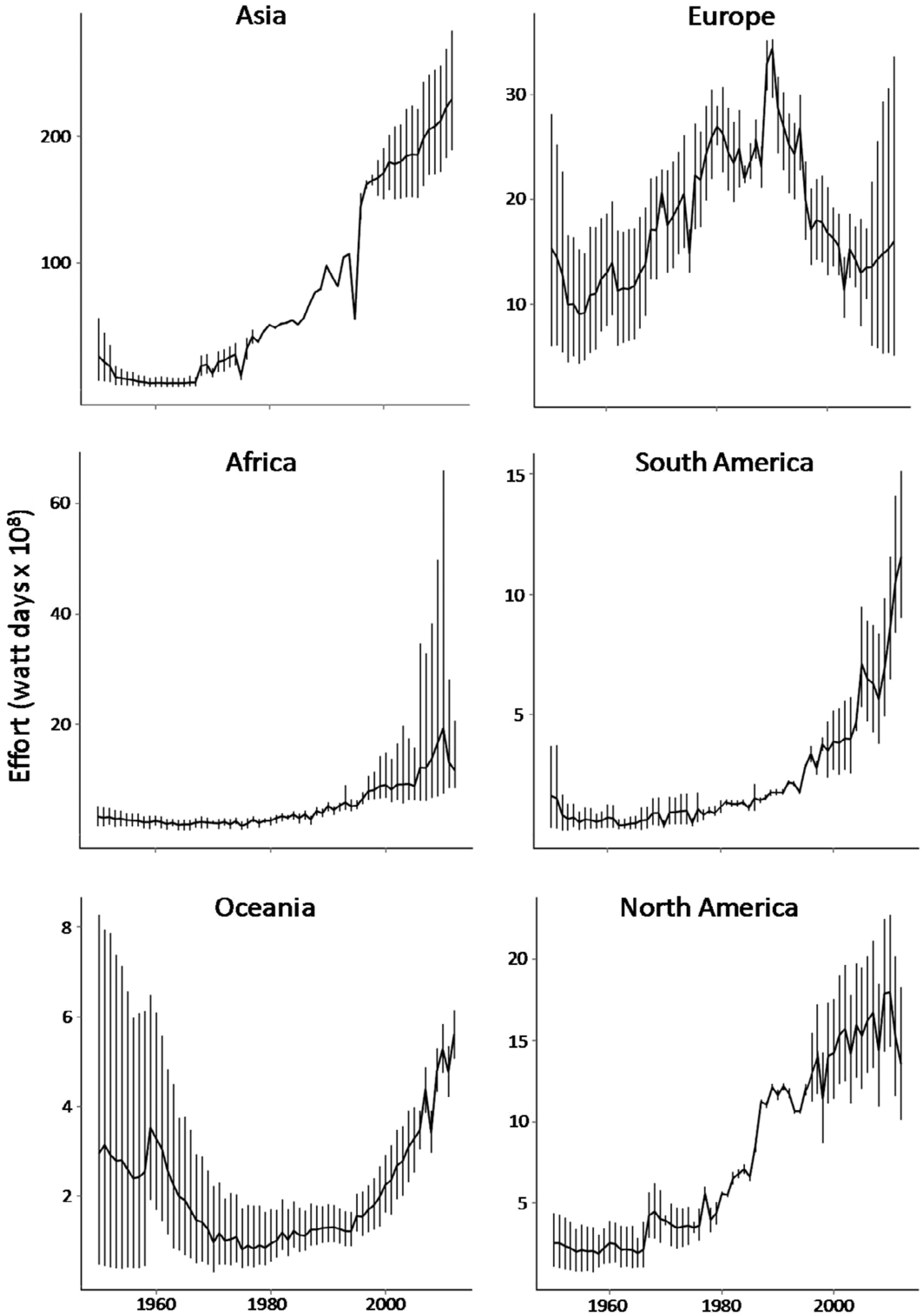

Figure 5 Regional fishing effort from 1950 to 2012. Error bars represent 95% confidence intervals.

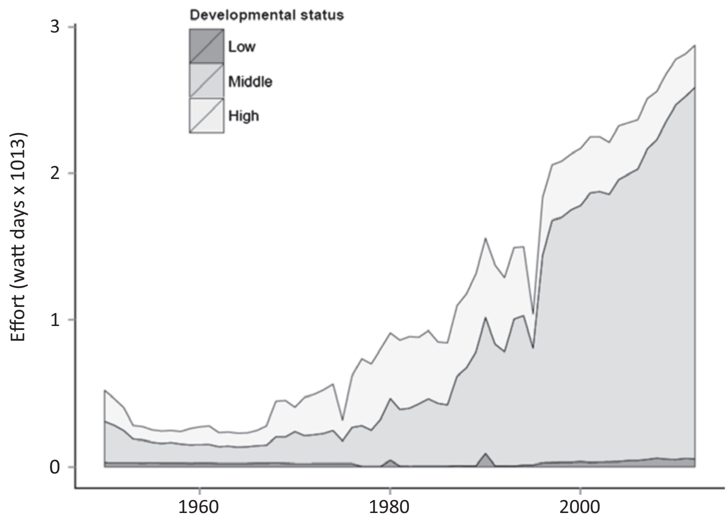

Figure 6 Fishing effort of highly developed (high), developing (middle) and non-developed (low) countries from 1950 to 2012.

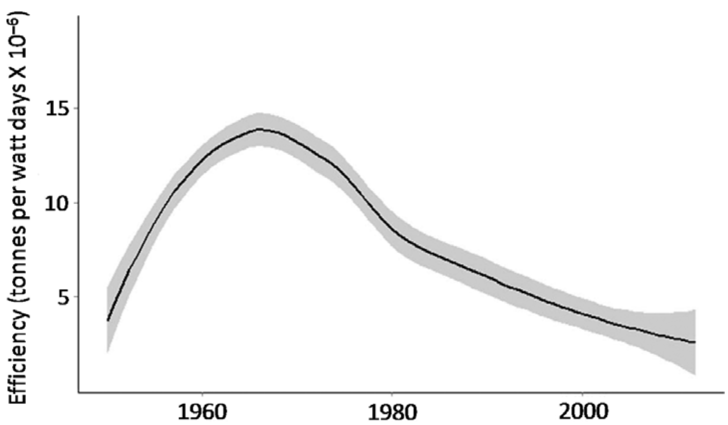

Figure 7 Local regression of relative efficiency (tonnes of wild-caught marine organisms per watt days of fishing effort) of the global fishing fleet. Shaded area represents 95% confidence intervals.

to the conservative effort estimates used by Watson and collaborators [i.e. estimates by Anticamara *et al.* (2011)], this study was likely to have underestimated the decline in catch rate given the present study estimates that there has been a greater increase in effort since the 1990s. Further, recent information suggests that the wild-caught marine landings data reported by FAO may be underestimated, and landings have been declining at a mean rate of 1.2 million tonnes per annum since 1996 (Pauly and Zeller 2016). If this is the case, then the decline in fishing efficiency since the 1970s reported herein may be an underestimate, and fishing efficiency may now be far lower than in 1950.

As stated above, our results indicate that the global fleet is considerably larger, and fishing effort greater, than the previous study to undertake this task (i.e. Anticamara *et al.* 2011). This is likely because Anticamara *et al.* (2011) were forced to forecast data to 2010 for all non-EU countries using the trend from the 1980s and early 1990s, and during this period of time, there was only a slight increasing trend. The data available for the present study indicated that there was a rapid expansion of the fleet throughout the 1990s and 2000s, thereby explaining the higher results herein. Further, our method for calculating the number of days fished annually takes into account the size of fishing vessels, and as the size of fishing vessels has increased through time, the fishing effort is also likely to be relatively greater in the recent years and in comparison with Anticamara et al. (2011).

The World Summit on Sustainable development in 2002 set a target for all world fish stocks to be at levels enabling maximum sustainable yield by 2015 (Anon 2002). Although fish stocks in many regions of the world are now considered to be harvested within target limits (Ricard et al. 2013), our results indicate that fishing capacity and effort continue to grow and that the World Summits goals are highly unlikely to have been achieved, and many sustainably fished stocks are likely being fished at maximum sustainable yield rather than maximum economic yield. A reduction in fishing capacity has been viewed as imperative in sustaining global fish stocks (FAO 2014) and maximizing economic potential of global fisheries (Arnason et al. 2009). Over-capacity is usually a result of open access to fisheries even if there is a total allowable catch in place (Beddington et al. 2007). This generally occurs because there is a high initial profitability of fisheries during which capacity increases rapidly. Over-capacity, once in place, is then often maintained by subsidies [see Sumaila et al. (2010) for a summary of fishery subsidies], which offer incentives to continue expansion even when fish stocks are reduced to beyond a point at which fishing would otherwise become economically unviable (Beddington et al. 2007).

There have been improvements in the management of many fisheries over the last twenty years, and we estimate that the fishing capacity of developed nations (Europe and North America in particular) had decreased by 37% in 2012 since maximum levels in 1991. This decline had only a minimal influence on a global scale, however, as developed nations only represented 11% of global fishing capacity in 2012. The large increases in Asia and South America have meant that the global trend continues to increase. Ye et al. (2013) found that global fishing capacity needed to be reduced by 36 to 43% from 2008 levels requiring a loss of 12 to 15 million fishers employed in this sector at a cost of US$96 to 358 billion. These authors also found that 68% of fisheries globally continue to be fished beyond maximum sustainable yield.

Our results suggest that this situation has considerably worsened as capacity increased by approximately 7% from 2008 to 2012, and if we apply these data to those of Ye et al. (2013), fishing capacity now needs to be reduced by 43 to 50% at an estimated cost of US$103 to 383 billion. While these costs seem exorbitant, the overexploitation of fish stocks was estimated to cost the global economy US$51 billion in 2004 alone, and meeting the World Summits 2015 aims would increase wild-capture fish production by an estimated 16.5 million tonnes, annual rent by US$32 billion, and provide considerable environmental and biodiversity benefits (Ye et al. 2013).

What complicates improvements to fisheries is that the greatest increases in both fishing capacity and fishing effort are occurring in developing nations and to a lesser extent in undeveloped nations. Developing nations were responsible for >80% of global fishing capacity and fishing effort in 2012 with undeveloped nations responsible for <10%. This is not necessarily a problem if these expansions are targeting underexploited stocks; however, the cosmopolitan nature of the global fleet means this is unlikely, particularly as the greatest increases are occurring in Asia where 60% of the world's population lives and the largest fishing fleets already exist. National maritime claims are often hotly disputed in this region.

It is difficult for nations with undeveloped or developing economies to implement fishery regulations designed to prevent further expansion due to the imminent socioeconomic cost involved; however, the costs, both social and economic, of removing fishing capacity are far greater than those involved with preventing expansion. Thus, at the very least, undeveloped and developing nations should, as a whole, aim to minimize, or prevent, unsustainable over-capitalization in wild-capture marine fishing.

Limitations, gaps and future direction

The bootstrapping techniques used in the present study require one major assumption: that the vessel characteristics and fishing practices (within each year, length class and fishing gear) of the EU fishing fleet are representative of the global fishing fleet. It avoids assumptions associated with parametric model-based methods and effectively eliminates any error that could be introduced when the reporting to FAO changed from GT to length categories in 1995. Given European fleets pioneered most fishing techniques and the region includes small-scale coastal fisheries in the Mediterranean, Baltic and Black seas through to the large scale, industrial fisheries of the north Atlantic, the fleet is likely to be relatively representative of most fishing practices and suitable for most calculations performed herein. However, there were several unusual results around the time of the transition from the FAO tonnage to length-based system in Asia, and due to the size of this fleet, it also resulted in a steep decline, followed by a rapid increase, in global capacity and effort during the mid-1990s. We believe that this is a result of the transition of reporting method at the country level as the trend stabilized soon after and other than this period of instability was relatively smooth throughout. There were also several unusual trends (particularly in the earlier years; e.g. Oceania) where the models did not perform as expected; however, the very broad confidence intervals during this period reflect the uncertainty around the estimates and highlight the lack of data available to drive the models.

Some caution needs to be exercised when using fishing nominal effort measures (e.g. watts or tonnage) for estimating stock health in a traditional fashion (i.e. like catch per unit effort) as they have differing implications depending on the gear utilized. For example, power has some influence on the ability of trawlers to catch fish, whereas for gillnetters or longliners, the ability to catch fish is more closely related to the length of the net/longline utilized. As such, traditional stock assessments, where available, are better indicators of fishing mortality and are more informative from a sustainable exploitation viewpoint. However, if an analogue to the usual catchability measure (q), relating energy-based 'effort' units and fishing power (proportion of stock removed) is calculated, it would then be possible to use these data to estimate stock health in a traditional fashion. Indeed, this is a potential direction of future research. Despite this, catch per unit effort does not always accurately reflect abundance (Rose and Kulka 1999; Harley *et al.* 2001; Maunder *et al.* 2006), and there has been an increase in the use of energy-based measures to allocate fishing effort in the management strategies (EU 2008, 2013).

The skill of the skipper and crew, advances in technology and logistical improvements (e.g. refuelling at sea and fridge/freezer ships) can all influence catch per unit effort (Squires and Kirkley 1999). When these factors are unaccounted for, it is termed 'nominal' fishing effort (reported here), and when they are accounted for, it is termed 'effective' fishing effort. It has been estimated that effective fishing effort has increased annually by 2 to 5% (Fitzpatrick 1996; Pauly and Palomares 2010), although, at times, the rate of increase is likely to be greater due to advances in technology that greatly increase fishing efficiency. This increase in efficiency has the ability to mask increases in real fishing effort and any decline in catch rate. Fishing capacity reduction schemes rarely account for effective fishing effort and it has been proposed that in most cases the least efficient vessels leave the fishery first, and therefore, increases in the average efficiency of the remaining vessels may completely eliminate the benefits of such schemes (Pascoe and Coglan 2000). The influence of effective fishing effort is an important consideration and would be likely to be highly spatially variable.

Due to the very high capacity of the Chinese fleet, error surrounding the effort of the fleet, whether intentional or not, can drive global trends, as was seen in the 1990s (Watson and Pauly 2001). However, China was relatively well represented within the FAO data set utilized herein, more so than several developed nations that claim to have the best fisheries management practices in the world.

Disappointingly, the quantity and quality of data have declined since the 1990s, and this introduces uncertainty into the fishing capacity and effort estimations in the recent years. It is understandable that historic records are incomplete, but there is no justification for non-reporting fleet characteristics to the FAO in the modern era. Further, some countries listing marine wild-caught landings do not provide any details on fleet characteristics. In such instances, surrogate countries had to be used, and this introduced a degree of uncertainty within the present study. Complicating the above, recent evidence suggests that landings data are also misreported to FAO (Pauly and Zeller 2016), and this may, or may not, relate to the reporting of vessel numbers. Poor reporting decreases the accuracy of studies as this and could potentially mask underlying trends. In many parts of the world, formal stock assessments are not undertaken, and it is only from studies such the present that information is obtained [the presence/absence of quantitative stock assessments globally can be investigated using the RAM legacy database (Ricard *et al.* 2013)].

Using the number of days fished by the EU fleet requires the assumption that these data are representative of global fishing fleets. As described above, the European fleet is incredibly diverse and is therefore likely to represent most variation that is present in fishing fleets globally. Despite this, it was notable that within the EU fishing fleet, a large number of fishing vessels fish relatively rarely, if at all. Although it is unclear how representative this is, globally it may be related to the introduction of quotas and total allowable catches and/or incentive schemes and subsidies. It is also possible that fishing effort has decreased in the recent years due to the introduction of quota management systems and the decline in the availability of important commercial species in the region, in particular Atlantic cod in the North Atlantic Ocean. Further, 25 of the 27 major stocks/fisheries in the Mediterranean Sea were recently considered over-exploited with the remaining two being data deficient (Anon 2012). These factors may have resulted in a decline in fishing, in terms of days fished annually, by the European fleet, which may mean that due to our extrapolations from their fleets we underestimated fishing effort elsewhere. However, many fisheries throughout the world are now considered fully exploited, or over-exploited, meaning the fishing practices of the EU are likely to be relatively representative in most instances. The reduction in the fishing capacity of the EU fleet suggests that it has adjusted to the decrease in the availability of some stocks, and the remaining fleet would, presumably, be operating normally. Unfortunately, due to a lack of historic data on the numbers of days fished annually, it was not possible to explore this spatially and temporally, and it is acknowledged that the present analysis may not be representative of fishing practices during the earlier period of the time series or for some regions.

Presumably, the differences in days fished result from technological differences in the gear and differing management practices used for differing species. For example, dredging had a significantly lower number of days fished than did any of the other gears, which probably results from this gear being predominantly used to target scallops and other benthic bivalves that have seasonally variable yield and hence highly seasonal fisheries. As a result, these fisheries were some of the earliest to introduce seasonal closures – at least as early as the 1940s and 1950s (Olsen 1955; Marshall 1960; Thayer and Stuart 1974). Concurrently, trawlers had a greater number of days fished than did other gear types, which is probably due to their flexibility and ability to target a variety of species as availability or market demand dictates.

Vessels have been reported to spend less time actually fishing in the recent years due to fisheries targeting ‘peak’ fishing periods (Arnason *et al.* 2009). However, reports from the 1950s suggest technical problems, breakdowns and underpowered vessels preventing long-range travel, resulted in averages of just 34–71 days fished annually in 1951 to 1953 in the North Atlantic cod fishery (Templeman and Fleming 1956), despite the species being incredibly abundant at the time and the fishery being highly lucrative. Fishing effort (days fished) on the Gulf of Maine cod fishing grounds remained relatively stable throughout the 1980’s; however, effort increased on the Georges Bank cod fishing grounds from 1978 to 1992 (Mayo *et al.* 1994). These conflicting patterns are typical of the conundrum faced in the present study: fishing effort changes as fisheries develop, fish stocks decline/increase, market preferences change, due to economic considerations and probably other reasons, while limited or no data are available to address this variation at either the spatial or the temporal level. Nevertheless, it is our contention that, barring perverse subsidies, due to the considerable investment involved in commercial fishing, fishermen will generally fish as often as they are able, and this has not changed throughout the time series we analysed. Thus, we are confident that this approach has not induced an unreasonable level of bias, particularly given uncertainties in other aspects of this task.

Another possible source of bias occurs when vessels fly flags of convenience, which is often carried out to avoid fisheries management controls and other regulations (Gianni and Simpson 2005; Calley 2012). Greater than 75% of vessels in some countries fly a flag of convenience (Gianni and Simpson 2005), and many of these countries have poor, or no, reporting to FAO. Further, it has been suggested that when reports are received by certain fisheries regulation agencies, they are often greatly deflated (Gianni and Simpson 2005). Using the catch composition of a fleet to establish surrogates is only valid when the fleet of a country fishes in a consistent manner, and this is unlikely to be the case when vessels originate from a variety of countries and do not necessarily fish anywhere near the country to which they are flagged. This compromises the accuracy of studies such as this and is a serious issue facing fisheries globally.

Conclusion

Our findings represent a considerable improvement on previous attempts to quantify global fishing capacity and effort. Both continue to rise indicating that overfishing is continuing to occur, and as a result, the efficiency of the global fleet has declined to levels below 1950, despite the considerable technological improvements, and expansion, of the global fishing fleet. Significantly, there have been reductions in both fishing capacity and effort in the recent years in certain regions and by developed nations as a whole. This suggest that fisheries reforms are beginning to have the desired effect, although the fishing fleets of developing nations, particularly in Asia, continue to rise, and these are, by far, the largest fleets of the world. It is in these countries where change needs to occur; otherwise, the efforts of the developed world will mean little on a global scale.

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Supporting Information

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

Data S1. Detailed methodology and additional statistical analyses.