A global, regional and national developmental status assessment of fishing capacity and fishing effort from 1950 to 2012

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Executive summary

Global marine wild capture landings have remained relatively stable over the last twenty years, however, stability cannot be inferred from landings alone without taking into account the quantity of fishing effort required to capture a given quantity of seafood. Thus, it is possible that the observed stability could be due to a combination of increasing fishing effort, the transfer of effort to previously under exploited stocks or inaccurate reporting by some countries.

There has only been one previous study that that attempted to estimate global fishing effort but this study lacked data for most countries post 1995 limiting its ability to predict recent trends. Since then, the Food and Agriculture Organization of the United Nations (FAO) has been able to create a relatively comprehensive database of the number of fishing vessels from most countries of the world.

Herein, we draw upon the FAO data, supplemented by other sources, to create a database of fishing capacity and fishing effort for each country reporting wild capture marine landings from 1950 to 2012. Specifically, we use individual vessel and fishing characteristics (gross tonnage, length, fishing gear, horsepower and days fished) that are comprehensively recorded by the European Union fishing fleet to infill fishing capacity and effort within the FAO data sources that contain broad gross tonnage and length categories. Using random sampling techniques, and bootstrapping, we were able to minimise the number of assumptions required to complete these analyses, and were able to estimate the uncertainty surrounding our estimates.

Vessel characteristics varied temporally and with fishing gear, while fishing activity varied with the vessel size and fishing gear; thus, these factors were accounted for when estimating fishing capacity (kilowatts) and fishing effort (kilowatt days). Due to a lack of historic fishing effort data it was not possible to account for temporal variation in fishing effort, however, evidence exists that the global fleet was relatively developed by the 1950s. Then as now, vessels fished as many days as possible.

Global fishing capacity has risen steeply since the 1970s, though the trend appears to be reaching a plateau. This has occurred due to a considerable reduction in Europe over the past decade, with more recent reductions occurring in North America and Africa, and there has been a deduction in the rate of increase in other regions. The fishing capacity of developed nations, as a whole, had decreased by 37 percent in 2012 from peak levels in 1991. Conversely, the fishing capacity of developing nations dramatically increased over the last 30 years and drives the global trend. Developing nations are responsible for >80 percent of fishing capacity. The fishing capacity of undeveloped nations has increases in recent years, however, these nations are currently responsible for <10% of the global fleet and therefore have little influence on global trends at present.

Global nominal fishing effort has, unsurprisingly, mirrored the trend in capacity to some extend, with rapid increases since the 1970s. This has been driven by the Asian fleet that are responsible for >10

times the fishing effort of any other region, and were nearly four times greater than all other regions combined in 2012. The fishing effort of Europe has shown a considerable decline since the early 1990s and is now at levels similar to that of the 1960s, though it has increased slightly in recent years. Most regions appear to be slowing in their rate of increase but this has not seen the global trend change, probably because modern fleets are comprised of larger vessels, which are likely to fish more days annually and therefore contribute a higher number of kilowatt days than do fleets of smaller vessels. Again, the greatest increases have occurred in developing nations with a small increase in undeveloped nations, and a decline in developed nations since peak levels in the 1990s. Trawlers are, by far, responsible for the greatest quantity of fishing effort with hook and line being second and other gear types comprising only a small proportion.

There were several limitations that potentially reduced the accuracy of our estimates in the present study. First, and foremost, many countries failed to report their fleet details consistently, if at all, to FAO. This obviously increases the depth of modelling required, which has the potential to introduce uncertainty. Disappointingly, many non-reporting countries are fully developed, have some of the largest fleets, and pride themselves as having well managed fisheries. Secondly, we had to rely on the EU fleet characteristics to estimate the capacity of other countries. While less than ideal, the EU fleet is likely to be relatively representative, and the bootstrapping routines indicated that there was limited error introduced in this process. Thirdly, we had to assume that the fishing patterns of the European Union fleet represented global patterns in order to convert fishing capacity to fishing effort. We believe this process introduces the largest mathematical uncertainty in our estimates. While we had a relatively comprehensive data set on which to base our models, the number of days fished is hugely variable and therefore unlikely to be representative at small temporal and spatial scales. We do, however, believe that the patterns are likely to be relatively representative on a regional, global and developmental status scale and are unlikely to introduce an unreasonable level of bias.

Despite the above limitations, our estimates are as comprehensive as is possible with the available data, and we are confident that the trends are representative at the global, regional and national developmental status scales. These results indicate that fishing capacity and effort continue to grow rapidly in some regions, which has continued to cause an increasing trend globally. The greatest increases continue to occur in the Asian region and, in particular, by developing countries. Although these countries are developing, the increasing fishing capacity and fishing effort is not necessarily targeted at undeveloped, underexploited or sustainably managed fisheries. In fact, the opposite is more likely given the status of many of the world’s fish stocks.

Our results strongly indicate that the global fleet, as a whole, is still undesirably large and imposing fishing effort on global fish stocks in excess of what is required for maximum economic yield or to maintain ecologically sustainable levels. As such, it is important that such increases are carefully monitored and managed to prevent over-capitalisation, by undeveloped and developing countries in particular, as it is difficult, expensive and socially destructive to remove fishing capacity once it is established.

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Introduction

Global seafood consumption has increased consistently over the last 50 years (9.9 kg to 19.2 kg per capita from the 1960s to 2012) and while aquaculture is contributing to a greater extent than ever before, wild capture fisheries remain the dominant source (FAO, 2014). Further, wild fisheries provide a large proportion of the protein required to sustain the expansion in aquaculture through feeds.

Global marine wild capture fish landings have remained relatively stable at 75 to 85 million tonnes since the early 1990s (FAO, 2012;2014) suggesting that the global fisheries may be fully exploited but potentially in a sustainable fashion. Landings alone, however, can be misleading as the proportion of overfished stocks is increasing while the proportion of under fished stocks has decreased (FAO, 2014). Global landings are therefore likely to be unsustainable and the observed stability is likely the result of increased fishing effort, the transfer of effort to previously under exploited stocks and misreporting by some countries (Watson and Pauly, 2001; Watson *et al.*, 2013; FAO, 2014).

Reducing fishing capacity (the quantity of fishing vessels participating in fisheries) and fishing effort (the amount of fishing) was 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 from global fisheries (Arnason, Kelleher and Willmann, 2009; Ye *et al.*, 2013), which is critical if these resources are to play a significant role in nourishing the worlds growing population. Global fishing capacity was estimated to be twice of what is required to catch the current global landings, which reportedly cost the global economy US$51 billion (80 percent CI of $37 billion and $67 billion) in 2004 alone (Arnason, Kelleher and Willmann, 2009). At present, however, there is a lack of quantitative information regarding the fishing capacity and effort that take the global marine wild catch. The only organisation that attempts to gather the data required to estimate this is the Food and Agriculture Organization of the United Nations (FAO) and their efforts are hampered by a lack of reporting by many countries (Anticamara *et al.*, 2011; Watson *et al.*, 2013), which stems from social complexities associated with fisheries management (Holt, 2009). Further, the fishing effort and capacity information reported in the literature varies widely in the measures employed, which makes it difficult to aggregate on a country level, let alone on a regional or global scale. 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).

Another factor influencing fishing effort is the skill of the skipper and crew, and advances in technology (Squires and Kirkley, 1999). These factors are often discussed in fisheries literature and when accounted for are referred to as ‘effective’ fishing effort but this is rare and thus ‘nominal’ fishing effort is most often reported. Ignoring the influence of effective fishing effort has the ability to mask the actual fishing capacity, fishing effort and catch rate of fisheries. Indeed, this may be another factor influencing the observed stability of global landings over the last two decades.

Fishing capacity and effort can be measured in a myriad of different ways. Published accounts include: 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. number of hooks, length of gillnet) (Walker, Hudson and Gason, 2005); the duration of fishing (e.g. time spent trawling) (Greenstreet, Spence and McMillan, 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 measures of fishing capacity is available in (Kirkley and Squires, 1999). The problem with these measures is that they vary considerably and it is not possible to combine them in a meaningful fashion to describe trends of mixed fleets (e.g. at a country level). Studies reporting fishing effort using a variety of methods and on a variety of differing spatial scales are provided in Appendix 1 of Anticamara *et al*., (2011).

Only one study has attempted to quantify fishing effort on a global scale, which was achieved by estimating fleet capacity, measured in 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 power’ of selected countries using this measure (FAO, 2014) and in an attempt to spatially restrict fishing effort to facilitate the recovery of Atlantic cod (*Gadus morhua*), countries within the European Union (EU) are assigned set numbers of KW days spatially (EU, 2008;2013).

Anticamara *et al.*, (2011) were, however, hampered by a lack of data in recent years (ending 1995 for most countries) and were therefore required to forecast greatly to estimate trends up until 2010. Since then, FAO have developed a relatively comprehensive database of the vessel numbers from most countries current to 2012. Using these data, along with other sources, the present study loosely follows methods of Anticamara *et al.* (2011) to provide a revised estimate of global fishing capacity (KW) and fishing effort (KW/days), from 1950 to 2012. These revised estimates are derived using random sampling techniques that eliminate many assumptions and use a far superior dataset (to 2012 for most countries). Bootstrapping also enables the uncertainty to be identified throughout much of the analyses. Therefore, the present study is considerably more accurate than those previous, and is also able to identify factors responsible for introducing uncertainty. This study can therefore provide guidance in the future direction of monitoring and managing fishing capacity and fishing effort of global fishing fleets.

Methods

Datasets

FAO #1: FAO global handbook 1950 to 1967. Accessed in 2010 and provides the annual gross registered tonnage at the country level, albeit for a limited number of countries and a restricted number of years.

FAO #2: FAO global fleet registrar 1970 to 1995. Accessed in 2010 and provides a breakdown of the number of vessels, by country, year, gross registered tonnage and fishing gear.

FAO #3: FAO fleet registrar 1970 to 2012. Provided by FAO in April 2014 and provides a breakdown of the number of vessels by country, year and length class.

EUROPA (http://ec.europa.eu/fisheries/fleet/): European Union vessel registrar. Provides individual vessel statistics (tonnage, length, horsepower, activity periods, fishing gears and more) for all European Union member countries that have a marine fishing fleet.

EU effort database (http://datacollection.jrc.ec.europa.eu/). Accessed in September 2014. This database includes fleet dynamics of European Union member countries including sea days and fishing days by length category and gear category from 2008 to 2011.

Tuna commissions: These include the International Commission for the Conservation of Atlantic Tunas (http://www.iccat.es/en/), the Indian Ocean Tuna Commission (www.iotc.org/), the Inter-American-Tropical-Tuna-Commission (www.iattc.org/Homeeng.htm), and the Western and Central Pacific Fisheries Commission (https://www.wcpfc.int/). These provide varying quantities of information on fleet statistics, effort, catch and the country in which the vessel is flagged, although the primary focus is on catch and effort.

CCAMLR (https://www.ccamlr.org/): Provides very detailed information on the 36 member and acceding countries that fish in Antarctic marine waters including fishing gear, vessel specifications and varying effort measures.

Data usage

All of the abovementioned data sources were investigated for their suitability for the present study. In doing so, we identified that vessels regularly fish in multiple reporting regions and it is rarely possible to integrate these data without inducing replication. For example, vessels targeting tuna regularly operate in waters within the Exclusive Economic Zone of the country in which they are flagged, but also operate in international waters where they report their fishing details to one of the international tuna commissions. Further, although the CCAMLR data is extremely thorough in every respect, 1/7th of the 42 active vessels in 2012 fished 20 or fewer days, and given these are very large, highly seaworthy vessels, it is almost certain that they were active in other fisheries.

As such, we chose not to use the data from the tuna commissions or CCAMLR as the benefits obtained from their inclusion do not outweigh potential replication biases that would be generated from their inclusion, and they will not be further discussed herein. In any case, presumably these vessels are included in the FAO datasets within the countries in which they are flagged.

Therefore, in order of preference, we used: 1) the EU data as it contained individual vessel details; 2) FAO dataset #2 as it contained fishing gear information; 3) FAO dataset #3 where necessary as it did not contain fishing gear information but contained data for many years that were absent in other data sets. It was necessary to rely solely on FAO dataset #1 for years 1950 to 1967, as none of the other datasets encompassed this time period.

Data processing

Process 1

This process utilises FAO's global handbook 1950 to 1967 (accessed on-line in 2010) that contains the annual total gross registered tonnage (GRT) of the fishing fleet of a selection of countries by fishing gear (D1 in Figure 1). We used linear models derived from the EU dataset (D4 in Figure 1) to estimate the fishing capacity, in KW, of a fleet with a given gross tonnage (GT) (P1 in Figure 1).

To identify whether fishing gear and year influenced vessel power within each GT class we performed a series of Kruskal-Wallis tests (heteroscedasticity could not be achieved to facilitate ANOVA – see Appendix 1 for Levene's test outputs) for each length and GT category within the EU dataset using R (R Core Team, 2014). In almost all cases, power varied with year and fishing gear (detailed in the results). Therefore, wherever possible, analyses were carried out using EU data from comparable years and vessel fishing gear categories. This, however, was not possible for the analysis of these early years (1950 to 1967) due to a paucity of data; thus, we utilised relationships derived from vessels of equivalent gear during this 17-year period.

Within the EU dataset, horsepower was the converted to KW (1 horsepower = 0.746 KW) and a linear relationship, along with 95 percent confidence intervals, was established between GT and KW. This relationship was created using the EU fleet registrar, which contains detailed data on the fleet dynamics (horsepower, GT of the European fishing fleet and is publicly accessible online. This registrar began in 1989; however, the year in which each vessel was originally commissioned is provided and thus, it is possible to identify vessels that were active between 1950 and 1969.

To convert the FAO 1950 to 1967 data to KW of fishing capacity, gross registered tonnage was converted to GT using the linear relationship (*GT = 1.85 gross registered tonnage - 4.1*) developed by Cross (2001). This was necessary to enable compatibility with the EU data. Further, we standardised the fishing gear of both datasets, and all of those used throughout, according to the International Standard Statistical Classification of Fishing Gear, 29th July 1980 (ftp://ftp.fao.org/fi/document/cwp/handbook/.../AnnexM1fishinggear.pdf). Using the linear models created from the EU fleet, we estimated the KW of fishing capacity of the FAO 1950 to 1967 dataset for each fishing gear category of each country using the 'predict ' function in R. There were insufficient lift net vessels in the EU data to develop a realistic model. Therefore, the fishing capacity attributed to the 15 years that Japanese lift net vessels were present in the FAO data was estimated from the 'gear not known or specified' relationship.

The previous analysis requires several assumptions: firstly, and 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); secondly, vessels that were active post 1989 but commissioned prior to 1967 are representative of the fleet between 1950 and 1967; thirdly, these vessels have not undergone major changes in their operational characteristics (i.e. engine replacements or major engineering enhancements); and finally, that they were fishing vessels throughout the entire period in which they have been operational.

Process 2

This process involves conversion of FAO #2 vessel numbers within GT class of each country, year and fishing gear into kilowatts of fishing capacity (P2 in Figure 1). The technique employed involves a bootstrapping routine that randomly samples from a donor dataset created from the EU data. Fishery research vessels, fishery training vessels, protection and survey vessels, motherships, fish carriers and non-fishing vessels were excluded from all analyses. Where possible, the donor group was created using EU vessels of the same fishing gear type and with vessels that were operational in the same year (method A). When there were fewer than 3 matching vessels in the EU dataset meeting these criteria, the donor group was generated using year and GT class only (method B) and, if there were still fewer than three available donors, the donor group was created from matching vessel GT category from the same decade (method C). If there was no information of vessel GT or length, the donor group was created using vessels of the same gear type and year (method D) and if there was no information on gear the donors were generated from vessels with the same GT category (method E). Should a vessel not meet any of the above conditions (i.e. due to having no size or gear information) the donor group included all vessels within the EU fleet from that year (method F).

To calculate fishing capacity, a random sample of the power of an equivalent number of vessels was taken from the donor group using the ‘sample’ function in R with replacement. This process was repeated 1000 times (i.e. bootstrapped) to create a distribution of possible annual capacities for the recipient group. To establish the best measure of central tendency for estimation of fishing capacity of the recipient, a Shapiro-Wilk test was used to determine whether the bootstrapped results were normally distributed: if normally distributed then the mean was used, if non-normally distributed, the median was used. When there were fewer than three vessels in the donor group (the minimum quantity required for a Shapiro-Wilk test), the mean was used. From the bootstrapped data, 5 and 95 percent confidence intervals were estimated using the ‘quantile’ function in base R.

The use of the EU data to complete this process required the same assumptions as Process 1.

Process 3

As per Process 2; however, there is no fishing gear information in the FAO #3 dataset (post 1995) and the vessel registry is reported in length categories. As such, donor groups were generated based on year and length class only (P3 in Figure 1). Therefore, only donor groups B to E can result from this process. Process 3 requires the same assumptions as Process 1 and Process 2 but also assumes that changes in the fishing gears within each length category of the EU fishing fleet are representative of changes globally.

Following Process 3, the European Union dataset was converted (P4 in Figure 1) to ensure compatibility with the three FAO datasets and D1, D2, D3 and D8 (P5 in Figure 1) were merged with D2 and D8 being used preferentially as they contain the greatest detail.

Process 4

This process involved the imputation of power at the country level for missing years within the time frame in which data were reported (P6 in Figure 1) – missing data prior to those first reported and post those last reported were estimated using a separate technique (see Process 5). This was achieved by creating generalised additive models (GAM) of each countries annual fishing capacity trend through time using the ‘gam’ function of the ‘mgcv’ R package and then using the ‘predict’ function to estimate the missing data and standard error surrounding the estimate. The standard error was then used to create 95 percent confidence intervals. Several model based methods and specialised imputation procedures were investigated for this task, however, none were as robust as the GAMs, which are able to effectively model the highly variable trends that were evident for some countries and also enable an estimate of standard error to be retrieved.

Process 5

Backcasting annual power (P6 in Figure 1), where necessary, to 1950 using autoregressive integrated moving average models (ARIMA). This is achieved by reversing the time series then using the 'autoARIMA' function from the forecast package in R. GAMs are data driven and are therefore unreliable for forecasting and backcasting.

Process 6

As per Process 5 but forecasting to 2012 where necessary (P6 in Figure 1).

Process 7

For countries in which no fishing fleet data exists, we identified a surrogate country by carrying out cluster analysis based on a Bray-Curtis dissimilarity matrix of the catch composition of each country (P7 in Figure 1). This was achieved using FAOs registry of global wild caught landings data that is publicly available for download using FishStatJ software (http://www.fao.org/fishery/statistics/software/fishstatj/en). Once the best possible surrogate was identified (i.e the country with the lowest dissimilarity, P8 in Figure 1) 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.

Process 8

For several countries there was insufficient data available for GAM and or ARIMA modelling or, these models created unrealistic estimates. In these instances, the last available value was carried forward, and where necessary the last available value was carried backward to complete the time series (P9 in Figure 1).

Process 9

Estimation of fishing effort (fishing days); this was achieved by extracting the publicly available fleet dynamics information from the EU (http://datacollection.jrc.ec.europa.eu/) (D6 in Figure 1) and then back-calculating the average days fished from the aggregated fleet data. This enabled mean annual fishing days to be estimated for >1200 combinations of vessel length, gear type and year combinations from 2008 to 2011. We were unable to achieve heteroscedasticity, thus two Kruskal-Wallis tests were used to determine whether the number of days fished annually varies with vessel length class and fishing gear. Where significant differences existed, multiple pairwise Mann-Whitney tests were performed to explore post-hoc differences with p-values corrected for multiple pairwise comparison (Benjamini and Yekutieli, 2001). Based on these results appropriate linear models were fit to the data numerically (P10 in Figure 1), thereby enabling fishing days to be estimated for length classes that were not reported in the EU effort data (i.e. the EU effort data was reported on four broad length classes whereas the FAO data is reported on a wide variety of classes that vary in each data set). To achieve the numeric linear model, the mean or median length of vessels from the EU fleet database within each length class of the EU effort dataset was used. Kolmogorov-Smirnov tests were used to test for normality (Shapiro-Wilk tests are not suitable for >5000 values): if normally distributed, then the mean was used, if non-normally distributed the median was used.

The aforementioned numeric linear models were fit 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 KW) and the number of days fished, as estimated by the above linear models (P11 in Figure 1).

When no information was available on vessel size (length or GT), the number of days fished was estimated by randomly sampling (1000 samples) the EU effort data set. This was bootstrapped using the methods outlined above and the mean/median days selected based on tests for normality.

The methods outlined above require several assumptions be made: 1) that the fishing activity of the EU fleet is representative of global fishing fleets, and 2) that the fishing activity of the EU fleet from 2008 to 2011 is representative of fishing activity throughout the entire time series.

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 developmental status capacity, it was possible to estimate the uncertainty that was introduced from Processes 2 and 3. This was achieved using random sampling techniques (bootstrapping) that were replicated 1000 times while data were being aggregated at the country, global, regional and developmental status scales. The mean/median and confidence interval were retrieved as per Process 2. The methods used at each level were as follows:

1) for Processes 2, by randomly sampling from the possible capacity estimates (bootstrapped results) for each fishing gear, year and GT class.

2) for Process 3, as per the above but only for each year and length class.

3) for Process 4, 95 percent confidence intervals were generated by the predict function when creating the GAMs. To incorporate this error into regional and global aggregations, a distribution of 1000 possible values was generate using the 'rnorm' function in R by using the GAMs standard deviation retrieved from the GAM model. A normal distribution was assumed. These data were then incorporated in the aggregation of random samples as per 1 and 2 above.

4) for Processes 5 and 6, as per method 3 but using the values predicted by the ARIMA models during forecasting and backcasting.

5) for Process 7, as fishing effort was calculated at the vessel size 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.

6) for Process 8, there is no reliable way to incorporate uncertainty into the difference between the surrogate and the country for which there is no information. To give some indication, we used the percent dissimilarity of the catch composition as a proxy for standard deviation and created a distribution of possible values as per 3 and 4 above. This method is non-quantitative as it does not take into consideration differences in the fishing methods, fishing capacity or fishing effort used to take this catch so needs to be interpreted with a degree of caution. Nevertheless, the results are likely to give some indication as to how reliable the estimates are and, if anything, probably overestimated uncertainty.

7) for P13, there is no way to estimate the error incorporated by carrying the last value forward or backward. As such, we assumed that the error was equal to that of the annual average for each year that was imputed, and a distribution of possible values was estimated as per processes 3 and 4 above.

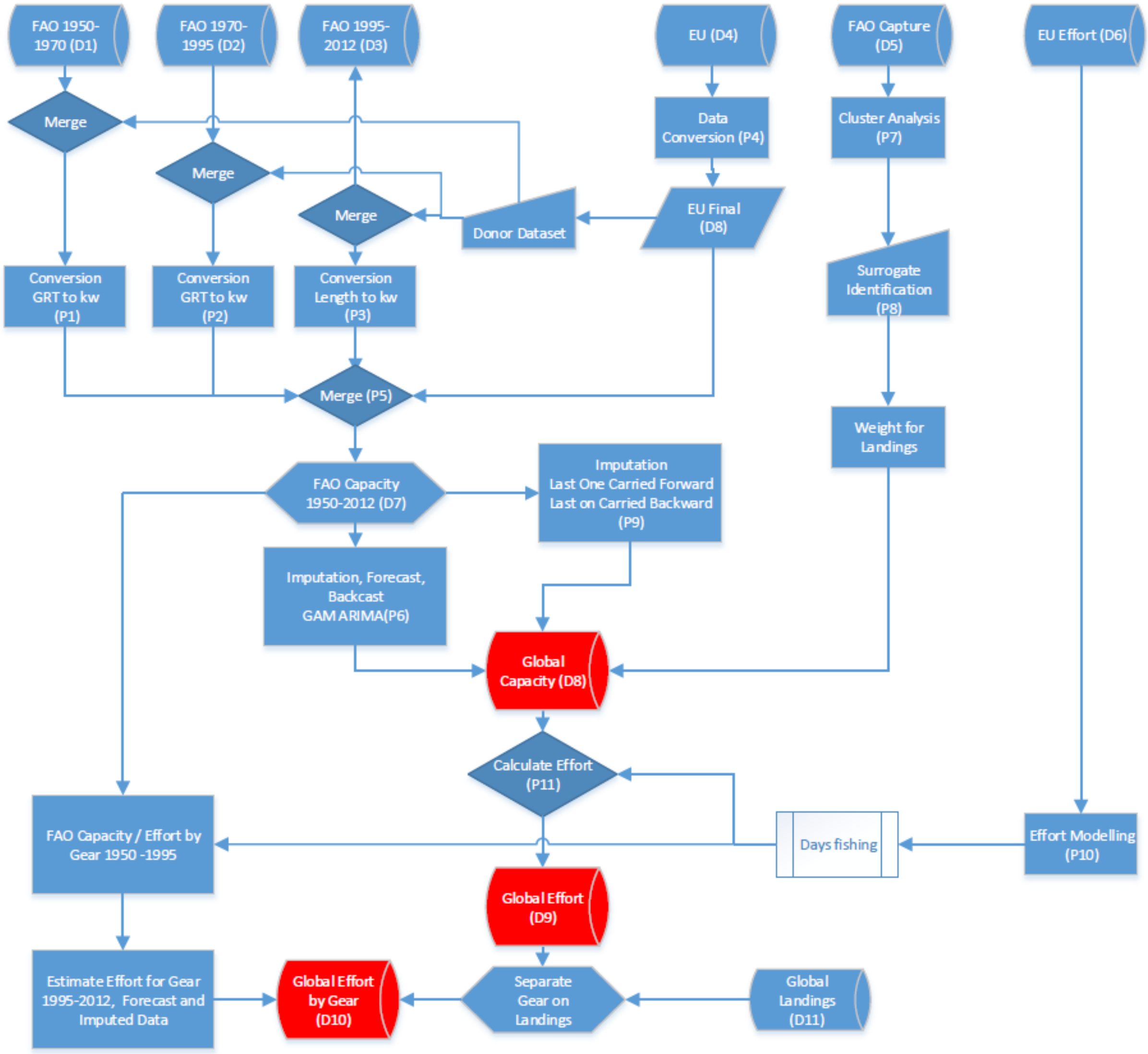


Figure 1: Diagrammatic representation of data processing.

Results

Data availability

Wild caught marine landings were recorded by 204 countries in 2013; as such, we estimated fishing capacity and fishing effort for each. In the majority of years, the bulk of the analyses were based on FAO data (Figure 2). Prior to 1970 a large proportion of estimates were derived from ARIMA backcasting and the proportion of forecast data began to increase toward the end of the time series. During the 1970s there was a notable lack of FAO data, therefore GAM was the most common method in most years. From 1989 onward, there was EU data available, which was used in preference of other data sources due to its high accuracy.

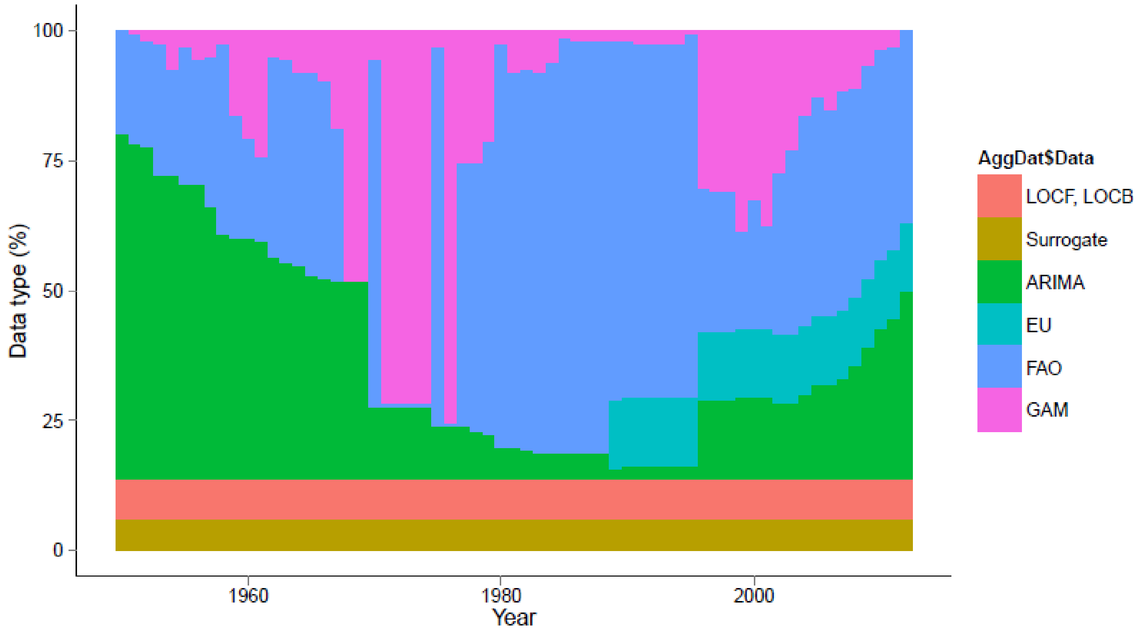


Figure 2: Data used annually for calculation of fishing capacity and effort. LOCF, LOCB refers to using the last value carried forward and last value carried backward method.

Surrogates, and carrying the last value forward/backward, was necessary for a small proportion of countries. The cluster analysis performed relatively well with most surrogate countries being relatively plausible and geographically close (Figure 3). Of note, several small Pacific island nations that had similar catch composition did not have any capacity or effort information. In such instances, the nearest surrogate was often the fourth or fifth least dissimilar country, which increases the uncertainty surrounding their use.

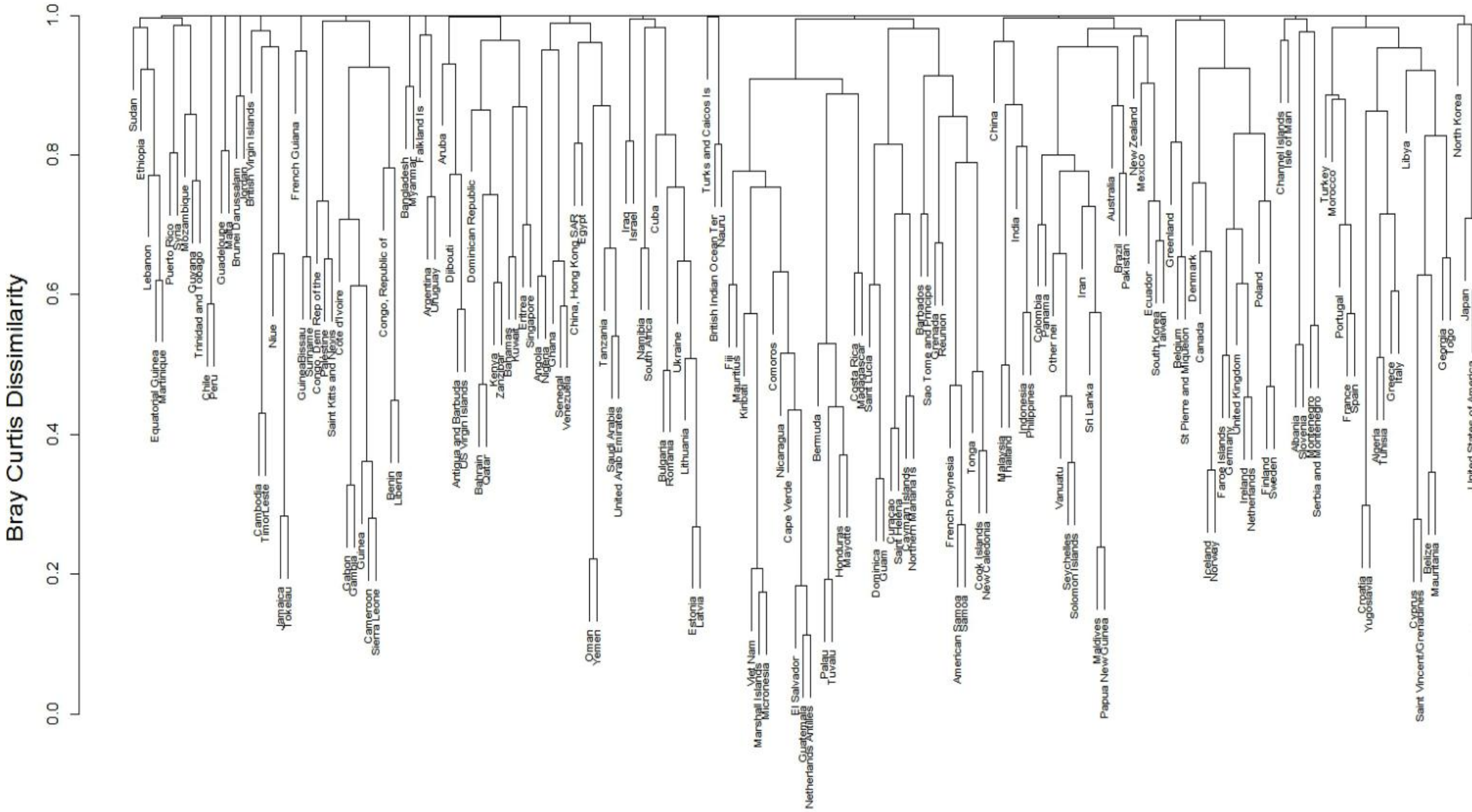


Figure 3: Cluster dendogram of the Bray-Curtis dissimilarity of the catch composition of each country registering marine catch to the FAO.

The influence of fishing gear type and year on vessel power

The power of vessels within each GT and length category varied significantly with both fishing gear type and year (Appendix 1). Thus, modelling of GT and KW (Process 1, models are located in Appendix 2) and the donor datasets for estimating the power of the vessels within each GT/length class (Process 2 and 3) were created using EU vessels from the same year and with equivalent gear where possible (method A). When this was not possible, vessels from the same year and GT/length class were used (method B). Few vessels did not meet these first two criteria and there was little appreciable difference in the error generated by using either of these methods (Figure 4). Most of the time that the method A and B were not able to be used was when the data contained no information on vessel size or fishing gear, and thus it was necessary to generate the donor dataset from all of the EU vessels from that year (method E). Although rare, this did result in greater uncertainty surrounding these estimates and percentage errors exceeding 100 percent (just visible in Figure 4).

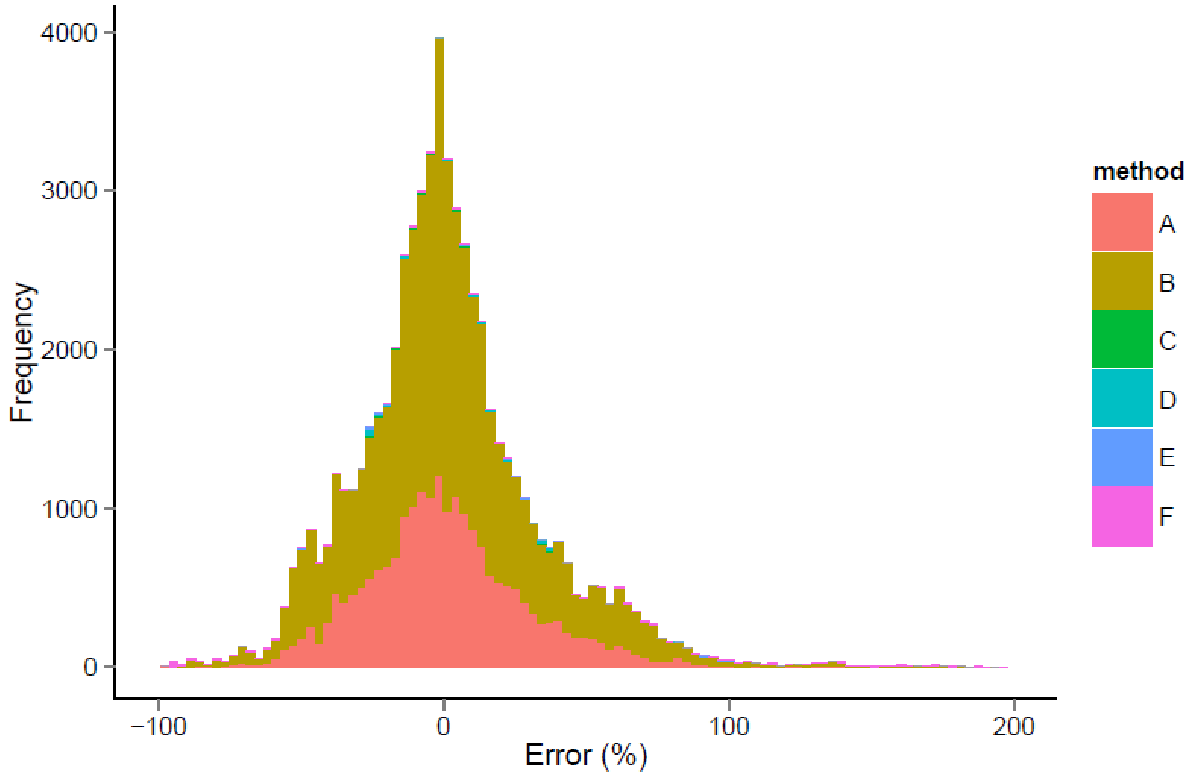


Figure 4: The positive and negative error (%) surrounding the mean/median (zero in the Figure) derived from Processes 2 and 3 in which possible fishing capacity was estimated for each length/ gross tonnage category of each country and year.

Method refers to the quality of the donor group available for bootstrapping: A = year, gross tonnage/length class and fishing gear; B = year, gross tonnage/length class; C = decade, gross tonnage/length class and fishing gear; D = gross tonnage/length class (decade); E = gross tonnage length class (all years); and, F = all vessel sizes and gears from that year (i.e. the size and gear type was unknown).

Fishing capacity

The capacity of the global fishing fleet was relatively stable until the 1970s before increasing consistently up until 2010 (Figure 5). From 2010 to 2012 there is some indication that the trend has stabilised, or even begun to decline slightly. However, an increasing reliance on forecasting since the late 1990s (Figure 2) has resulted in a greater uncertainty in latter years. The trend fluctuates throughout the 1990s even though this was the period for which the FAO dataset was most complete and, as a result, had the least error 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 throughout this period of time.

The fishing capacity of the Asian fleet is an order of magnitude greater than any other region (Figure 6) and the large increase in the mid-1990s was responsible for the jump 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 throughout the time series in all regions other than Europe and Oceania, although most regions show a stabilising trend in the last few years of the time series. The European fleet reached a maximum around 1990 and has subsequently declined to around 1960 levels. Oceania increased from 1980 onward but showed a decreasing trend from 1950 to 1970. During this period there was a substantial lack of data for this region, and capacity estimation relied heavily on ARIMA modelling and, an increasing trend in the 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 is more likely to have been similar to 1970 levels throughout this period.

The trend in fishing capacity was heavily dependent on national developmental status with developing nations responsible for the greatest proportion of effort and also responsible for the greatest increase throughout the time series (Figure 7). In the last few years, however, there is some indication that the trend has stabilised and begun to decline. The fishing capacity of developed nations increased slightly throughout the time series until around 2000. After this time this category had a decreasing trend. 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.

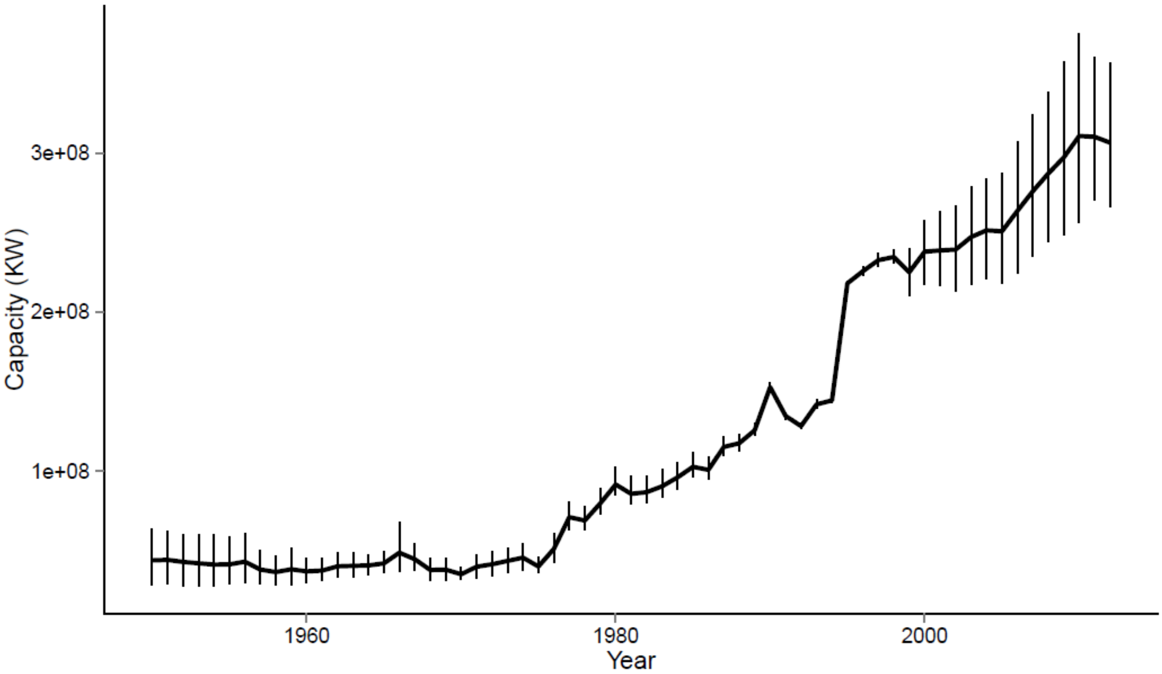


Figure 5: Global fishing capacity from 1950 – 2012.

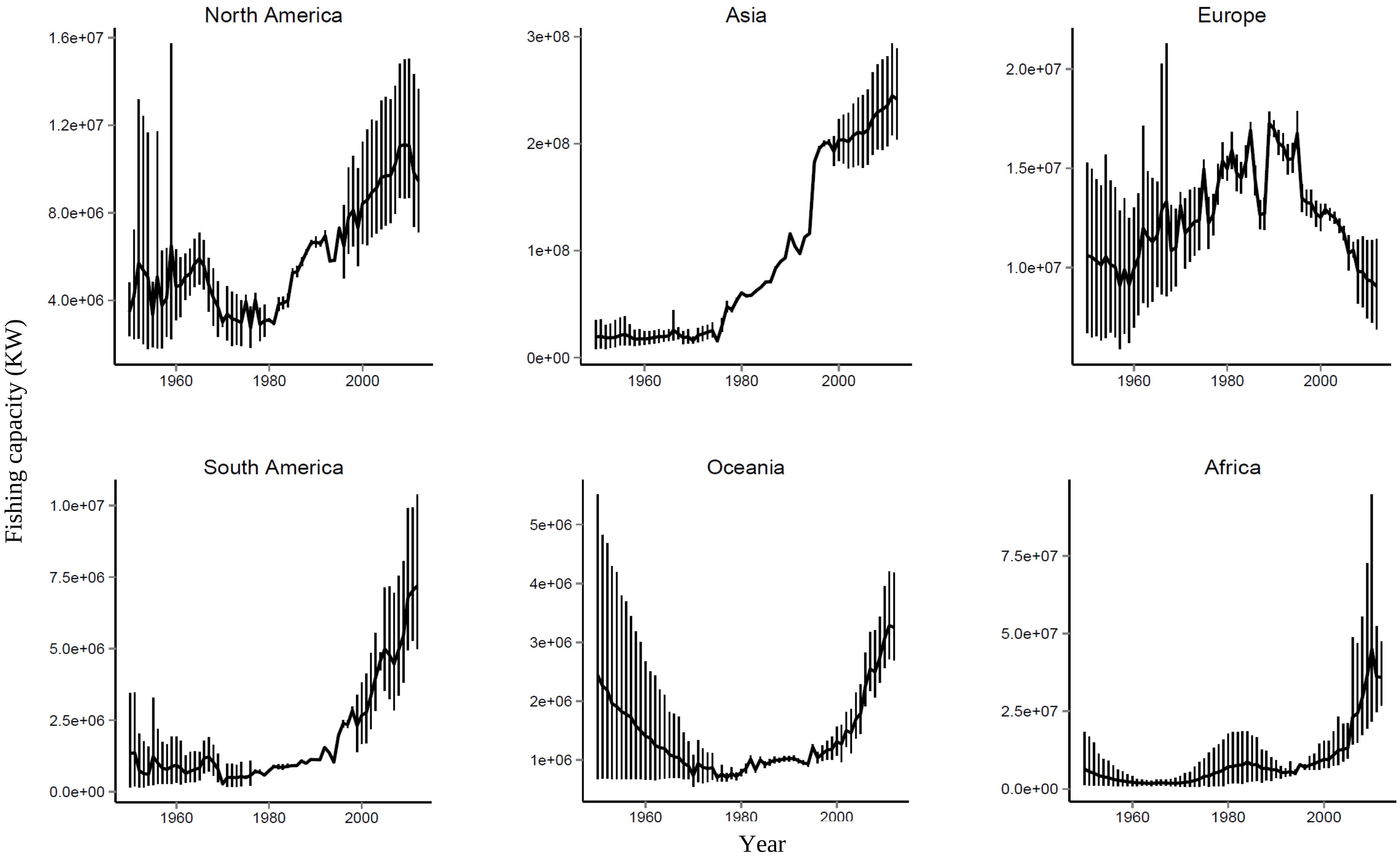


Figure 6: Regional fishing capacity from 1950 – 2012.

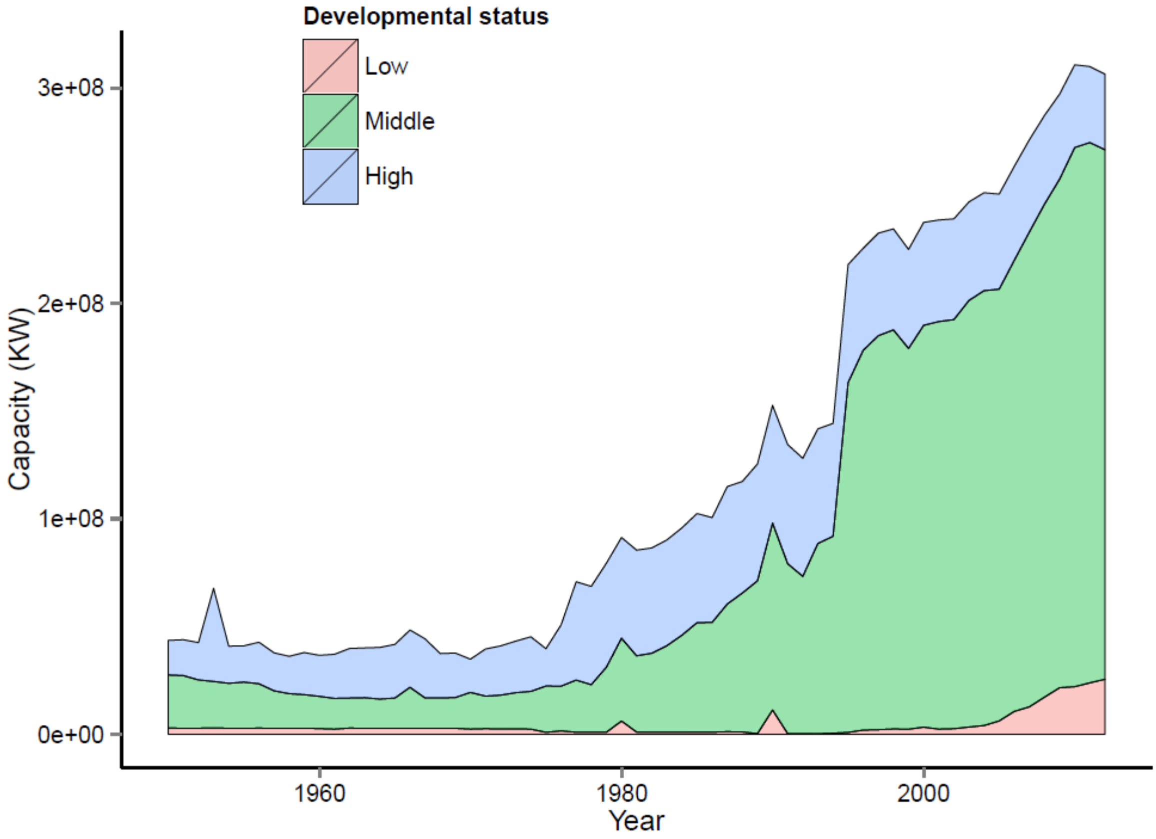


Figure 7: Fishing capacity of highly developed (high), developing (medium) and non-developed (low) countries from 1950 – 2012.

Conversion of capacity to effort

The EU fishing effort database contained >1200 estimates of annual days for vessels of a variety of vessel size and fishing gears. The time series was too brief to develop a meaningful relationship with which to estimate how annual fishing effort has varied temporally and the dominance of this data source meant there was no possibility to develop a relationship using the limited historic data sources available (e.g sources listed by Anticamara *et al.* (2011)). Data from France for 2009 was removed from these analyses due to a suspiciously high proportion of zero days fished by their fleet during that year and because this anomaly was not supported by the literature.

The number of days fished was highly variable, even within each fishing gear and length category (Figure 8). It was not possible to meet heteroscedasticity requirements and we performed a two-way analysis of variance to analyse this variation; as such, two Kruskal-Wallis tests were used to test each variable individually. These tests indicated that there was significant variation in the number of days fished with 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 (Figure 8). Few multiple pairwise comparisons of fishing gear were different: notably, the number of days fished by trawlers and pot/trap vessels tended to be greater than the other categories (Table 3, Figure 8). Further, there were few significant differences between the other vessel types and those that were, were only slightly so (Table 3). Therefore, to avoid introducing bias by further 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 vessel categories and the last with all fishing gears for use when there was no information on fishing gear. Kolmogorov-Smirnov tests indicated that the data within each length category were non-normally distributed (Table 4), thus, we estimated the median length of vessels within each length class in order to create the linear models 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 linear models describing these relationships are shown in Table 5 and the resulting equations for the conversion of fleet capacity to fishing effort in kilowatt days are:

$$\textit{Days fished} = 2.012(\textit{length}) + 80.649$$

for trawlers and pot/trap vessels, and:

$$\textit{Days fished} = 2.004(\textit{length}) + 54.603$$

for all other fishing gear types, and:

$$\textit{Days fished} = 2.360(\textit{length}) + 59.\ 500$$

for all fishing gear types, and:

$$\text{Days fished} = 93.375 \text{ (95 percent CI: 88.772, 97.413)}$$

bootstrapped result for all sizes and all gear types.

The number of days fished annually for each length/GT estimated by the above 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 (Figure 8).

Table 1: Kruskal-Wallis rank sum test of variation in the mean number of days vessels fish annually with the 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: Post-hoc pairwise Mann-Whitney 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

Table 3: Post-hoc pairwise Mann-Whitney tests of variation in the number of days fished annually with fishing gear category.

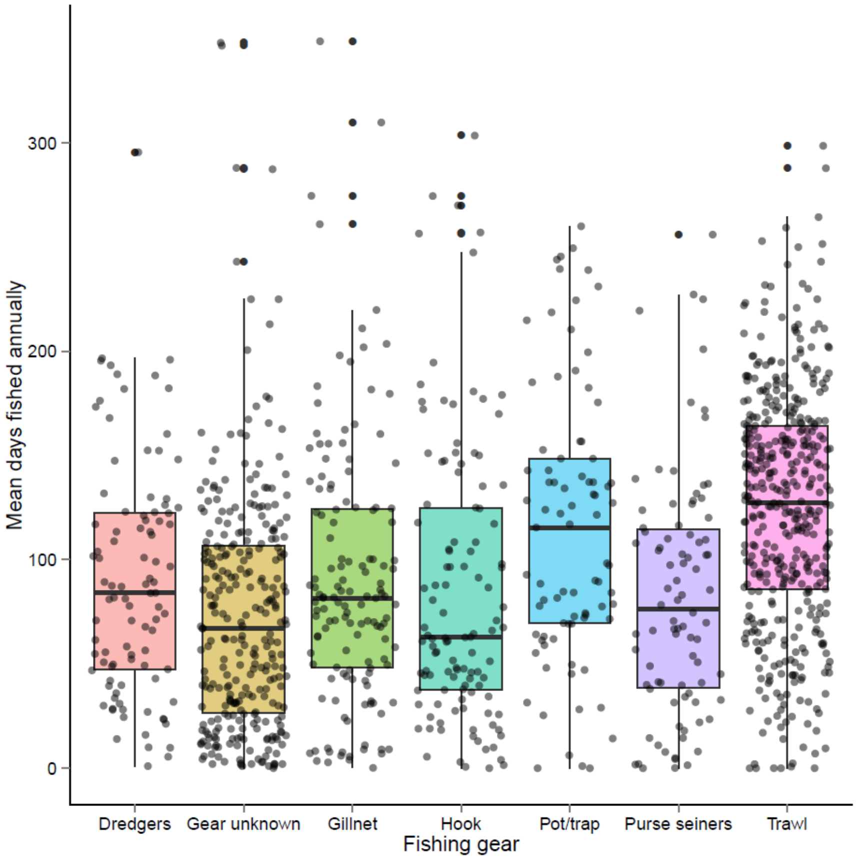
	Dredgers	Gear unknown	Gillnet	Hook	Pot/trap	Purse seine
Gear unknown	0.051	-	-	-	-	-
Gillnet	1.000	0.062	-	-	-	-
Hook	0.870	0.953	0.870	-	-	-
Pot/trap	0.056	<0.001	0.051	0.004	-	-
Purse seine	1.000	0.870	1.000	1.000	0.010	-
Trawl	<0.001	<0.001	<0.001	<0.001	0.487	<0.001

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 of each category is provided as each test suggested the data were non-normally distributed; thus the median was used for creation of the linear regression of days fished and vessel length.

Length category	D value	*p*	Median
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

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



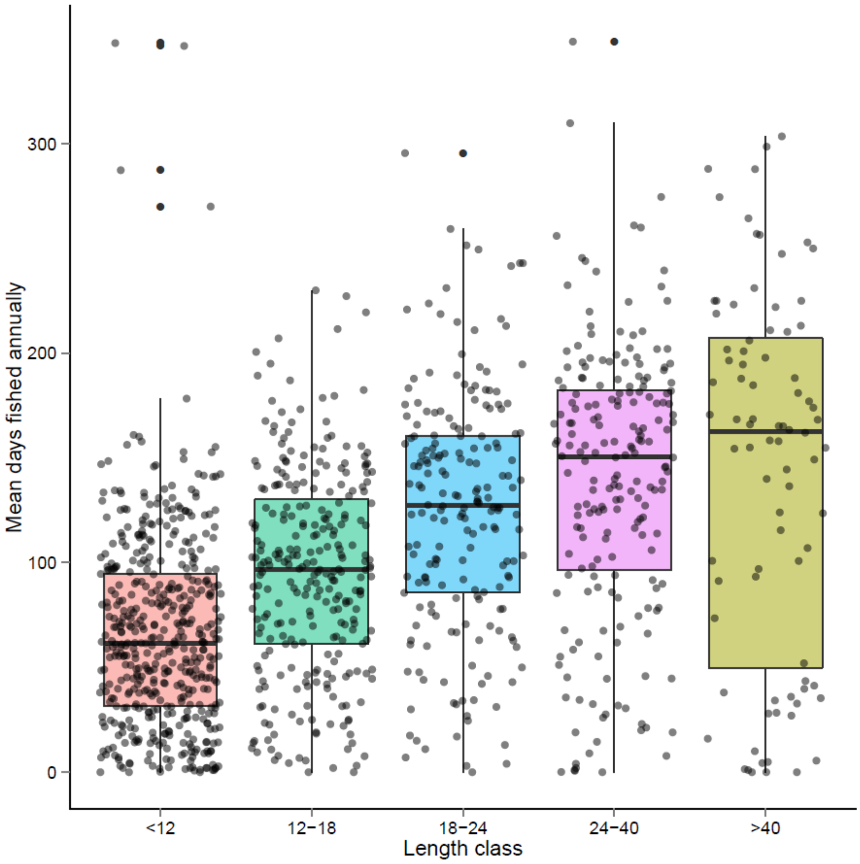


Figure 8: Variation in the mean annual days fished by fishing gear (bottom) and vessel length category (top) and by derived from the EU fishing fleet 2008 – 2011.

Global nominal fishing effort

Global nominal fishing effort increased throughout the time series and more than tripled from 1950 to 2012 (Figure 9). Interestingly, the downturn observed in fishing capacity in later years was not observed in fishing effort, presumably because vessel size has increased and larger vessels fish more days on average. Again, there is a considerable quantity of noise during the mid-1990s, however, this did not alter the overall increasing trend throughout the time series. This noise was generated by the Asian fleet (Figure 10), which dominated global fishing effort at greater than 10 times that of any other single region and nearly 4 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 onward in most regions (Figure 10). 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 greatest increase throughout the time series occurring in developing nations (Figure 11). Developing nations are also responsible for the majority of global fishing effort. The fishing effort of developed nations has been in decline since maximum levels in the 1980s and 90s but its efficiency may have been increasing as a faster rate for these countries. 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 Figure 7 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.

The overwhelming majority of fishing effort is carried out by trawling with moderate levels of hook and line fishing and only small amounts reported from other gears (Figure 12). The data provided to FAO by many countries included only trawling effort so this result may not be entirely accurate. Further, no gear information was available for much of the time series; as such, the trends observed in Figure 12 are dictated by fishing activity during 1970 to 1995 and may not be reflective of earlier of later periods of time.

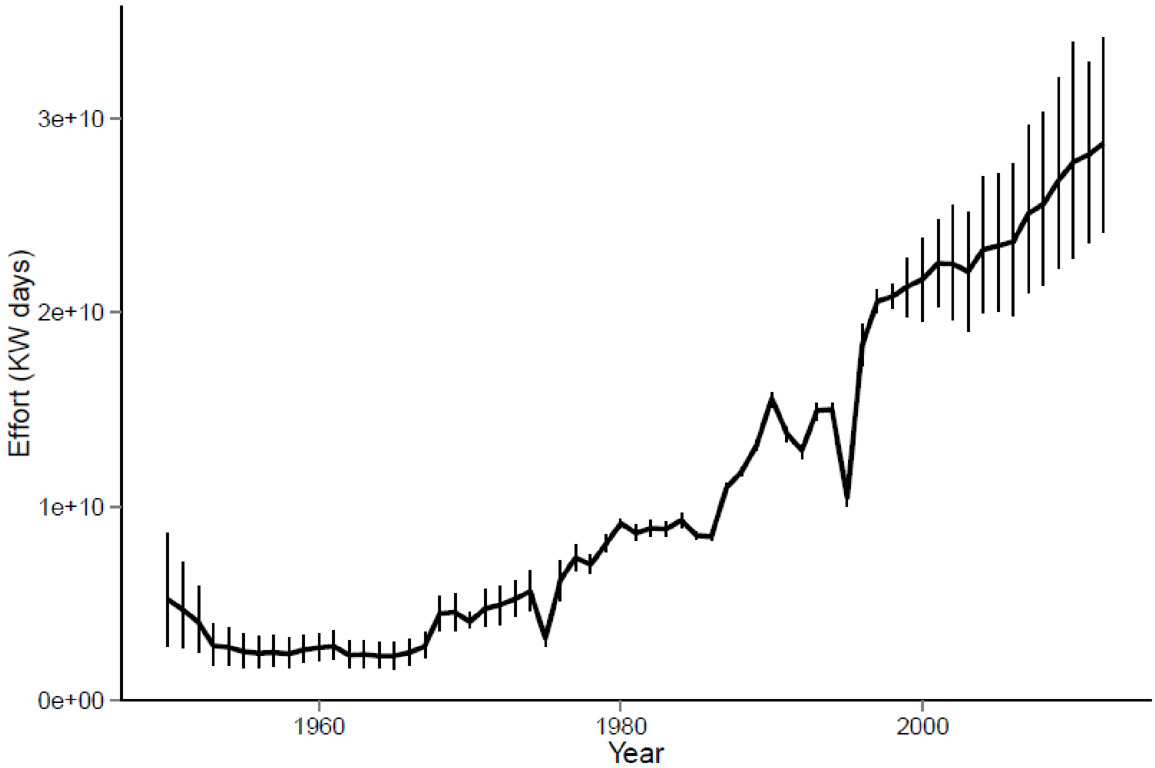


Figure 9: Global fishing effort from 1950 – 2012.

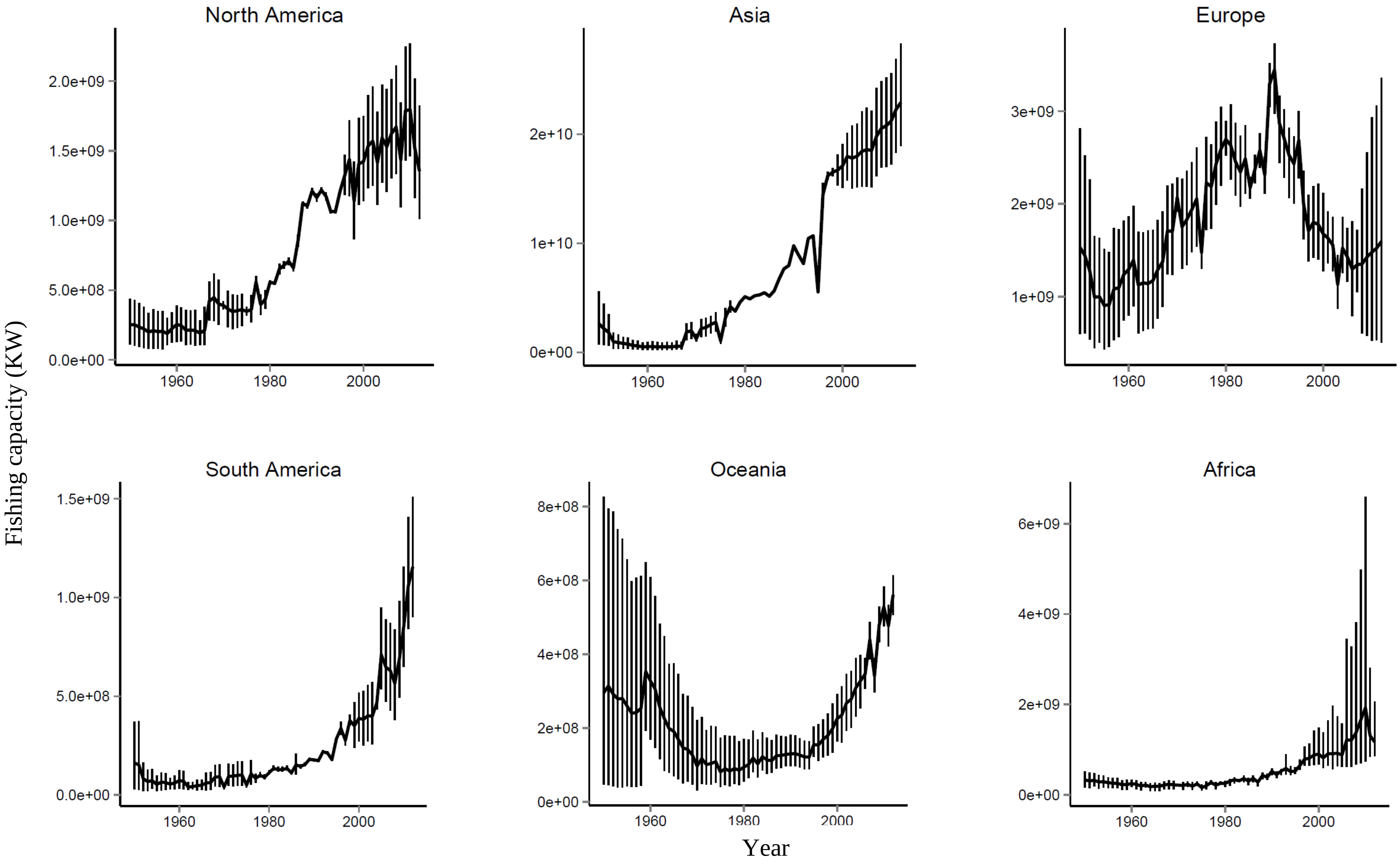


Figure 10: Regional fishing effort from 1950 – 2012.

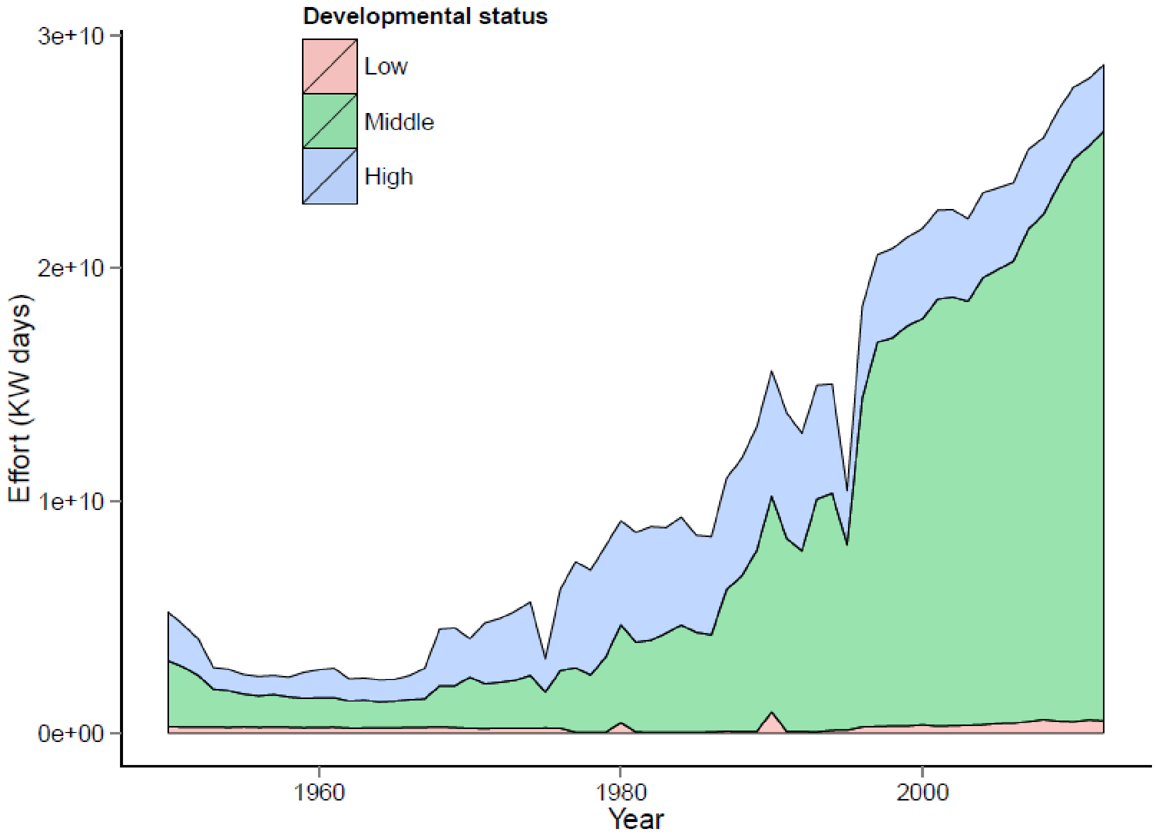


Figure 11: Fishing effort, by developmental status, of the global fishing fleet.

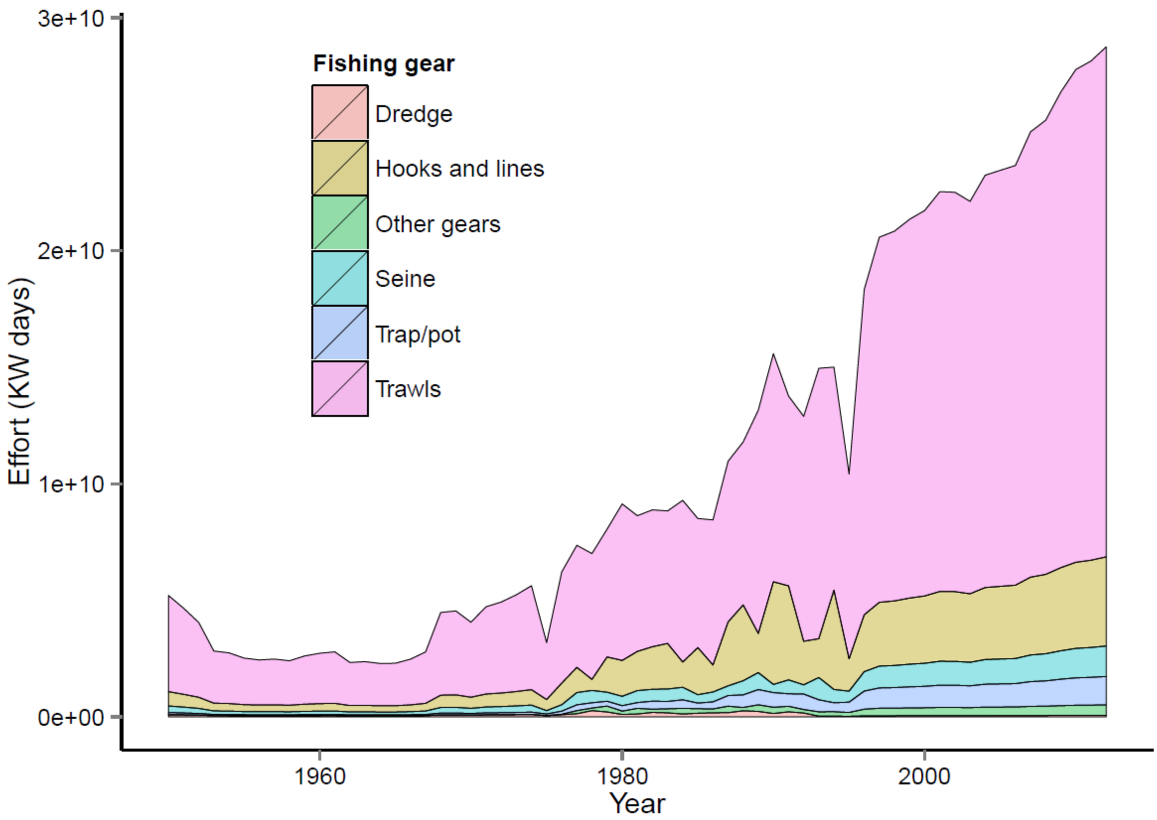


Figure 12: Fishing effort, by fishing gear category, of the global fishing fleet.

Discussion

Global fishing capacity and nominal 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 both fish stocks and/or the overall efficiency of the global fishing fleet.

The World Summit on Sustainable development in 2002 set an optimistic target for all world fish stocks to be at levels enabling maximum sustainable yield by 2015 (Anon, 2002). Our results indicate that fishing capacity and effort continue to grow rapidly and that these goals will not be achieved. A reduction in fishing capacity has been viewed as imperative in sustaining global fish stocks (FAO, 2014) and maximising economic potential of global fisheries (Arnason, Kelleher and Willmann, 2009). Overcapacity is usually a result of open access to fisheries even if there is a total allowable catch in place (Beddington, Agnew and Clark, 2007). This generally occurs due to high initial profitability of fisheries with the problem being enhanced by subsidies (see Sumaila *et al*. (2010) for a summary of fishery subsidies), which offer incentive to continue expansion when fish stocks are reduced to beyond a point at which fishing would otherwise become economically unviable (Beddington, Agnew and Clark, 2007).

There have been improvements in the management of many fisheries over the last decade and we estimate that the fishing capacity of developed nations had decreased by 37 percent in 2012 since maximum levels in 1991. However, developed nations only represented 11 percent of global fishing capacity in 2012 meaning this decline has minimal influence on a global scale. Ye *et al*. (2013) found that global fishing capacity needed to be reduced by 36 to 43 percent 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 percent of fisheries globally continue to be fished beyond maximum sustainable yield.

Our results suggest that the above situation is now considerably worse with fishing capacity increasing by approximately 7 percent from 2008 to 2012 and, if applying this data to those of Ye *et al.*, (2013), fishing capacity now needs to be reduced by 43 to 50 percent 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 annually and provide considerable environmental and biodiversity benefits (Ye *et al.*, 2013).

Complicating the above situation is that the greatest increases in both fishing capacity and fishing effort are occurring in developing nations with an increasing trend also occurring in undeveloped nations, albeit to a lesser extent. Developing nations were responsible for >80 percent of global fishing capacity and fishing effort in 2012 with undeveloped nations responsible for <10 percent. 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 lived and the largest fishing fleets already exist.

It is difficult for nations with undeveloped or developing economies to implement fishery regulations designed to prevent further expansion due to the socio-economic 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 minimise, or prevent, unsustainable overcapitalisation in wild capture marine fishing.

Some caution needs to be exercised when using fishing nominal effort measures such as KW (or tonnage) for estimating stock health in a traditional fashion (i.e. like catch per unit effort). This is because power has differing implications depending on the gear utilised. For example, power has some influence of 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 utilised. If the catchability (q) energy based ‘effort’ units and fishing power (proportion of stock removed) is calculated it is then possible to use these data to estimate stock health in a traditional fashion as is done with catch per unit effort. Indeed, this is a potential direction of future research that would enable KW, or other power based methods, to be used to assess fishing effort quantitatively.

The skill of the skipper and crew, as well as advances in technology, also influence catch per unit effort (Squires and Kirkley, 1999). When these factors are unaccounted for it is termed ‘nominal’ fishing effort, which we report here, and when they are accounted for it is termed ‘effective’. The only studies that we are aware of that have estimated how effective fishing effort has increased through time found an average annual increase of 2 to 5 percent (Fitzpatrick, 1996; Pauly and Palomares, 2010), although, at times, the rate of increase is likely to be greater due to advances in technology that revolutionise fishing efficiency. This increase in efficiency has the ability to mask increases in fishing effort and a decline in catch rate. That is each unit of effort becomes more effective each year. Further, fishing capacity reduction schemes rarely account for effective fishing effort and it has been proposed that in most cases the least efficient vessels that leave the fishery first and increases in the efficiency of the remaining vessels may completely eliminate the benefits of such schemes (Pascoe and Coglan, 2000). The influence of effective fishing effort is another area of exploration that requires further research, particularly as it is likely to vary over various temporal and spatial scales.

Limitations and data quality

The random sampling techniques utilised in the present study requires one major assumption: that the power 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 bias that could be introduced when the reporting to FAO changed from GT categories to length categories in 1995. Given European fleets pioneered most fishing techniques and the region includes a broad diversity of fisheries ranging from small scale coastal fisheries in the Mediterranean, Baltic and Black seas to the large scale, industrial fisheries of the north Atlantic, the fleet is likely to be representative of most fishing practices and suitable for most calculations performed herein.

Many countries provide FAO with a relatively poor breakdown of fleet statistics. Most commonly, countries did not report the fishing gear that the vessel used, which we found was a significant factor dictating vessel power. It was also fairly common for countries to report their entire fleet as ‘trawlers’, which is likely to be inaccurate on most, if not all, occasions. We recognise the reporting difficulties when vessels use multiple gear types but better reporting is essential. Less commonly, but of greater detriment to the present study, some countries provide no information regarding vessel size whatsoever. In doing so, these countries force studies such as this to assume they are following trends observed elsewhere, which may not always be the case.

China was believed to have misreported landings for a period of time during the 1990's as a result of incentives provided to officials who create the greatest regional increases in productivity (Watson and Pauly, 2001). 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 1990's (Watson and Pauly, 2001). However, more recent studies have found that although landings from China's Exclusive Economic Zone appear to have been inflated, their landings of their long distance fleet appear to be underreported (Pauly *et al.*, 2014). This may deflate global landings and fishing effort due to the prominence and wide ranging nature of their fishing fleet, however, China was relatively well represented within the FAO data set utilised herein, more so than some developed nations that claim to have some of the best fisheries management practices in the world.

Disappointingly, the quantity and quality of data has declined since the 1990s and this introduces uncertainty into the fishing capacity and effort estimations in 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. Using the percent dissimilarity we were able to estimate this uncertainty but this method is not necessarily accurate.

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. We are uncertain of how representative this is globally. It is possible that fishing effort has decreased in 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 overexploited 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 would have introduced a bias into global calculations. However, many fisheries throughout the world are now considered fully exploited, or overexploited, 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, 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 some regions. In particular, the fishing effort is unlikely to be representative at small spatial scales but is reasonably likely to be representative at the global, regional and developmental status level.

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 highly 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 be spending less time actually fishing in recent years due to fisheries targeting ‘peak’ fishing periods (Arnason, Kelleher and Willmann, 2009). These authors do not provide a reference for this claim but the theory is certainly plausible and, if this is occurring, it is almost certainly enhanced by the introduction of stricter management regulations (e.g. spawning closures and quota management) in recent years. Nevertheless, reports from the 1950s suggest technical problems, breakdowns and underpowered vessels preventing long range travel resulted in averages of just 34 to 71 days fished annually in 1951 to 53 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, and no data are available to address this variation at either the spatial or temporal level. Nevertheless, it is our contention that due to the considerable investment involved in commercial fishing, fishermen will, as a rule, 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, and is a substantial improvement on the methods used by Anticamara *et al*. (2011).

Another possible source of bias occurs when vessels fly flags of convenience, which is often done to avoid fisheries management controls and other regulations (Gianni and Simpson, 2005; Calley, 2012). Greater than 75 percent 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. It has also 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 manner consistently 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 in which they are flagged. Further, where data does exist, both catch composition and fleet characteristics are suspiciously low in many instances. This behaviour compromises the accuracy of studies such as this, and is a serious issue facing fisheries globally.

While the abovementioned limitations have undoubtedly introduced bias into the estimation of both fishing capacity and fishing effort, it must be noted that the most recent data available are far more thorough that those utilised previously, which has indefinitely improved the quality of the results reported here. Further, the present study was statistically more rigorous than those previous and wherever possible encompassed, and provided, the uncertainty surrounding estimates. Provided this level of reporting to the FAO can be maintained into the future, and improved upon wherever possible, it will be possible to accurate monitor the global fishing fleet into the future, which will prove critical if we are to reduce the overcapacity and overfishing that appears to be continuing throughout much of the world.

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Appendix 1: Kruskal-Wallis tests exploring variation in the power of vessels in each length/GT class with fishing gear and year.

This appendix displays statistical outputs of Levene's test for homogeneity of variance of power (kilowatts) with fishing gear category and year. These were carried out to determine whether the data were suitable for a two-way ANOVA to explore this relationship. The data were not, however, normally distributed and could not be transformed to meet heteroscedasticity using standard techniques. Thus, two Kruskal-Wallis tests (displayed below) were used to determine whether power varied with fishing gear and year. Significance codes: '***' <0.001, '**' 0.01, '*' 0.05, '.' 0.1.

Length categories

6-11.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group      8  1646.3 < 2.2e-16 ***
      458735

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    117  270.03 < 2.2e-16 ***
      456440

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 56169.17, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 33146.42, df = 117, p-value < 2.2e-16 ***
```

12-17.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group      8  246.24 < 2.2e-16 ***
      101348

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    113  38.492 < 2.2e-16 ***
      101064

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 9265.252, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 6100.142, df = 113, p-value < 2.2e-16 ***
```

Up to 5.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group      8  1537.8 < 2.2e-16 ***
      276637

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    110  208.85 < 2.2e-16 ***
      270353
```

```
      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 11944.37, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 47058.76, df = 110, p-value < 2.2e-16 ***
```

Unknown length

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     8  123.11 < 2.2e-16 ***
      16961

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    91  15.963 < 2.2e-16 ***
      16796

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 5792.425, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 2608.916, df = 91, p-value < 2.2e-16 ***
```

24-29.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     7  74.041 < 2.2e-16 ***
      25636

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    75   25.53 < 2.2e-16 ***
      25529

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 885.9262, df = 7, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 3227.684, df = 75, p-value < 2.2e-16 ***
```

18-23.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     7  89.608 < 2.2e-16 ***
      54401

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    88  37.599 < 2.2e-16 ***
      54212

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 1939.513, df = 7, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 4212.345, df = 88, p-value < 2.2e-16 ***
```

75-99.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
       Df F value    Pr(>F)
group   5  21.369 < 2.2e-16 ***
      687

Levene's Test for Homogeneity of Variance (Year)
       Df F value    Pr(>F)
group  49  23.055 < 2.2e-16 ***
      643

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 134.2551, df = 5, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 398.9132, df = 49, p-value < 2.2e-16 ***
```

45-59.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    6  22.635 < 2.2e-16 ***
      2716

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
group   68  20.649 < 2.2e-16 ***
      2651

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 333.1923, df = 6, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 847.5631, df = 68, p-value < 2.2e-16 ***
```

30-35.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     8  38.994 < 2.2e-16 ***
      11306

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    68  14.354 < 2.2e-16 ***
      11239

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 728.013, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1643.46, df = 68, p-value < 2.2e-16 ***
```

36-44.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    8   104.3 < 2.2e-16 ***
      8187

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
```

```
group   62  33.441 < 2.2e-16 ***
      8133

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 1472.456, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1154.31, df = 62, p-value < 2.2e-16 ***
```

60-74.9 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    3  23.286 1.106e-14 ***
      1297

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
group   60  10.009 < 2.2e-16 ***
      1237

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 290.3091, df = 3, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 753.2544, df = 60, p-value < 2.2e-16 ***
```

>100 m

```
Levene's Test for Homogeneity of Variance (Fishing gear)
       Df F value    Pr(>F)
group   1   14.05 0.0002227 ***
      242

Levene's Test for Homogeneity of Variance (Year)
       Df F value    Pr(>F)
group  23  23.223 < 2.2e-16 ***
      220

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 1.7331, df = 1, p-value = 0.188

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 212.17, df = 23, p-value < 2.2e-16 ***
```

GT categories

0-4.90 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
          Df F value    Pr(>F)
group      8  3631.1 < 2.2e-16 ***
      517199

Levene's Test for Homogeneity of Variance (Year)
          Df F value    Pr(>F)
group    116  365.27 < 2.2e-16 ***
      516873

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 27819.11, df = 8, p-value < 2.2e-16 ***
```

```
      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 57179.03, df = 116, p-value < 2.2e-16 ***
```

4.90-14.305 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
          Df F value    Pr(>F)
group      8  346.59 < 2.2e-16 ***
      114350

Levene's Test for Homogeneity of Variance (Year)
          Df F value    Pr(>F)
group    106  89.331 < 2.2e-16 ***
      114244

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 8919.627, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 6133.595, df = 106, p-value < 2.2e-16 ***
```

14.305-23.55 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     8  70.304 < 2.2e-16 ***
      30293

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group   101  14.751 < 2.2e-16 ***
      30196

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 1060.909, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 2389.055, df = 101, p-value < 2.2e-16 ***
```

23.55-32.82 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     7  5.7812 1.043e-06 ***
      17164

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    93  8.9881 < 2.2e-16 ***
      17078

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 439.8622, df = 7, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1383.042, df = 93, p-value < 2.2e-16 ***
```

88.3-180.8 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     8  77.113 < 2.2e-16 ***
```

```
      29412

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)    
group    66  13.373 < 2.2e-16 ***
      29351                      

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 783.8901, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1465.078, df = 66, p-value < 2.2e-16 ***
```

41.99-88.3 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)    
group     8  43.566 < 2.2e-16 ***
      37570                      

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)    
group    82  13.221 < 2.2e-16 ***
      37493                      

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 893.5134, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 2347.672, df = 82, p-value < 2.2e-16 ***
```

1845.8-3695.8 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
       Df F value    Pr(>F)    
group   4  23.644 < 2.2e-16 ***
      749                      

Levene's Test for Homogeneity of Variance (Year)
       Df F value    Pr(>F)    
group  46  11.545 < 2.2e-16 ***
      707                      

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 117.5903, df = 4, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 465.5899, df = 46, p-value < 2.2e-16 ***
```

32.82-41.99 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)    
group     7   14.62 < 2.2e-16 ***
      14240                      

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)    
group    83  8.8154 < 2.2e-16 ***
      14164
```

```
      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 520.8275, df = 7, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1669.579, df = 83, p-value < 2.2e-16 ***
```

273.3-458.335 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    8  85.917 < 2.2e-16 ***
      7347

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
group   64  23.889 < 2.2e-16 ***
      7291

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 748.0862, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1255.685, df = 64, p-value < 2.2e-16 ***
```

458.335-920.807 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    7  12.391 1.008e-15 ***
      2947

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
group   54  17.612 < 2.2e-16 ***
      2900

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 336.1578, df = 7, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 615.1905, df = 54, p-value < 2.2e-16 ***
```

180.8-273.3 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
         Df F value    Pr(>F)
group     8   42.93 < 2.2e-16 ***
      10844

Levene's Test for Homogeneity of Variance (Year)
         Df F value    Pr(>F)
group    62  6.5547 < 2.2e-16 ***
      10790

      Kruskal-Wallis rank sum test (Fishing gear)
Kruskal-Wallis chi-squared = 775.9206, df = 8, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 1701.183, df = 62, p-value < 2.2e-16 ***
```

3695.8-7395.8 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
       Df F value    Pr(>F)
group   2  10.915 3.153e-05 ***
      202

Levene's Test for Homogeneity of Variance (Year)
       Df F value    Pr(>F)
group  24  9.9778 < 2.2e-16 ***
      180

      Kruskal-Wallis rank sum test(Fishing gear)
Kruskal-Wallis chi-squared = 1.6243, df = 2, p-value = 0.4439

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 162.4037, df = 24, p-value < 2.2e-16 ***
```

920.807-1845.8 t

```
Levene's Test for Homogeneity of Variance (Fishing gear)
        Df F value    Pr(>F)
group    4  12.184 1.031e-09 ***
      1204

Levene's Test for Homogeneity of Variance (Year)
        Df F value    Pr(>F)
group   49  10.592 < 2.2e-16 ***
      1159

      Kruskal-Wallis rank sum test(Fishing gear)
Kruskal-Wallis chi-squared = 132.5158, df = 4, p-value < 2.2e-16 ***

      Kruskal-Wallis rank sum test (Year)
Kruskal-Wallis chi-squared = 453.4343, df = 49, p-value < 2.2e-16 ***
```

Appendix 2: Linear models of fishing power (KW) and GT

Linear models of power (KW) and the aggregate GT of each EU country from 1950 to 1967. These relationships were used to estimate the fishing capacity of other countries from the FAO global yearbook 1950 to 1967. Plots of these relationships are also presented with 95 percent confidence intervals in red.
Significance codes: <0.001 '***', 0.01 '**' , 0.05 '*', 0.1 '. '

Trawls

```
Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)         -1.911e+03  5.389e+02  -3.547 0.000436 ***
Gross tonnage        3.053e+00  3.903e-02  78.213  < 2e-16 ***

Residual standard error: 9225 on 397 degrees of freedom
Multiple R-squared:  0.9391, Adjusted R-squared:  0.9389
F-statistic:  6117 on 1 and 397 DF,  p-value: < 2.2e-16
```

Gillnets and entangling nets

```
Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)         631.75164  212.15268   2.978  0.00307 **
Gross tonnage         3.73829    0.07917  47.216  < 2e-16 ***

Residual standard error: 3590 on 412 degrees of freedom
Multiple R-squared:  0.844,  Adjusted R-squared:  0.8436
F-statistic:  2229 on 1 and 412 DF,  p-value: < 2.2e-16
```

Hooks and lines

```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)         705.0632   229.8820   3.067  0.00237 **
Gross tonnage         3.4765     0.1301  26.715  < 2e-16 ***

Residual standard error: 3384 on 290 degrees of freedom
Multiple R-squared:  0.7111, Adjusted R-squared:  0.7101
F-statistic: 713.7 on 1 and 290 DF,  p-value: < 2.2e-16
```

Dredges

```
Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)         606.23817   92.88542   6.527 6.14e-10 ***
Gross tonnage         2.14744    0.03577  60.042  < 2e-16 ***

Residual standard error: 1102 on 187 degrees of freedom
Multiple R-squared:  0.9507, Adjusted R-squared:  0.9504
F-statistic:  3605 on 1 and 187 DF,  p-value: < 2.2e-16
```

Traps

```
Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)         158.22316   35.13609   4.503 1.05e-05 ***
Gross tonnage        3.97741    0.06399  62.155  < 2e-16 ***

Residual standard error: 460 on 240 degrees of freedom
Multiple R-squared:  0.9415, Adjusted R-squared:  0.9413
F-statistic:  3863 on 1 and 240 DF,  p-value: < 2.2e-16
```

Seine nets

```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        237.9154    54.8664   4.336 2.32e-05 ***
Gross tonnage       2.5555     0.0679  37.638  < 2e-16 ***

Residual standard error: 716 on 195 degrees of freedom
Multiple R-squared:  0.879,  Adjusted R-squared:  0.8784
F-statistic:  1417 on 1 and 195 DF,  p-value: < 2.2e-16
```

Surrounding nets

```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)         61.19053  116.62289   0.525      0.6
Gross tonnage       4.16202    0.08616  48.308   <2e-16 ***

Residual standard error: 1543 on 237 degrees of freedom
Multiple R-squared:  0.9078, Adjusted R-squared:  0.9074
F-statistic:  2334 on 1 and 237 DF,  p-value: < 2.2e-16
```

Lift nets

```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        0.001899   8.897517   0.000    1.000
Gross tonnage       7.744892   5.074380   1.526    0.136

Residual standard error: 7.755 on 33 degrees of freedom
Multiple R-squared:  0.06594,Adjusted R-squared:  0.03763
F-statistic:  2.33 on 1 and 33 DF,  p-value: 0.1365
```

Gear not known or not specified

```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        159.1187    40.9271   3.888 0.000196 ***
Gross tonnage        2.5716     0.2593   9.918 5.29e-16 ***

Residual standard error: 185.8 on 88 degrees of freedom
Multiple R-squared:  0.5278, Adjusted R-squared:  0.5225
F-statistic: 98.37 on 1 and 88 DF,  p-value: 5.293e-16
```

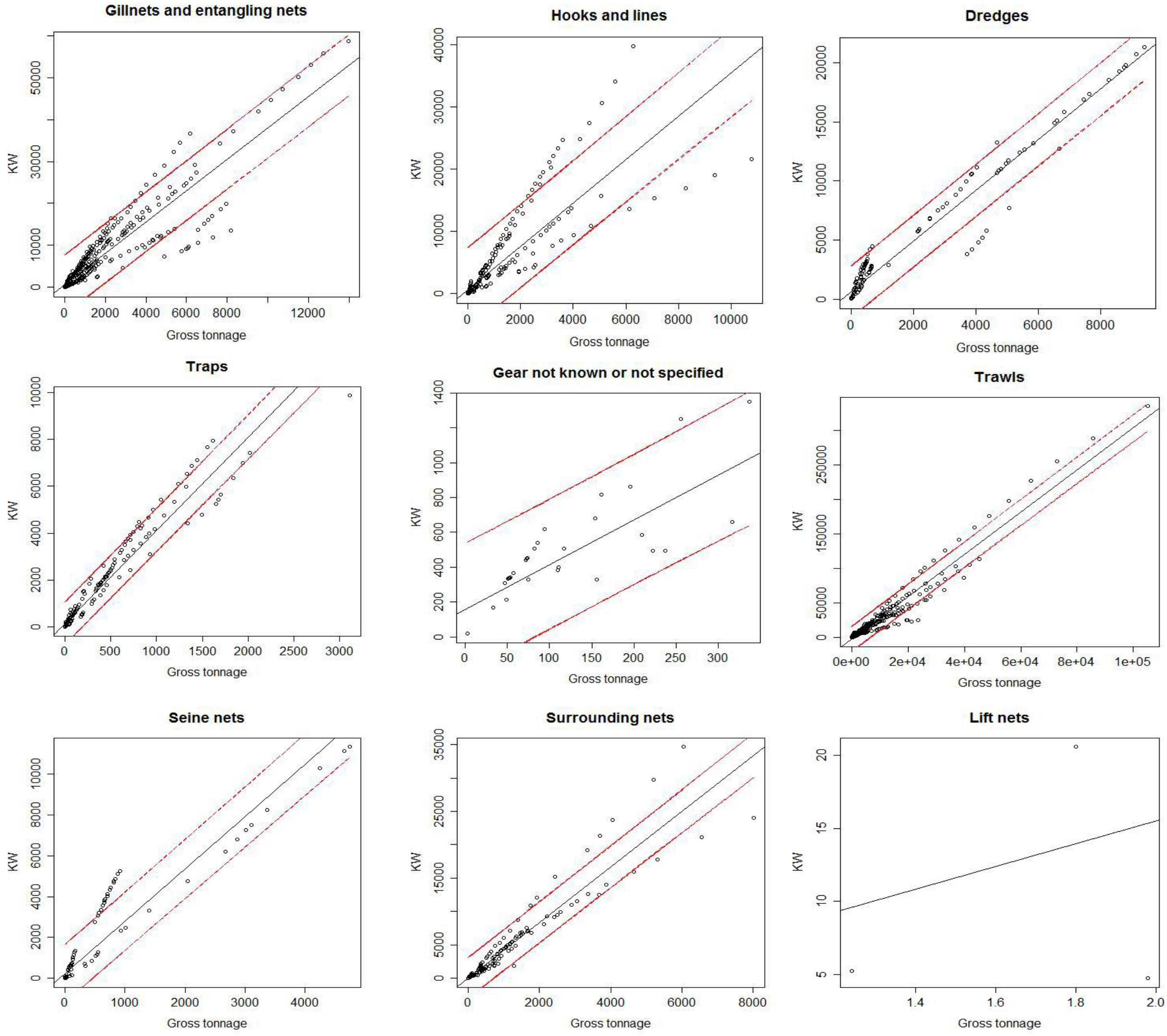

Figure A2.1: Linear regression of KW and GT for each EU member country from 1950 to 1968. Confidence intervals (95 percent) in red.