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An Overview of Serial Depletions of Global Marine Fisheries 1950 to 2019

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An Overview of Serial Depletions of Global Marine Fisheries 1950 to 2019

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ABSTRACT

Overfishing is a global issue that poses a significant risk to the entire ocean ecosystem in diminishing biodiversity and ecosystem function. This thesis examined the pattern and pace of fisheries depletions due to commercial fishing during the past 70 years. The Food and Agriculture Organization of the United Nations (FAO) Division of Fisheries and Aquaculture maintains a database of global hauls of marine taxa (reported in metric tonnes) from 1950 – 2019. These data were queried to determine the total number and sequence of fisheries depletions documented by the historic record. Analysis of this database showed progressive, linearly-increasing exploitation of marine/aquatic taxa from 619 in 1950 to 2,459 in 2019. Depletions of taxa, on the other hand, were observed to increase exponentially (ca. 5% annually) such that nearly 25% of exploited taxa are currently depleted. The current trends of exploitations and depletions projected forward in time produces a textbook example of a Malthusian Catastrophe in 2056. At that time, exponentially-increasing depletions will equal linearly-increasing exploitations. The ecological impact of the Malthusian Catastrophe and its cascading effects across the global ocean ecosystem are unknown, but likely herald the demise of the commercial fishing industry and potential collapse of the entire marine ecosystem.

INTRODUCTION

The ocean provides many ecosystem services for humanity including organisms used for food, livestock feed, and fertilizer. However, industrialization of global fishing during the past 70 years enabled wholesale extraction and overfishing of many marine/aquatic taxa leading to significant declines in stocks of commercially valued species. Indeed, overfishing is a topic of international concern, particularly as climate change and degradation of ocean environments with pollution are also creating cascading impacts to the global ocean ecosystem (Worm et al. 2006; Pinsky & Byler, 2016).

To better understand and articulate impacts of industrial fishing on the global ocean ecosystem, this thesis endeavored to document the scope and magnitude of serial depletions of fisheries (Blasiak, 2015; Watson et a., 2014; Sirinivasan et al. 2012; Cardinale et al. 2011; Pauly, 2008). The full database of fisheries data from the United Nations Food and Agriculture Organization Division of Fisheries and Aquaculture was used (FAO, 2023). Data on hauls of 2,459 marine and aquatic taxa from 1950-2019 were examined to document the timing, pace, and number of depletions. This data provides a comprehensive assessment of the status of global fisheries and the impacts of industrial fishing on marine/aquatic ecosystems.

To begin, overfishing must be properly defined. According to the United Nations Food and Agriculture Organization (FAO, 2001) there is a difference in the definitions of "overfished" and "overfishing." *Overfished* is "…a term used when the abundance of the stock is too low, meaning below the limiting biomass reference point." (FAO, 2001). *Overfishing*, is "…when the fishing mortality being exerted on the stock is too high, meaning above the limit fishing mortality reference point." (FAO, 2001) Therefore, the term "overfished" will refer to the fish stock remaining in the ocean, whereas the term "overfishing" will refer to the action of catching fish at an unsustainable rate particular to that population of fish (FAO, 2001).

Humans fishing activity disturbs ocean ecosystems. To contextualize impacts of humanity on global stocks of marine taxa, human fishing activity was divided into three time intervals by Jackson et al. (2001): 1) Aboriginal, 2) Colonial, and 3) Global (industrial). The Aboriginal time interval refers to the "…exploitation of near-shore, coastal ecosystems by human cultures with relatively simple watercraft and extractive technologies" (Jackson et al., 2001). Thus, aboriginal fishing refers to subsistence-level exploitation of fish stocks or artisanal commercial fisheries. Fishing intensity during the Aboriginal interval had relatively low ecosystem impacts and was generally sustainable. The Colonial interval involved expanded exploitation into deeper waters and development of a market economy for marine/aquatic taxa to meet global demand for human food, livestock feed, and fertilizer. The Global (industrial) period refers to the current International Fishing-Industrial Complex (IFIC) and associated intense exploitation of the "…coastal shelf and oceanic fisheries integrated into global patterns of resource consumption with more frequent exhaustion of fisheries" (Jackson et al., 2001). Nations progressed through each fishing interval consequent to varying societal and economic factors. For example, the America's and Australia transitioned from the Aboriginal interval to the Colonial interval at different times.

Large-scale industrial fishing practices began as the Colonial interval waned in the late nineteenth century. The introduction of steam powered sea vessels (trawlers) greatly increased the ability to catch large quantities of fish at one time with very large nets (Blackford, 2009). At this time railroad networks were also greatly expanding on the continents. Railroad networks connected ports to inland communities so seafood became more accessible to those who did not live near a coast. Global agricultural activity was also expanding and this led to greater demand for fertilizers and livestock feed. Thus, global socio-cultural evolution toward modern civilization produced ever-increasing demands on marine/aquatic fisheries. Greatly increased and improved infrastructure and technology for Global fishing introduced remarkable efficiency and intensity of exploitation, especially during the post-World War II period (after 1945). As the Global period intensified, the global tonnage of fish hauls increased exponentially as a commodity of global trade (Fig. 1).

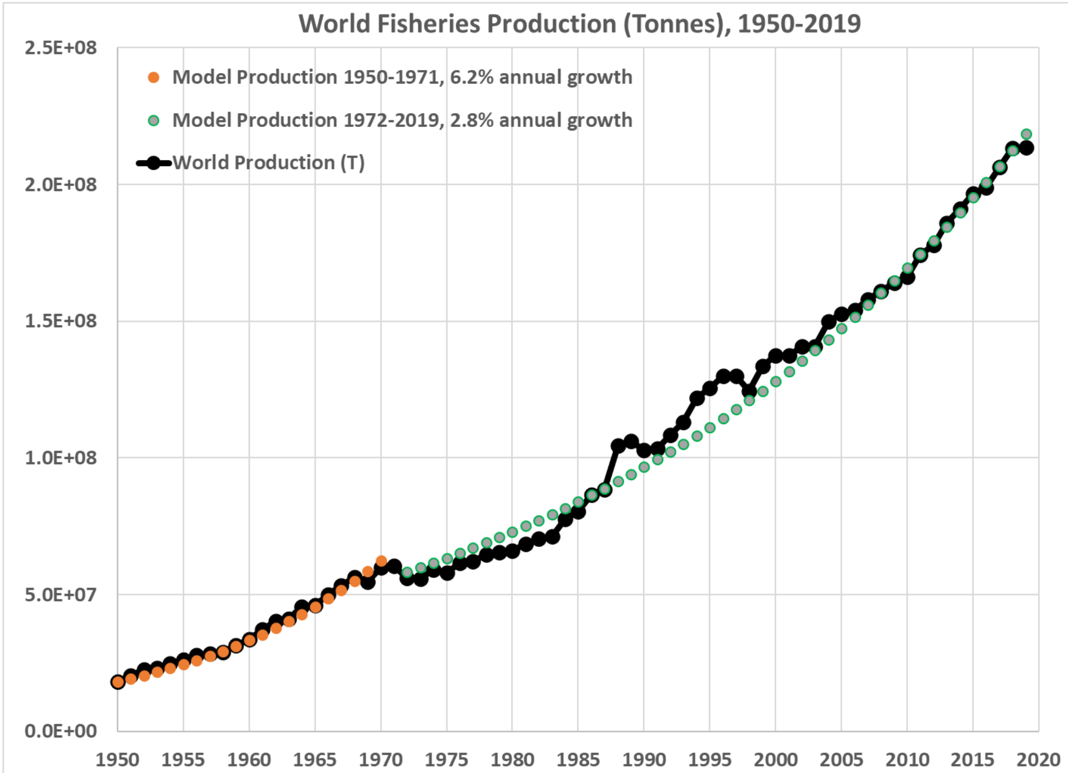

Fig. 1. World fisheries production (tonnes) from 1950-2019. Black is total annual fisheries production from marine/aquatic environments and aquaculture. Orange dots = modeled 6.2% annual growth 1950-1971; Green dots = modeled 2.8% annual growth from 1972-2019. Data from UN FAO Division of Fisheries and Aquaculture (https://www.fao.org/fishery/en/home; accessed 24 March 2023).

Around 1970, the IFIC introduced fleets of large factory ships with capacity to remain at sea catching and processing fish for months at a time (Blackford, 2009). During this time, the ocean was viewed as a non-depletable resource that could sustainably yield 200 – 350 million metric tonnes of fish per year (Blackford, 2009). Subsequent depletions of fish stocks and population collapses of important commercial species demonstrated that industrialized fishing fleets could exceed sustainable capacities (Blackford, 2009). An early harbinger of the impact of industrial fishing fleets was collapse of the California sardine fishery (Radovich, 1982; Ueber and MacCall, 1992). The collapse of the Atlantic cod fishery in the late 1980's and early 1990's is another prime example of how fisheries can be severely depleted. This is partially a result of the conflict between scientists who were aware of overexploitation and the overestimation of available fish stock and the politicians who allowed socioeconomic concerns to stall a response until the fishery was in complete crisis (Chapman, 1999). The delayed response ultimately resulted in a moratorium on the fishery in 1992 (Chapman, 1999). When John C. Crosbie, the federal Minister of Fisheries and Oceans, announced the moratorium on cod in Newfoundland he reported that "…since 1990, the spawning stock biomass had fallen by three-quarters due to primarily ecological factors" (Schrank and Roy, 2013). Despite the claim of "ecological factors" there was no doubt about the role that overfishing had played in the collapse and several scientists of the time came forward to refute ecological factors being the reason for the collapse. Hutchings and Myers (1994) formed their argument around water temperatures of the time and noted that water temperatures were colder in the 1800s than the 1980s and 1990s, yet there was no collapse. They concluded that the recent exploitation had resulted in fewer reproductive age members and fewer members of each age class within the species (Schrank and Roy, 2013). There was an overall lack of evidence supporting an environmental cause for the decline in Atlantic cod which caused Hutchings and Myers (1994) to conclude there is "…overwhelming support to the hypothesis that human exploitation precipitated the commercial extinction of Northern cod (Schrank and Roy, 2013)." The stock was, at the time, expected to recover after a 2-year moratorium. However, the stock did not recover within 2 years and the species is still attempting to recover fully (Schrank and Roy, 2013). The case of the Atlantic cod collapse is one of the many examples in which a species was decimated due to commercial practices.

The depletion of marine taxa not only collapses the population of that particular species but has the potential to significantly impact the ecosystem as a whole. Species exhibit complicated relationships and the depletion, or complete removal, of a mid-trophic level species on which higher level species rely on for a food source can cause cascading effects that can extend all the way to the apex predator.

Modern fishing trends depleted the majority of commercial fish populations (Pikitch, 2012). Serial depletions of global marine fisheries accelerated with the development of fishing vessels with unprecedented technology, such as stream trawlers (Pauly et al., 2005). These larger vessels were able to target larger fish that dwelled further offshore and in deeper water than previous target species. The new target species were previously believed to be immune from fishing efforts due to inadequate fishing technology (Pauly et al., 2005). Overfishing can be truly devastating to an ecosystem in terms of biodiversity and can disrupt the entire food web. Fish are not the only species being impacted by over-exploitation. Overfishing may lead to collapse of an entire ecosystem since every organism is reliant on others.

METHODS

The Food and Agriculture Organization of the United Nations (FAO) Division of Fisheries and Aquaculture maintains a database of global hauls of marine taxa (reported in metric tonnes) from 1950 – 2019. (https://www.fao.org/fishery/en/home). For this study, the entire database was downloaded (representing 2,459 marine taxa from 1950-2019) and ingested into spreadsheet software. The majority of database entries track individual species, but there are also categories of aggregated organisms. For example, there are categories for “molluscs NEI”, crustaceans NEI”, “seaweeds NEI” where “NEI” is an abbreviation meaning “Not Elsewhere Indicated” in the database. These categories combine statistics from many species being exploited at relatively low levels in local to regional fisheries. For this reason, throughout the thesis, exploited organisms are referred to as taxa. Annual hauls of most taxa were reported in metric tonnes, but many marine mammals and marine/aquatic reptiles were reported as numbers of individuals captured. These data were included in counts of exploited species, but were excluded from analyses of tonnage since the mass of individuals was unknown. The remaining database documenting the mass of exploited marine/aquatic taxa numbered 2,229 taxa.

The total global tonnage of hauls for each year was calculated by summing annual tonnage for all included taxa (Fig. 1). Data was also totaled for each decade by summing global annual totals over ten years. Time series of these data provided trends in global fisheries exploitation (Figs. 1,2).

The total number of taxa exploited annually were determined for each year from 1950 to 2019. Taxa were considered exploited if the haul (tonnage) in any year was greater than zero. In the spreadsheet, counts of the total number of exploited taxa were determined using the filter function for all cells > 0 tonnes (Fig. 3).

The annual increment of newly exploited taxa (*dX/dT*) was determined for 1951-2019 by subtracting the number of exploited taxa in a current year from the number of exploited taxa in the previous year:

$$\frac{dX}{dT} = X_y - X_{y-1} \quad (1)$$

where *dX/dT* is the annual increment in exploited taxa, X_y is the total number of exploited taxa in a year (y); X_{y-1} is the total number of exploited taxa in the previous year (Fig. 4).

Overfishing depletes fisheries over the interval of their exploitation. Commonly, as new taxa are exploited, the pattern of exploitation follows a logistic curve (Meadows et al. 1972; Fig. 5). Early exploitation is typically characterized by rapidly growing (sometimes exponential) increases in annual hauls as fishing approaches the maximum sustainable yield. However, quite frequently early rapid growth of fisheries hauls results in substantial overshoot followed by a brief interval of stasis (level annual fish hauls) then collapse of the population and the fishery as a consequence of overfishing (Fig. 5).

To aid identifying depletion trends for individual taxa, spreadsheet cells were color-coded to reflect the percentage haul relative to the maximum for each year. Color-coding was accomplished using a conditional formatting function in the spreadsheet. Values ranging from 100% to 90% of the maximum haul were shaded green, values equal to 50% of the maximum haul were colored yellow, and values ranging from 10% to 0% of the maximum haul were shaded red. The interpolated colors shade spreadsheet cells relative to the ranges specified with the conditional formatting parameters to create a bar smoothly shaded from green (maximum haul) to red (minimum haul; Fig. 6). Fisheries were identified as depleted when the annual haul fell below 10% after being exploited for at least a year. For every year, the total number of depletions was determined (Fig. 7).

The annual increment of depletions (*dD/dT*) was determined in the same manner as the annual increment of exploitations:

$$\frac{dD}{dT} = D_y - D_{y-1} \quad (2)$$

where *dD/dT* is the annual increment in depleted taxa, D_y is the total number of depleted taxa in a year (y); D_{y-1} is the total number of depleted taxa in the previous year. Figure 8 shows the plot of annual increment of depleted taxa.

The top 25 species that were exploited per decade were obtained using tonnage totals. This was done by separating the original tonnage spreadsheet into decade increments, summing the total tonnage by species over 10 years, and sorting the totals from highest to lowest. Once this was completed for each decade, the trophic level for each taxon was determined from data reported in FishBase (Froese and Pauly, 2023). Fishbase is a global biodiversity database and currently includes information for over 33,000 different species. In order to find the trophic level data, each species of the top 25 was queried in the data base. Trophic level information is typically included in the database under the heading for "Ecology" of each taxon. For instances in which several trophic levels were reported for a taxon, the average trophic level was calculated and reported here. Once all trophic levels for the top 25 exploited species were found, the average trophic level was calculated for the top 25 and reported for each decade. This method was conducted because in a 1998 study it was found that the mean trophic level of caught species decreased from 1950 to 1994 (Pauly et al., 1998). The data for this study was found in the Food and Agricultural Organization (FAO) landing statistics and estimates trophic levels for a total of 220 species containing both fish and invertebrates. The study concluded that mean trophic level decreased from around 3.3 in 1950 to less than 3.1 in 1994 (Pauly et al., 1998). The FAO database has since been updated to account for the years after 1994 and now has data through 2019. Therefore, another analysis can be done on trophic level and compared to the 1994 values to see if trophic level has continued to decrease at a similar or increased rate.

Finally, the catch per unit effort was considered. FAO reports fishery hauls in tonnes per year. Another common universal measurement for catch is catch per unit effort (CPUE). This method is used to compare the tonnage caught to the effort being exerted. As fishing technology advances, it is reasonable to conclude that the amount of effort required to catch a higher tonnage of fish declines. However, as fisheries become depleted it may require greater effort to sustain high yields. Using previous research on CPUE, an estimate for CPUE and its contribution to exploitations and depletions presented in this study was performed.

RESULTS

The total mass of marine and aquatic taxa extracted from the ocean, freshwaters, and aquaculture was calculated for the years 1950-2019 (Fig. 1). From 1950 to1971, total global fish hauls increased exponentially with an annual growth rate of 6.2% (Fig. 1). After 1971, global mass of fishery hauls continued to grow exponentially, but the annual growth rate declined from 6.2% to 2.8% (Fig. 1). In 1950, the total yield of global fisheries was 1.81 x 10^7 tonnes. In 2019, the total mass of organisms extracted by the IFIC was 2.14 x 10^8 tonnes, a nearly 12-fold increase in 70 years.

By decade, global fishery tonnage also increased (Fig. 2).

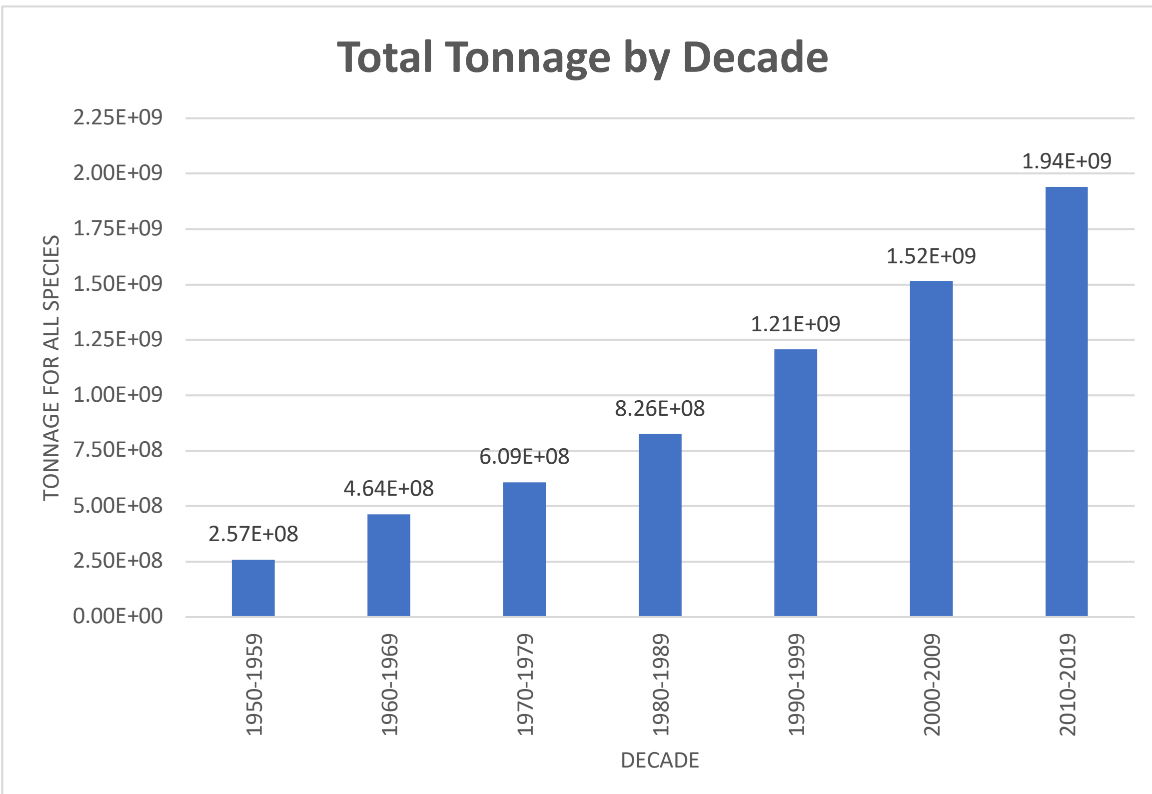

Fig. 2. Total tonnage of marine and aquatic taxa extracted from the ocean per decade.

From 1950-1959, the total mass of fisheries production was 2.60 x 10^8 tonnes. From 2010-2019, total global hauls amounted to 1.94 x 10^9 tonnes. Thus, over 70 years, the decadal tonnage of marine/aquatic organisms extracted from the biosphere increased more than 7-fold.

As the global tonnage of organisms extracted by fisheries increased, so did the number of exploited species. The total number of exploited species increased from 619 in 1950 to 2,459 in 2019, a 4-fold increase over 70 years (Fig. 3). From 1950 to 1994, the number of exploited taxa increased linearly ($r^2 = 0.993$) similar to the regression equation:

$$X = 15T - 27{,}801 \quad (3)$$

where X is the number of exploited taxa and T is the year.

From 1995 to 2019, the number of exploitations accelerated substantially. In 1995, there were 1,385 exploited taxa. In 2019, this number increased to 2,459. From 1995-2019, the number exploitations also increased approximately linearly ($r^2 = 0.963$), roughly approximating the regression equation:

$$X = 42T - 82581 \quad (4)$$

where X is the number of exploited taxa and T is the year.

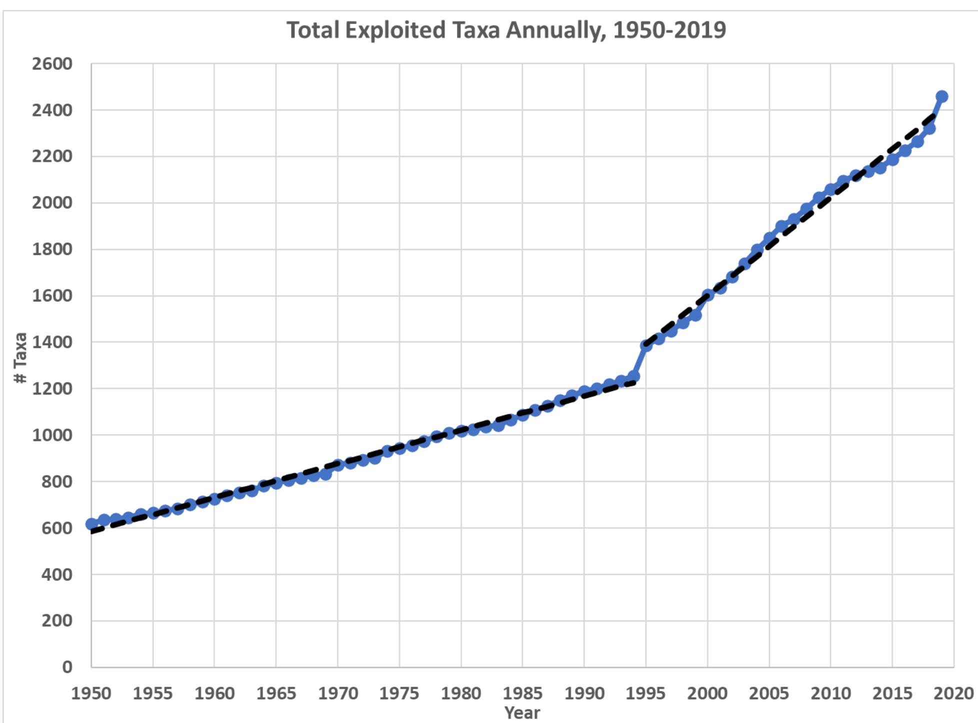

Fig. 3. Total number of exploited taxa annually from 1950-2019. A significant increase in number and annual increment of exploited taxa occurs after 1994. Dashed black lines are regression lines for data segments from 1950-1994 and 1995-2019.

From 1950 to 1994, the average annual rate of increase in exploitations averaged 14.5 ± 6.8 new taxa per year. From 1995-2019, the average rate of exploitation of new taxa increased to 48.1 ± 29.8 per year, a greater than 3-fold increase (Fig. 4). Cumulative depletions are representative of when a species drops to less than 10 percent of the maximum haul for that species and includes when a species is depleted for multiple years in a row. Depletions start at 0 in 1950 and initially increase slowly, but accelerate continuously through the period of record (Fig. 7). In 2019, there were 591 depleted taxa.

Figure 5 illustrates a common exploitation profile of fisheries mimicking logistic growth. The exploitation begins with relatively modest annual hauls but grows rapidly (sometimes exponentially) to the maximum sustainable yield.

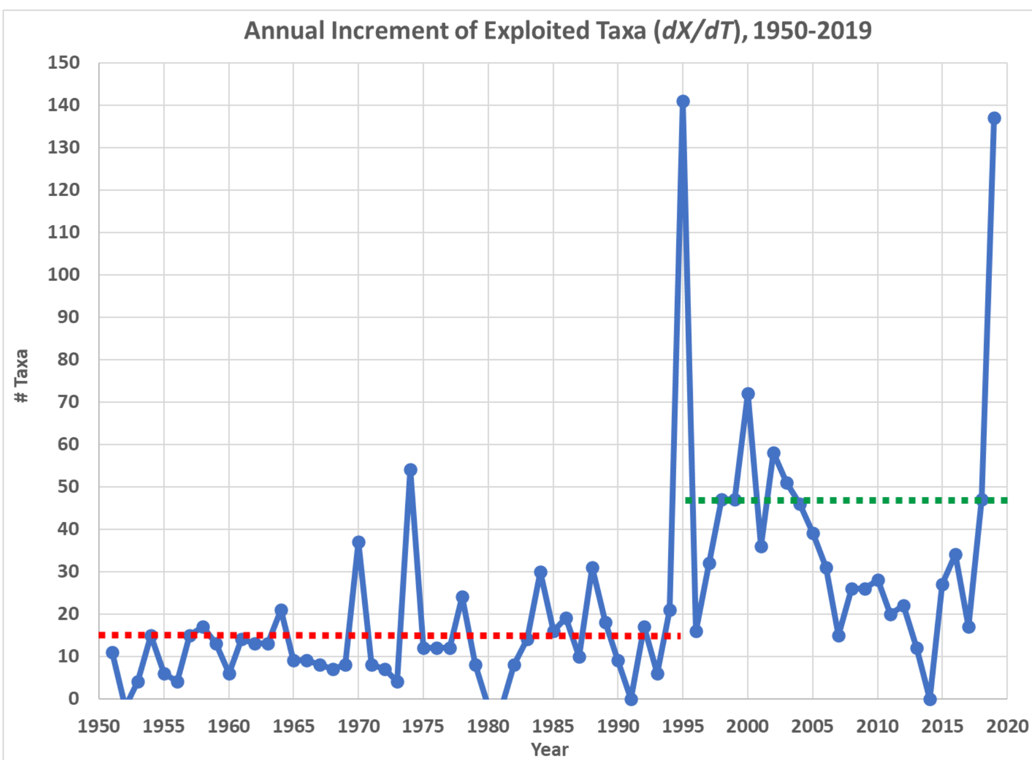

Fig. 4. Annual increment of exploited taxa (*dX/dT*) from 1951-2019 (blue). Red dashed line is the mean annual increment of exploited taxa from 1950-1994 (14.5 ± 6.8). Green dashed line is mean annual increment of exploited taxa from 1995-2019 (48.1 ± 29.8).

Frequently, the maximum sustainable yield is exceeded, resulting in overshoot, followed by a brief interval of varying but somewhat level production (stasis), then relatively rapid population collapse resulting in declining annual yields and depletion.

Figure 6 was used first to aid identification of the year that exploitation of a taxon commenced and to visualize the production cycle (growth to maximum yield to depletion). As exploitation ensues, cell colors change in order from red to green. Cells changing color order from dark green to dark red are indicative of declining yields. When the hauls fall below 10% of the maximum yield, the fishery is categorized as depleted. The empty spaces occurring at the beginning of records indicates the taxon was not yet being exploited. Fisheries were determined to be depleted when the tonnage of the annual haul fell below 10% of the historic maximum tonnage over the period of exploitation (Blackford, 2009).

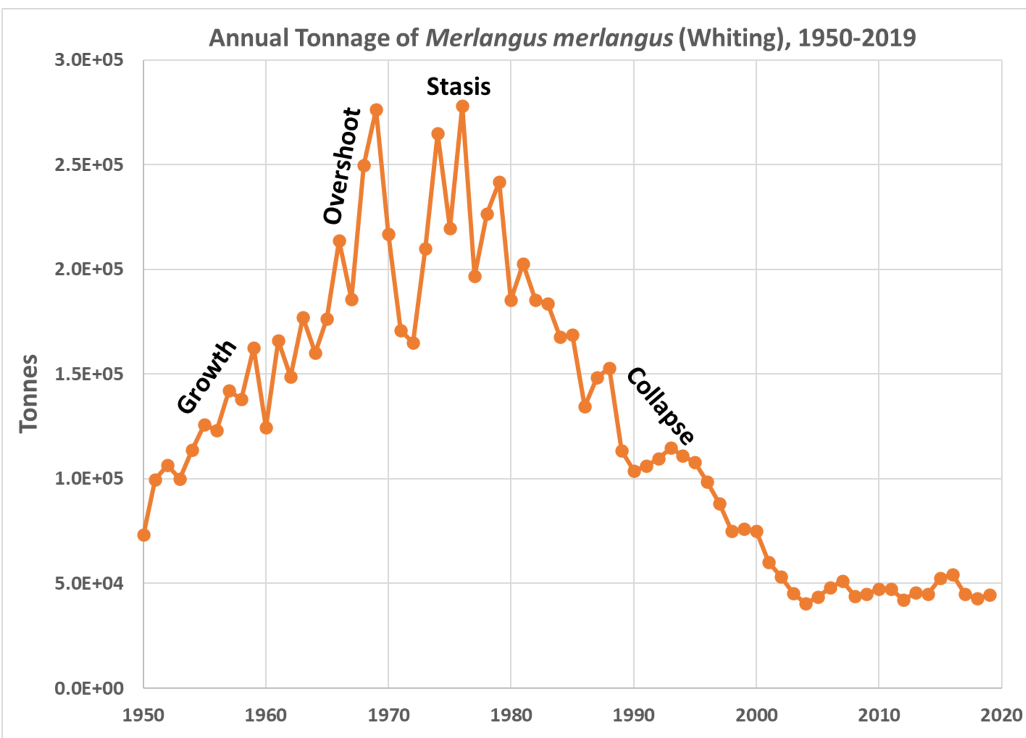

Fig. 5. Annual production in tonnes of *Merlangus merlangus* (Whiting) from 1950-2019. The production curve displays approximately logistic growth of annual production with early growth (nearly exponential), overshoot as annual catches exceed sustainable capacity, a

brief interval of stasis with varying but relatively level production, followed by population collapse and declining fish yields to depletion.

For this study, the maximum annual tonnage for each exploited organism was determined using the =MAX function in the spreadsheet software. Once the maximum yield was determined, the annual tonnage was converted to a percentage of the maximum for each year of the exploitation record for each organism.

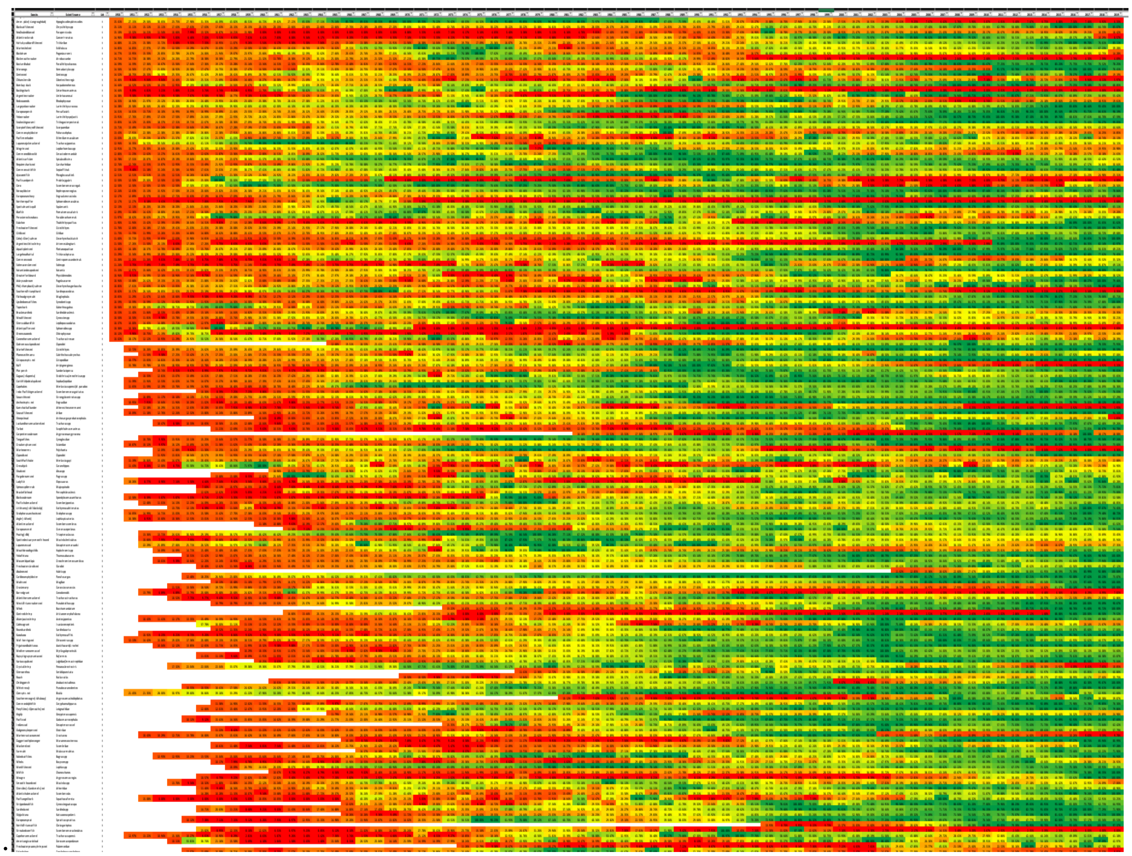

Fig 6. Color-coding of a sample of fish haul data. Each row indicates history of fish hauls for a single taxon from growth to maximum yield (red to green), then declining yield to depletion (green to red). Color-coding was derived using the conditional formatting function of the spreadsheet software as described above.

Cumulative annual depletions are depicted in Figure 7. There were no depleted taxa in 1950, but this is likely an artefact because annual haul data were unavailable prior to 1950. Ten depletions were already evident in the following year (1951). Depletions then increased steadily at a relatively constant annual proportion (exponential growth) of approximately 5% per year through the period of record (Fig. 7, black dots).

The annual increment of depletions is illustrated in Fig. 8. There is some observed interannual variability in the number of newly depleted taxa each year, but new depletions generally increase over the period of record, ranging from 10 in 1950 to 104 in 2012.

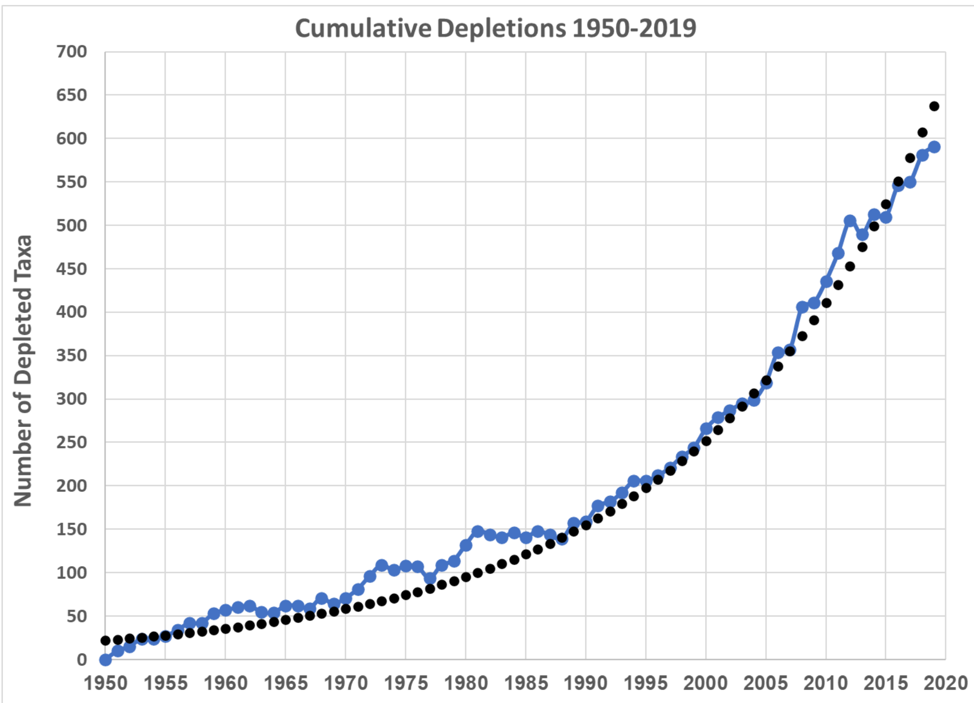

Fig. 7. Cumulative depletions of fished taxa from 1959-2019 (blue) and model depletions using growth factor of 5% annually (black dots). Data from FAO Fisheries and Aquaculture Division.

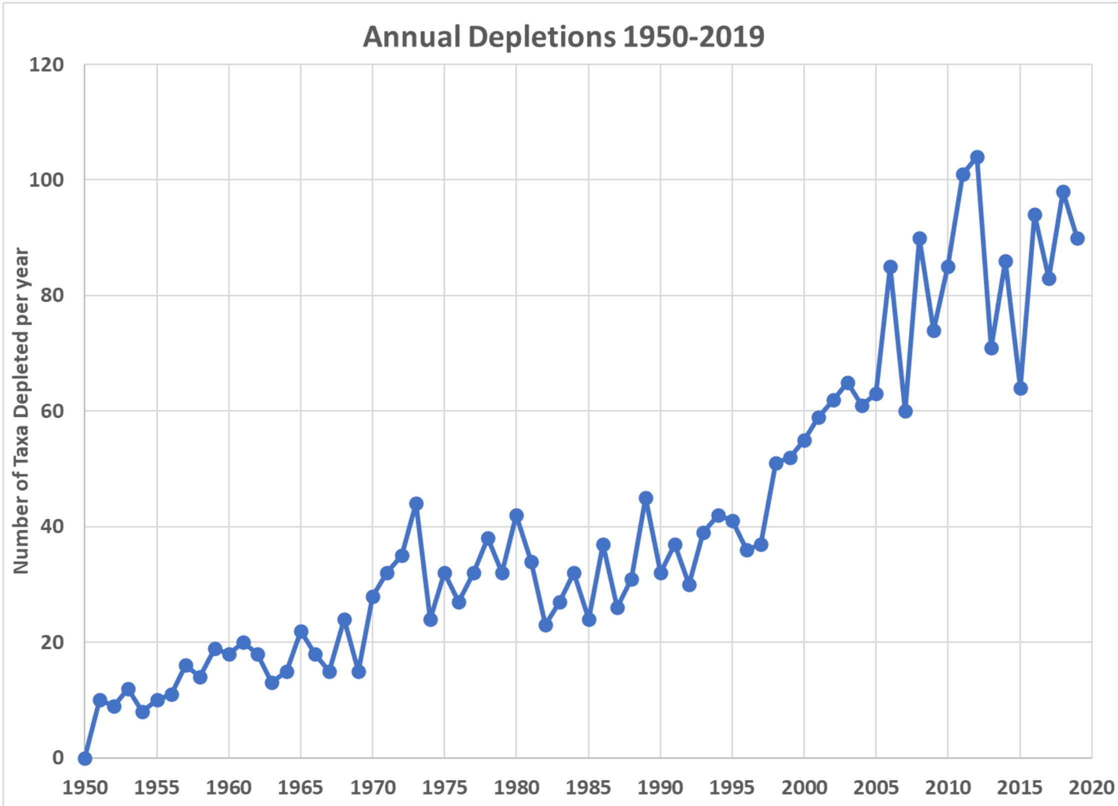

Fig. 8 Annual increment in depleted taxa, 1950-2019. Data from FAO Fisheries and Aquaculture

Given the observed 5% annual growth of depletions, it may be expected that depletions double approximately every 14 years (Bartlett, 1993). Assuming the observed linear growth of exploitations (Fig. 3) and observed exponential growth of depletions (Fig. 7) continue into the future, exploited taxa (ca. 4,000 in total) will be depleted in 2056 and the global fisheries system will experience a Malthusian Catastrophe (Fig 9; Malthus, 1798; Welling, 1888; Ogilvy, 1891; Isaacson, 1912; Krebs 2008; Macfarlane, 2008).

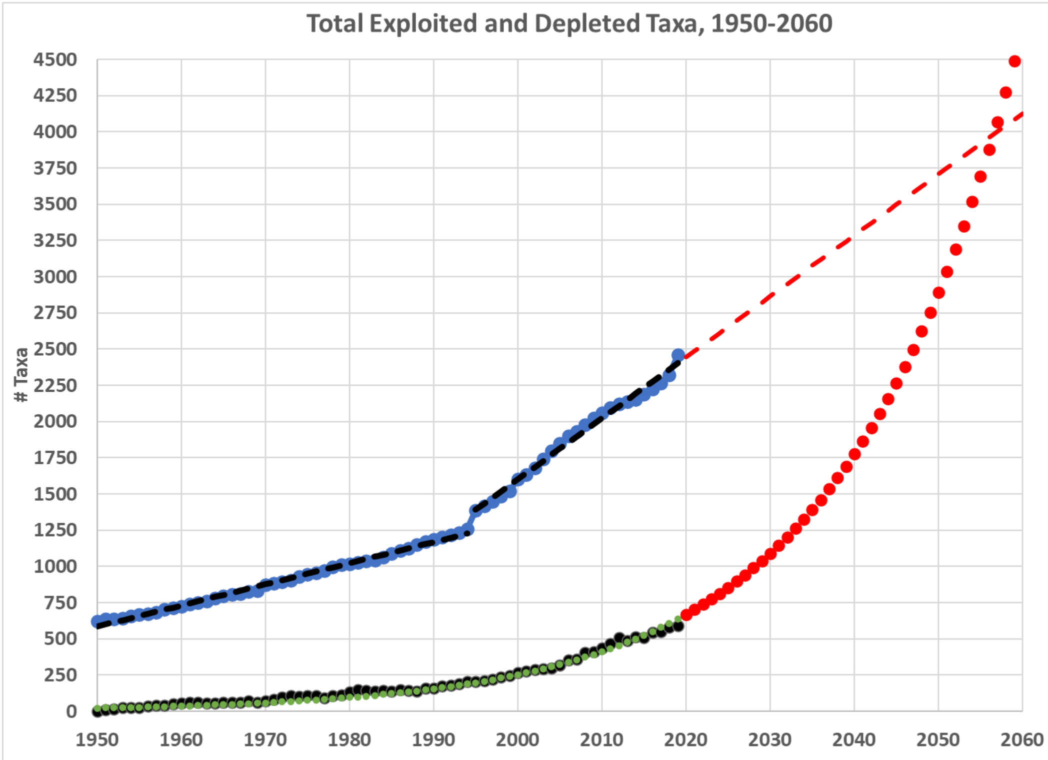

Fig. 9. Total Exploited and Depleted Taxa projected from 1950 – 2060. Exploited taxa (blue dots) with linear regression segments (black dashes) from Fig.3 extended to 2060 (red dashes). Depleted taxa (black dots) with modeled 5% annual growth (green dots) projected to 2060 (red dots). Note that the line for exploitations and the curve for depletions cross in 2056, indicating all exploited taxa will be depleted.

To better understand the extent to which exploited taxa were depleted, total annual depletions (Fig. 7) were represented as proportions of total exploitations for each year from 1950-2019. The number of depletions were divided by the number of exploitations for any given year, then multiplied by 100 to yield % of exploited taxa that were depleted:

$$\% = \frac{D_y}{X_y} \text{ x } 100$$

Where % is the percentage of exploited taxa that are depleted in each year, D_y is the number of depleted taxa in each year, X_y is the number of exploited taxa in each year (Fig. 10).

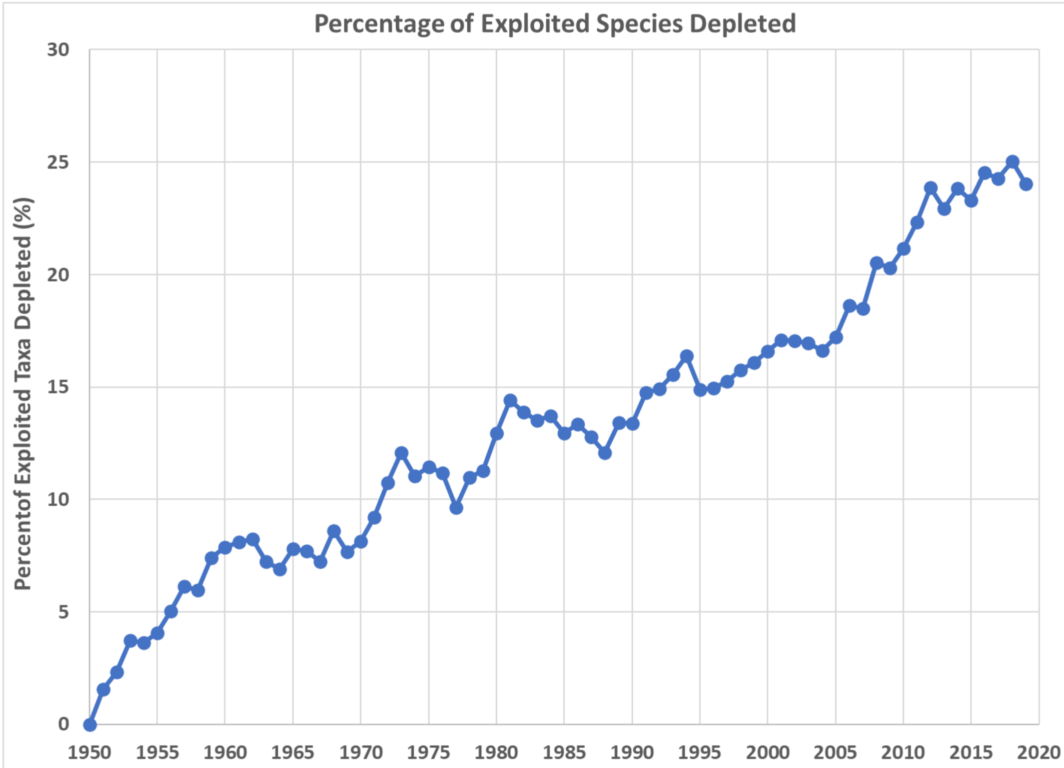

Fig. 10. Percentage of exploited species 1950-2019.

The percentage of exploited taxa increases from 0% in 1950 to almost 25% over the period of record. As the annual number of depletions is increasing exponentially (5% per year) and the annual number of exploitations is increasing linearly, the percentage of exploited taxa is increasing over time (Fig. 10).

Trophic level was used in order to determine shifts in the overall trophic level of the top 25 exploited taxa in each decade (Fig. 11). In general, as industrial fishing depletes high-value (high trophic level predators), newly exploited taxa are targeted from lower trophic levels across the marine/aquatic food webs to replace the mass of depleted organisms and meet global demand for fisheries products. Trophic level categories are 1 (primary producers), 2 (herbivores or primary consumers), 3 (secondary consumers), 4 (tertiary consumers), and 5 (apex predators). Species with a trophic level of 1 are primary producers such as algae and phytoplankton. These organisms are then consumed by slightly larger organisms with a trophic level of 2 (herbivores or primary consumers). Most small pelagic fish such as sardines, herring, and anchovies, have a trophic level of 3 and have been reported to be caught in large quantities. Average trophic levels were found from the top 25 species caught per decade using FishBase. The average trophic level of catch during 1950-1959 was 3.356. The next decade, 1960-1969, the trophic level dropped to 3.196 before rising to 3.254 in the 1970's. This was the only decade that an increase in trophic level was seen. The specific reason for this slight upwards shift is unclear, but could have been caused by a variety of factors such as number of available mature taxa, or fishing effort. There was a decrease in average trophic level every following decade. The lowest trophic level can be seen in 2010-2019 where the value is only 2.4096. Overall, there was a 0.9464 drop between 1950 and 2019. This can be further broken down to an average of a 0.01352 decrease per year.

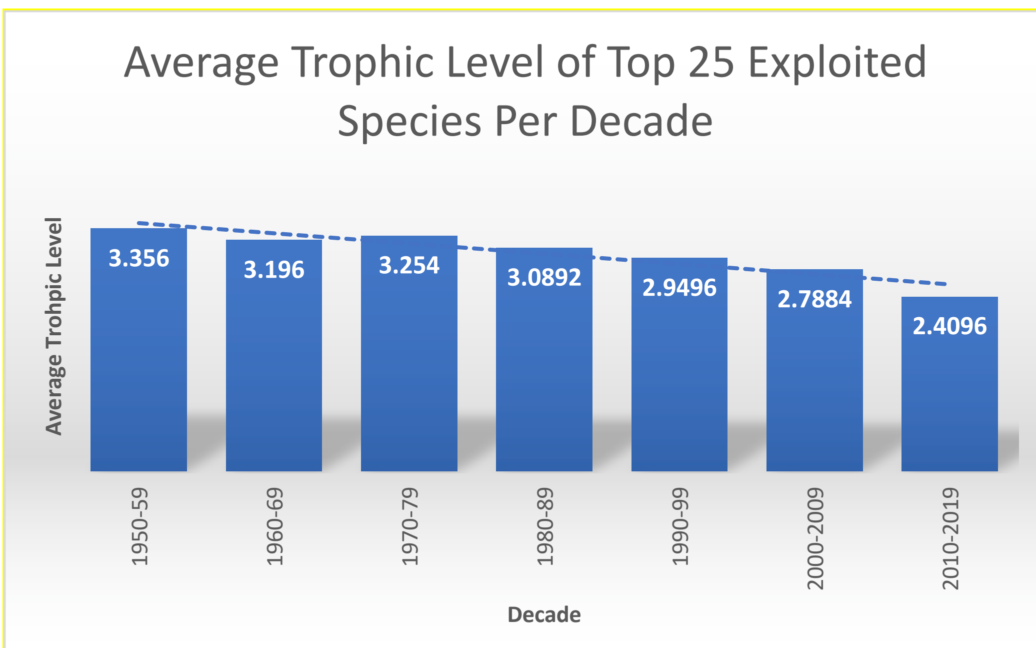

Fig. 11. Average trophic level of species per decade from 1950 – 2019 calculated using Fishbase.

In a 2014 study the CPUE was analyzed for fishing communities in the Red Sea (Fig. 12; Tesfamichael et al., 2014). The three countries in which this study was conducted were Eritrea, Sudan, and Yemen. Using an interview-based analysis with local fisherman it was found that CPUE ultimately declined as time went on (Tesfamichael et al., 2014). Findings from this study are best presented within the following graphs:

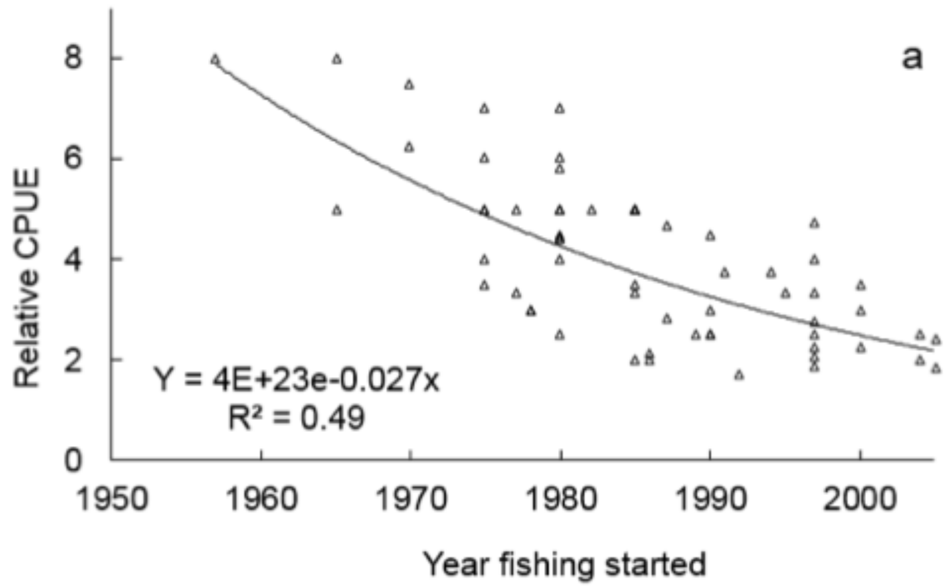

Fig. 12. Graph A which depicts the CPUE for Eritrea from the 1950's up until 2007 (Tesfamichael et al., 2014).

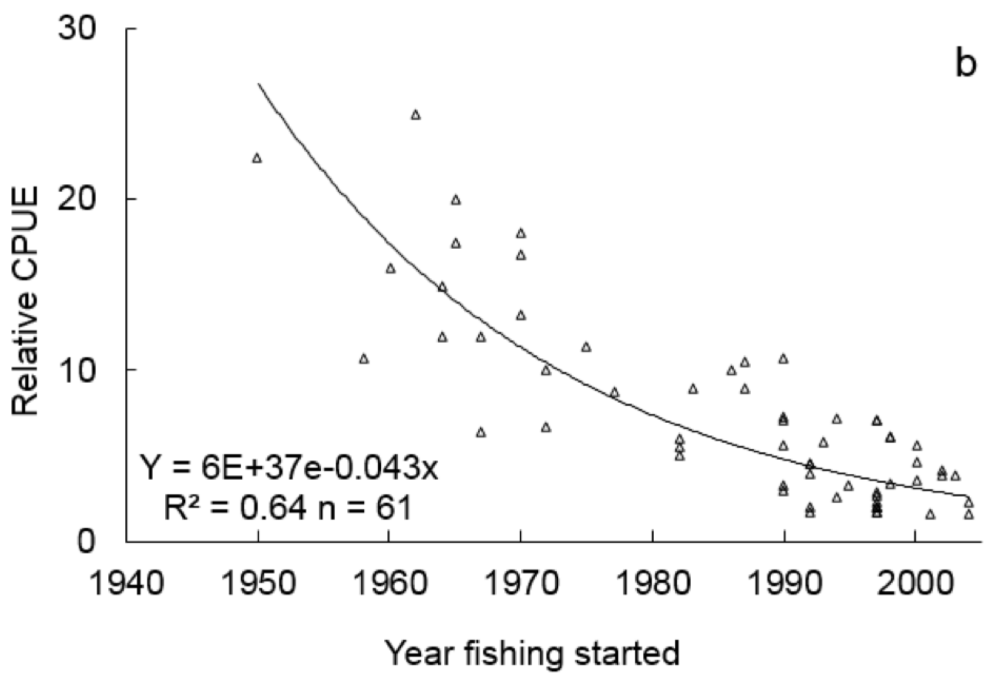

Fig 11. Graph B is the CPUE for Yemen from 1950 to 2007 (Tesfamichael et al., 2014). From the graphs presented in this study it can be concluded that CPUE has declined over time in the researched countries.

DISCUSSION

Analysis of serial depletions of global fisheries showed substantial impacts on the global ocean/aquatic ecosystem. Over 70 years, the number of exploitations increased linearly in two steps (Fig. 3). From 1950 to 1994, the total number of exploited taxa increased from 619 to 1,256. Regression analysis indicated the best-fit regression equation ($r^2 = 0.993$) to the data was:

$$X = 15T - 27{,}801 \quad (3)$$

Where X was the number of exploited taxa and T was the year. From 1994 to 1995, the number of exploited taxa jumps from 1,256 to 1,385 and then follows and exhibits a new linear trajectory to 2019 with a slope nearly 3-times steeper (($r^2 = 0.963$):

$$X = 42T - 82{,}581 \quad (4)$$

where X is the number of exploited taxa and T is the year. In 2019, the total number of exploited taxa was 2,459, a nearly 4-fold increase over 70 years (Figs. 3, 9).

From 1950-1994, the average annual increment of exploited taxa was 12.8 per year. The average annual increment in exploited taxa increase 3.5-fold to 41.1 from 1995-2019 (Fig. 4).

As increasing numbers of taxa were exploited, so too did numbers of depleted taxa increase. However, global depletions were observed to increase exponentially at a rate of ca. 5% per year with an observed doubling time of approximately 14 years (Fig. 7). Thus, in 1951 there were 10 depleted taxa (Figs. 7,9) and in 2019 the total number of depleted fisheries was 591. Since the global numbers of exploited taxa were increasing linearly and the global numbers of taxa being depleted was growing exponentially, it was possible to project the timing of the

Malthusian Catastrophe (i.e., the timing of the event when the exponentially-increasing depletions equaled the linearly-growing exploitations; Malthus, 1798; Welling, 1888; Ogilvy, 1891; Isaacson, 1912; Krebs 2008; Macfarlane, 2008) assuming current trends continued into the future. The Malthusian Catastrophe was projected in 2056, heralding the moment when exploited taxa (ca. 4,000) would also become depleted and effectively end global fisheries production.

The consequence of global fisheries experiencing a Malthusian Catastrophe would not likely disrupt the abundance of global food for human consumption. Boss et al. (2018) demonstrated that all global fisheries and aquaculture contributed only 0.8% of the food energy output of the global agricultural system. Absent input from global fisheries and aquaculture, the global agricultural system would still provide 99.2% of its current total energy yield, and this gross quantity is approximately 2.5-times greater than the metabolic demand of the human population (Boss et al., 2018).

The Malthusian Catastrophe in this instance would be largely ecological. Depleting thousands of marine/aquatic organism populations worldwide would almost certainly disrupt ecosystems. However, it is not clear precisely what those disruptions might be or how they might initiate cascading ecological effects that could, ultimately, result in the collapse of the global ocean ecosystem as it is known today. Collapse of the global ocean ecosystem would be catastrophic for the biosphere and pose a potentially fatal blow to human civilization.

The number of cumulative depletions occurring can be used to estimate the health and viability of fish stocks within any given year. Despite minor fluctuations, cumulative depletions follow a general trend of exponentially increasing over time. The largest differences between years occur in the late 2000’s and 2010’s which can be correlated to the advancements made in the commercial fishing industry to increase net hauls (Pauly et al., 2005). This increasing trend can also be used to illustrate how human civilization is treating the ocean as an inexhaustible resource and causing increasing damage to the ecosystem. Figure 10 depicts the number of cumulative depletions within the context of exploitations, as a percentage. While the percentage of exploited species that are depleted follows the same general trend as cumulative depletions, using this type of comparison allows for a more comprehensive understanding of fish stocks as a whole. In 1951, only 1.57% of the species that were being exploited were depleted. However, 24.03% of exploited species were depleted by 2019 and depletion percentage peaked in 2018 at 25.03%. The database used for the purpose of this analysis does not include all species being hauled from the ocean but considering that 2,459 species are included it is reasonable sample and likely indicative of overall depletions worldwide. Therefore, by 2019, about 25% of marine taxa being exploited from the oceans were depleted.

In addition to cumulative depletions, the number of annual depletions provides data on the number of new species being depleted per year. There is significant variation within Figure 8 and it does not follow an exponential curve as closely as the cumulative depletions. However, the general trend of annual depletions is that they increase over time meaning that there are increasing new depletions each year. This is both a product of increasing exploitations and the fishing industries' tendency to shift their focus to new species as old ones become depleted.

Comparing the number of cumulative to annual depletions allows for conclusions to be made about the number of species that are being depleted for multiple years in a row compared to the number of newly occurring depletions. There is a divergence between cumulative and annual almost immediately (around 1955). This indicates that once species become depleted is it more likely that they are depleted for multiple years instead of for only one year before recovering. The fishing industry, therefore, extracts marine taxa to the point of depletion in which they cannot recover in a short period of time and require multiple years to replenish their population before they are considered suitable to be targeted again. If only looking at the number of annual depletions the status of fish stocks does not appear to be in crisis, but cumulative depletions are imperative for illustrating the total number of species that are depleted in any given year. Based on depletions alone it is reasonable to conclude that global marine fisheries are in a state of crisis and that rate at which species are being extracted is simply not sustainable. The global fisheries industry is, indeed, on a trajectory to experience a Malthusian Catastrophe and the larger impacts or implications of that event with respect to the global ocean ecosystem are unknown.

It is estimated that 38 million tonnes of small pelagic species were caught in 2000 and made up 44% of the total marine haul for that year (Pauly et al., 2005). Large species that are regularly available at restaurants and stores for purchase consume the small pelagic species and typically have a trophic level of 4 or 5 meaning these organisms are very high in nutrients and require less tonnage of catch in order to fill the same level of demand that lower trophic level species would (Pauly et al., 2005). Examples of these kind of species include cod, salmon, snapper, tuna, etc. Due to the higher trophic level value of these species, they were the first species to be largely targeted by marine fisheries because they would be the most profitable. However, these species are considerably larger, typically 3 or 4 times of the length of small pelagic species, than species of lower trophic levels meaning they require a more substantial period of time to reproduce and reach maturity making the populations very susceptible to becoming overfished and depleted (Pauly et al. 2005). Higher trophic level species, such at Atlantic cod, have a longer life cycle and take a longer period of time to reach maturing making it harder for such species to recover from overfishing. With higher trophic level species being targeted first by fisheries, they are likely to become depleted first causing new target species to need to be identified. However, once higher-level species are depleted there will need to be a shift to lower trophic level species who still have abundant populations which leads to what is referred to as “fishing down the marine food web” which was an idea first proposed in 1998 by Pauly et al (Pauly et al., 1998). This process has the potential to collapse entire food webs and ecosystem, dramatically changing the species diversity and distribution around the globe.

Depletions of lower trophic level species, this would include most fish, can cause dependent populations such as seabirds, marine mammals, and larger fishes to decline due to a decrease in the food supply (Pikitch, 2012). The depletion of a fish species in an ecosystem will have a cascading effect that can lead all the way up to the apex predator. For example, if a fish in a lower trophic level, such as sardines, is severely depleted then this will impact the larger fish that directly feed on the sardines, then the seals that eat the larger fish, and eventually the orcas that feed on seals. If the sardines were to be depleted to a level from which they could not recover, then eventually the whole ecosystem would collapse due to the lack of food and the species would either die off or be forced to relocate to a new location that had a proper food supply. Furthermore, this concept can also be applied in the reverse. If higher trophic level fish are the target of overfishing than focus will have to be diverted to lower trophic level species.

In a 1998 study it was found that the mean trophic level of caught species decreased from 1950 to 1994 (Pauly et al., 1998). Using 220 species it was concluded that trophic level dropped from about 3.3 to 3.1 in a 44-year time period (Pauly et al., 1998). Due to the decline of mean trophic level through 1994, it was assumed that this trend would continue through 2019 when analyzed in the context of this study.

The data that has been put forth offers an overview of the status of marine fisheries over 70 years. The tonnage being pulled from the ocean has increased dramatically in the given time-period. However, when also considering the drop in average trophic level it is reasonable to conclude that a higher tonnage of catch is required in 2019 than in 1950 to meet the same demand. The average trophic level being 3.356 from 1950-1959 indicates that species higher up in the marine food web were originally being targeted and ultimately fished out. As time moved forward, and depletions increased, the availability of such higher-level organisms declined causing fisheries to shift their focus and catch efforts to organisms that were more abundant. Since these organisms have a lower trophic level, they were not included in the initial fishing efforts, and they had not yet been exploited. This process continued as more species became exploited and depleted until some of the most exploited species were primary producers in 2010-2019. Overfishing and depletions led to the process of fishing down the marine food web in order to keep the fishing industry profitable and meet global consumer demand. If the same process continues moving forward, without allowing proper time for species to reproduce and mature, then there will eventually be very little species that would produce a considerable catch haul. Primary producers are able to grow and reproduce quickly so it is reasonable to conclude that a majority of marine catch would rely on these organisms, especially since this process has already begun.

To further emphasize the importance of the trophic level values, it indicates that present exploitation patterns that have been evaluated are ultimately not sustainable. The 1998 research conducted by Pauly et al looked at average trophic level from 1950 to 1994 and found that levels went from around 3.4 to 3.1 and therefore dropped at an average rate of 0.1 per decade. This is consistent with findings presented in this study and also contributes nearly 30 additional years of data. However, it is observed that between 1990 and 2019 the average trophic level dropped a total of 0.54 points. The average decrease per decade is now 0.18. The declination rate nearly doubled from when it was 0.1 from 1950-1990. This is indicative of an increase in both exploitations and yearly tonnage haul. The rate at which average trophic level is currently declining is not sustainable and if the current projections continue the average trophic level of catch will drop to 1.0 by 2089. The average haul of marine fisheries would be entirely primary producers and the tonnage required to meet the same demand would be exponentially more than the current haul. Furthermore, if the trend continues and the majority of haul is primary producers it indicates that other species have been fished out and it is likely that entire food chains and ecosystems will have collapsed one a much larger scale than what has already been observed.

In addition to a decrease in average tropic level across decades and the cascading effects that will follow a higher tonnage haul would also be required to keep up with global demand. Once higher-level species, such as salmon and cod, are depleted fisheries will have to begin catching smaller, less nutritious fish in order to keep up with global demand. Therefore, when considering the risks of overfishing there is much more to take into account than just the fish itself. The continued over-exploitation of fisheries has the potential to collapse the entire ocean ecosystem and completely change the species distribution. If fisheries were to collapse in such a manner, there would also be a profound impact on the availability of fish for commercial and domestic consumption.

Governments have failed to properly regulate fisheries and the fishing industry as a whole. Many of the worlds' fish populations are extremely overexploited or depleted as a result of overfishing. As discussed previously, overfishing occurred as a result of more efficient practices, economic incentives, and worldwide population growth. However, the continued allowance of commercial fishing companies to capture amounts of fish populations at an unsustainable rate has contributed greatly to the issue. Without proper regulations in place companies are allowed to catch as much fish as possible without regard to the ecosystem itself. This presents problematic because if fish species are not given proper time to reproduce the population will be fished completely and the species will be lost. Fisheries management has so far been ineffective in sufficiently protecting ecosystems from degradation because it normally focuses on maximizing the catch of a single target species and ignores the habitat, predators, and other ecosystem components (Pikitch at al., 2004). However, there are a few laws and policies in place in order to prevent overfishing. One of these is the Magnuson-Stevens Act that was first passed in 1976 (NOAA). This is the primary law that governs marine fisheries in United States federal waters. Prior to this law international waters began twelve miles offshore and could be fished by any unregulated foreign company. However, the Magnuson-Stevens Act extended the United States' jurisdiction to two hundred nautical miles and also created eight fishery management councils. There have since been several revisions to the original Magnuson-Stevens Act including the passing of the Sustainable Fisheries Act in 1996 and the Magnuson-Stevens Reauthorization Act in 2007 (NOAA).

Despite there being some regulations in place by governments they are not doing enough to prevent overfishing because fish stocks are still being overexploited. Unfortunately, the regulations around fisheries usually get impacted by political bias and are not fully focused on the protection of ecosystems. Furthermore, most policies, such as the Magnuson-Stevens Act only apply to one country and it is difficult to provide a blanket regulation that multiple countries can agree upon due to political and economic differences. Therefore, while countries such as the

United States have regulations other countries might not have any leading to overfishing in other parts of the world that will have a global impact in the long term.

Upon examining the different failures to regulate the fishing industry and the risk of overfishing it is important to discuss possible solutions in order to determine what actions can be taken in order to preserve ocean ecosystems. The first measure that needs to be taken in order to prevent further overfishing is the implementation of stronger policies that impose regulations on the fishing industry. As discussed previously, there have historically not been strong regulations in place to manage overfishing. However, Rights-Based Fisheries Management (RBF) focuses on balancing economic and ecological goals and could have the potential to shape new regulations (Barner at al., 2015). If a balance between these two factors can be found and maintained then it has the potential to reduce overfishing. A recent analysis of RBF's has shown that fishery success can depend as heavily on social factors, such as leadership, as it does on the actual policy strategy (Barner at al., 2015). It is therefore important to involve fisherman in policy making in order to receive feedback from the people whom the policy will directly impact the most. If the fisherman and people in charge of directly enforcing a policy are not in agreement than the policy will ultimately fail.

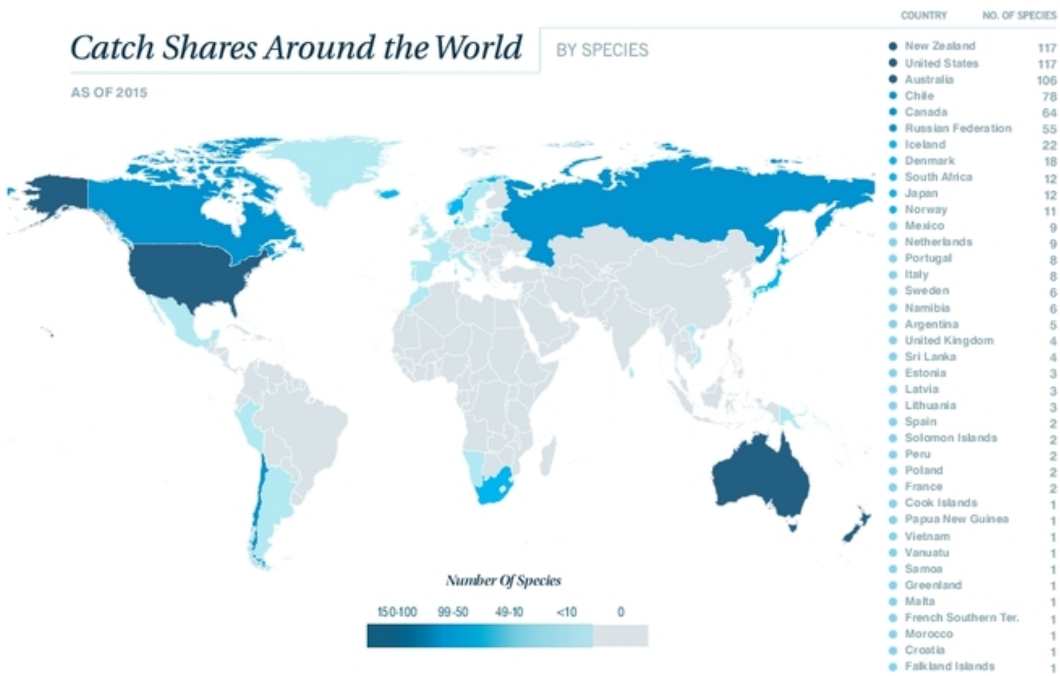

Fig. 12 (Barner at al., 2015). Shows the number of RBF's, also known as catch shares, that were in place around the world as of 2015, as well as the number of species they impact.

Based on this there does appear to be progress being made in terms of fishing regulations. However, there are also countries that have no RBF's in place.

Another solution to overfishing is the establishment of protected marine reserves. Marine reserves are an important tool to preserve the biodiversity of an ecosystem and "well-designed, permanent, enforced marine reserves result in long-term increases in species abundance, biomass, and whole community diversity. (Barner et al., 2015, pg 258)." Marine reserves allow fish to grow out of the juvenile stage without the risk of being caught, protect fish populations as a whole and also keep the entire food web from collapsing. However, marine reserves must be established through government agencies, and this is a time-consuming process that can be subject to political bias. Currently less than 1% of the total ocean is strongly or fully protected (Barner at al, 2015). In order to best protect fish species, more marine reserves should be established worldwide.

Additionally, analyses of fish populations reveal that species abundance is on a continued decline. Such analyses stem from previously understudied fisheries that make up 80% of the global fish catch and, therefore, present a much more comprehensive understanding of the declining global fishery landscape (Pikitch, 2012). Since past studies focused on specific target fish stocks, such as herring and other top predators, they have failed to accurately represent the true status of fish stocks. Conducting research on fisheries as a whole, over an extended period of time will allow for a more comprehensive understanding to be formed which can then be used for implementing fishing regulations globally. A shift from single species management towards a more ecosystem-based approach would allow the focus to center on the entire ecosystems' health rather than the abundance of a single species. An ecosystem-based approach would take into account the "profound impacts that fishing can have on habitat, nontarget species caught as bycatch, genetic diversity and integrity, competition and predation, and other aspects of the structure and function of the marine ecosystems (Pikitch, 2012)." Furthermore, previous studies have focused on maximum sustainable yields (MSY) for individual species, but these MSY metrics have become used for upper limits instead of goals. It has been recommended that target points should actually lie much lower than the MSY point in order to allow buffer space against ecological, economic, and social risks of continued overfishing (Pikitch, 2012). In a switch to an ecosystem-based approach it could turn out that fishing levels need to be set well below the MSY in order to avoid unwanted impacts on other species of the ecosystem which can lead to catastrophic cascading effects. This could assist with forming fishing regulations that fully account for the vulnerability of different marine taxa. The first step towards an ecosystem-based approach to address the previous concerns would be to gather a database that looks at fishing rates across the globe which can then be turned into an ecosystem model.

There have been numerous reports done in attempt to document and quantify overfishing after it became clear that modern fishing practices could not remain sustainable. In addition to the data presenting within this report, a report done in 2006 by a group of American, European, and Canadian researchers stated that by 2003, 29 percent of global marine fisheries were in a state of collapse (Blackford, 2009). The report focuses on tracking overall catch in million metric tonnes and does not analyze individual species or track total depletions. However, combining their estimate that 29% of fisheries are in a state of collapse with the 25% of species being depleted from this study, paints a bleak future for global marine fisheries if some kind of intervention does not occur.

Based on the data presented in the 2014 study that looked at catch per unit effort, it is reasonable to conclude that a similar trend could be observed globally leading to a general decrease in CPUE. CPUE is typically used a measurement to estimate fish stock abundance and can indicate that as CPUE declines so does the fish stock. This conclusion is consistent with total tonnage that has been shown to be increasing, as seen in Figure 1 and Figure 2. Therefore, it can be concluded that CPUE will decline as tonnage and exploitations increase.

The overall outlook for global marine fisheries moving forward is a continued increase in tonnage, with more depletions that ultimately result in a lower average trophic level. The effects of such predictions would include a global collapse in marine ecosystems as well as a dramatic decrease in species abundance and diversity. It is reasonable to conclude that the rate at which fish are being extracted from the ocean is not sustainable and has been this way for some time. The trend is not predicted to change, but only get worse due to the ability for fishing vessels to haul in more tonnage with less overall effort due to advancements within the field. Without serious intervention, the commercial fishing industry will soon decimate global fish populations and deplete a nonrenewable resource.

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