TECHNICAL ASSESSMENT FOR IMPROVE FISHERIES

SECTOR: OCEAN

AGENCY LEVEL: GOVERNMENT

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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EXECUTIVE SUMMARY

Emissions in fisheries are driven by fuel use, which is directly proportional to fishing effort, the product of fishing vessel capacity and time spent fishing. In addition to their fuel emissions, fisheries also remove biomass from the ocean, a portion of which would otherwise sink and become sequestered in the deep sea floor. The focus of this solution is to Improve Fisheries in order to achieve carbon drawdown in two ways:

1) Reduce excess fishing effort and vessel-hours spent fishing, hence reducing fuel use in fisheries and the related greenhouse gas emissions, and
2) Rebuild large pelagic fish biomass, thereby increasing the amount of carbon sequestered and stored as sinking biomass in the deep sea.

Optimal management, including reduction of excess effort, is projected to allow a 44 percent increase in fuel efficiency of fisheries (because fuel use is directly proportional to effort), an increase in fish biomass up to the Biomass at Maximum Sustainable Yield across fisheries, and up to 15 percent greater annual seafood catch (OECD, 2012; Parker et al., 2018; World Bank, 2017). The total addressable market for reducing fuel emissions is approximately 100 million tons, representing total projected wild fishery landings in 2050. For rebuilding fish stocks, the total addressable market is approximately 9 million tons. Rebuilding fish stocks applies to a subset of the fisheries landings included in the reducing fuel emissions model, because only large, pelagic fishes that are overfished are included.

Under a projected *Plausible* Scenario, total adoption was 63 million tons landings in 2050 for reducing fuel emissions and 6 million tons landings in 2050 for rebuilding fish stocks. The total adoption under a *Ambitious* scenario was 88 million tons landings in 2050 for reducing fuel emissions and 8 million tons landings for rebuilding fish stocks. The total adoption under the *Maximum* scenario in 2050 was 100 millions tons and 9 million tons landings for reducing fuel emissions and rebuilding fish stocks, respectively.

The resulting climate impact of the Improve Fisheries solution is a cumulative reduction in carbon emissions of 1.01, 1.54, and 1.94 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious,* and *Maximum* Scenarios respectively, accounting for the reduction in fuel use and the increase carbon sequestration due to rebuilding depleted large pelagic fish stocks. In addition to this carbon impact, improving fisheries by reducing excessive effort and rebuilding biomass could increase ecosystem functioning, increase catch, and decrease costs associated with fuel as well as the cost to governments of subsidies. However, the potential loss of employment in the fishing sector is considerable, and must be mitigated. Our results align with the only other published estimate of the carbon emissions benefit of reducing excessive effort in fisheries that we found.

1 LITERATURE REVIEW

1.1 STATE OF THE PRACTICE

Project Drawdown defines *Improve Fisheries* as reforms and improvements in the management of wild-capture fisheries to reduce excess effort, overcapitalization, and overfishing. This solution reduces the number of vessel-days engaged in fishing efforts to optimal levels needed to catch the Maximum Sustainable Yield and allows depleted fish stocks to rebuild to Biomass at Maximum Sustainable Yield, thereby reducing fuel use and allowing for greater carbon sequestration in wild fish biomass, without reducing wild fish catch in the long-term. Wild-capture fisheries produce carbon emissions, primarily due to fuel use of fishing vessels, reduce carbon storage and sequestration in large fish biomass by depleting these species, and have a number of other climate impacts, including reducing carbon sequestration of ocean sediments (i.e. via sediment resuspension by bottom trawls). Estimates of global CO2 emissions from the main engine combustion of fuel in marine fisheries range from approximately 130 million tons of CO2 to approximately 207 million tons of CO2 annually (Greer et al., 2019; Parker et al., 2018; Tyedmers et al., 2005). There are various possible approaches to reducing fuel use and carbon emissions from fisheries, including improving vessel fuel efficiency. However, analyses suggest that the most important driver of fuel use in fisheries is the amount of fishing effort, and that the most promising route to reducing fuel emissions from fisheries lies in reducing over-capacity and effort and rebuilding depleted fish stocks (Hoegh-Guldberg et al., 2019; Parker et al., 2018; Tyedmers et al., 2005; World Bank, 2017; Ziegler et al., 2016; Ziegler & Hornborg, 2014). Moreover, marine vertebrates can play a role of blue carbon sinks by storing carbon in their biomass and depositing it to the deep ocean after death, and it is estimated that they represent an oceanic blue carbon stock of 0.7 Gt (Bar-On et al., 2018).

1.1.1 Improving fishery and fuel emissions.

Fuel use in fisheries, and hence emissions, is directly proportional to effort, a measure of the amount of fishing taking place. While catch has not increased significantly since approximately 1985 and declined slightly since 1990, effort has increased significantly and consistently (Figure 1.1). Since the early 1990s, catch has stabilized, while fishing effort has nearly doubled in the same time period (Bell et al., 2017). As a result of increasing effort, annual CO2 emissions have grown by about 40 million tonnes/year since the 1990s, despite modest improvements in vessel engine efficiency over time (Greer et al., 2019). Various reviews and models have estimated that the fishing capacity and fishing effort reductions of 36 to 50 percent would be needed to achieve the ecologically and economically optimal levels, and that reducing effort by that amount would allow fish populations to rebuild and would not result in any reduction in long-term catch (Bell et al., 2017; Sumaila & Tai, 2020; Ye et al., 2013).

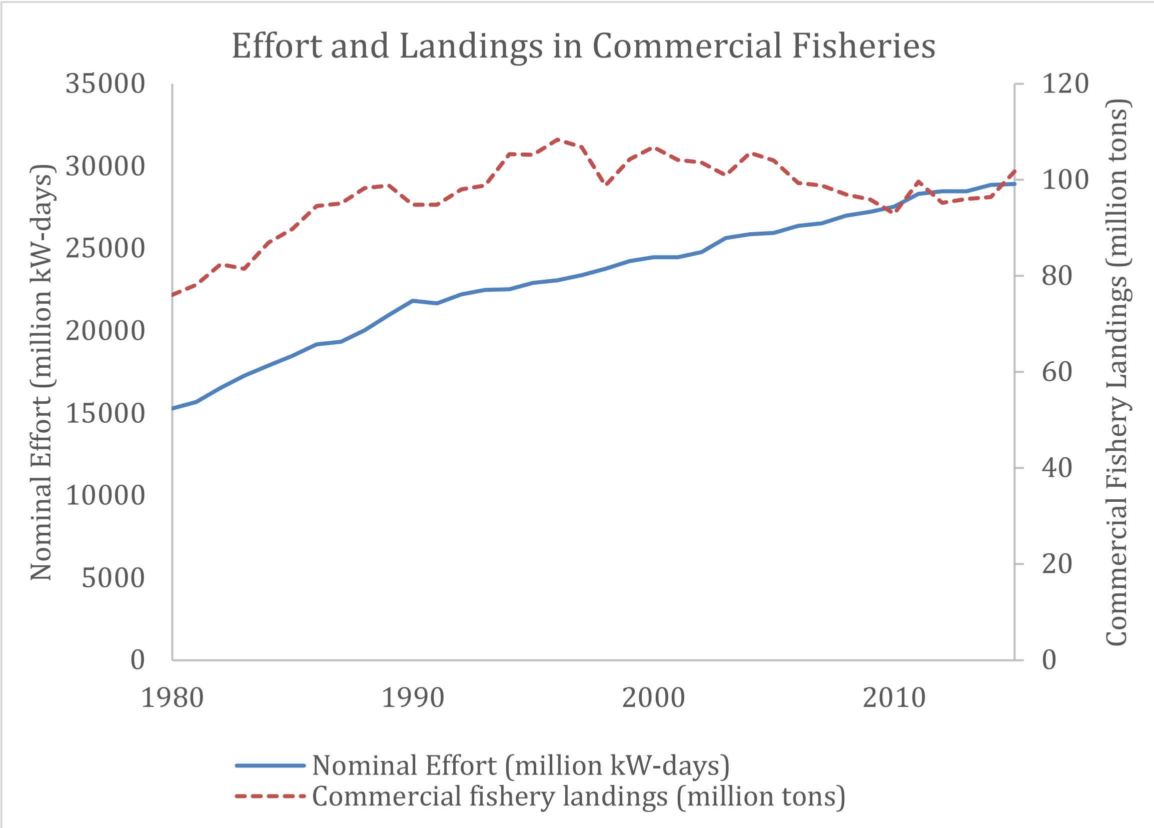

Figure 1.1. Nominal Effort and Landings in Commercial Fisheries, 1980-2015.

Reducing emissions from wild-capture fisheries is promoted as one of the top potential ocean-based solutions to climate change in the report from the High Level Panel for a Sustainable Ocean Economy (Hoegh-Guldberg et al., 2019). Specific priorities highlighted in the report which could help achieve this aim include eliminating harmful fisheries subsidies, strengthening international collaboration to end Illegal, Unregulated and Unreported (IUU) fishing, and improving fisheries management.

Causes and consequences of overcapacity and overfishing

Fishing effort can be described in terms of the number, size, and engine power of fishing vessels (also known as fishing capacity), the amount of time that vessels spend fishing, or a combination (i.e., a product of the power of the total global fishing fleet and the average hours spent fishing per vessel). The global increase in effort is driven by overcapacity (too many fishing vessels), overfishing, and stock depletion (the more fish stocks decline, the more time and fuel vessels must use to catch the same amount of fish). Hours or days spent at sea fishing tends to be fairly stable across regions and over time (though it does vary between the industrial and artisanal sector), while fleet capacity has increased steadily. When days fished per vessel is stable, the increase in capacity is directly proportional to an increase in effort (Ye et al., 2013). Excessive effort in fisheries depletes the biomass of fish populations, which forces fisheries to fish longer and farther from shore in order to maintain the same catch, creating a feedback loop of decreasing stock size and increasing effort. The ratio between catch and effort is described as Catch-Per-Unit-Effort (CPUE), which is used as a rough approximation of abundance (although it is also affected by other factors such as fishing technology). Reductions in CPUE are indicative of excessive effort and fish stock depletion.

Fuel use in fisheries is often reported in units of Fuel Use Intensity (FUI), which measures the amount of fuel used to catch and land a ton of fish or shellfish. Fuel Use Intensity can be derived by dividing direct measurements of fuel used by fishing vessels in a given fleet with the metric tons of catch landed by that fleet (Parker et al., 2018; Parker & Tyedmers, 2015; Tyedmers et al., 2005). FUI thus provides a metric of the relative fuel efficiency of fisheries as a source of food provisioning. Similarly, FUI can be used to estimate carbon emissions intensity per ton of landings as well as total emissions from fisheries. FUI and emissions intensity vary by fishing gear type, species, region, and over time. A recent analysis found that between 1990 and 2011, carbon emissions from global fisheries has increased by 28 percent while landings have remained stable; thus, emissions intensity per ton of landings has increased by over 20 percent. Drivers of the increase in FUI and emissions intensity of fisheries include a shift toward targeting more carbon-intensive species (e.g. crustacean fisheries), as well as trends towards increasing overcapacity and stock depletion (Parker et al., 2018).

Drivers of over-capacity and excessive effort in fisheries include open-access fishing policies, leading to a race to fish and "tragedy of the commons;" illegal, unregulated, and unreported (collectively IUU) fishing; harmful fishing subsidies (including fuel subsidies for fishing vessels); and stock depletion. Fishing subsidies are a major driver of overfishing and excessive effort in fisheries. According to Sumaila and Tai, nearly 30 billion USD out of a total of 35 million USD in annual fisheries subsidies are provided to large-scale industrial rather than small-scale fisheries, and 60 percent of these subsidies to large-scale fisheries are capacity-enhancing, meaning they provide incentives for over-capitalization and overfishing (Sumaila & Tai, 2020). The role of reducing subsidies as a driver to improving fisheries and reducing fishing vessel emission is further addressed under "Trends to Accelerate Adoption" below.

1.1.2 Improved fishery and fish biomass.

The ocean plays an important role in global carbon cycling, as a major carbon sink sequestering 2.5 GtC yr^{-1} or 22% of global anthropogenic CO_2 emissions (Friedlingstein et al., 2019). The majority of studies on the oceanic carbon cycle has focused on phyto- and zooplankton's role in carbon sequestration and sinking to the deep-ocean (Moore et al., 2004), and the role of higher trophic level marine organisms has been omitted. However, in recent years, there are an increasing number of studies exploring the potential of marine vertebrates in the biological carbon pump (Lavery et al., 2010; Pershing et al., 2010; Trueman et al., 2014) and to date, it is estimated that they represent an oceanic blue carbon stock of 0.7 Gt (Bar-On et al., 2018). These large animals can store carbon through eight different ways: 1) trophic cascade carbon, 2) biomixing carbon, 3) bony fish carbonate, 4) whale pump, 5) twilight zone carbon, 6) biomass carbon, 7) deadfall carbon, 8) marine vertebrate mediated carbon, as described in Figure 1.2:

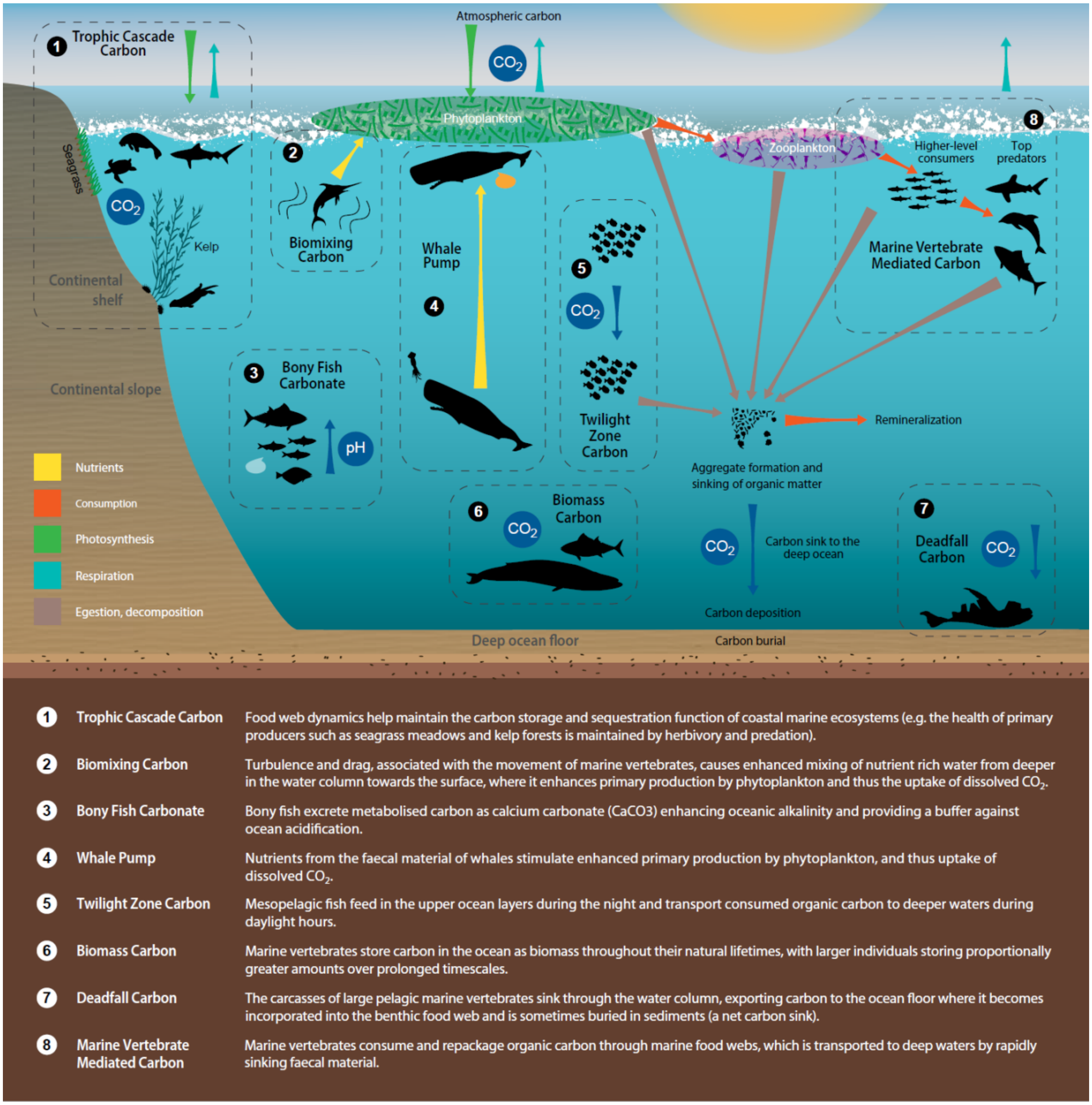

Figure 1.2. A conceptual model of marine vertebrate carbon services (Lutz & Martin, 2014).

The biomass carbon and deadfall carbon have been quantified globally both for large fish (Mariani et al., 2020) and marine mammals (Pershing et al., 2010).(Mariani et al., 2020) estimated the capacity of large pelagic fish to sequester carbon in the deep sea after their natural death and how this capacity had decreased due to global fishing. These large pelagic fish included dense and large-bodied (> 30 cm in total length) fusiform fish species, including most tunas, mackerels, sharks and billfishes, since their carcasses are most likely to sink rapidly. Landings of these large-bodied fish represent only 9.5% of the total fish catches in 2014. Based on their analysis, since 1950, the world's fishing fleets have extracted 318.4 Mt of large fish from the ocean, and prevented the sequestration of 21.8 ± 4.4 Mt carbon from fish bodies into the deep sea (Mariani et al., 2020). (Pershing et al., 2010) estimated that rebuilding whale populations to the pre-whaling levels would remove 0.2 Mt of carbon each year through sinking whale carcasses. Other fish species have not been considered in similar global quantifications, as the pathways of carbon sequestration are not clearly understood, and because other species such as small pelagic fish are more likely to die from predation. The estimations of carbon sequestration by whales and dolphins are more uncertain as their carcasses are known to float after death, and thus might be partly grazed in the sea surface rather than sink to the bottom right after death. We are taking a very conservative approach and we quantified carbon sequestration of large fish following (Mariani et al., 2020).

Other mechanisms of marine vertebrates carbon cycling have an important role in ocean carbon sequestration, however global quantifications do not exist. Fish produce carbonate ($CaCO_3$) as a by-product of osmoregulation that could increase carbon sequestration, while the chemical reaction also produces some CO_2 and modifies ocean chemistry (Perry et al., 2011; Wilson et al., 2009). The large-scale removal of ocean apex predators can shift the structure and functioning of ecosystems (McCauley et al., 2015) as some species such as sperm whales play a key role in the creation of biogeochemical hotspots, increasing the export of carbon in the deep ocean (Lavery et al., 2010). Future studies could bring some more understanding of how all of those mechanisms contribute to global carbon cycling.

For the Drawdown modelling, we are only quantifying the rate of carbon sequestration by dead bodies of large pelagic fish sinking to the deep ocean. Large-bodied fusiform fish species include tunas, mackerels, sharks and billfishes. Currently, some of the stocks are experiencing overfishing or are already overfished. Of assessed tuna stocks, 36% are overfished and 30% of stocks are experiencing overfishing (ISSF, 2020). For billfishes, only 39% have healthy biomass levels and 22% are still experiencing overfishing (Pons et al., 2017). Further overfishing will cause a gradual decrease in both the biomass of fish that remains in the oceans as well as the sustainable yield, providing risk for food security. Applying regulations and enforcements to fish at the maximum sustainable yield (MSY) would result in biomass recovery and possibly even higher catches in the long term. Biomass recovery would significantly enhance the carbon sequestration due to the dead bodies of large fish sinking to the deep ocean, both by increasing the total biomass of such fish in the ocean through stock rebuilding and by increasing the proportion of the fish that die in the ocean and sink rather than being removed through fishing. As such, increase carbon sequestration in large fish biomass by reducing overfishing and rebuilding stocks contributes to the potential climate benefit of improving fisheries and can help achieve drawdown.

1.2 Total Addressable Market

1.2 Adoption Path

1.2.1 Current Adoption

Because the model of fuel emissions is predicated on the projection of a decrease in fishing effort relative to current levels, the current adoption on a global scale is zero by definition. However, regional analysis of fishing effort from the 1950s through 2010 demonstrates that in some regions, current levels of fishing effort are near optimal levels while a greater decrease is required in other regions. The largest increase in fishing effort and capacity over the past 40 years occurred in Asia. In North America, South America, and Africa, fishing capacity increased throughout the time series but began to stabilize in the last few years. In Europe, fishing capacity peaked around 1990 and then declined back to approximate 1960 levels, whereas in Oceania fishing capacity decreased between 1950 and 1970 but has increased since the 1980s. Regional difference in effort trends mirror the trends in capacity. In general, the fishing effort of developed nations peaked in the 1980s-1990s while the fishing effort in developing nations has continued to increase (Bell et al., 2017). The potential drivers of these regional trends are discussed below.

- Europe: The success of fisheries management in Europe is variable, with overfishing continuing in the Mediterranean Sea and Black Sea fisheries, but improving trends in the other European fisheries (Hilborn, Amoroso, Anderson, Baum, Branch, Costello, de Moor, et al., 2020). Due to the regional improvements in fisheries management and related reductions in over-capacity, fish stocks in some non-Mediterranean European fisheries have been increasing and rebuilding toward sustainable abundance levels in recent years, likely driving a decrease in Fuel Use Intensity (Cardinale et al., 2013; Parker & Tyedmers, 2015). For example, analyses of changes in fuel use in Swedish fisheries suggest that the most significant driver of increasing Fuel Use Efficiency in the region is the improvement in fish stock size (Ziegler & Hornborg, 2014).
- North America: According to global meta-analyses (Hilborn, Amoroso, Anderson, Baum, Branch, Costello, de Moor, et al., 2020; NOAA, 2019), fish stock biomass and fishing mortalities are at or near optimal sustainable levels in the Eastern Bering Sea and California Current eco-regions. Catch-per-unit effort, an indicator of stock health and a major driver of fuel use efficiency in fisheries, increased by an average of over 2 percent per year between 2000 and 2015 (Rousseau et al., 2019). This fisheries management success story has been attributed to the requirements regarding rebuilding stocks and ending overfishing that are encompassed in the Reauthorization of

the Magnuson-Stevens Act, the main fisheries regulation in the United States (National Research Council, 2013; Oremus et al., 2014).

- Oceania: According to global meta-analyses (Hilborn, Amoroso, Anderson, Baum, Branch, Costello, de Moor, et al., 2020) or specifically Australian region (FRDC, 2021), fish stock biomass and fishing mortality are at or near optimal sustainable levels in the Australian and New Zealand regions. Australian fisheries had much higher fuel use and emissions per unit catch than the global average, due largely to high reliance on carbon intensive gear types and target species, e.g. trawl fisheries targeting crustaceans (Parker et al., 2018). However, in some cases decreases in effort and overcapacity in recent years has led to decreases in fuel use; for example, after government buy-backs of excess vessel capacity in the northern prawn fishery, substantially reduced fuel use was recorded (Parker et al., 2018).
- Asia: In general, effort and capacity in Asia are continuing to rise, but individual case studies provide evidence that reducing overcapacity can lead to fuel use reductions. For example, Taiwanese fishing fleet capacity was reduced in 2005 leading to reductions in fuel use in that fishery (Parker et al., 2018).

For the fish biomass model, among assessed stocks, only the stocks of tunas, mackerels, sharks and billfishes (hereafter: large pelagic fish) that according to the relevant Regional Fisheries Management Organizations (RFMOs) are experiencing overfishing, or are already overfished, are considered. There are also healthy stocks that are well managed and fished at MSY. Those stocks are not considered in our analysis. Therefore the current adoption is set as zero, meaning that there is currently a lack of sustainable fishing practices on the depleted stocks. Many stocks in the included taxonomic groups are unassessed, particularly many shark species. To address these species, we relied on average estimated B/Bmsy values for unassessed species within those taxonomic groups as reported in (Christopher Costello et al., 2012).

1.2.2 Trends to Accelerate Adoption

There are several trends which could accelerate efforts to improve fishing.

- *End IUU fishing.* Illegal, unregulated, or unreported (IUU) fishing accounts for 8-14 million mt of fish catch annually. This fishing leads to stock depletion as well as several ancillary concerns such as forced labor and other human rights abuses at sea, and consumes a substantial amount of fuel. Several countries have recently made significant progress identifying and addressing IUU fishing (Hutniczak et al., 2019), and recent technological advances, increasing demand for transparency, and international cooperation have the potential to greatly advance the ability to stop IUU fishing (Long et al., 2020).

- *Reduce fishing in the high seas.* High seas fisheries account for a disproportionate amount of fuel use while landing only a small minority of the global fishing catch, and as much as 54 percent of the high seas fishing grounds are only profitable due to large government fishing subsidies (Sala et al., 2018). It is estimated that closing the high seas would lead to stock rebuilding, reduce inequality in fisheries benefits, and allow for greatly reduced fishing effort without any loss in fish catch (Sumaila et al., 2015; White & Costello, 2014). While fully closing the high seas is improbable politically, the Parties to the Nauru Agreement (PNA) countries, which control 25 percent of the global tuna catch, have set a precedent for large-scale high seas closures, most recently closing more than 4.5 million square kilometers of the high seas to purse seine tuna fishing (Pacific Island Forum Fisheries Agency, 2020).
- *End harmful fishing subsidies*, defined as subsidies that increase overcapitalization and encourage overfishing. This category of fishing subsidies includes fishery fuel subsidies, defined as "the price differential between what other users and fishers pay for fuel in a given economy" (Sumaila et al., 2008). Ending of harmful fishing subsidies is covered under UN Sustainable Development Goal Target 14.6 and the subject of ongoing World Trade Organization negotiations as of 2020. These subsidies lead to overcapacity, overfishing, stock depletion, and excessive effort and fuel use (Martini & Innes, 2018; Sumaila et al., 2008, 2010, 2016, 2019).
- *Improve fisheries management to rebuild fisheries and achieve Maximum Sustainable Yield.* As demonstrated by the improvements in U.S. fisheries following Reauthorization of the Magnuson-Stevens Act (National Research Council, 2013; Oremus et al., 2014) and in European fisheries following implementation of the Common Fisheries Policy (Cardinale et al., 2013), strong regulations regarding overfishing and rebuilding can be effective in rebuilding depleted fished stocks and reducing effort to levels more closely approaching Maximum Sustainable Yield. A variety of tools have been demonstrated to be effective in rebuilding fisheries, including setting quotas, shifting from open-access to rights-based management strategies such as Individual Transferable Quotas, and implanting Marine Protected Areas. Different approaches have proven effective in different regions of the world, and a variety of tools are needed to manage fisheries more effectively in various regions (Worm et al., 2009).

1.2.3 Barriers to Adoption

Political and economic obstacles are the key barriers that can limit the adoption of this solution. Most fisheries are operated under open access, which leads to a Tragedy of the Commons and race to fish that results in overcapacity. Once a fleet is overcapitalized via investment in more fishing vessels than is optimal for exploiting the resource, there is significant political pressure for the government to support the fisheries economically, and governments also choose to subsidize fisheries in order to increase net exports and/or national food security. Fishing subsidies maintain overcapitalization and excessive effort even when it is no longer economically viable to fish in the absence of subsidies. Subsidies also prevent market-driven corrections such as increases in fuel efficiency or decreases in fishing effort when fuel prices rise (Bell et al., 2017; Sumaila et al., 2008, 2010, 2019). However, there is considerable attention now being given to global efforts to reduce harmful fisheries subsidies in accordance with UN Sustainable Development Goal 14.6, and the reduction in these fisheries is a current (as of 2020) focus of World Trade Organization negotiations (Martini & Innes, 2018; Sakai et al., 2019).

The open-access nature of fisheries that underlies overcapitalization and excessive effort is deeply ingrained in both law and practice, so there are significant political, legal and social obstacles to shifting to access systems (e.g. rights-based management) that would disincentivize overcapitalization and overfishing (Ye et al., 2013); however, there are a growing number of examples of successful implementation of rights-based management and reductions in over-capacity and overfishing, particularly in North America and Oceania (Worm et al., 2009).

Moreover, the lack of stock assessment data can also limit the adoption of this solution. Currently, only 1% of fished species representing 20% of the global catch (Christopher Costello et al., 2012) are assessed, which means that the majority of the stocks lack data to inform management decisions. Yet, a global analysis of the state of unassessed stocks reveals that over 64% of the unassessed stocks are overexploited (Christopher Costello et al., 2012). While the commercially important exploited tuna stocks are assessed (ISSF, 2020), a number of billfish stocks have not been assessed (Pons et al., 2017). Although at least one-quarter of shark species are believed to be threatened due to overfishing according to the IUCN Red List, the majority of shark stocks do not have a formal stock assessment (Cortés & Brooks, 2018). More broadly, the majority of fish stocks worldwide remain unassessed (Christopher Costello et al., 2012). The lack of formal stock assessment data makes it difficult to set accurate rebuilding targets for all large fish species and to include all species and stocks that need improvements in their management.

Climate change effects may also harm the rebuilding of marine life. Studies conclude that global ocean animal biomass consistently declines with climate change and that these impacts are amplified at higher trophic levels (Lotze et al., 2019). However, the same fisheries improvements that are projected here to increase carbon sequestration by rebuilding fish biomass and decrease fuel emissions be reducing fishing vessel effort could also buffer fisheries from the effects of climate change. Gaines et al. (Gaines et al., 2018) found that under most climate change projections, fisheries reforms could more than make up for the negative impacts of climate change and lead to higher fisheries yields and profits, whereas in the absence of such reforms, fisheries yields are expected to decrease more than previously believed. However, large fishes have a high potential for recovery and are less likely to be affected by climate warming.

1.2.4 Adoption Potential

The adoption potential for this solution is considerable. Improving fisheries is currently receiving significant international attention, as it comprises a core goal of UN Sustainable Development Goal 14 and has important economic and food security benefits as well as environmental benefits. The OECD estimated that the total potential for reduction in fisheries' fuel use via fisheries management practices range from 20-80 percent reductions in fuel use, depending on the fishery (OECD, 2012; Parker et al., 2018).

Several studies have estimated how an optimal fisheries reform scenario would affect effort and catch. Based on data from the World Bank, FAO, and Garcia and Newton (1997), Ye et al (Ye et al., 2013) estimated that an optimal global Maximum Sustainable Yield for fisheries would be achieved at the 1989-1991 level of fishing effort, which represents a 36-43 percent effort reduction compared to the 2008 level of global fishing effort. In a more recent study, Bell et al. (Bell et al., 2017) found that because effort and capacity continued to increase between 2008 and 2012, a greater reduction in effort would now be needed, and achieving optimal effort and yield would require a 43-50 percent reduction in capacity and effort relative to 2012. In line with those results, based on bio-economic modeling, the World Bank recommended that global fishing effort would need to be reduced to 44 percent below 2012 levels (World Bank, 2017) to achieve ecologically and economically optimal levels.

However, immediate reductions in effort of this magnitude would cause extreme economic disruption and job loss and face political opposition. As an alternative, the World Bank modeled a gradual reduction in fishing effort, defined as a 5 percent annual reduction in effort from 2013 levels until the optimal level of a 44% reduction in effort is achieved, approximately eight years after implementation begins, followed by maintenance at that optimal level (World Bank, 2017).

The High Level Panel for a Sustainable Ocean Economy approached estimating the potential emissions reduction from improving fisheries based on the potential for future changes in Catch-Per-Unit-Effort (CPUE), as driven by future changes in both effort and landings (with fisheries reforms leading both to increased landings in the long-term and to decreased effort, hence increasing CPUE). By applying projected changes in effort and landings from (World Bank, 2017) to the fuel use and emissions in fisheries model created by (Parker et al., 2018), they estimated that increasing CPUE by improving fisheries could reduce the emissions from fishing by 81 MtCO2e per year (Hoegh-Guldberg et al., 2019).

Currently, fish stocks are below their production potential because of overfishing, and the business-as-usual scenario projects further collapse for many of the world's fisheries (C. Costello et al., 2016). Most high seas fisheries, which include tuna fisheries, are highly subsidized and would not be taking place profitably without government support (Sharp & Sumaila, 2009). It has been estimated that applying management reforms to global fisheries such as fishing at MSY could generate annual increases exceeding 16 million metric tons (MMT) of catch, $53 billion in profit, and 619 MMT in biomass relative to business as usual (C. Costello et al., 2016). Recovery of the majority of fish species can happen quickly, with the median fishery taking under 10 years to reach recovery targets (Duarte et al., 2020). A relationship between fishing pressure and changes in stock abundance, as well as between management intensity and fishing pressure has been already found (Hilborn, Amoroso, Anderson, Baum, Branch, Costello, Moor, et al., 2020). In countries such as the USA, Canada, Japan, New Zealand, Chile and Atlantic European Union countries, the concern about overfishing has resulted in legal and enforcement responses and the decline in fishing pressure can be directly tied to changes in legislation and subsequent management (Hilborn, Amoroso, Anderson, Baum, Branch, Costello, Moor, et al., 2020). Even many fishing countries in Asia such as Indonesia, India, and the Philippines show high potential for improving their fishery and are already securing their fish stocks (C. Costello et al., 2016). It is important to note that rebuilding over-exploited fish stocks would not only enhance carbon sequestration but also ensure more sustainable seafood production, limiting the shift towards livestock protein, and provide savings by limiting harmful subsidies. Also, more sustainable fishing practices will have a positive impact on other non-target species such as marine mammals, turtles and seabirds populations that are threatened as bycatch (Burgess et al., 2018).

Nature-Based Solutions (NBS) are already part of the Paris Agreement and an increasing number of countries are adding NBS to their climate change programmes (Seddon et al., 2019). Most of these NBS to climate change focus on carbon sequestration by primary producers in terrestrial or coastal ecosystems; however, there is a growing call to include more blue carbon sinks as NBS (Duarte et al., 2020; Trueman et al., 2014).

1.3 Advantages and disadvantages of Improve Fisheries

1.3.1 Similar Solutions

Improving fisheries is related to Seafloor Protection, which may attain similar benefits via setting aside some portion of the ocean as no-take marine reserves or as Marine Protected Areas that restrict some types of fishing. Protecting seafloor habitat alone may not result in a reduction in fisheries fuel use if the fishing effort is shifted toward other areas, therefore it is best considered as a complementary measure to fisheries improvement. While the improve fisheries solution focuses on fuel use and associated emissions reductions due to reduced fishing effort, the ocean protection solution focuses on increases in carbon sequestration in ocean seafloor habitat. In contrast, the improving fisheries solution derives its emissions reduction by recognizing that fishing effort is nearly twice the optimal level of effort that would be needed to achieve Maximum Sustainable Yield from fisheries, therefore it is possible to reduce effort and emissions without reducing catch. This approach has the advantage of maintaining the global fish catch, which has tremendous importance as a source of food security, protein, and micronutrients, particularly in coastal developing countries (Hicks et al., 2019).

1.3.2 Arguments for Adoption

In addition to reducing carbon emissions from fisheries, there are numerous advantages to adopting this solution, including:

- Effort and overfishing reductions modeled here would also allow for global stocks of exploited fish and invertebrate to rebuild to more than double the current biomass, increasing ecosystem functioning of marine ecosystems and communities and the associated ecosystem services (World Bank, 2017).
- Reducing effort and the resulting rebuilding of fish stocks could allow harvests to increase in the long-term while remaining sustainable. With rebuilt fish stocks and appropriate effort levels, the maximum economic yield (MEY) of fisheries would increase by about 10 million tons compared to recent harvests, thus increasing global food availability (World Bank, 2017).
- The sustainable management of fish resources thus sustainable seafood production has an important role in future food supply for the growing population (Christopher Costello et al., 2019).
- Reducing harmful capacity-increasing fishing subsidies such as fuel subsidies for fisheries, an integral aspect of implementing this solution, would result in a cost savings for fishing countries ranging from an estimated 5 billion USD to 20 billion USD annually (Sumaila et al., 2008, 2010, 2016). Alternatively, an approach of shifting subsidy payments from away from capacity-enhancing subsidies such as fuel payments and towards capacity-neutral approaches such as direct income for fishers has the potential to increase fishers' income. Additionally, the capacity-enhancing subsidies disproportionately benefit large industrial fisheries, thus shifting toward other types of subsidies is predicted to increase equity by benefiting small scale fishers (Martini & Innes, 2018).
- The sustainable management of ocean resources is in line to fulfil Sustainable Development Goal no. 14 of the United Nations.

1.3.3 Additional Benefits and Burdens

Here this solution is compared with other solutions in the ocean sector in terms of ecosystem, social and climate impact. While the climate impact of Improve Fisheries is moderate, it has high environmental and social benefits as well as high global adoption potential.

Table 1-1 Ocean Solutions Comparison.

Ecosystem Services is subjective based on impacts on biodiversity, habitat restoration, protection from extreme weather events etc. **Social Justice Benefits:** If solution is causing positive impact on local societies. **Climate Impact:** GHG reduction potential in GT CO2 eq, $_{2020\text{-}2050:}$ low >1, middle between 1 and 3, high <3. **Global Adoption Potential:** TOA in Mha: low > 100, middle between 100 and 400, high < 400; TAM is applicable for only two solutions Improve Fisheries and Improve Aquaculture therefore direct comparison with other ocean solutions is not possible, however, both solutions represents high total adoption potential. n/a – not applicable.

	Ecosystem Services	Social Justice Benefits	Climate Impact	Global Adoption Potential
Conventional fishery	Low	Low	n/a	n/a
Conventional aquacultures	n/a	Medium	n/a	n/a
Conventional seaweed farming	Medium	Medium	Low	n/a
Improve Fisheries	**High**	**High**	**Middle**	**High (TAM 94 million tons landings)**
Improve Aquaculture	n/a	Medium	Middle	High (TAM 126 million tons live weight)
Seaweed Farming	Medium	Medium	High	High
Macroalgae Forests Protection	High	High	Middle	Middle
Macroalgae Forests Restoration	High	High	Middle	Middle
Coastal Wetlands Protection	High	High	Middle	Low
Coastal Wetlands Restoration	High	High	Middle	Low
Seafloor Protection	High	Medium	High	High

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[1]) is what constituted the results.

Agency Level

The government is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, the governments that manage and regulate fisheries are the most critical player in implementation.

2.2 DATA SOURCES

For the improving fisheries model based on fuel use reduction, the functional unit is in tons of landings from commercial fisheries, while data on the conventional fuel use is available in terms of Fuel Use Intensity, defined as fuel use per landed catch in liters per ton. The primary source of data for Fuel Use Intensity is the Fisheries Energy Use Database (FEUD) maintained and provided by Dr. Robert Parker (R. Parker, pers. comm., 2020). Additional FUI data were extracted from published meta-analyses addressing fuel use and greenhouse gas emissions from capture fisheries (Greer et al., 2019; Parker et al., 2018; Parker & Tyedmers, 2015; Tyedmers et al., 2005). As FUI varies dramatically by fishery, we calculated a weighted

[1] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

average of FUI by weighting the data incorporated into the model according to the prevalence (percentage of landings) of each fishery type, defined by region and gear.

To project the change in FUI under fisheries reform scenarios, we modeled an increase in FUI resulting from a decrease in effort without a change in catch. Multiple references have demonstrated that due to overcapacity, fishing effort could be reduce by 36-60 percent with no decrease in catch (Bell et al., 2017; Sumaila & Tai, 2020; World Bank, 2017; Ye et al., 2013). To translate this result into a percentage efficiency gain under the improve fisheries solution, we assume that a decrease in effort results in a directly proportionate decrease in fuel use, resulting in a proportionate decrease in fuel-use-per-landings or FUI.

FUI is projected to decrease with sustainable fishing, mainly due to the reduction in fuel use, but also to a lesser extent due to the increases in landings that are possible in the long-term once fish stocks have rebuilt. To estimate this benefit, we modeled FUI under the Improve Fisheries scenario incorporating the reduced effort and fuel use as described above, and the increased landings at equilibrium for sustainably managed global fisheries, as projected in the Sunken Billions report (World Bank, 2017).

Landings data are used both to convert FUI into annual fuel use estimates and to model the total addressable market (see below). Landings data up to 2018 were extracted from the Food and Agriculture Organization Fisheries Divisions' State of World Fisheries and Aquaculture Report (FAO, 2020a) and online database (FAO, 2020b) and the Sea Around Us reconstructed global catch database (Pauly et al., 2020). Projections of landings under an Improve Fisheries scenario were derived from the projections in the Sunken Billins report (World Bank, 2017), with estimated potential catch at MSY projections also calibrated using the projections in (L. S. Teh et al., 2017). For the improving fisheries model based on fish biomass, the functional unit is in tons of landings for large pelagic fish from commercial fisheries and the climate impact is an additional ton of carbon sequestered by sunken biomass when fishing occurs at MSY. Because the RRS model does not account for carbon sequestration, we used a negative Indirect emissions climate variable to derive carbon sequestration. To calculate the additional annual sunken biomass of large fish, equations from (Mariani et al., 2020) were used that are based on five variables – fish stock biomass (B), stock biomass at MSY (B_{msy}), fishing mortality (F), fishing mortality at MSY (F_{msy}), and natural mortality (M). These stock status data were obtained where available from the relevant stock assessment published by the RFMO, summary stock status data published in the latest report of the International Seafood Sustainability Foundation (ISSF), or the RAM Legacy Stock Assessment Database (ISSF, 2020; *RAM Legacy Stock Assessment Database*, 2020), with natural mortality data extracted for each species from (Froese & Pauly, 2014). For unassessed stocks, average data for the taxonomic group was extracted from (Christopher Costello et al., 2012).

2.3 Estimating the Addressable Market.

2.3.1 'Total Addressable Market' Definition

The addressable market for improving fishery and fuel emissions is defined as total landings from commercial fisheries and is in units of tons.

Based on a range of sources, we have estimated a total landings of approximately 94 million tons in all areas worldwide in 2014. Landings are projected to increase to approximately 100 million tons globally in 2050. The sources for these data are the FAO and the Sea Around Us project and the Sunken Billions report as described above (FAO, 2020a, 2020b; Pauly et al., 2020; World Bank, 2017). Future landings were projected from the data sources by extrapolating from current (2000-2015) trends. To ensure a realistic time series of landings data, we set the maximum landings at no more than 115 million tons in the most optimistic projection, as that reflects the estimate of Maximum Sustainable Yield in rebuilt fisheries according to (World Bank, 2017). In addition, we set the minimum landings at no less than 93 million tons, the minimum that was found in the data set of reconstructed landings (which incorporates unreported catch) since 1990 according to the Sea Around Us data (Pauly et al., 2020), as it is unlikely that global fishery landings will fall below 1990 levels.

The addressable market for improving fishery and fish biomass is defined as total landings from commercial fisheries of large pelagic fish that are currently overfished or experiencing overfishing and is in units of tons. Based on a range of sources, we have estimated a total landings of these large pelagic fish of approximately 8.5 million tons in all areas worldwide in 2014. Future large fish landings were projected as described above so in 2050 they amount 9 million tons. The two models used landings as TAM, however because the models are estimating different climate impact (fuel emissions vs. negative indirect emissions as additional carbon sequestered in fish biomass) there is no overlap of TAMs in the two models.

2.4 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

Because this solution is predicated on the projection of a decrease in fishing effort relative to current levels, the current adoption is defined as zero tons landings.

2.4.2 Project Drawdown Scenarios

Five custom adoption scenarios are projected with the following details.

1. ***Custom adoption scenario one***: This scenario assumes that by 2050, fisheries reforms to achieve rationalized effort are implemented in 25 percent of global fishing fleets.
2. ***Custom adoption scenario two***: This scenario assumes that by 2050, fisheries reforms to achieve rationalized effort are implemented in 50 percent of global fishing fleets.
3. ***Custom adoption scenario three***: This scenario assumes that by 2050, fisheries reforms to achieve a trajectory toward rationalized effort are implemented in 75 percent of global fishing fleets.
4. ***Custom adoption scenario four:*** This scenario assumes an annual 5 percent decrease in effort until full adoption of the optimal level of effort is attained, based on the "moderate path" as described by the World Bank's "Sunken Billions Revisited" report (World Bank, 2017): "the moderate path is designed so that, starting from the observed 2012 level, the global fishing effort is gradually reduced at the annual rate of 5 percent from 2013 onward, until the long-run optimal level is attained."
5. ***Custom adoption scenario five:*** This scenario extrapolates the observed decrease in fishing effort in regions that have begun the process of fisheries rationalization to the global scale, modeled as an annual 2 percent decrease in effort globally, based on historical trends (over the last 15 years) in Europe and the U.S., as determined from data provided by Yannick Rousseau, pers. comm.

Impacts of improving fisheries from 2020-2050 were generated based on three Project Drawdown scenarios (PDS), which were assessed in comparison to a *Reference* Scenario where the solution's market share was fixed at the current levels. The three PDS scenarios are:

Plausible Scenario - This scenario represents the "average of all" custom adoption scenarios as listed above.

Ambitious Scenario – This scenario represents the "high of all" custom adoption scenarios as listed above.

Maximum Scenario – This scenario presents an optimistic growth scenario, which is represented by the highest individual custom adoption scenarios listed above.

2.5 INPUTS

2.5.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Fuel Use Intensity (FUI)	Liters/ton	235-982	608	89	5
Efficiency of solution (reduction in FUI)	Percent	37-53	45	7	4
Carbon sequestered in sinking biomass	Tons C/ton landings	0.02-1.89	0.336	22	3

Table 2-1 Climate Inputs.

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[2].

The calculation used to estimate the fuel emission in liter/hectare is described below

- Data on fuel usage of fishing per landing (FUI) is available in liter/ton
- Total fuel usage for global fishing fleets in a year = fuel usage per landing (liter/ton) * total annual seafood landed (ton/year) = fuel usage in ton/year

The fuel emissions factor used to convert fuel usage per year to greenhouse gas emissions was taken from the model input, which is 0.00268892 tons CO2-eq per liter for Gas/Diesel oil.

[2] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

To calculate the additional annual sunken biomass of large fish when fishing at MSY, equations from (Mariani et al., 2020) were used as described below:

1. Optimally fished sinking biomass

$$SB_{opt} = \frac{M}{M + F_{msy}} \times B_{msy} \times (1 - \mathrm{e}^{-(\mathrm{M}+F_{msy})})$$

2. Current sinking biomass

$$SB_{ref} = \frac{M}{M + F_{current}} \times B_{current} \times (1 - \mathrm{e}^{-(\mathrm{M}+F_{current})})$$

The four variables were obtained from RFMO stock assessments, ISSF report, RAM database, and Fishbase database (Froese & Pauly, 2014; ICCAT, 2019; ISSF, 2020; *RAM Legacy Stock Assessment Database*, 2020). For unassessed stocks, average data for the taxonomic group was extracted from (Christopher Costello et al., 2012). Data were selected based on the following 6-step approach:

1. Use RFMO stock assessment if available.
2. Use ISSF data if RFMO stock assessment data not available.
3. Use RAM database data if stock assessment and ISSF data are not available.
4. Assessed stocks within each of the above taxonomic groups were included if B<Bmsy,or F>Fmsy, or they were IUCN listed as Vulnerable, Near Threatened, Threatened, Endangered, or Critically Endangered.
5. Unassessed stocks of each taxonomic group were included using the following methodology:
    a. Evaluate the unassessed species within the taxonomic group as a whole.
    b. Use estimate from (Christopher Costello et al., 2012) for the taxonomic group in question for B/Bmsy
    b. Use average M across taxon group based on data in (Froese & Pauly, 2014).
    c. Use total shark biomass estimate from (Worm et al., 2013).
    d. For tuna and mackerel, calculate the average total biomass per species for each group from (Juan-Jordá et al., 2011), calculate number of unassessed species within each group that meet conditions for inclusion in the solution, multiply to determine an estimated total biomass of unassessed species and use that value as "total unassessed biomass" for the taxonomic group (Juan-Jordá et al., 2011).
6. To calculate F for unassessed stocks, we used the equation:

$$F_{msy} = -\ln[1 - \left(\frac{1 - e^{-M}}{2 - \frac{B}{B_{msy}}}\right)]$$

with $F = M$; derived from the relationships $\frac{U}{U_{msy}} = 2 - B/B_{msy}$ (Christopher Costello et al., 2012) and $F = -\ln(1 - U)$ (Worm et al., 2013) and assuming $F = M$ when the stock is near equilibrium and fished at F_{msy} (Francis, 2011).

Afterwards, the additional carbon sequestered by sunken biomass of large fish was calculated as an annual difference between $SB_{opt}/landings$ and $SB_{current}/landings$ and multiplied by the average carbon content in fish biomass.

2.5.2 Financial Inputs

Financial inputs and effects are not modeled here because the agency and likely costs for improving fisheries occur at the government level.

2.5.3 Other Inputs

Not applicable

2.6 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that the infrastructure required for the solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org.

Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: Fuel use in fisheries is directly proportional to effort, such that a decrease in effort results in the same percentage decrease in fuel use.

Assumption 2: We assume, based on previous models, that rationalizing fishing effort would result in an increase in landings in the long-term, following a short-term reduction in landings that allows the fishery stocks to rebuild (Hoegh-Guldberg et al., 2019; World Bank, 2017).

Assumption 3: To adopt a conservative estimate, only dense and large-bodied (> 30 cm in total length) fusiform fish species, including most tunas, mackerels, sharks and billfishes (24 tuna, 20 mackerel, 15 billfish, and 85 shark species) are considered since their carcasses are most likely to sink rapidly.

Assumption 4: Based on previous studies showing the deadfall of large pelagic fish into the deep sea (Drazen et al., 2012; Higgs et al., 2014), assumed that, in the open ocean, carcasses of the deceased fish sink to the bottom rather than being eaten in surface waters.

Assumption 5: Assumed that each fish contains, on average, 12.5% (± 2.5%) of carbon relative to its whole-body wet weight (Bar-On et al., 2018; Czamanski et al., 2011).

2.7 Integration

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process.

Improve Fisheries is part of Drawdown's new Ocean sector. Integration of this sector with the other Drawdown sectors will be developed after all the Ocean solutions are complete.

2.7.1 The Ocean model

The Drawdown Ocean model classifies the ocean into 42 possible ocean zones using three dimensions:

1. "Cover and climate" dimension: a primarily physical climate- and bathymetry- and cover-based classification of the ocean into the following regions, 4 zones for the deep ocean (biological desserts, equatorial waters, bloom waters and transition waters), 2 zones for shallow and slope waters (shallow waters and slope waters), and 1 ice-covered zone (sea ice covered waters).
2. "Access" dimension: there are political instruments in place that can limit how large parts of the ocean are used, the most common are Exclusive Economic Zones (EEZ) and Marine Protected Areas (MPA). EEZs are broadly defined by a 200 nautical mile offset from the seacoast of a country and as such collectively represent a significant fraction of the total ocean area. EEZs also coincide with the most accessible waters because of their definition; EEZ waters are closest to shore. And while EEZs tend to be shallow waters, they are not always shallow and can cross slope waters and extend into the deep

ocean. The access dimension classifies whether waters are in or out of a national jurisdiction as defined by an EEZ.

3. "Depth" dimension: the open ocean can be broadly subdivided into three layers, the epipelagic (0 to 200 m), the mesopelagic (200 to 1000 m), and bathypelagic (1000 m to bottom). Since the bottom of the epipelagic zone corresponds to the maximum depth of the coastal or shallow waters, these two ocean zones are by definition excluded from the mesopelagic and bathypegic layers.

	Zone	Epipelagic	Mesopelagic	Bathypelagic
EEZ waters	**Ice**	23.39	15.44	9.48
	Shallow	17.75	-	-
	Desert	33.83	33.83	33.17
	Slope	34.72	34.72	27.65
	Equator	13.16	13.16	13.13
	Bloom	58.95	58.95	55.16
	Transition	19.47	19.47	19.01
Outside EEZ waters	**Ice**	17.20	17.07	16.71
	Shallow	0.155	-	-
	Desert	67.24	67.24	67.19
	Slope	28.18	28.18	25.83
	Equator	31.65	31.65	31.64
	Bloom	33.14	33.14	33.12
	Transition	60.45	60.45	60.33

Table 2-2. Project Drawdown Ocean model zones.

This ocean classification has about one third the number of zones in the Drawdown Land Model in large part because the large-scale cover and climate of the oceans are not independent while cover and climate are independent on land.

2.7.2 The Ocean Sector and solutions

Project Drawdown has investigated eight ocean-based solutions and their potential to avoid GHG emissions or sequester carbon. The ocean-based solutions form two main groups: a group of protection and restoration solutions and a group of approaches to improving fisheries and aquaculture operation.

The protection and restoration solutions focus on blue carbon sinks, and their potential to sequester carbon. They include protection and restoration of coastal wetlands and macroalgae ecosystems, as well as seafloor protection from bottom trawling activities (Figure 2.1). The adoption of protection solutions involves the expansion of marine protected areas and other conservation tools such as bottom trawling bans. The adoption of solutions focusing on restoration additionally requires active restoration programs. The climate impact of solutions from this sector, include avoiding carbon emissions or enhanced carbon sequestration and are designated for the government agency level.

The second group of solutions explores the potential of improving fishery, improving aquacultures and seaweed farming. The fishery can be improved by reducing fishing effort and restoring large fish biomass. The climate impact, therefore, includes avoiding carbon emissions from fuel usage and enhanced carbon sequestration in sunken large fish biomass and the implementation of this solution involve governments. *Improving Aquaculture* solution assumes shifting from fuel-based energy systems to hybrid systems partly based on renewables thus, include climate impact based on avoiding GHG emissions. The *Seaweed Farming* solution explores the potential of expanding seaweed production and its climate effect on the enhancement of carbon sequestration in the deep sea together with unharvested biomass (Figure 2.1). The agency-level for the two last solutions involve farmers.

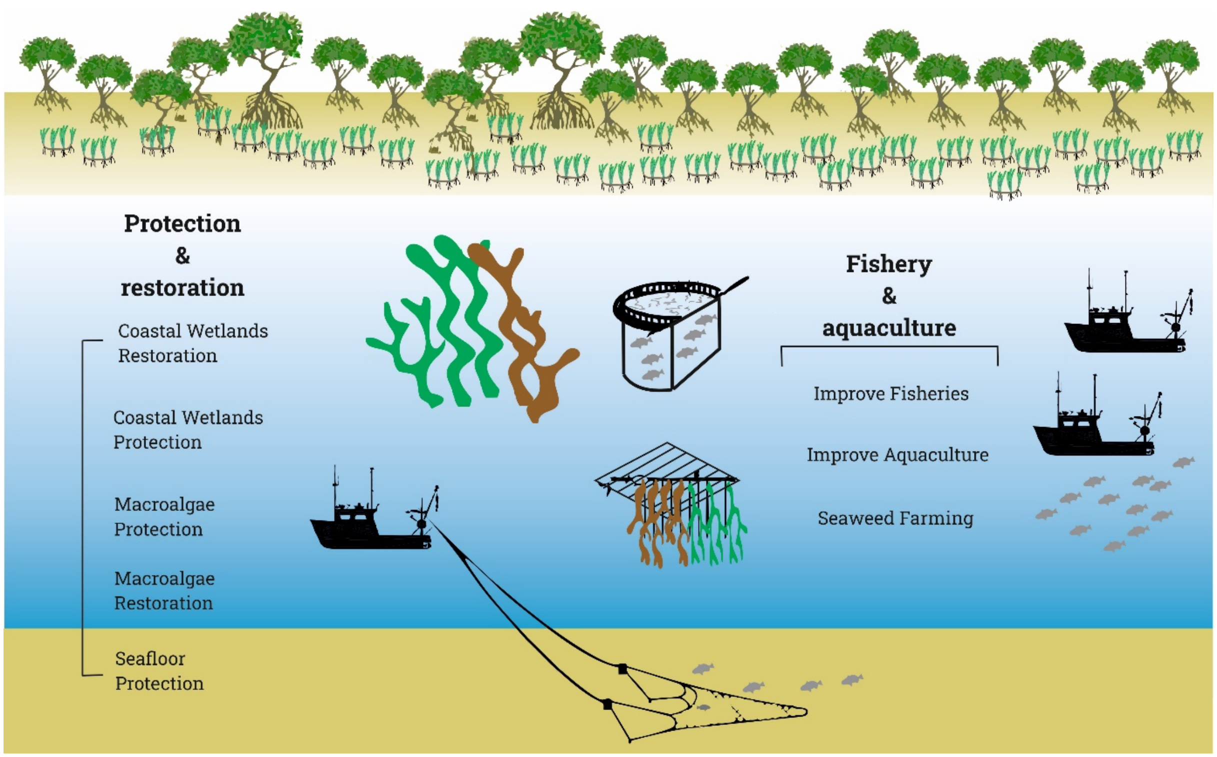

Figure 2.1. Schematic of all Drawdown ocean-based solutions.

3 RESULTS

3.1 ADOPTION

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

For the reduction in fuel emissions from fishing vessels, total adoption in the *Plausible* Scenario is approximately 62.9 million tons landings, representing adoption by 62.7 percent of global fisheries. Total adoption in the *Ambitious* Scenario is approximately 88 million tons landings, representing adoption by 87.7 percent of global fisheries. Total adoption in the *Maximum* Scenario is approximately 100 million tons landings, representing the theoretical maximum of full adoption by 100 percent of global fisheries.

Solution	Units	Current Year (2014)	World Adoption by 2050		
			Plausible	Ambitious	Maximum
Improve Fisheries	tons landings	0.00	62,893,656.34	87,960,948.13	100,251,301.24
	(% Market)	0.0%	62.7%	87.7%	100.0%

Table 3-1 World Adoption of the Solution (reducing fuel emissions).

For the rebuilding of depleted fish stocks, total adoption in the *Plausible* Scenario is approximately 3.5 million tons landings, representing adoption by 37.8 percent of fisheries on depleted stocks of large pelagic fish species. Total adoption in the *Ambitious* Scenario is approximately 5.7 million tons landings, representing adoption by 62.8 percent of applicable fisheries. Total adoption in the *Maximum* Scenario is approximately 8 million tons landings, representing adoption by 87.8 percent of applicable fisheries.

Solution	Units	Current Year (2014)	World Adoption by 2050		
			Plausible	Ambitious	Maximum
Fish Biomass	tons landings	0.00	5,697,682.45	7,966,521.29	9,072,742.76
	(% Market)	0.0%	62.8%	87.8%	100%

Table 3-2. World Adoption of the Solution (rebuilding depleted fish stocks).

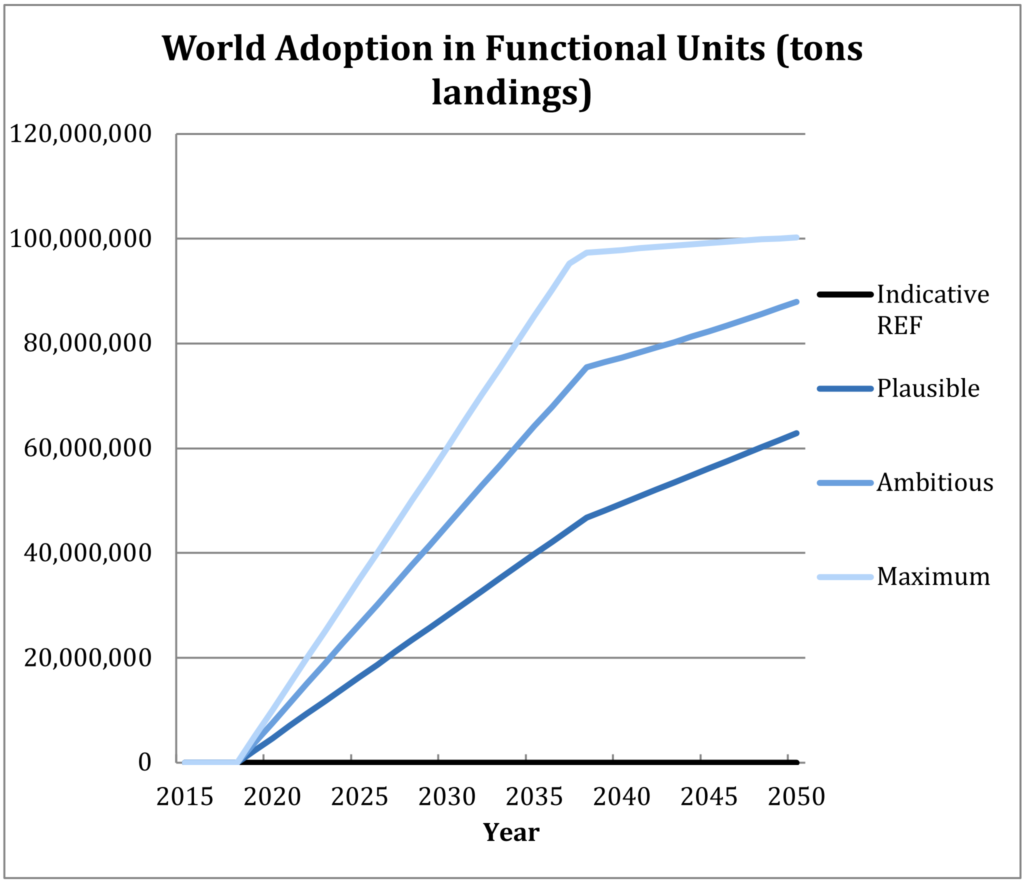

Figure 3.1 World Annual Adoption 2020-2050 (reducing fuel emissions).

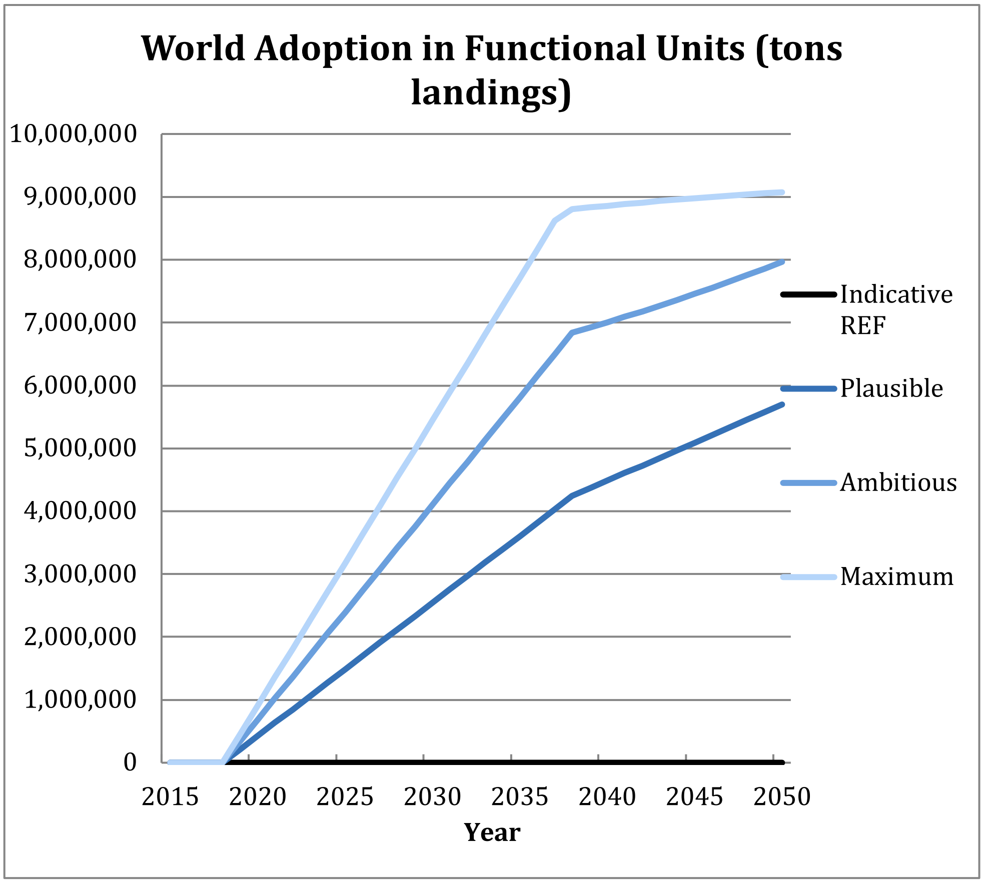

Figure 3.2. World Annual Adoption 2020-2050 (rebuilding depleted fish stocks).

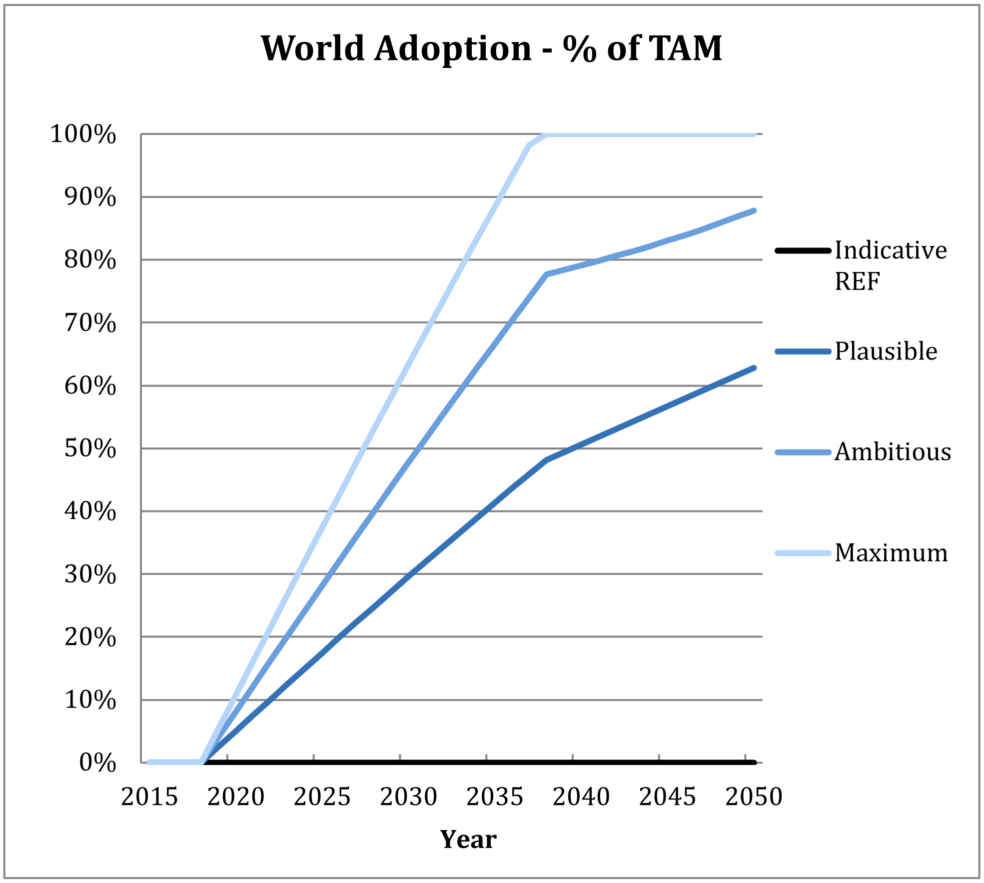

Figure 3.3 World Annual Adoption in %.

3.2 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Climate impact for reducing effort and fuel emissions is 0.97, 1.49, and 1.87 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious,* and *Maximum* Scenarios respectively. Climate impact for rebuilding depleted large pelagic fish stocks adds an additional 0.04, 0.05, or 0.07 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious,* and *Maximum* Scenarios respectively.

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050

	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	*(Gt CO2-eq/year)*	*(Gt CO2-eq/year)*
Plausible Fuel Emissions	0.05	0.97	0.02	0.05
Plausible Rebuilding Fish Stocks	0.0019	0.04	0.0009	0.0019
Plausible Total	0.0519	1.01	0.0209	0.0519
Ambitious Fuel Emissions	0.07	1.49	0.04	0.07
Ambitious Rebuilding Fish Stocks	0.0027	0.05	0.0014	0.0027
Ambitious Total	0.0727	1.54	0.0414	0.0727
Maximum Fuel Emissions	0.08	1.87	0.05	0.08
Maximum Rebuilding Fish Stocks	0.0030	0.07	0.0018	0.0030
Maximum Total	0.0830	1.94	0.0518	0.0830

Table 3-3 Climate Impacts

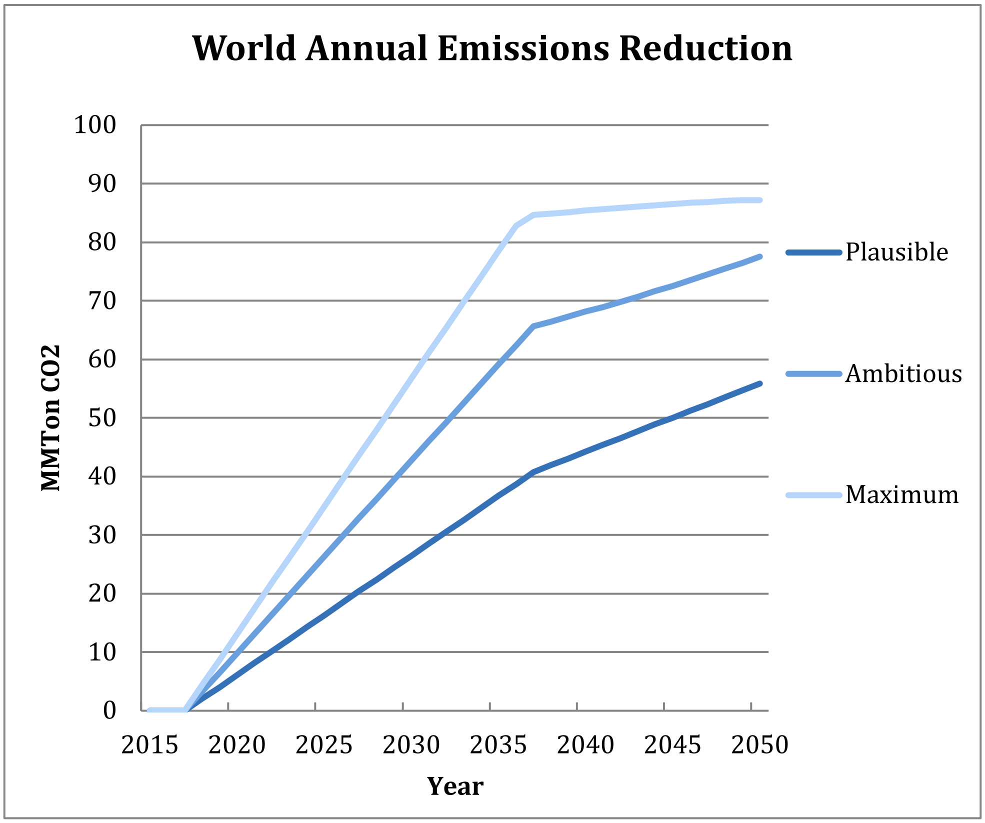

Figure 3.3 World Annual Greenhouse Gas Emissions Reduction

Scenario	**GHG Concentration Change in 2050**	**GHG Concentration Rate of Change in 2050**
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible Fuel Emissions	0.08	0.000
Plausible Rebuilding Fish Stocks	0.0029	0.000
Plausible Total	0.0829	0.000
Ambitious Fuel Emissions	0.12	0.01
Ambitious Rebuilding Fish Stocks	0.0045	0.0002

Ambitious Total	0.1245	0.0102
Maximum Fuel Emissions	0.15	0.01
Maximum Rebuilding Fish Stocks	0.0056	0.0002
Maximum Total	0.1556	0.0102

Table 3-4. Impacts on Atmospheric Concentrations of CO2-eq.

3.3 Other Impacts

Not applicable

4 Discussion

Although fishing can be a relatively low carbon emissions method of food production, particularly compared with other high protein food sources, the emissions intensity of wild-caught fish is highly variable (Greer et al., 2019; Parker et al., 2018; Parker & Tyedmers, 2015; Tyedmers et al., 2005; Ziegler et al., 2016). Fisheries in total account for approximately 4 percent of emissions related to food production globally, providing a substantial opportunity for emissions reduction (Hoegh-Guldberg et al., 2019). Reducing excess effort and rebuilding fish stocks provide the most promising avenue for emissions reduction (Hoegh-Guldberg et al., 2019; Ziegler & Hornborg, 2014). Numerous studies document the overcapacity of commercial fisheries and demonstrate that by rationalizing effort, fuel use and emissions due to fishing could be reduced by nearly 50 percent without reducing catch (Hoegh-Guldberg et al., 2019; OECD, 2012; Sumaila & Tai, 2020; World Bank, 2017; Ye et al., 2013). As a result, we found that reducing overcapacity and matching fishing effort to the optimal effort needed to catch Maximum Sustainable Yield could avoid a cumulative 0.38 – 1.27 gigatons of $CO_{2\text{-eq}}$ by 2050. These climate outcomes alone support the importance of reducing overfishing and improving fisheries, but this solution also has numerous ancillary benefits, including restoring balance to marine ecosystems by rebuilding depleted fish stocks and increasing landings with implications for food and nutritional security. Rebuilding depleted fish stocks, which falls within the UN Sustainable Development Goal 14, is achievable by 2040 for most depleted fish species through reducing overfishing, and accomplishing this goal would enhance ocean ecosystem functioning and ecosystem services (Duarte et al., 2020), increase fisheries profit and catch (C. Costello et al., 2016), and buffer fisheries from the negative impacts of climate change (Gaines et al., 2018).

The economic impacts of improving fisheries are not modeled here but merit consideration. Currently, fisheries on average operate at an economic loss of an estimated US 4-5 billion USD (Ye et al., 2013), due to overcapacity and overexploitation, and the industry is largely maintained by government subsidies (Sala et al., 2018; Sumaila et al., 2010, 2016). By decreasing costs associated with fuel and other inputs that scale with effort, these changes would decrease the cost of fishing per ton of catch, while increasing revenue in the long-term by increasing the sustainable catch by 10 to 15 million tons per year. As a result, the reform measures could increase economic rent of fisheries by over 30 billion USD annually, allowing the fisheries to operate profitably even in the absence of subsidies (Ye et al., 2013). Harmful, capacity-enhancing fishery subsidies alone cost governments an estimated 20 billion USD per year, money which could be redirected into more beneficial services (Sumaila et al., 2016).

Despite these numerous benefits, there are significant potential economic and social costs to consider, particularly loss of employment. Fishing directly employs approximately 50 million people worldwide (L. Teh & Sumaila, 2013), and reducing effort in fisheries would necessitate reducing fisheries employment, with a loss of up to 12 to 15 million fishing jobs (Ye et al., 2013). Considering the importance of fisheries as an employment sector, it is essential that fisheries reforms be designed in a way that mitigate these employment impacts. In particular, attention should be paid to ensure that fishery reforms and resulting job loss not disproportionately affect low-income or otherwise marginalized fishing communities. An OECD bio-economic model found that simply redirecting fisheries subsidies from capacity-enhancing to other types of subsidies (e.g., from fuel subsidies to direct income payments to fishermen) could help achieve fishing effort reduction and stock rebuilding goals while increasing total income of fishers, especially for small-scale fisheries (Martini & Innes, 2018). In some regions and circumstances, vessel buybacks could be implemented to compensate fishermen who leave the fishing industry. Set at a price that would entice fishermen to voluntarily leave the fishery, buybacks at a total, one-time cost of 96 to 358 billion USD to achieve the effort reductions modeled in this solution, a cost which could be recovered within about seven years through the increased economic rents of a rationalized global fishing fleet (Ye et al., 2013).

In addition, forced labor and other serious labor abuses are prevalent in fisheries in the high seas and in regions with poor regulations (Sala et al., 2018; Tickler et al., 2018). Overfishing and human rights violations share common drivers, including overcapitalization, subsidies, and IUU fishing, and solutions that address these drivers via enhanced regulations and enforcement could achieve social and environmental goals simultaneously (Lindley & Techera, 2017; Tickler et al., 2018). Overall, different policy prescriptions will be appropriate for different fisheries and regions, but care should be take to redirect some of the cost recovery to buffer the effects of lost employment.

4.1 Limitations

Given the substantial potential economic impacts, both positive and negative, as described above, further detailed analysis of the economics of this solution would benefit future updates. The solution does not include the emissions reduction benefit derived from increased catch that could result by rebuilding fish stocks to optimal levels because data available to accurately estimate the magnitude of this benefit globally are scarce; however, inclusion the rebuilding effect could allow for further declines in Fuel Use Intensity (liters fuel used per ton of catch) and bolster the avoided emissions calculation for this solution, so it would be useful to estimate this benefit in future iterations. The scenario modeling and Fuel Use Intensity database are based on global landings, not catch, of fisheries, i.e. discards are excluded. Currently, sufficient data are not available to calculate fuel use on a per catch rather than per landings basis; however, implementing policies to reduce discards could allow for greater carbon reduction benefits and may be addressed in a future solution.

4.2 Benchmarks

The High Level Panel for a Sustainable Ocean Economy modeled the emissions reduction benefit from reducing fuel use in fisheries, based on Robert Parker's fuel use and greenhouse gas emissions data and the effort reduction and increased landings modeled under the World Bank's optimized fishing performance white paper "The Sunken Billions Revisited (Hoegh-Guldberg et al., 2019; Parker et al., 2018; World Bank, 2017). They estimated that reducing fuel use in fisheries could result in reducing annual emissions by 0.081 gigatons CO2-eq per year by 2050. These values are the same as those estimated in this study *Maximum* scenario, as *Maximum* scenario use exactly the same adoption as Hoegh-Guldberg et al., 2019.

Source and Scenario	**(Ocean) Mitigation Impact (i.e. Gt $CO_{2\text{-}eq}$ in 2030)**	**(Ocean) Mitigation Impact (i.e. Gt $CO_{2\text{-}eq}$ in 2050)**
(Hoegh-Guldberg et al., 2019)	-	0.08
Plausible Scenario	0.02	0.05
Ambitious Scenario	0.04	0.07
Maximum Scenario	0.05	0.08

Table 4-1 Benchmarks.

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Ambitious Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours