Supplemental material for Rethinking sustainability in seafood: Synergies and trade-offs between fisheries and climate change

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S1. Fisheries descriptions and key assumptions

Here, we provide information about each fishing fleet and key assumptions related to our hypotheses including: 1) information about the selectivity of the fishing gear and concerns related to bycatch and protected species; 2) whether or not the fleets engage in fishing activities outside the U.S. exclusive economic zone (EEZ).

*S1.1 U.S. purse-seine fleet*

Purse-seining is less selective than other fishing methods that catch fish one-at-a-time because this gear type captures everything that it surrounds, including protected species (NOAA Fisheries, 2019a). Skipjack tuna (*Katsuwonus pelamis*) is the principal species targeted but this fleet also catches large quantities of other tuna species, as well as non-tuna species bycatch. Of particular concern is the catch of species like whale sharks, silky sharks, oceanic whitetip sharks, juvenile bigeye tuna, and juvenile yellowfin tuna or any others whose status is overfished or overfishing (Restrepo et al., 2017).

These fleets operate within the EEZ of countries in the Western Pacific Ocean and on the high seas (Williams and Terawasi, 2016). Fishing trips can last up to several months (Gillett, 1986; Gillett et al., 2002; Joseph, 2003). During a trip, the vessels are active during the day and at night (Walker et al., 2010; Langley, 2011). Limits on fishing effort exist within the sovereign waters of the Nauru Agreement parties (Federated States of Micronesia, Republic of Kiribati, the Marshall Islands, Nauru, Palau, Papua New Guinea, the Solomon Islands and Tuvalu) and a fishing day is defined as 24 hours in these areas (Havice, 2013).

Most of the tuna caught by U.S. purse-seine vessels is caught in the WCPFC-CA (Figure 1), with 39 vessels participating in 2015 (NOAA Fisheries, 2016). Between 2011-2015, the mean annual catch of this fleet was ~2.5 x105 tonnes of tuna of which approximately 92% was caught outside the U.S. EEZ.

*S1.2 American Samoa longline fleet*

Albacore tuna (*Thunnus alalunga*) is the principal species targeted by this fleet. Longlines are considered less selective because fleets catch a substantial amount of bycatch (Watson and Bigelow, 2014), some of which includes endangered or threatened species of marine mammals, sea turtles, sharks, striped marlin, and seabirds. A fishery observer program was implemented in this fishery due to concerns over protected species (primarily sea turtles) interactions with the fishery. In 2015, 20 vessels participated in this fishery (NOAA Fisheries, 2017a).

This fleet operates inside and outside the US EEZ, primarily around American Samoa. Although this fleet operates outside the U.S. EEZ, the data was not available to estimate the activity of this fleet on the high seas. Effort hours were obtained from logbooks.

*S1.3 American Samoa troll fleet*

Although commercial troll fisheries target various species, including tuna, mahi-mahi, ono, and billfishes (NOAA Fisheries, 2017b), the majority of the catch by mass is skipjack tuna (*Katsuwonus pelamis*). While troll gears are highly selective, there are concerns related to bycatch of striped marlin. In 2015, 13 vessels participated in this fishery (NOAA Fisheries, 2017b). In this fleet, fishing occurs in nearshore or federal waters year-round, with trips lasting less than a day.

*S1.4 Hawaii deep-set longline fleet*

Bigeye tuna (*Thunnus obesus*) is the principal species targeted by this fleet. Longlines are considered less selective because the fleet catches a substantial amount of bycatch including endangered or threatened protected species including mammals, sea turtles, sharks, striped marlin, and seabirds. In 2015, 139 vessels participated in this fishery in 2015 (NOAA Fisheries, 2017c).

This fleet operates inside and outside the US EEZ, primarily around Hawaii. Although this fleet operates outside the U.S. EEZ, the data was not available to estimate the activity of this fleet on the high seas. We estimated the vessel operation time by using the “soak time”, approximately 21 hours per day (Bayless et al., 2017).

*S1.5 Hawaii troll fleet*

Although commercial troll fisheries also target wahoo and mahi-mahi, the majority of the catch by mass is yellowfin tuna (*Thunnus albacares*). This fleet generally fishes at an average distance of 7-12 km from shore, with a maximum distance of about 45 km from shore (NOAA Fisheries, 2017d). Although troll gears are highly selective, there are concerns related to bycatch of striped marlin. In 2015, 2117 vessels participated in this fishery in 2015 (NOAA Fisheries, 2017d).

*S1.6 North Pacific surface methods fleet*

Albacore is the principal species targeted and there is little bycatch associated with this fleet (cf. Table 5 in (PFMC, 2017a)). The surface methods include pole-and-line, and troll gears. Due to the United States – Canada Albacore Treaty, this fleet has access to fish 18 km offshore Canadian waters (NOAA Fisheries, 2017e). Likewise, Canadian fisherman have access to fish 18 km offshore U.S. waters. Including Canadian vessels, 565 vessels participated in this fishery in 2015 (cf. Table 5 in (PFMC, 2017a)).

This fleet operates across the North Pacific and along the coast of North America as far north as Canada and as far south as Mexico, both inside the EEZs of Canada and the U.S. and on the high seas. Although an older technical description of this fleet reported operating hours of 14-15 hours per day (Dotson, 1980), we assumed the operating characteristics of the albacore troll fishery in New Zealand was similar to those of the North Pacific troll fishery. In that fleet, more recent data indicated the mean operating time is 12 hours (Kendrick and Bentley, 2010).

S2. Fuel use intensity methods

We calculated fuel use intensity (FUI, l fuel tonnes catch-1) with estimates of fuel consumption estimates and catch statistics (Eq. S1). We obtained catch statistics for each fleet operating within their respective domains (Tables A1-A6 in Appendix A available at: <https://doi.org/10.6071/M3768B> and for fleet fishing activity within the U.S. EEZ (Tables A6 and A7) and fleet fishing activity outside the U.S. EEZ (Tables A6 and A8) (WPRFMC, 2012; WPRFMC, 2015; PFMC, 2017c; NOAA Fisheries, 2017f; WPRFMC, 2017).

*S2.1 Fuel consumption methods*

We calculated fuel consumption with main engine power (kW), engine load factor, fishing effort (hours), engine speed and fuel type that corresponds to specific fuel oil consumption (SFOC, g kWh-1), and density of fuels (g l fuel-1) (Eq. S2). The engine speeds are either medium-speed diesel (MSD) or high-speed diesel (HSD) and the fuel types are either distillates or heavy fuel oil (HFO). The distillates are either marine diesel oil (MDO), marine gas oil (MGO), or ultra-low sulfur diesel (ULSD).

We used vessel registry data to obtain engine speed and fuel type information (Table S1), and main engine power (Table S2). We calculated the engine load factor for each fleet (Equation S3). We used 90% maximum engine power at vessel design speed (Goldsworthy and Goldsworthy, 2015) and we obtained the vessel average speed and vessel design speed from the Marine Traffic database (marinetraffic.com; Table S3).

The aggregated annual effort (hours) was estimated as the product of the aggregated annual effort (days) and the estimated daily vessel operating time (hours) for the U.S. purse seine, Hawaii troll and longline, and the North Pacific surface methods (pole-and-line and troll gear) fleets. The aggregated annual effort was provided in hours for the American Samoa troll and longline fleets. The daily effort (hours) in the case of the Hawaii troll fleet was estimated as the quotient of the Main Hawaiian Islands (MHI) catch per unit effort (CPUE) in pounds of yellowfin tuna per day fished and the MHI CPUE in pounds of yellowfin tuna per hour fished. The aggregated annual effort (days) for the Hawaii deep-set longline fleet was estimated as the product of the annual number of trips and the average number of days per trip. In all cases, the aggregated annual effort was for time spent fishing and searching for fish but does not include steaming to and from the fishing grounds. We estimated the daily vessel operating time (hours) for the Hawaii longline fleet using “soak time” from observer data (Bayless et al., 2017). We estimated daily vessel operating hours for the U.S. purse seine fleet from a VMS study of purse seine vessels operating in the WCPFC convention area (Langley, 2011). We estimated daily vessel operating hours for the North Pacific surface methods fleet from a fleet that targets the same species with the same gear but in a different fishing region (Kendrick and Bentley, 2010). In all other cases (e.g. American Samoa troll, American Samoa longline, and Hawaii troll) we assumed the daily vessel operating hours were equivalent to the aggregated annual effort hours. We obtained fishing effort from logbooks for each fleet operating within their respective domains (Table S4), fleets operating in the U.S. EEZ (Table S5), and fleets operating on the high seas (Table S6) from regional fishery management organizations.

We obtained the specific fuel oil consumption (SFOC) data from (ICF International, 2009). The SFOC is 213 and 203 g kWh-1 in for HFO and distillates, respectively. We used weighted averages of the fuel product densities of distillates and HFO from our Petroleum Refinery Life Cycle Inventory Model (PRELIM) simulations (Table S7) (Abella and Bergerson, 2012).

S3. Total fuel-cycle climate forcing methods

*S3.1 Crude oil refinery process*

We estimated the relative contributions to each climate forcing constituent for the crude oil refinery process (Eq. S4). We used PRELIM (Abella and Bergerson, 2012) to simulate the fuel product densities, lower heating values, and GHGs for our analysis (Tables B1-B7 in Appendix B available at: https://doi.org/10.6071/M3768B). In our simulations, we selected 62 different oil field assays, two different refinery types (hydro-cracking and coking), and a variety of refinery configurations for each product slate (Table B8). To reflect differences depending on the conversion configuration, we used a mix of refinery processes and fuel blends to achieve the desired fuel quality (sulfur levels) for each marine fuel by weighting the refinery simulation outputs (refinery GHG emissions, lower heating values and the fuel densities) by the frequency of occurrences of a particular oil field assay in the refinery emissions analysis (Table B9). We used the mean values and 95% confidence intervals for the crude oil refinery GHG emission factors, fuel product lower heating values, fuel product densities (Table S8), and GWPs (Table S9) as inputs to Equation S5. Results by fuel type and sulfur level are presented in Figure B1 (available in Appendix B: <https://doi.org/10.6071/M3768B>).

*S3.2 Crude oil extraction process*

We estimated the relative contributions to each climate forcing constituent for the crude oil extraction phase (Eq. S5). We matched the crude extraction emissions to the corresponding oil field assays used in our refinery emissions analysis. As inputs to Equation S5, we used the crude oil extraction emissions data from the literature and technical reports (Table B10) (COWI et al., 2014; Brandt et al., 2015; Duffy, 2015; Gordon et al., 2015; Tormodsgard, 2015), calculated the mean values and 95% confidence intervals for the crude oil extraction GHG emission factors (Table S10) and GWP values (Table S9), used the ratio of crude feed input to the fuel product output obtained in PRELIM (Table S8), and allocated the crude oil GHG emissions by climate forcing constituent using the pump-to-well crude oil emission factor provided in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (Wang, 2011). Results by fuel type and sulfur level are presented in Figure B2 (Appendix B: <https://doi.org/10.6071/M3768B>).

*S3.3 Fishing vessel-exhaust emissions*

We estimated the relative contributions to each climate forcing constituent of the vessel-exhaust phase (Eq. S6). To estimate the LLCF vessel-exhaust emissions of the U.S. tuna fleet we used the emission factors (Table S11) and GWPs (Table S12) obtained in technical reports and the literature. We calculated the aerosol SLCFs (Eqs. S7 and S8) and we reviewed recently published plume sampling studies and calculated the mean and 95% confidence intervals 0.85 (± 0.14) and 0.48 (± 0.16) g BC kg fuel-1 for MSD diesel and HSD engines, respectively (Lack et al., 2008; Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014). Results by fuel type and sulfur level are presented in Figure B3 (Appendix B: <https://doi.org/10.6071/M3768B>).

*S3.4 Summary of fuel cycle emissions*

Our total fuel-cycle climate forcing calculation is the sum of climate forcing from the oil refinery, oil extraction, and vessel-exhaust phases of the fuel cycle (Eq. S9).

We calculated the total fuel-cycle climate forcing over time (1996-2015) by marine fuel type (distillates and HFO), fishing territory (U.S. EEZ and high seas) and engine type (MSD and HSD) on a 20-y and 100-y time horizon (Eq. S9). To construct historical (1996-2015) fuel sulfur levels for each fishing territory, we used data found in technical reports, the literature, and statistics from the U.S. Energy Information Administration (Tables B11 and B12). We used weighting factors to estimate the mean net (sum of all constitutents) total fuel-cycle climate forcing associated with ships burning HFO and distillates in the U.S. EEZ and the high seas (Table B13-B16). Results by fuel type and sulfur level are presented in Figure B4 (Appendix B: <https://doi.org/10.6071/M3768B>).

# S4. Protein-and-species-specific climate forcing of tuna

We calculated the protein-and-species-specific climate forcing of tuna over time (1996-2015) (Eq. S10). Inputs to Equation S10 include FUI (Figs. 1 and 2), total fuel-cycle estimates (20-y and 100-y time horizons) (Fig. S2), and fishing vessel engine speeds and fuel types (Table S1), and protein yields of tuna.

# S5. Comparison to farmed protein sources

We compared our climate forcing per unit tuna protein to other protein sources using Equation S11. Inputs to Equation S11 include the GHG emissions of farmed protein sources (Table S13), the fraction of GHG emissions that can be allocated to farming activites for each type of farmed protein (Table S14), the allocation of each farming activity to each GHG constituent (CO2, CH4, N2O) for farmed proteins (Tables S15 and S16), and global scale GWPs (Table S9).

# Equations (S1-S11)

# S1. Fuel use intensity calculations

The mean fuel use intensity (FUI, l fuel tonnes catch-1) was calculated using:

(S1)

where *FC* is the annual fuel consumption of each tuna fleet (l fuel yr-1), *Mcatch* is the mass of tuna or pelagic species catch (tonnes yr-1), *i* is the fishing region (Western Central Pacific Ocean convention area, American Samoa, Hawaii, or the North Pacific region of North America), *j* is the fishing gear (troll, purse seine, surface methods, or longline), *k* is the fishing territory (inside or outside the U.S. EEZ), *l* is the year (1996-2015), and *m* is the species of tuna (albacore, bigeye, skipjack, or yellowfin). The subscript k applies to the scenario where we disaggregate the effort and catch between the high seas and the EEZ. In the case in which we do not disaggregate the effort and catch between the EEZ and high seas, the k is omitted.

# S2. Fuel consumption

We used activity-based methods to estimate the fuel consumption, FC (l fuel), for each fleet as follows:

(S2)

where *PM,avg* is the fleet average main engine power (kW), *LFavg* is the average fleet load factor, *teff*is the fishing effort (days), *fFQ* is the fraction of the fleet using a particular fuel type, *SFOC* is the specific fuel oil consumption (g kWh-1), *ρ* is the density of the fuel type (g l fuel-1), and *n* is the fuel type (HFO, MDO, MGO, or ULSD).

# S3. Main engine load factor

The main engine load factor, *LFavg*, can be calculated using (Goldsworthy and Goldsworthy, 2015):

(S3)

where *vacg* is the vessel’s average speed, *vd* is the vessel’s design speed, and Lmax is the fraction of maximum engine power used at a vessel's design speed

# S4. Crude oil refinery climate forcing

We estimated the relative contributions to each climate forcing constituent for the refinery process (*CFref*, g CO2e l fuel-1) following:

(S4)

where *EFGHG,ref*is the GHG emission factor for fuel refining (g CO2e MJ fuel product-1), *falloc,ref*is the fraction of each climate forcing constituent that can be allocated to the refining GHG emission factor (g pollutant g CO2e-1), *LHV* is the lower heating value, *GWP* is the global warming potential, *o* is the constituent (CO2, CH4, N2O, NOx, SO2, OC, and BC), *p* is the fuel sulfur level, and *q* is the time horizon (20-y or 100-y).

# S5. Crude oil extraction climate forcing

We estimated the relative contributions to each climate forcing constituent for crude oil extraction, *CFext* (g CO2e l fuel-1) using:

(S5)

where *EFGHG,ext*is the GHG emission factor for crude extraction (g CO2e MJ crude oil-1), *falloc,ext* is the fraction of each climate forcing constituent that can be allocated to the GHG emission factor (g pollutant g CO2e-1), and *rfeed* is the ratio of crude feed input to the fuel product output (MJ crude MJ fuel product-1).

# S6. Vessel exhaust climate forcing

The exhaust emissions, *CFexh* (g CO2e l fuel-1), were calculated using:

(S6)

where *EFexh*is the exhaust emission factor (g CO2e kg fuel-1).

# S7. Sulfur dioxide exhaust emissions

The sulfur dioxide emissions, *EFexh,SO2* (g SO2 kg fuel-1), are directly related to fuel sulfur (Faloona, 2009; Lack and Corbett, 2012) and were calculated using:

(S7)

where *fS*is the fuel sulfur fraction (g S kg fuel-1), 2 is the ratio of molecular weights of SO2 to S, and *fSO2*is the fraction of fuel sulfur emitted as SO2 (97.8%) (ICF International, 2009).

# S8. Organic carbon exhaust emissions

The emission factor for OC, *EFOC* (g OC kg fuel-1), was calculated using:

(S8)

where *EFexh,BC*is the exhaust emissions of black carbon, *POM* is 120% of the OC, the ratio of *POM* to *BC* is 1.4 (Petzold et al., 2011; Fuglestvedt et al., 2010) and *r* is the engine type (MSD or HSD).

# S9. Total fuel-cycle climate forcing emissions over time

We used the following formula to estimate the total fuel-cycle climate forcing emissions over time, *CFtot,ts* (g CO2e l fuel-1):

(S9)

where *s* is the weighted mean of the fuel quality of marine fuels (distillates or HFO).

# S10. Climate forcing of tuna protein

We estimated the climate forcing of tuna protein, *CFt, prot* (kg CO2e kg tuna protein-1):

(S10)

where *fchar* is the fuel and engine type characteristics of each fleet, *fyield* is the retail yield of landed tuna, and *fprot* is the fraction of the retail yield that is protein. The subscript k applies to the scenario where we disaggregate the effort and catch between the high seas and the EEZ. In the case in which we do not disaggregate the effort and catch between the EEZ and high seas, the k is omitted.

# S11. 20-y time horizon climate forcing of farmed protein sources

We estimated the climate forcing of farmed protein sources on a 20-y time horizon, *CFf,prot* (kg CO2e kg protein-1):

(S11)

where *GHGprot,100-y* is the greenhouse gas emissions for a given protein source on a 100-y time horizon, *ff,alloc*is the fraction of GHGs allocated to a particular farm activity, *fGHG,alloc*is the allocation of a farm activity to a GHG emission, *GWP20-y* is the global warming potential of a gas constituent on a 20-y time horizon, and *GWP100-y* is the global warming potential of a gas constituent on a 100-y time horizon, *t* is the farmed protein source (beef, pork, chicken, farmed salmon, farmed prawns, tofu, and legumes), *u* is the farm activity (for beef, pork, and chicken n=5; for aquaculture n=9; for legumes and tofu n=2), and *v* is the GHG constituent (CO2, CH4, and N2O).

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Figures (S1-S2)



# **Figure S1: Mean climate forcing for the total fuel-cycle over time by engine type and fishing territory.**

Mean values represent the weighted average of the fuel quality of marine fuels including distillates and heavy fuel oil (HFO). The fishing territories include the U.S. exclusive economic zone (EEZ) and outside the U.S. EEZ. Left panel (A,C,E,G): Medium Speed Diesel engines. Right panel (B,D,F,H): High-Speed Diesel engines. First and third rows (A,B,E,F): Distillate fuels. Second and fourth rows (C,D,G,H): HFO fuels. First and second rows (A,B,C,D): 20-y time horizon. Third and fourth rows (E,F,G,H): 100-y time horizon. The shaded regions represent the 95% confidence interval.



# **Figure S2: Marine mammal bycatch ratio of the Hawaii deep-set longline fleet partitioned by territory.**

The bycatch ratio is the number of marine mammals (individuals) caught relative to the total catch including non-target species (in tonnes). The territory is partitioned between catch in the U.S. EEZ (dark red) and catch outside the U.S. EEZ (dark blue).

Tables (S1-S16)

# **Table S1:** **Fuel quality data and engine speed of selected commercial tuna gear types a**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Gear | f Distillates | n Distillate Vessels b | f HFO | n HFO Vessels c | f MSD | n MSD Vessels d | f HSD | n HSD Vessels e |
| Purse seine | 0.71 | 12 | 0.29 | 5 | 1 | 14 | 0 | 0 |
| Troll/Surface methods f | 1 g | 9 | 0 | 0 | 0.5 | 1 | 0.5 | 1 |
| Longline | 1 g | 9 | 0 | 0 | 0 | 0 | 1 | 1 |

a Source of engine revolutions per minute (RPM) and fuel quality: IHS Sea-web database.

b Fuel type assumed to be distillate if 4-stroke engine.

c Fuel type assumed to be heavy fuel oil (HFO) if 2-stroke engine.

d Medium-speed diesel (MSD) if RPM 300 ≥ and < 1400.

e High-speed diesel (HSD) if RPM ≥ 1400.

f Surface methods (SF) include troll and pole-and-line fishing gear.

g Due to limited data, we assume all vessels in this fleet use distillates.

# **Table S2: Main engine power of selected U.S. commercial tuna fleets**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Fleet region | Flag | Fleet gear | Target Tuna Species | Mean engine power (kW) a | Vessels  (n) | Source |
| North Pacific | U.S. | Surface methods b | Albacore | 303 (± 33) | 48 | (AAFA, 2017) |
| WCPFC-CA c | U.S. | Purse Seine | Skipjack | 2721 (± 159) | 35 d | (WCPFC, 2017) |
| Hawaii | U.S. | Troll | Yellowfin | 322 (± 95) | 8 e | (WCPFC, 2017) |
| Hawaii | U.S. | Longline | Big Eye | 363 (± 20) | 131 f | (WCPFC, 2017) |
| American Samoa | U.S. | Troll | Skipjack | 376 (± 47) | 31 g | (WCPFC, 2017) |
| American Samoa | U.S. | Longline | Albacore | 332 (± 52) | 10 h | (WCPFC, 2017) |

a Mean (95% confidence intervals)

b Surface methods include troll and pole-and-line fishing gear.

c Western Central Pacific Fisheries Commission convention area (WCPFC-CA).

d Filtered by flag: “United States of America” and fishing methods: “With purse lines (purse seine)”.

e Filtered by flag: “United States”, fishing methods: “Trolling lines”, and registered port: “Honolulu”.

f Filtered by flag: “United States”, fishing methods: “Drifting longlines”, and registered ports: “Honolulu and Hilo”.

g Filtered by flag: “United States”, fishing methods: “Trolling lines”.

h Filtered by flag: “United States”, fishing methods: “Drifting longlines”, and registered ports: “Pago Pago and Utulei”.

# **Table S3:****Main engine load factors categorized by fleet region and gear type a**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fleet region | Fleet gear | Target Tuna Species | Mean Load Factor | n Vessels |
| North Pacific | Surface methods b | Albacore | 0.59 (± 0.06) | 13 |
| WCPFC-CA c | Purse Seine | Skipjack | 0.64 (± 0.04) | 35 |
| Hawaii | Troll | Yellowfin | 0.54 (± 0.14) | 5 |
| Hawaii | Longline | Big Eye | 0.60 (± 0.03) | 95 |
| American Samoa | Troll | Skipjack | 0.60 (± 0.05) | 26 |
| American Samoa | Longline | Albacore | 0.60 (± 0.08) | 10 |

a Vessel design speeds and main engine speeds from Marine Traffic.com

b Troll and pole-and-line fishing gear.

c Western Central Pacific Fisheries Commission convention area.

# **Table S4. Aggregated annual fishing effort (hours) by fleet region and gear type**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Year | U.S. purse seine a,b,c | Hawaii troll a,d,e,f | Hawaii longline g,h,i,j,k,l | American Samoa  longline m | | American Samoa  troll n | North Pacific Surface methods a,o,p | | |
| 1996 | 168828 | 186639 | 151537 | 6366 | 4442 | | | 165804 |
| 1997 | 178759 | 185253 | 171574 | 18334 | 3144 | | | 191136 |
| 1998 | 155586 | 175682 | 175028 | 16112 | 1405 | | | 142824 |
| 1999 | 122483 | 189955 | 178713 | 27420 | 1981 | | | 248304 |
| 2000 | 119172 | 166063 | 187464 | 36973 | 1149 | | | 167040 |
| 2001 | 125793 | 162927 | 227306 | 81291 | 1655 | | | 178980 |
| 2002 | 139034 | 154461 | 267609 | 127023 | 1362 | | | 142752 |
| 2003 | 112552 | 167449 | 279815 | 118408 | 1044 | | | 161280 |
| 2004 | 102621 | 179867 | 306760 | 94076 | 1204 | | | 149712 |
| 2005 | 76138 | 173211 | 321499 | 86331 | 862 | | | 134076 |
| 2006 | 59586 | 168670 | 308832 | 104334 | 884 | | | 132264 |
| 2007 | 66207 | 175010 | 318044 | 123288 | 723 | | | 132972 |
| 2008 | 172138 | 174078 | 306990 | 99178 | 808 | | | 111660 |
| 2009 | 201931 | 175240 | 282118 | 103897 | 424 | | | 155796 |
| 2010 | 192000 | 175818 | 271293 | 95633 | 308 | | | 154140 |
| 2011 | 188690 | 177398 | 286954 | 81143 | 711 | | | 176124 |
| 2012 | 208552 | 188187 | 300542 | 89011 | 389 | | | 180324 |
| 2013 | 198621 | 168335 | 305838 | 72096 | 673 | | | 155076 |
| 2014 | 205241 | 169892 | 299851 | 55847 | 1063 | | | 145656 |
| 2015 | 175448 | 154839 | 318966 | 56048 | 1144 | | | 140808 |

a Aggregated annual effort (hours) estimated as the product of aggregated annual effort (days) and estimated daily vessel operating time (hours).

b Estimated daily vessel operating time (hours): 24 (Langley, 2011).

c Aggregated annual effort (days) (Williams and Terawasi, 2016).

d Aggregated annual effort (days): Years 1996-2003, Western Pacific Regional Fisheries Management Council (WPRFMC) 2010 Annual Report (cf. Fig. 122) (WPRFMC, 2012); Year 2004, WPFMC 2013 Annual Report (cf. Fig. 114) (WPRFMC, 2015); Years 2005-2015, WPFMC Stock Assessment and Fishery Evaluation (SAFE) Report (cf. Table A-101) (WPRFMC, 2017).

e Daily effort (hours) estimated as quotient of Main Hawaiian Islands (MHI) catch per unit effort (CPUE) in pounds of yellowfin tuna per day fished and MHI CPUE in pounds of yellowfin tuna per hour fished; effort hours assumed to be equivalent to vessel operating hours.

f MHI troll CPUE: Year 2003, WPRFMC 2010 Annual Report (cf. Fig. 127) (WPRFMC, 2012); Year 2004, WPFMC 2013 Annual Report (cf. Fig. 116) (WPRFMC, 2015); Years 2005-2015, WPRFMC Stock Assessment and Fishery Evaluation Report (SAFE) 2015 report (cf. Table A-103) (WPRFMC, 2017); because the CPUE in pounds of yellowfin tuna per hour fished is only available for the years 2003-2015, the CPUEs for 2003 were used for the years 1996-2002.

g Aggregated annual effort (hours) estimated as product of aggregated annual trips, estimated days trip-1, and estimated daily vessel operating hours.

h Aggregated annual trips: Years 1996-2005, WPRFMC 2005 Annual Report (cf. Fig. 24) (WPRFMC, 2006); Years 2006-2015, WPRFMC SAFE 2015 report (cf. Table A-89) (WPRFMC, 2017).

i Days per trip: Years 1996-2005, WPRFMC 2005 Annual Report 2005 report (cf. Table 4) (WPRFMC, 2006).

j Days per trip between 2006-2015 were estimated as quotient of aggregated annual sets and aggregated annual trips.

k Aggregated annual sets: Years 2006-2015, WPRFMC SAFE 2015 report (cf. Table A-89) (WPRFMC, 2017).

l Estimated daily vessel operating time assumed to equal "soak time" from observer data, reported to average 21 hours (Bayless et al., 2017).

m Aggregated annual effort (hours): NOAA PIFSC database (no longer public).

n Aggregated annual effort (hours): WPRFMC 2013 Annual Report (logbook hours, cf. Table 22) (WPRFMC, 2015). Data for 2014-2015 from the NOAA PIFSC database (no longer public); effort hours assumed to be equivalent to vessel operating hours.

o Aggregated annual effort (days): Pacific Fishery Management Council (PFMC, 2017b).

p Estimated daily vessel operating time (hours): 12 (Kendrick and Bentley, 2010).

# **Table S5: Aggregated annual fishing effort (hours) in the U.S. exclusive economic zone of two fishing fleets**

|  |  |  |
| --- | --- | --- |
| Year | Hawaii longline,a,b,c,d,e | North Pacific surface methods e,f,g,h |
| 1996 |  | 43056 |
| 1997 |  | 61080 |
| 1998 |  | 36816 |
| 1999 |  | 153996 |
| 2000 |  | 107400 |
| 2001 |  | 112260 |
| 2002 |  | 100128 |
| 2003 |  | 132540 |
| 2004 |  | 135504 |
| 2005 |  | 123108 |
| 2006 |  | 119748 |
| 2007 | 150742 | 130176 |
| 2008 | 152395 | 99288 |
| 2009 | 122897 | 147168 |
| 2010 | 84598 | 130608 |
| 2011 | 124695 | 164832 |
| 2012 | 134225 | 175764 |
| 2013 | 117201 | 149652 |
| 2014 | 93276 | 144540 |
| 2015 | 118876 | 138876 |

a Aggregated annual effort (hours) estimated as product of aggregated annual trips, estimated days trip-1, and estimated daily vessel operating hours.

b Number of trips: product of number of trips in EEZ of main and remote Hawaiian Islands and ratio of number of deep-set (or tuna) trips to number of all trip types (deep-set or tuna trips and shallow-set or swordfish trips).

c Days per trip estimated as quotient of number of sets and number of trips in EEZ of main and remote Hawaiian Islands.

d Number of trips and number of sets in EEZ of main and remote Hawaiian Islands (NOAA Fisheries, 2019b).

e Estimated daily vessel operating time assumed to equal "soak time" from observer data, reported to average 21 hours (Bayless et al., 2017).

f Aggregated annual effort (hours) estimated as the product of aggregated annual effort (days) and estimated daily vessel operating time (hours).

g Surface methods includes troll and pole-and-line.

hAggregated annual effort (days): Pacific Fishery Management Council (PFMC, 2017b).

i Estimated daily vessel operating time (hours): 12 (Kendrick and Bentley, 2010).

# **Table S6: Aggregated annual fishing effort (hours) of two fishing fleets on the high seas.**

|  |  |  |
| --- | --- | --- |
| Year | Hawaii longline a,b,c,d,e | North Pacific surface methods f,g,h,i |
| 1996 |  | 122748 |
| 1997 |  | 130056 |
| 1998 |  | 106008 |
| 1999 |  | 94308 |
| 2000 |  | 59640 |
| 2001 |  | 66720 |
| 2002 |  | 42624 |
| 2003 |  | 28740 |
| 2004 |  | 14208 |
| 2005 |  | 10968 |
| 2006 |  | 12516 |
| 2007 | 223247 | 2796 |
| 2008 | 223106 | 12372 |
| 2009 | 228832 | 8628 |
| 2010 | 252872 | 23532 |
| 2011 | 235521 | 11292 |
| 2012 | 245224 | 4560 |
| 2013 | 277011 | 5424 |
| 2014 | 280041 | 1116 |
| 2015 | 268973 | 1932 |

a Aggregated annual effort (hours) estimated as product of aggregated annual trips, estimated days trip-1, and estimated daily vessel operating hours.

b Number of trips estimated as product of number of trips outside EEZ of main and remote Hawaiian Islands and ratio of number of deep-set (or tuna) trips to number of all trip types (deep-set or tuna trips and shallow-set or swordfish trips).

c Days trip-1 estimated as quotient of number of sets and number of trips outside the EEZ of main and remote Hawaiian Islands.

d Number of trips and number of sets outside EEZ of main and remote Hawaiian Islands (NOAA Fisheries, 2019b).

e Estimated daily vessel operating time assumed to equal "soak time" from observer data, reported to average 21 hours (Bayless et al., 2017).

f Aggregated annual effort (hours) estimated as the product of aggregated annual effort (days) and estimated daily vessel operating time (hours).

g Surface methods includes troll and pole-and-line.

h Aggregated annual effort (days): Pacific Fishery Management Council (PFMC, 2017b).

i Aggregated annualeffort (days) was multiplied by 12 hours

# **Table S7: Mean density of marine fuels including distillates and heavy fuel oil a**

|  |  |  |
| --- | --- | --- |
| Year | Mean distillate density (g l fuel -1) | Mean heavy fuel oil density (g l fuel -1) |
| 1996 | 882 (± 15) | 989 (± 18) |
| 1997 | 882 (± 15) | 989 (± 18) |
| 1998 | 882 (± 15) | 989 (± 18) |
| 1999 | 882 (± 15) | 989 (± 18) |
| 2000 | 882 (± 15) | 989 (± 18) |
| 2001 | 882 (± 15) | 989 (± 18) |
| 2002 | 882 (± 15) | 989 (± 18) |
| 2003 | 882 (± 15) | 989 (± 18) |
| 2004 | 882 (± 15) | 989 (± 18) |
| 2005 | 882 (± 15) | 989 (± 18) |
| 2006 | 882 (± 15) | 988 (± 18) |
| 2007 | 840 (± 12) | 986 (± 19) |
| 2008 | 840 (± 12) | 988 (± 18) |
| 2009 | 840 (± 12) | 988 (± 18) |
| 2010 | 839 (± 12) | 988 (± 18) |
| 2011 | 839 (± 12) | 988 (± 18) |
| 2012 | 839 (± 12) | 987 (± 19) |
| 2013 | 840 (± 13) | 986 (± 19) |
| 2014 | 840 (± 14) | 980 (± 19) |
| 2015 | 840 (± 13) | 980 (± 19) |

a Mean values (95% confidence intervals) from PRELIM simulations (Abella and Bergerson, 2012).

# **Table S8: Mean refinery GHG emissions, lower heating values, and densities of marine fuels with varying fuel sulfur levels a**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fs% | GHGs (g CO2e MJ crude-1) | Crude feed input b (MJ crude MJ fuel-1) | LHV (MJ kg fuel-1) | Density (g l fuel-1) |
| *Ultra-low sulfur diesel* | |  |  |  |
| 0.0015 | 9.99 [9.24, 10.72] | 0.99 | 41.0 (± 0.0) | 825.0 (± 0.7) |
| *Marine gas oil* | |  |  |  |
| 0.05 | 8.63 [7.50, 9.77] | 1.02 | 41.3 (± 0.1) | 839.6 (± 7.3) |
| 0.1 | 7.58 [6.47, 8.70] | 1.02 | 41.0 (± 0.1) | 839.7 (± 7.0) |
| 0.35 | 6.36 [5.33, 7.39] | 1.02 | 41.1 (± 0.1) | 839.7 (± 6.1) |
| 1 | 5.99 [4.28, 7.68] | 1.02 | 41.1 (± 0.0) | 834.5 (± 3.3) |
| *Marine diesel oil* | |  |  |  |  |
| 0.55 | 4.23 [3.52, 4.92] | 1.03 | 41.1 (± 0.1) | 883.6 (± 8.4) |
| 0.75 | 3.94 [3.28, 4.58] | 1.03 | 40.5 (± 0.1) | 883.3 (± 8.9) |
| 1.5 | 3.11 [2.49, 3.70] | 1.04 | 40.0 (± 0.2) | 914.3 (± 10.5) |
| *Heavy fuel oil* | |  |  |  |  |
| 0.5 | 1.36 [0.92, 1.72] | 1.05 | 39.7 (± 0.2) | 938.8 (± 11.1) |
| 2.6 | 0.99 [0.86, 1.11] | 1.05 | 39.1 (± 0.1) | 984.5 (± 9.5) |
| 3.5 | 0.95 [0.81, 1.08] | 1.05 | 38.8 (± 0.1) | 998.0 (± 8.4) |

a Mean (95% confidence intervals) from bootstrap analysis (Orloff and Bloom, 2014).

b Crude feed input values were obtained from PRELIM (Abella and Bergerson, 2012).

# **Table S9: Global warming potentials used in the crude oil extraction, crude oil refinery, and farmed protein climate forcing analysis**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| GWP a | CO2 b | CH4 c | | N2O d | NOx c,d,e,f | SO2 c,e,g | OC c,e,h | BC c,e,i |
| 20-y | 1 | 86 | 268 | | -19 [-39, 0.5] | -183 [-287,-35] | -187 [-213, -133] | 1,936 [1,540, 2,391] |
| 100-y | 1 | 34 | | 298 | -7.8 [-12, -3.4] | -50 [-81, -8.3] | -54 [-61, -38] | 545 [435, 665] |

a Global warming potential (GWP) in (g CO2e g pollutant-1).

b Values include carbon-climate feedback taken from (Myhre et al., 2013)

c Mean values [95%confidence intervals] from bootstrap analysis (Orloff and Bloom, 2014).

d Given as NO2.

e Direct effects (aerosol-radiation interaction)

f Mean global values (n=4) from (Shindell et al., 2009); (Fuglestvedt et al., 2010), four regions (Collins et al., 2013), and (Aamaas et al., 2015)

g Mean global values (n=3) from (Shindell et al., 2009; Fuglestvedt et al., 2010; Aamaas et al., 2015).

h Mean global values (n=3) from (Bond et al., 2011), four regions (Collins et al., 2013), and (Fuglestvedt et al., 2010).

i Mean global values (n=5) from (Fuglestvedt et al., 2010; Bond et al., 2011; Bond et al., 2013), four regions (Collins et al., 2013), average summer and winter; aerosol-radiation interaction and semi-direct effects (Aamaas et al., 2015).

# **Table S10: Mean results for crude oil extraction GHG emissions**

|  |  |
| --- | --- |
| Fs% | GHGs a (g CO2e MJ crude-1) |
| *Ultra-low sulfur diesel* | |
| 0.0015 | 12.0 [9.8, 14.1] |
| *Marine gas oil* | |
| 0.05 | 12.8 [10.7, 14.7] |
| 0.1 | 12.5 [10.6, 14.2] |
| 0.35 | 12.2 [10.6, 13.7] |
| 1 | 10.3 [8.6, 11.9] |
| *Marine diesel oil* | |
| 0.55 | 12.4 [9.1, 15.4] |
| 0.75 | 12.1 [11.0, 13.3] |
| 1.5 | 11.4 [10.3. 12.5] |
| *Heavy fuel oil* | |
| 0.5 | 13.1 [10.5, 15.6] |
| 2.6 | 10.2 [8.8, 11.5] |
| 3.5 | 10.8 [9.2, 12.4] |

a Mean (95%confidence intervals) from bootstrap analysis (Orloff and Bloom, 2014).

# **Table S11: Exhaust emission factors for well-mixed GHGs and nitrogen oxides by fuel type a**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fuel type | Emission factor pollutants (g kg fuel-1) | | | |
| CO2 | CH4 | N2O | NOx |
| Heavy fuel oil | 3,183 | 0.03 | 0.16 | 52 |
| Marinediesel oil | 3,183 | 0.02 | 0.15 | 52 |
| Marine gas oil | 3,183 | 0.02 | 0.15 | 52 |

a Source: (ICF International, 2009)*.*

# **Table S12: Global warming potentials used in the vessel exhaust climate forcing analysis**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| GWP a | CO2 b | CH4 c | N2O d | NOx c,d,e,f | SO2 c,e,g | OC c,e,h | BC c,e,i |
| 20-y | 1 | 86 | 268 | -20 [-28,-12] | -95 [-135,-55] | -187 [-213, -133] | 1,936 [1,540, 2,391] |
| 100-y | 1 | 34 | 298 | -13 [-17, -6.2] | 27 [-39, -16] | -54 [-61, -38] | 545 [435, 665] |

a Global warming potential (GWP; g CO2e g pollutant-1)

b Values include carbon-climate feedback (Myhre et al., 2013).

c Mean values [95%confidence intervals] from bootstrap analysis (Orloff and Bloom, 2014).

d Given as NO2.

e Direct effects (aerosol-radiation interaction).

f Mean shipping values (n=4) from (Endresen et al., 2003) as given in (Fuglestvedt et al., 2010), (Eyring et al., 2007) as given in (Fuglestvedt et al., 2010), (Fuglestvedt et al., 2008) as given in (Fuglestvedt et al., 2010), and four regions (Collins et al., 2013).

g Mean shipping values (n=4) taken from (Endresen et al., 2003) as given in (Fuglestvedt et al., 2010), (Eyring et al., 2007) as given in (Fuglestvedt et al., 2010), and (Lauer et al., 2007) as given in (Fuglestvedt et al., 2010), (Fuglestvedt et al., 2008) as given in (Fuglestvedt et al., 2010).

h Mean global values (n=3) from (Bond et al., 2011), four regions (Collins et al., 2013), and (Fuglestvedt et al., 2010).i Mean global values (n=5) from (Fuglestvedt et al., 2010; Bond et al., 2011; Bond et al., 2013), four regions (Collins et al., 2013), average summer and winter; aerosol-radiation interaction and semi-direct effects (Aamaas et al., 2015).

# **Table S13: Mean GHG emissions of selected farmed protein sources on a 100-y time horizon**

|  |  |
| --- | --- |
| Protein Source | GHGs a |
|  | (kg CO2e kg protein-1) |
| Legumes b | 3.1 [2.5, 3.7] |
| Tofu c | 3.6 [1.8, 5.5] |
| Farmed salmon d,i | 19.2 [15.6, 22.6] |
| Chicken e,i | 20.5 [18.8, 22.2] |
| Pork f,i | 29.1 [27.7, 30.6] |
| Farmed shrimp g,i | 42.3 [34.5, 50.1] |
| Beef h,i | 144 [134, 153] |

a Mean (95% confidence intervals) from bootstrap analysis (Orloff and Bloom, 2014).

b Mean values (n=57; (Clune et al., 2017)) include variety of legume types and farming practices (organic, conventional, irrigated, non-irrigated, etc.). Normalized to a unit protein using a mean value of 0.25, based on protein contents of chickpeas (0.24), lentils (0.26), cowpeas (0.25) and green peas (0.25) on a dry basis (Iqbal et al., 2006).

c Mean values (n=5) from: (n=2) (Smetana et al., 2015), (n=1) (Blonk et al., 2008), and (n=2) (Head et al., 2011). Means include a variety of farming practices and life cycle boundaries (consequential and attributional). We used mean protein content of tofu on a dry basis for four varieties and two locations, 0.52 (Min et al., 2005).

d Mean values (n=20) from: (n=19) (Clune et al., 2017), (n=1) (Ziegler et al., 2013). Mean values include a variety of aquaculture practices and feed compositions. To our knowledge, all studies included are attributional. For the studies that were not normalized to bone free meat (Ziegler et al., 2013; McGrath et al., 2015; Liu et al., 2016), we divided live weight by the ratio of carcass weight to live weight, 0.4, and the ratio of retail weight to carcass weight, 1, as given in (Nijdam et al., 2012).

e Mean values (n=97) from: (n=95) (Clune et al., 2017), (n=1) (McCarthy et al., 2015), and (n=1) (Katajajuuri et al., 2008). Mean values include a variety of animal husbandry methods (intensive, free-range, etc.). For the studies that were not normalized to bone free meat (McCarthy et al., 2015; Katajajuuri et al., 2008), we divided the live weight by the ratio of carcass weight to live weight, 0.7, and the ratio of retail weight to carcass weight, 0.8, as given in (Nijdam et al., 2012).

f Mean values (n=129; Clune et al., 2017) include a variety of animal husbandry methods (conventional, organic, and different methods for manure handling) with different system boundaries (consequential and attributional).

g Mean values (n=13) from: (n=3) (Sun, 2009; Blonk et al., 2008) as given in (Clune et al., 2017), (n=1) (Teah et al., 2015), (n=2) (Cao et al., 2011), (n=1) (Mungkung, 2005) as given in (Cao et al., 2011), (n=4) (Santos et al., 2015), (n=1) (Farmery et al., 2015), and (n=1) (Baruthio and et al., 2008) as given by (Farmery et al., 2015). Mean values from (Jonell and Henriksson, 2015) were excluded because the emissions from this study were between 3 times to more than an order of magnitude larger than the other studies considered in our analysis. Mean values include a variety of aquaculture practices and feed compositions. Mean values were normalized to the retail yield by dividing the live-weight by the retail yield, 0.63, as given in (Tidwell et al., 2011).

h Mean values (n=165; Clune et al., 2017) include a wide variety of animal husbandry methods (culled dairy cattle, rangeland beef, etc.) with different system boundaries (consequential and attributional).

i Normalized to unit protein by dividing GHG emissions per retail yield by ratio of protein to retail yield, 0.20 (Nijdam et al., 2012).

# **Table S14: Fractional allocation of greenhouse gas emissions by farm activity for farmed protein sources.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Activity | Chicken a | Pork a | Beef a | Salmon b | Prawns c | Legumes d | Tofu d |
| Crop agriculture | 0.44 | 0.38 | 0.04 | 0.29 | 0.18 | 0.6 | 0.37 |
| Crop processing and transport | 0.1 | 0.23 | 0.01 | 0.16 | 0.01 | 0.4 | 0.63 |
| Enteric fermentation |  | 0.04 | 0.6 |  |  |  |  |
| Manure management | 0.29 | 0.24 | 0.3 |  |  |  |  |
| On-farm fossil fuel | 0.18 | 0.1 | 0.06 | 0.04 | 0.26 |  |  |
| Fishery production |  |  |  | 0.11 | 0.27 |  |  |
| Fishery processing and transport |  |  |  | 0.23 | 0.02 |  |  |
| Livestock production (poultry) |  |  |  | 0.09 |  |  |  |
| Livestock processing and transport |  |  |  | 0.01 |  |  |  |
| Feed milling |  |  |  | 0.05 | 0.05 |  |  |
| Smolts/fingerlings/larvae production and transport |  |  |  | 0.02 | 0.04 |  |  |
| “Other” |  |  |  |  | 0.17 |  |  |

a Source: (Steinfeld, 2006).

b Farm activity fractions from (Pelletier and Tyedmers, 2007; Pelletier et al., 2009).

c Farm activity fractions from (Cao et al., 2011).

d Source: (Blonk et al., 2008)*.*

# **Table S15: Fractional allocation of farm activities to individual GHGs for livestock and crop-based proteins a**

|  |  |  |  |
| --- | --- | --- | --- |
| Source | CO2 | CH4 | N2O |
| Crop agriculture | 0.20 | 0 | 0.80 |
| Crop processing and crop transport | 1 | 0 | 0 |
| Enteric fermentation | 0 | 1 | 0 |
| Manure management | 0 | 0.47 | 0.53 |
| "Other" | 1 | 0 | 0 |
| On-farm fossil fuel | 1 | 0 | 0 |

a Source: (Steinfeld, 2006)*.*

# **Table S16: Fractional allocation of aquaculture activities to individual GHGs for farmed fish a**

|  |  |  |  |
| --- | --- | --- | --- |
| Source | CO2 | CH4 | N2O |
| Crop agriculture | 0.20 | 0 | 0.80 |
| Crop processing and crop transportation | 1 | 0 | 0 |
| Poultry production | 0.37 | 0.13 | 0.49 |
| Poultry processing and transport | 1 | 0 | 0 |
| Fishery production | 1 | 0 | 0 |
| Fishery processing and transport | 1 | 0 | 0 |
| Feed milling | 1 | 0 | 0 |
| Smolts/fingerlings/larvae production and transport | 1 | 0 | 0 |
| On-farm fossil fuel | 1 | 0 | 0 |
| "Other" | 1 | 0 | 0 |

a Source: (Pelletier and Tyedmers, 2007; Pelletier et al., 2009)