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Emissions and climate forcing of seafood production

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Environmental Systems

by

Brandi L. McKuin

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2018

The Dissertation of Brandi L. McKuin is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Wiley et al. (2013) "Microalgae cultivation using Offshore Membrane Enclosures for Growing Algae (OMEGA)", Journal of Sustainable Bioenergy Systems, doi: 10.4236/jsbs.2013.31003
Trent et al. (2013) "Offshore Membrane Enclosures for Growing Algae (OMEGA): A Feasibility Study Wastewater to Biofuels", CEC
Report No.CEC-500-2013-143 available at: http://www.energy.ca.gov/2013publications/CEC-500-2013-143/CEC-500-2013-143.pdf
McKuin, B. and Campbell, J.E., (2016) "Emissions and climate forcing from global and Arctic fishing vessels", JGR: Atmospheres, doi:
10.1002/2015JD023747
McKuin, B., Stohs, S., and Campbell, J.E. (2018) "Synergies and trade-offs between sustainable seafood practices and climate change", *In Preparation*
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"Emissions and climate forcing from global and Arctic fishing vessels", American Geophysical Union Fall Meeting, San Francisco, December 13, 2016.
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"Sustainable tuna fishing is bad for climate—here's why", New Scientist, January 3, 2017, available at: https://www.newscientist.com/article/2116650-sustainable-tuna-fishing-is-bad-for-climate-heres-why/

ABSTRACT

Consumer demand for sustainably sourced seafood has given rise to eco-label initiatives such as the Marine Stewardship Council and consumer advocacy groups such as Monterey Bay Aquarium's Seafood Watch. The sustainability metrics of these groups include bycatch avoidance (with a particular emphasis on protected species) and stock abundance but have yet to include the climate impact of seafood production activities. The literature related to the sustainability of seafood generally reflects the emphasis of these eco-label initiatives with an abundance of studies related to stock assessment and eco-system effects of bycatch but comparatively few studies dedicated to the life-cycle assessment of seafood production activities. The dearth of seafood life-cycle assessments that have been conducted are narrowly focused on greenhouse gas emissions during fishing activities. Although greenhouse gas emissions of fishing activities is important, these studies have overlooked the climate implications of several policies (current and proposed) that may influence the sustainability of seafood. First, policy aimed at improving air quality by reducing the sulfur levels in marine fuels may impact the sustainability of seafood because fishing vessels are heavily reliant on diesel fuel and are known to be high emitters of short-lived climate forcing pollutants (including black carbon, sulfur oxides, and organic carbon). Furthermore, as seafood is a globally traded commodity that is typically shipped as freight on large container vessels, the importance of fuel quality in seafood life-cycle assessments may not be limited to the fishing phase of the seafood supply chain. Second, the consumer-driven policy of major retailers to only source seafood caught with highly selective fishing gears—in order to avoid the collateral damage of bycatch—may influence the sustainability of seafood because these gear types may require more fuel per fish caught compared with less selective gear types. Third, it has been argued that a proposed policy to ban

fishing the high seas would allow the high seas to serve as an ecological bank. However, this proposal could impact the sustainability of seafood because fishermen may use less fuel by fishing in coastal areas. Furthermore, restricting fishing activities to coastal areas would mean that fishermen would be subject to more stringent fuel sulfur laws in regions where emission control laws have been enacted. Despite the potential benefits of these policies—improved air quality, reduced bycatch, and improved stock abundance—the climate impact of these sustainable fishing practices is largely unknown. This dissertation seeks to study the climate impact of these practices so as to broaden the discourse surrounding sustainable fishing practices.

This work is divided in three research efforts. First, this research investigates the role of fishing vessels in the context of global shipping inventories. It develops a global inventory of fuel consumption and emissions of short-lived climate forcing pollutants of fishing vessels. A first-order global and Arctic estimate for the emissions and climate forcing of combined long-lived climate forcing (i.e. well mixed-greenhouse gases) and short-lived climate forcing emissions from fisheries using recently published plume-sampling data from an ensemble of ships is developed. Second, this research evaluates the climate impact of current and proposed policies (fuel quality policy to improve air quality, consumer-driven retailer policy to source seafood from highly selective fishing gears, and the proposed ban of fishing the high seas) in the context of U.S. tuna fisheries. A first-order climate forcing assessment of fishing activities of selected U.S. tuna fleets was conducted and the results were compared to land-based protein sources. Third, this research investigates the role of short-lived climate forcing pollutants upstream of the fishing phase of the seafood supply chain. A life-cycle assessment model was developed that includes fishing, processing, and the transport of two Alaskan pollock seafood products. Short-lived climate forcing pollutants were added to an existing model of battered-and-breaded white-fish fillets. Furthermore, a first-order assessment of a pollock surimi product, crab-flavored sticks (i.e. imitation crab), was compared to climate forcing associated with battered-and-breaded pollock fillets.

1. Emissions and climate forcing from global and Arctic fishing vessels

1.1. Chapter Summary

Fishing vessels were recently found to be the largest source of black carbon ship emissions in the Arctic, suggesting that the fishing sector should be a focus for future studies. Here a global and Arctic emissions inventory for fishing vessel emissions of short-lived and long-lived climate forcers based on vessel size, fuel sulfur content, engine type, and operational characteristics was developed. Previous work generally underestimated emissions of short-lived climate forcers due to a failure to account for small fishing vessels as well as variability in emission factors. In particular, black carbon emissions were underestimated by an order of magnitude. Furthermore, the order-of-magnitude estimate of the net climate effect from these fishing vessel emissions suggests that short-lived climate forcing may be particularly important in regions where fuel has a low sulfur content. These results have implications for proposed maritime policies and provide a foundation for future climate simulations to forecast climate change impacts in the Arctic.

1.2. Introduction

Atmospheric emissions from ships are a potentially critical source of regional climate forcing *[Aliabadi et al., 2015; Corbett et al., 2010a]*. While land-based emissions are generally larger than ship emissions, emissions from ships have a unique spatial distribution because they are injected into the atmosphere along vessel routes and at low vessel chimney heights. This spatial distribution of ship emissions is particularly important for short-lived climate forcers (SLCFs) that have climate forcing properties that are spatially explicit *[Winther et al., 2014; Coello et al., 2015]*.

SLCFs such as black carbon (BC), organic carbon (OC), and sulfur dioxide (SO_2), and nitrogen oxides (NOx = NO_2 +NO) have short atmospheric lifetimes and can cause both climate warming and cooling *[Myhre et al., 2013]*. BC has an atmospheric lifetime ranging from days to approximately 2 weeks. The BC climate effect results in warming and is recognized as the second most important emission after CO_2 in terms of anthropogenic climate forcing *[Bond et al., 2013]*. OC, NOx, and SO_2 are often co-emitted with BC and generally have an overall cooling effect *[Shindell and Faluvegi, 2009; Faloona, 2009; Eyring et al., 2010]*. NOx emissions from ships produce ozone (O_3) and hydroxyl radicals (OH), which reduce the lifetime of methane (CH_4). The net climate effect of ship NOx depends on the balance of warming (due to O_3) and cooling (due to CH_4) *[Holmes et al., 2014; Eyring et al., 2010; Myhre et al., 2011]*. As a consequence of the short atmospheric lifetimes of SLCFs, their climate impacts occur on relatively short time scales (less than 30 years), and their spatial distribution is heterogeneous *[Collins et al., 2013; Baker et al., 2015]*. Therefore, the resulting climate forcing from SLCFs is also inhomogeneous. The heterogeneous distribution of emissions makes diagnosing the regional and global climate impacts complex for SLCFs *[Baker et al., 2015; Shindell et al., 2009]*. When SLCFs are considered together with CO_2, management choices to mitigate climate change can be significantly different from considering CO_2 alone *[Unger et al., 2010; Peters et al., 2011]*.

Fishing vessels were recently discovered to be the largest source of ship SLCF emissions in the Arctic, suggesting that fishing studies are an important focus area for improved estimation *[Winther et al., 2014]*. The Arctic region may be of particular interest for understanding fishing emissions because the vessel emissions occur in more northerly places in comparison to land-based emissions. Ships operating in the Arctic may emit up to 50% more BC than in other regions due to highly variable engine loads depending on ice conditions and ice breaking requirements *[Lack and Corbett, 2012]*. A net warming from SLFCs may also be enhanced in the Arctic. For instance, there may be less cooling from SO_2 emissions in the Arctic because the indirect aerosol effect is reported to be weaker than the direct sulfate forcing due to less efficient cloud formation. Due to inactive photochemistry during the winter, the changes in OH concentrations due to NOx emissions from ships are small *[Ødemark et al., 2012]*. The effect of OH on CH_4 lifetime is further limited by continuous low temperatures in the Arctic *[Ødemark et al., 2012]*. Furthermore, the Arctic climate is particularly sensitive to BC both in the atmosphere and from deposition on snow and ice *[Quinn et al., 2008; Bond et al., 2013; Flanner, 2013]*. However, emission estimates for Arctic fishing vessels have relied on rough assumptions regarding BC emission factors which is an important area for future work *[Winther et al., 2014]*.

In addition to Arctic fishing emissions, there is also reason to suspect that global SLCF emissions from fishing vessels have been underestimated in previous inventories. Previous work has investigated the impact that fishing gears have on fuel consumption and emissions *[Tyedmers, 2001; Ziegler and Hansson, 2003]*. While many inventories of maritime emissions include only large vessels, estimates of emissions of small vessels suggest that fishing vessel CO_2 emissions are 2 to 7 times larger than reported in previous inventories *[Tyedmers et al., 2005]*. However, emissions estimates of small vessels have only focused on long-lived climate forcers (LLCFs), namely CO_2, methane (CH_4), and nitrous oxide (N_2O), whereas SLCFs have been overlooked.

While the global contribution of SLCF emissions from all maritime vessels has been studied extensively *[Corbett and Koehler, 2003; Endresen et al., 2007; Lack et al., 2008; Eyring et al., 2010; Dalsøren et al., 2009; Fuglestvedt et al., 2010]*, our study seeks to address four critical knowledge gaps that are specific to fishing vessels. First, global maritime SLCF emission studies focus on vessels larger than 100 gross tonnage (GT) which excludes an estimated 1.3 million fishing vessels *[Endresen et al., 2007]*. Second, previous work has used constant BC emission factors based on a limited data set from a single study of only two ships *[Sinha et al., 2003]* overlooking an expanded literature of measurements than includes a wide range of engine speeds, engine types, fuel qualities associated with regional fuel sulfur control laws, and the ship-to-ship variability of a diverse fleet *[Lack et al., 2008]*. For example, most fishing vessels operate medium speed diesel (MSD) engines with distillate fuels within nonroad equipment fuel quality standards *[Lack et al., 2009]* and are reported to emit twice as much BC as slow speed diesel (SSD) engines (used to operate transport ships) *[Lack et al., 2008; Wang and Minjares, 2013]*. Third, this study did not find any previous work that has estimated the climate forcing associated with fishery SLCF emissions. Thus, the net climate forcing from fisheries remains largely unknown.

In addition to regional and global inventories, an improved understanding of fishing vessel emissions is also of importance for advancing food sustainability. Demand for sustainably certified seafood is growing rapidly, as major global retailers have promised to source fish and crustaceans from sustainable sources *[Sampson et al., 2015]*. Fishing vessel emissions have recently emerged as one important sustainability criterion for seafood *[Parker et al., 2015; Smith et al., 2010; Thrane et al., 2009]*. These emission concerns have led to eco-label initiatives such as Seafood Watch that are working to inform consumers about greenhouse gas (GHG) impacts of the seafood industry *[Parker et al., 2015; Pelletier and Tyedmers, 2008]*.

Given the importance of fishing vessel emissions and the critical knowledge gaps related to fishing vessel size and emission factors, this study seeks to develop a revised global and Arctic emissions inventory. The hypothesis of this study is that previous global inventories of commercial shipping may be understated due to the lack of inclusion of smaller fishing vessels (<100 GT) and previously assumed emission factors that did not account for the more extensive measurements across a range of engine speeds, engine types, fuel quality and regional fuel sulfur control laws, and the ship-to-ship variability of a diverse fleet. This study provides a global and Arctic estimate for the emissions and climate forcing of combined LLCF and SLCF emissions from fisheries using recently published plume-sampling data from an ensemble of ships *[Lack et al., 2008; Cappa et al., 2014; Buffaloe et al., 2014]*. This analysis considers the impact of newly enacted regulations on emissions of fuel sulfur, engine type and operational characteristics of the fishing fleet. Further, a first estimate of the contribution of SLCFs to the climate forcing of seafood per unit protein was provided and this impact was compared to other non-seafood protein sources.

1.3. Methods

1.3.1. Fuel Consumption

The global fisheries fuel consumption was calculated using a catch-based approach. This approach is based on the global median fuel use intensity (FUI = 0.639 L of fuel used per kilogram of live weight fish landings) from the Fisheries Energy Use Database and global catch statistics *[Parker and Tyedmers, 2015]*. The global average annual landed catch (2000–2010) is 80 Tg *[FAO, 2015a]*. The average annual landed catch for countries that have emission control areas (ECAs) including North America and the European Union (2000–2010) is 14 Tg *[FAO, 2015b]*. The majority of global fish landings, approximately 88%, occur within exclusive economic zones (EEZs) *[Sumaila et al., 2015]*. Thus, it was estimated approximately 68 Tg of landings occur outside of ECAs and 12 Tg of landings occur inside the EEZs of ECAs. The weighted average of the fuel density is 0.86 kg l^{-1}. The global fisheries fuel consumption was calculated using the following formula:

$$FC = FUI \cdot \rho \cdot GC \qquad (1)$$

where *FC* is the fuel consumption (Tg fuel), *FUI* is the fuel use intensity (l fuel/kg live-weight fish landings), ρ is the fuel density (kg fuel/l fuel), and *GC* is the global average annual landed catch (Tg live-weight fish landings).

For the Arctic, the catch-based approach was not used because the fuel use intensity and catch data were not readily available. Instead, a recently published estimate of 2.0 Tg fuel yr^{-1} was used based on ship track data *[Winther et al., 2014]*.

1.3.2. Global Commercial Fishing Vessel Characterization

The emission estimates were based on the following vessel characteristics. The average engine power of commercial fishing vessels is 701 kW for the main engine and 55 kW for the auxiliary engine *[ICF International, 2009]*. The average size of decked fishing vessels is 20 GT (around 10-15 meters). Only a small fraction of vessels, 1% of the global fishing fleet, are larger than 100 GT (or longer than 24 m) (Food and Agriculture Organization of the United Nations, 2005, Fisheries and Aquaculture topics, Fishing vessels: http://www.fao.org/fishery/topic/1616/en). Globally, 88% of the installed main engines of commercial fishing vessels operate MSD, and 12% operate high speed diesel (HSD) engines *[Trozzi, 2010]*. Marine distillate oil (MDO, also called marine gas oil or MGO) is the most commonly used fuel for fishing boats and other MSD engines *[ICF Consulting, 1999]*. However, a small fraction of fishing boats use heavy fuel oil (HFO) *[Trozzi, 2010]*.

1.3.3. Fuel Specifications

The fuel specifications for this model are based on current policies related to emission controls. MARPOL 73/78 (short for marine pollution) is the principal international instrument covering prevention of pollution of the marine environment by ships. According to MARPOL Annex VI, Regulation 14, ships 400 GT or greater operating in designated emissions control areas (ECAs) are required to use on board fuel oil with a sulfur content of no more than 0.1% (all sulfur contents are by weight) effective January, 2015. The ECAs include the Baltic Sea area, North Sea area, North American area (covering designated coastal areas off of the United States and Canada), and United States Caribbean Sea area (including Puerto Rico and the United States Virgin Islands). Outside the ECAs the maximum fuel sulfur content is 3.5% but reduction to 0.5% in 2020 are under consideration. For ships less than 400 GT, state flag regulations apply. The average fishing vessel is likely to be in a weight class less than 400 GT and thus exempt from international sulfur and particulate matter (PM) control laws. Globally the maximum allowable fuel sulfur for state flag regulations is as low as 0.001% and as high as 1%. Based on the regulations described above, the following approach was used. Inside ECAs a fuel sulfur content of 0.051% (±0.050%) was used. Outside ECAs a weighted average of fuel sulfur contents for MGO, MDO, and HFO was used. The global commercial fishing fleet operates over 96% of installed engines with MGO or MDO, and the remaining 4% operate on HFO *[Trozzi, 2010]*. The average fuel sulfur contents of MGO, MDO and HFO are 0.38% (±0.21%), 0.65% (±0.37%), and 2.7% (±0.7%), respectively *[Notteboom et al., 2010; Lack et al., 2011]*. The resulting fuel sulfur content outside ECAs was 0.59% (±0.31%). MGO and HFO are reported to have fuel densities of 0.86 and 0.98 kg l^{-1}, respectively *[Energy and Environmental Analysis, Inc, 2000]*. A lower heating value of 42.8 and 39.5 MJ kg^{-1} for marine distillates (MGO and MDO) and HFO was used, respectively *[Wang, 2011]*.

1.3.4. Emission Factors

The BC emission factor was calculated using three approaches. First, an average of all available emission factor data for MSD and HSD engine types was used *[Lack et al., 2008; Petzold et al., 2010; Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014]*. Second, the emission factor was estimated based on a weighted average of engine and fuel types. Third, the emission factor was estimated by binning the data and a weighted average of the bins based on the frequency of fuel types, vessel types, and engine loads used in the fishing sector. Published emission factors from plume intercept and test-rig sampling studies were used (Table 1.1) *[Lack et al., 2008; Petzold et al., 2010; Petzold et al., 2011; Buffaloe et al., 2014]*. The emissions of BC are influenced by the fuel sulfur content, engine type, maintenance, and other operational characteristics such as engine load or engine speed *[ICF International, 2009; Lack et al., 2011; Cappa et al., 2014]*.

The BC emission factor for each fuel sulfur content weighted by engine speed and fuel type (second approach), EF^{Alt_BC} (g BC / kg fuel) was calculated with the following equation:

$$EF_l^{Alt\_BC} = \sum_{k=1}^{2} \sum_{j=1}^{2} f_{j,k,l}^{char} \cdot EF_{j,k,l}^{BC} \qquad (2)$$

where f^{Char} is the fraction of fishing vessels with engine type j (1= MSD, 2= HSD), fuel type k (k=1=MDO, k=2=HFO), and fuel sulfur content, Fs (% wt.), l (1=≤0.1 and 2=>0.1), EF^{BC} is the mean BC emission factor reported for each engine type, fuel type, and Fs(% wt.). The inputs for f^{Char} are given in Table A.4. The inputs for EF^{BC} are given in Table A.1.

The BC emission factor using binned data and a weighted average of the bins based on the frequency of fuel types, vessel types, and engine loads used in the fishing sector (third approach) was calculated using equations 3-5.

The available data was binned and weighted as a function of fuel sulfur content as follows:

$$EF_l^{BC} = \sum_{m=1}^{2} f_m^C \cdot EF_{l,m}^{BC} \qquad (3)$$

where $EF_{l,m}^{BC}$ (g BC/kg fuel) is the average emission factor for fuel sulfur content l, f^C is the global fraction of catch using gear m (trawl or gillnet) The BC emission data was sorted into bins (marine diesel engine type, fuel type, fuel sulfur content, and engine load percentage) and when possible used statistical software to generate probability distributions for each bin using Kolmogorov-Smirnov, Anderson-Darling, and Chi-squared statistics *[Mathwave Data Analysis and Simulation, 2015]*. The distribution from each bin was sampled 10,000 times with a Monte Carlo simulation to calculate the average and standard deviations of BC emissions for each bin. Fuel sulfur (F_s, units wt %) wass binned into two categories for low (0.05% ± 0.05%) and high

(0.59% ± 0.31%) content. The inputs for f_m^C are given in Table A.2. The inputs for $EF_{l,m}^{BC}$ are given in Table A.3.

The BC emission factor as a function of fuel sulfur and fishing gear, $EF_{l,m}^{BC}$ (g BC/kg fuel), was calculated as follows:

$$EF_{l,m}^{BC} = \sum_{j=1}^{2} \sum_{k=1}^{2} f_{j,k,l}^{Char} \cdot EF_{j,k,l,m}^{BC} \qquad (4)$$

where f^{Char} is the fraction of the global fishing fleet with the vessel characteristics engine type *j* (MSD or HSD) and fuel type *k* (MDO or HFO). To estimate the BC emissions as a function of engine load, the load profiles used for trawl and gillnet gear were assumed to be valid for the global fishing fleet *[Ziegler and Hansson, 2003]*. The engine load for a trawler is 90% for 20% of the time, 80% for 50% of the time and 30% for the remaining 30% of the time. The load on the engine of a gillnet vessel is 95% for 10% of the time, 80% for 30% of the time, and 20% for the remaining 60% of the time. The estimated fraction of the total catch that is caught using gillnet and trawling fishing gear is 38% and 62%, respectively. The inputs for $f_{j,k,l}^{Char}$ are given in Table A.4. The inputs for $EF_{j,k,l,m}^{BC}$ are given in Table A.5.

The BC emission factor as a function of engine type, fuel type, fuel sulfur level, and fishing gear, $EF_{j,k,l,m}^{BC}$ (g BC/kg fuel), was calculated using the following formula:

$$EF_{j,k,l,m}^{BC} = \sum_{i=1}^{5} f_{i,m}^{t} \cdot EF_{i,j,k,l}^{BC} \qquad (5)$$

where f^t is the fraction of time the ship is run at load i, and $EF^{BC}_{i,j,k,l}$ is the BC emission factor as a function of load i, engine type j, fuel type k, and fuel sulfur level l. The engine loads included five bins (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%). The inputs for $f^t_{i,m}$ are given in Table A.6. The inputs for $EF^{BC}_{i,j,k,l}$ are given in Table A.7.

The emission factor for OC (EF_{OC}, g OC / kg fuel) was calculated as a function of BC and the ratio of particulate organic matter (POM) and BC:

$$EF_{OC} = EF_{BC} \cdot \frac{POM}{1.2 \cdot BC} \qquad (6)$$

where the POM is 120% of the OC and the ratio of *POM* to *BC* is 1.4 *[Petzold et al., 2011; Fuglestvedt et al., 2010]*.

SO_2 emissions are directly related to fuel sulfur *[Lack and Corbett, 2012; Faloona, 2009]*. The SO_2 emission factors (EF_{SO2}, g SO_2 / kg fuel) were calculated as a function of the fuel sulfur content:

$$EF_{SO_2} = f_S \cdot 2 \cdot f_{SO_2} \qquad (7)$$

where f_S is the fuel sulfur fraction (g S / kg fuel), 2 is the ratio of molecular weights of SO_2 to S, and f_{SO2} is the fraction of fuel sulfur emitted as SO_2 (97.8%) *[ICF International, 2009]*. The emission factors of LLCFs were taken from a technical report on mobile source port–related emission inventories *[ICF International, 2009]*.

Table 1.1: *Black carbon emission factors from the literature as a function of engine type [a], fuel typeb, estimated engine speed, and fuel sulfur content.*

Engine Type[b]	Fuel Type[c]	Engine Speed (% of max)	N[d]	Fuel Sulfur (% wt)	Black Carbon ($g\ kg^{-1}$ fuel)	Reference
MSD	MGO/MDO	Idle	6	≤0.1	1.28 (± 0.66)	[Buffaloe et al., 2014]
MSD	MGO/MDO	Idle	1	0.4±0.6	1.06	[Lack et al., 2008]
HSD	MGO/MDO	Idle	3	≤0.1	1.42 (± 1.50)	[Buffaloe et al., 2014]
MSD	MGO/MDO	1-20%	10	≤0.1	1.06 (± 1.11)	[Buffaloe et al., 2014]
MSD	MGO/MDO	1-20%	2	0.4±0.6	1.5	[Lack et al., 2008]
HSD	MGO/MDO	1-20%	3	≤0.1	0.30 (± 0.19)	[Buffaloe et al., 2014]
HSD	MGO/MDO	1-20%	1	0.4±0.6	0.28	[Lack et al., 2008]
MSD	MGO/MDO	21-40%	3	≤0.1	2.05 (± 2.53)	[Buffaloe et al., 2014; Cappa et al., 2014]
MSD	MGO/MDO	21-40%	6	0.4±0.6	0.90 (± 0.67)	[Lack et al., 2008]
HSD	MGO/MDO	21-40%	3	≤0.1	0.55 (± 0.34)	[Buffaloe et al., 2014]
HSD	MGO/MDO	21-40%	1	0.4±0.6	0.19	[Lack et al., 2008]
MSD	MGO/MDO	41-60%	9	≤0.1	0.53 (± 0.60)	[Buffaloe et al., 2014; Cappa et al., 2014; Petzold et al., 2011]
MSD	MGO/MDO	41-60%	31	0.4±0.6	0.92 (± 0.65)	[Lack et al., 2008]
HSD	MGO/MDO	41-60%	8	≤0.1	0.39 (± 0.18)	[Lack et al., 2008]
HSD	MGO/MDO	41-60%	2	0.4±0.6	0.53	[Buffaloe et al., 2014]
MSD	HFO	41-60%	2	2.2	0.33	[Petzold et al., 2010; Petzold et al., 2011]
MSD	MGO/MDO	61-80%	5	≤0.1	0.87 (± 0.65)	[Buffaloe et al., 2014; Petzold et al., 2011]
MSD	MGO/MDO	61-80%	9	0.4±0.6	1.20 (± 0.75)	[Lack et al., 2008]
HSD	MGO/MDO	61-80%	5	≤0.1	0.53 (± 0.42)	[Buffaloe et al., 2014]
HSD	MGO/MDO	61-80%	2	0.4±0.6	0.58	[Lack et al., 2008]
MSD	HFO	61-80%	3	2.2	0.20 (± 0.13)	[Petzold et al., 2010; Petzold et al., 2011]
MSD	MGO/MDO	81-100%	13	≤0.1	0.68 (± 0.54)	[Buffaloe et al., 2014; Cappa et al., 2014; Petzold et al., 2011]
MSD	MGO/MDO	81-100%	1	0.4±0.6	0.06	[Lack et al., 2008]
HSD	MGO/MDO	81-100%	9	≤0.1	0.33 (± 0.21)	[Buffaloe et al., 2014]
HSD	MGO/MDO	81-100%	2	0.4±0.6	0.22	[Lack et al., 2008]
MSD	HFO	81-100%	5	2.2	0.05 (± 0.02)	[Petzold et al., 2010; Petzold et al., 2011]
MSD	MGO/MDO	>100%	2	≤0.1	1.64	[Buffaloe et al., 2014]
MSD	MGO/MDO	>100%	1	0.4±0.6	0.50	[Lack et al., 2008]
HSD	MGO/MDO	>100%	1	0.4±0.6	0.56	[Lack et al., 2008]
MSD	HFO	>100%	1	2.2	0.07	[Petzold et al., 2010]

[a]The uncertainty represents the standard deviations. Number weighted volume equivalent diameter particle size distribution for refractory black carbon (campaign average) 92 nm. Particle size distribution information not provided. Total aerosol particle size distribution 15, 40–60, and 25 nm for modal parameters 1, 2, and 3, respectively. Particle number size distribution 5 and 6, 27 and 25, and 120 and 55 nm for modal parameters 1, 2, and 3, respectively, measured at engine loads 10 and 100%, respectively. Number weighted volume equivalent diameter particle size distribution for refractory black carbon <60 and 100 nm for modal parameters 1 and 2, respectively.
[b]MSD: medium speed diesel, HSD: high speed diesel.
[c]MGO: marine gas oil, MDO: marine distillates oil, HFO: heavy fuel oil.
[d]Number of observations.

1.3.5. Global Warming Potential

While climate models are often used to quantify the climate forcing for an industrial sector, here a range of global warming potentials (GWPs) were used to provide a first approximation of climate forcing from the fishing industry. The GWPs for SLCFs have a large spread in model estimates and significant differences between observations and model results. The level of scientific confidence is low for GWPs that include aerosol-cloud interactions and land surface albedo effects for BC *[Myhre et al., 2013]*. Due to the large uncertainty, the climate forcing was separately reported for total effects (direct and indirect) and only direct effects *[Bond et al., 2013; Shindell et al., 2009; Bond et al., 2011]*. SLCFs with equivalent 100-year GWPs have different impacts on climate, temperature, rainfall, and the timing of these impacts. Because questions have been raised about the appropriateness of using the 100-year GWP metric to compare SLCFs and LLCFs, the 20-year GWPs were included to evaluate the short-term climate impacts *[Fuglestvedt et al., 2010; Boucher and Reddy, 2008]* (Table 1.2). As a special case, the GWPs of SLCFs for the Arctic were also considered *[Ødemark et al., 2012]*. Owing to the fact that the density of shipping traffic and the climate impacts of NOx emissions peak in the summer, we use a seasonal (summer) shipping sector GWP for the Northern Hemisphere for the Arctic calculations *[Aamaas et al., 2015; Ødemark et al., 2012]*.

Table 1.2: *Direct and indirect global warming potential (GWP)* ***[a]*.**

GWP	CO_2[b]	CH_4[b]	N_2O[b]	NOx[c,d]	SO_2[e]	OC[f]	BC[g]
Global 20-Year Time Horizon:							
Direct	1	85	265	-14 (-21, -8)	-78 (± 70)	-160 (-320, -60)	2,100 (420, 3,700)
Indirect	1	85	265		-190 (± 171)		1,100 (-150, 2,500)
Total (including indirect)	1	85	265	-14 (-21, -8)	-268 (± 241)	-160 (-320, -60)	3,200 (270, 6,200)
Global 100-Year Time Horizon:							
Direct	1	30	264	-6 (-10, -4)	-19 (± 20)	-46 (-92, -18)	590 (140, 1,100)
Indirect	1	30	264		-57 (± 49)		310 (-40, 600)
Total (including indirect)	1	30	264	-6 (-10, -4)	-76 (± 69)	-46 (-92, -18)	900 (100, 1,700)
Arctic 20-Year Time Horizon:							
Direct	1	85	264	24	-71	-151	2,037
Indirect	1	85	264		-205		764
Total (including indirect)	1	85	264	24	-276	-151	2,801
Arctic 100-Year Time Horizon:							
Direct	1	30	265	-0.7	-19 (± 20)	-43	579
Indirect	1	30	265		-57 (± 49)		217
Total (including indirect)	1	30	265	-0.7	-76 (± 69)	-43	796

[a] Uncertainties ranges or standard deviations are given where available. Units are g CO_2-e / g pollutant.
[b] [Myhre et al., 2013]
[c] Nitrogen oxides (NOx) calculated as NO_2
[d] Global values [Fuglestvedt et al., 2010]; Arctic values [Aamaas et al., 2015]
[e] Global values [Shindell et al., 2009]; Arctic values [Ødemark et al., 2012]
[f] Global values [Bond et al., 2011]; Arctic values [Ødemark et al., 2012]
[g] Global values [Bond et al., 2013]; Arctic values [Ødemark et al., 2012]

1.4. Results

1.4.1. Fuel Use

The catch-based estimate of global fishing fuel use of this study is 44 Tg yr^{-1} which is similar in magnitude to previous catch-based estimates *[Tyedmers et al., 2005]* Alternative approaches to estimating global fishing fuel use are considerably smaller. Bottom-up estimates (based on ship activity and engine power capacity data) and top-down estimates based on fuel consumption are approximately 16 and 6 Tg yr^{-1}, respectively *[Smith et al., 2014]*. Bottom-up estimates are thought to underestimate fishing fuel use because the engine data do not include ships smaller than 100 GT which excludes an estimated 1.3 million fishing vessels *[Endresen et al., 2007]*. The top-down consumption approach may be accurate for estimating global marine fuel use, but the top-down approach suffers from large uncertainties with respect to allocating fuel use to fishing ships as opposed to other types of ships *[Smith et al., 2014]*. The catch-based approach of this study suggests that fishing is responsible for 15% of global marine fuel use. The larger fraction for fishing vessels in this study as opposed to other studies is important for understanding fishing vessels emissions but may also impact the estimates of global climate forcing for all ships to the extent that emission factors and the spatial and temporal distribution of emissions are unique for fishing as opposed to other shipping sectors.

1.4.2. Emission Factors

The literature review of BC emission factors and the calculated fuel combustion emission factors for fishing vessels are presented in Tables 1 and 3, respectively. The first BC emission factor, averaging all data for MSD and HSD engines, is 0.79 ± 0.06 g/kg (mean ± standard error; $n = 146$

measurements). The second set of BC emission factors, weighted by engine and fuel types, is 0.92 and 0.86, for low ($F_s = 0.051\%$) and high ($F_s = 0.59\%$) fuel sulfur levels, respectively. The third set of BC emission factors, the binned approach, is somewhat larger than the first BC emission factor results (0.88 and 0.84 for ECAs and non-ECAs, respectively) because the emission factors were weighted by engine types and fishing engine loads. The BC emission factor estimates of this study are two or more times larger than previously assumed emission factors of 0.18 and 0.35 g/kg for global and Arctic inventories, respectively (Table 3). The previously assumed global estimate originates from a small data set ($n = 11$) that included two transport ships (SSDs) but not ships that are representative of the fishing sector *[Sinha et al., 2003]*. The previously assumed Arctic estimate originates from a larger data set but includes a large number of transport ships (SSD engines) that are not representative of the fishing industry *[Corbett et al., 2010b]*. However, fishing ships which are primarily MSD vessels operating with high fuel sulfur content have twice the emissions factors as SSD engines which are used in transport ships *[Lack et al., 2008; Lack et al., 2009]*. Thus, our BC estimates are higher because we account for a broader range of data and an ensemble of engine types and engine loads that are specific to fishing.

The uncertainty in the BC emissions reflects the different emissions observed between the study types (test rig versus plume sampling), between different plume sampling studies, and between different ships in the same plume-sampling study. In general, the BC emissions from the test-rig study were smaller than the emissions from plume-sampling studies. The difference between test rigs and plume sampling could be a result of different vessel and engine ages. The test rig was reported to be substantially newer at the time of the study than some of the vessels in the plume-sampling studies *[Cappa et al., 2014]*. When comparing the BC emissions of MSD engines, the emissions were lower in the ≤0.1% fuel sulfur category (ECAs) except at engine loads between 0–20% and 80–100%. When the BC emissions data was compiled using weightings for the typical engine loads used in fishing operations, similar emission factors for both low and high fuel sulfur contents were found. These results are consistent with a recent test-rig study that used high sulfur HFO, and low sulfur distillate fuels on the same engine and found BC emissions were unaffected by fuel type *[Mueller et al., 2015]*.

The emission factors and uncertainty for SO_2 were directly related to the fuel sulfur content. The sulfur in fuels used by fishing vessels is regionally dependent due to sulfur control laws in ECAs and non-ECAs. In ECAs the SO_2 emissions are lower than in non-ECAs by an order of magnitude.

Table 1.3: *Emissions Factors for Combustion of Marine Fuels Used in Commercial Fishing Vessels for This and Other Studies*[a]

F_S(wt %)	EF_{CO2}	EF_{CH4}	EF_{N2O}	EF_{NOx}[b]	EF_{SO2}	EF_{OC}	EF_{BC}	Reference
				Global, Emission Control Area (ECA)				
0.05 (±0.05)	3,183	0.02	0.15	52 (±13)	1 (±1)	1.5 (±1.1)	0.88 (±0.66)	*This study*
				Global, Non-ECA				
0.6 (±0.3)	3,183	0.02	0.15	52 (±13)	12 (±6)	2.1 (±0.7)	0.84 (±0.42)	*This study*
2.3	2,927			52	40			*[Eyring et al., 2005]*
	3,160							*[Tyedmers et al., 2005]*
0.5	3,170				10			*[Endresen et al., 2007]*
0.5	3,179	0.05	0.08	65	10	0.61	0.18	*[Dalsøren et al., 2009]*
0.2	3,114	0.06	0.16	51	2.6			*[Smith et al., 2014]* [c]
0.5	3,114	0.06	0.16	51	9.8			*[Smith et al., 2014]*[d]
				Arctic, Non-ECA				
0.6 (±0.3)	3,183	0.02	0.15	52 (±13)	12 (±6)	2.1 (±0.7)	0.88 (±0.66)	*This study*
2.6	3,167			76	52.7		0.36	*[The Arctic Council, 2009]*
0.5	3,114				10	1.1	0.35	*[Corbett et al., 2010a]*
							0.35	*[Browse et al., 2013]*
0.5	3,183	0.02	0.2	58	9.9	0.39	0.35	*[Winther et al., 2014]*
							0.35	*[Mjelde et al., 2014]*

[a] All emission factor (EF) units are grams of pollutant per kilogram of fuel. Average and standard deviations are reported for this study.
[b] Nitrogen oxides (NOx) calculated as NO_2.
[c] Emission factors used for marine gas oil (MGO) or marine distillates oil (MDO).
[d] Emission factors used for heavy fuel oil (HFO).

1.4.3. Global and Arctic Emissions

The hypothesis of this study was that previous global inventories of commercial ships may be understated due to the lack of inclusion of smaller fishing vessels (<100 GT) and the use of a single emission factor that does not account for engine speed, engine type, fuel quality, and the ship-to-ship variability of a diverse fleet. The global and Arctic fuel consumption and emissions are summarized in Table 1.4 for the results of this and previous studies *[Tyedmers et al., 2005; Endresen et al., 2007; Dalsøren et al., 2009; Smith et al., 2014; Greer, 2014; Eyring et al., 2005]*. It was found that the global fishing fleet emits 139 Tg CO_2 yr^{-1}. The global fuel consumption and CO_2 emissions estimates of this study are more than twice all previously reported estimates except for one study which also accounted for smaller fishing vessels *[Tyedmers et al., 2005]*. That study has similar results to this work because there have been only modest changes in the FUI and global catch statistics over the last decade. The estimates of SLCFs of this study are generally several times previous estimates for SO_2 and an order of magnitude greater than previous estimates for BC and OC because of the larger fuel use and emission factor estimates of this study.

A recent emission inventory for the Arctic found that fishing vessels were the dominant source of maritime BC emissions in this region *[Winther et al., 2014]*. The fuel consumption data from the inventory of Winther et al. (2014) and the updated emission factors of this study were used to estimate that the Arctic fishing fleet emits 105 (±26), 23 (±12), 2.9 (±1.4), and 1.7 (±0.9) Gg yr^{-1} of NOx, SO_2, OC, and BC, respectively. The Arctic BC emissions estimate is 2 to 5 times the central estimates of previous work due to the larger emission factor used in this study.

Table 1.4: *Annual fuel consumption and emissions from fishing vessels.*

Year	Fuel Use (Tg)	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	NOx[a] (Gg)	SO_2 (Gg)	OC (Gg)	BC (Gg)	Source
Global:									
2001	23.6	69,000			1,219	950			[Eyring et al., 2005][b]
2001	42.0	134,000							[Tyedmers et al., 2005][c]
2000	20.0	63,400				200			[Endresen et al., 2007][b]
2004	13.2	42,010	0.6	1.0	859	132	7.9	2.4	[Dalsøren et al., 2009][b]
2011	6.0	19,000	2.9	0.9	520	55			[Smith et al., 2014][d]
2012	16.0	11,000	0.7	2.4	834	261			[Smith et al., 2014][b]
2012	43.8	139,420	0.9	6.6	2,278 (±570)	402 (± 214)	63 (± 34)	37 (± 20)	This studyc
Arctic:									
2004	1.0	3,230			78	54		0.36	[The Arctic Council, 2009][b]
2004		3,200			58	10	1.1	0.35	[Corbett et al., 2010a][b]
2004								0.3- 0.9	[Browse et al., 2013][b]
2012	2.0	6,383	0.2	0.4	117	20	0.8	0.71	[Winther et al., 2014][b]
2012								0.40	[Mjelde et al., 2014][b]
2012	2.0	6,430	0.04	0.3	105 (± 26)	23 (± 12)	2.9 (± 1.4)	1.7 (± 0.9)	This study[b]

[a] Nitrogen oxides (NOx) calculated as NO_2.
[b] Fuel and emissions estimate using a bottom-up engine activity approach.
[c] Fuel estimate from the sum of the products of catches (by species) and the corresponding species-specific fuel use intensity estimates.
[d] Fuel and emissions estimate using a top-down approach from international sales of bunker fuel summed up by country.

1.4.4. Global Fuel-Specific Climate Forcing

The global fuel-specific climate impacts of the SLCF and LLCF emissions from fisheries for a 20 year and 100 year time horizon including the direct (aerosol-radiation interaction) and total (aerosol-cloud interactions and land surface albedo for BC) effects were estimated using the emission estimates and a range of published GWP values of this study (Figure 1.1). The LLCF forcing was not sensitive to the time horizon, fuel sulfur content, consideration of direct or indirect effects, or GWP uncertainty. The LLCF emissions resulted in a warming of 2800 g CO_2e/L fuel and were dominated by CO_2.

For the global SLCF forcing, this analysis begins by considering the baseline forcing using mean emission factors and GWPs. For the ECAs, F_s (wt %) 0.051, the mean climate forcing of SLCFs was dominated by the BC warming effect for all time horizons and for both direct and total climate effects. For the 20 year time horizon ECAs, the net warming was 25% and 49% greater than considering LLCFs alone for the direct and total effects, respectively. For the 100 year time horizon ECAs, the net warming resulted in relatively small differences from considering LLCFs alone. For non-ECAs, F_s (wt %) 0.590, the BC warming effect was outweighed by the SO_2, NOx, and OC cooling effects, resulting in reductions of 3–42% compared with LLCFs alone. The difference between ECA and non-ECA results is due to the fact that the emission factors increased with fuel sulfur content for SO_2 but not for BC, OC, or NOx.

Due to uncertainties in emission factors and GWPs, the net climate forcing (combined LLCF and SLCF forcing) ranged from a net cooling effect of 5719 g CO_2e/L fuel (Figure 1.1, F_s (wt %) 0.9) to a net warming effect of 10,408 g CO_2e/L fuel (Figure 1.1b, F_s (wt % 0.001) across all fuel sulfur contents, all time horizons (20 and 100 year) and all climate impacts (direct and total). The cooling end of this range is associated with a high fuel sulfur content (0.9%), a short time horizon (20 year), the largest emission factors and GWP values for cooling SLCFs (NOx, SO_2, and OC), and the smallest emission factor and GWP value for BC. The warming end of this range is associated with a low fuel sulfur content (0.001%) and emission factors and GWP values that weight the BC emissions over the SO_2emissions.

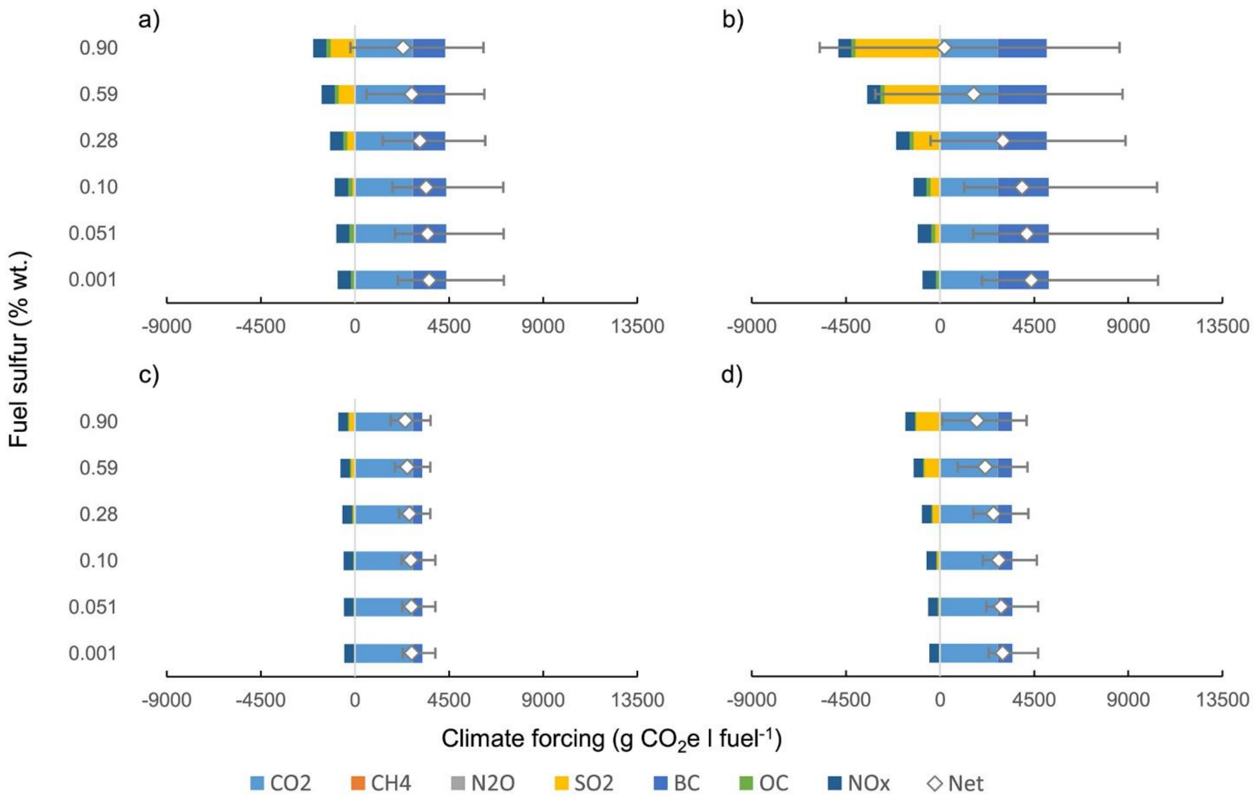

Figure 1.1: *Global fishing vessel climate forcing emission factor for fuel including direct effects (left), total effects (right), 20-yr time horizon (top), and 100-yr time horizon (bottom). The direct effect includes only aerosol-radiation for SLCFs whereas the total effects include aerosol-cloud interaction for OC and SO_2, and land surface albedo for BC The error bars represent standard deviations due to uncertainty in emissions factors and global warming potential.*

1.4.5. Arctic Fuel-Specific Climate Forcing

The fuel-specific climate impacts of the fishery emissions in the Arctic region are summarized in Figure 1.2. Although the Arctic is currently a non-ECA (high fuel sulfur content), here the results for the case of a designated ECA for this region was also included. This analysis begins by considering the baseline forcing using mean emission factors and GWPs. For the 20 year time horizons, the SO_2 and OC cooling effects were outweighed by the BC and NOx warming effects for both ECA and non-ECAs. For ECAs, the net warming was 85% and 100% greater than considering LLCFs alone for the direct and total effects, respectively. For the non-ECAs, the net warming was 60% and 6% greater than considering LLCFs alone for the direct and total effects, respectively. For 100 year time horizons, the trends observed for the Arctic region are similar to global fuel-specific climate forcing. For the ECAs (total and direct effects) and the direct effects non-ECA, the warming of BC outweighs the cooling effects of SO_2, NOx, and OC. For the non-ECA total effects, the warming BC is outweighed by the cooling effects of the SLCFs. The mean ECA scenarios result in increases in warming of 12 and 16% greater than considering LLCFs alone for the direct and total climate effects, respectively. For the mean non-ECAs, the cooling of SO_2, NOx, and OC outweigh the warming effect of BC for the total effects. The mean non-ECA scenarios result in a net warming increase of 60% and a net cooling decrease of 10% compared with LLCFs alone for the direct and total climate effects, respectively.

The error bars in Figure 1.2 represent the low and high SLCF values associated with the range of emission factor and GWP values. The net climate forcing (combined LLCFs and SLCFs forcing) results in a net warming for all climate effects (direct and total) and time horizons (20 year and

100 year) of 331 g CO_2e/L (Figure 1.2b, F_s (wt % 0.9)) to 7488 g CO_2e/L(Figure 2b, F_s (wt % 001)).

1.4.6. *Total Climate Forcing*

The mean climate forcing (total effects) of 101 and 116 Tg CO_2e global emissions for the combustion of marine fuels used in fisheries was estimated for 20 year and 100 year time horizons, respectively. Of these totals, the SLCF forcing resulted in a warming from BC that was largely offset by cooling from SO_2, NOx, and OC. While the net SLCF contribution resulted in negligible effects at a global scale, the climate forcing in ECAs resulted in significant warming effects on a 20 year time horizon. In ECAs, approximately 33 and 23 Tg CO_2e yr^{-1} was estimated for the total effect 20 year and 100 year time horizons, respectively. Of this total, 11 and 0.9 Tg CO_2e yr^{-1}can be attributed to SLCFs for the 20 year and 100 year time horizons, respectively.

In the Arctic, the regional emissions for the combustion of fuels used by fisheries results in approximately 6.9 and 5.9 Tg CO_2e yr^{-1} with approximately 0.41 and −0.65 Tg CO_2e yr^{-1} forcing from SLCFs for the 20 year and 100 year time horizons, respectively. This study used a reported fuel consumption of fisheries (2020 Mg) *[Winther et al., 2014]* and a fuel density of 0.86 kg/L in its calculations. Policy discussions suggest that the Arctic may be designated an ECA in the future, lowering the sulfur fuel content of the region. In this case the regional forcing would be 13 and 7.6 Tg CO_2e yr^{-1} for the 20 year and 100 year horizons, respectively.

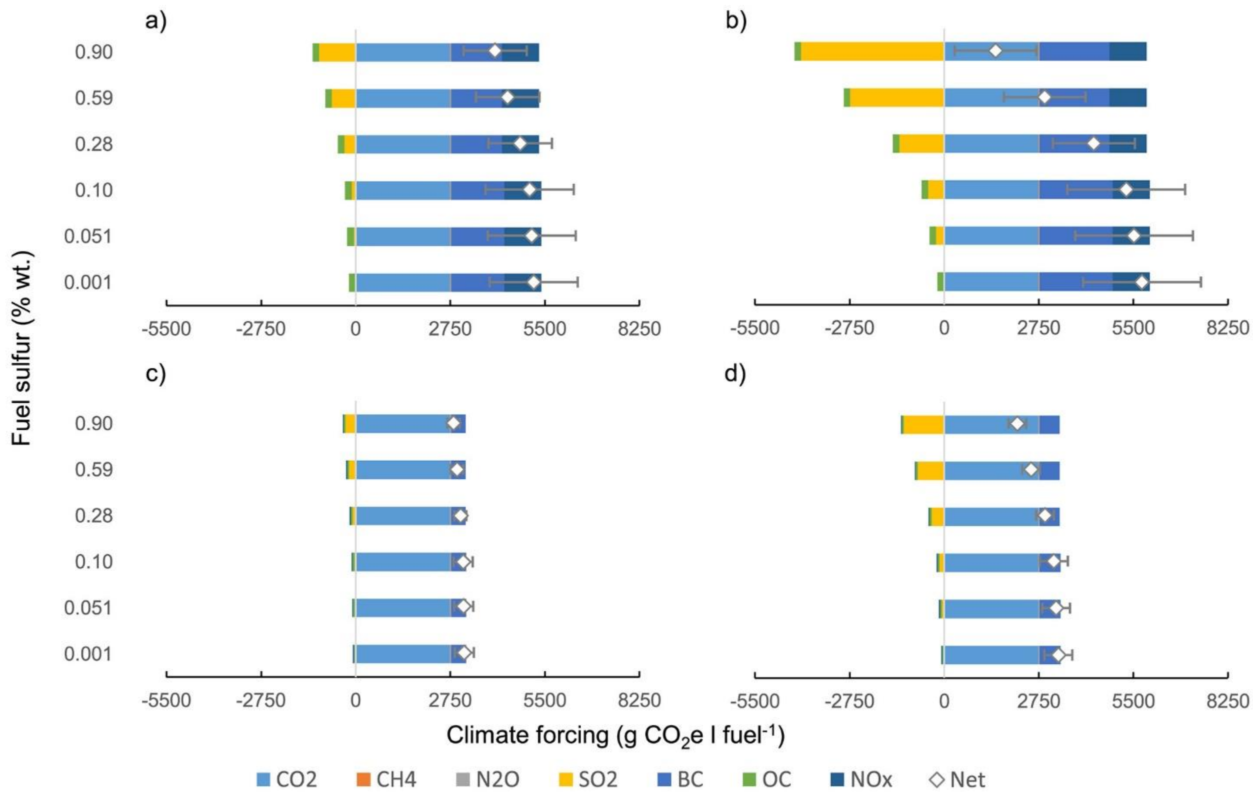

Figure 1.2: *Arctic fishing vessel climate forcing emission factor including direct effects (left), total effects (right), 20-yr time horizon (top), and 100-yr time horizon (bottom). The direct effect includes only aerosol-radiation for SLCFs whereas the total effects include aerosol-cloud interaction for OC and SO_2, and land surface albedo for BC. The error bars represent standard deviations due to uncertainty in emissions factors and global warming potential.*

1.4.7. Food-Specific Climate Forcing

While SLCF emissions are needed for understanding global and regional climate change, they can also be useful for understanding climate impacts of food decisions when they are reported on a basis of food mass. Here a first estimate of the food-specific climate forcing (kg CO_2e/kg protein) is provided that includes both LLCFs and SLCFs. The emissions of fisheries are compared to other foods prior to processing and transport. The median published values of fuel use of 0.32, 0.95, and 2.58 L fuel/kg catch were used for fisheries targeting small pelagics, large pelagics, and crustaceans, respectively *[Parker and Tyedmers, 2015]*. The comparison to land-based protein includes only the median published values for life cycle emissions from land-based LLCFs (feed production, enteric fermentation, manure management, on-farm fuel use, etc.) *[Parker and Tyedmers, 2015]*. Land-based foods do not include SLCF emissions because their SLCF forcing is small in comparison to LLCF forcing *[Unger et al., 2010]*. The live weights reported in Parker and Tyedmers (2015) were normalized by the relative yield factors in the meat chain (carcass weight of live weight and retail meat weight of carcass weight) and protein fractions *[Nijdam et al., 2012]*. The median land-based protein LLCFs were allocated to farm activities based on technical reports and literature values *[Steinfeld et al., 2006; Blonk et al., 2008; Nijdam et al., 2012; Pelletier et al., 2009; Pelletier and Tyedmers, 2007; d'Orbcastel et al., 2009; Vergé et al., 2013; Cao et al., 2011; Pelletier and Tyedmers, 2010]*. The results summarized in Figure 1.3 show climate forcing (total effects, 20 year and 100 year time horizon scenarios) that varies widely among all protein sources. Beef protein has the largest climate forcing while vegetable protein has the smallest. There are also differences related to the choice of time horizon. Comparing the impacts from the 20 year (Figures 1.3a and 1.3b) to the 100 year time horizons (Figure 1.3c and 1.3d), it is evident that there is a negligible change in climate forcing for vegetable protein and aquaculture but substantial differences for beef, pork, chicken, and wild-caught seafood. In the case of land-based protein this increase in climate forcing for the 20 year time horizon can be attributed to the increase in the GWP of CH_4.

The mean climate impacts from wild-caught seafood (total effects, 20 year and 100 year time horizon scenarios) also vary widely within this category. One explanation for this variability is the different types of seafood considered here. Crustaceans have the greatest climate forcing, while small pelagics have the least. A second explanation for the variability in climate impacts for wild-caught seafood is the choice of time horizon. When considering the impacts for a 20 year time horizon, the climate forcing is 143% and 74% of the climate forcing for a 100 year time horizon for seafood caught in ECAs and non-ECAs, respectively. Lastly, the regional sulfur control laws have a role in the variability in climate forcing of wild-caught seafood. For seafood caught in ECAs (Figures 1.3b and 1.3d) there is significant warming from SLCFs for a 20 year time horizon (149% of total climate forcing over LLCFs alone), whereas for a 100 year time horizon the warming from BC is largely offset by the cooling from NOx. For seafood caught in non-ECAs (Figures 1.3a and 1.3c), there is significant cooling from SLCFs (58% and 78% of total climate forcing over LLCFs alone for 20 year and 100 year time horizons, respectively).

Comparison of wild-caught seafood to other animal-based protein sources can help to put climate impacts in perspective. For a 20 year time horizon, the median fisheries climate impact (26 kg CO_2e/kg protein) is lower than chicken, farmed salmon, and farmed trout (32, 30, and 29 kg CO_2e/kg protein, respectively) when only LLCFs are considered. When the net cooling from SLCFs is included for catches caught in non-ECAs, the median fisheries climate impact is smaller, 15 kg CO_2e/kg protein (Figure 1.3a), than all forms of animal protein considered here.

However, when the net warming from SLCFs is included for catches caught in ECAs, the median fisheries impact is significantly larger, 39 kg CO_2e/kg protein (Figure 1.3b), and elevated to a similar climate impact as farmed whitefish (41 kg CO_2e/kg protein). The climate impact of large pelagics, 39 kg CO_2e/kg protein, is similar to farmed whitefish when only LLCFs are considered. When the net cooling from SLCFs is included for catches in non-ECAs, 31 kg CO_2e/kg protein (Figure 1.3a), the large pelagics climate impact is smaller than farmed whitefish and similar to chicken. For catches in ECAs, on the other hand, the net warming from SLCF significantly increases the climate impact of large pelagics, 56 kg CO_2e/kg protein (Figure 1.3b), to having a similar impact as pork, 63 CO_2e/kg protein. In the scenarios with the largest SLCF net warming, crustacean fisheries are elevated to having similar climate forcing as beef.

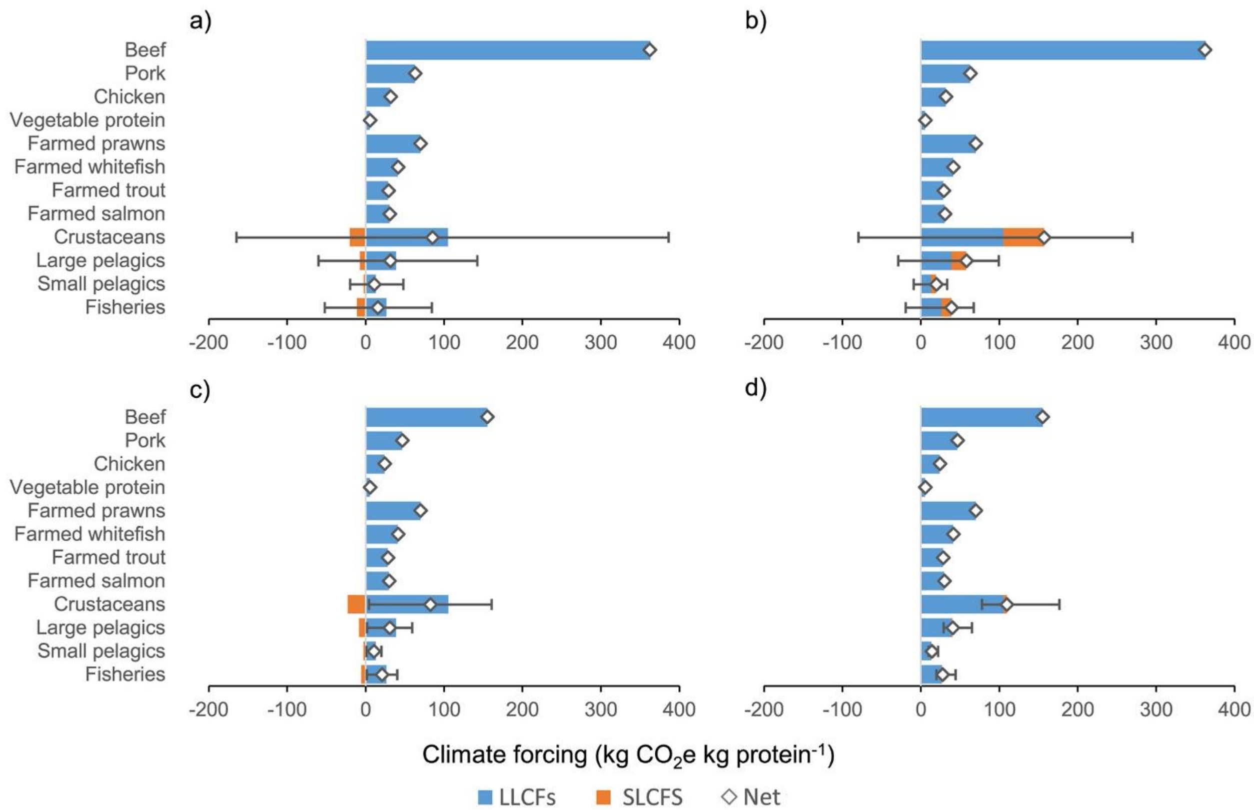

Figure 1.3*: Climate forcing of fisheries and other food sources including long-lived climate forcers (LLCFs) shown in blue and short-lived climate forcers (SLCFs) shown in orange. Fishery protein is based on total climate effects (direct and indirect). Top panel (a,b): 20-yr time horizon. Bottom panel (c,d): 100-yr time horizon. Left panel (a,c):Scenarios for emission control areas (ECAs). Right panel (b,d):non-ECAs. Error bars represent standard deviations for SLCF emissions factors and GWPs.*

1.4.8. Parameter Sensitivity

A sensitivity analysis was undertaken to identify which components of the climate forcing assessment made the largest contributions to uncertainty. The results of our sensitivity analysis are presented as tornado plots in Figure 1.4. The sensitivity simulations were based on a baseline fuel sulfur of 0.051% with low and high values of 0.001% and 0.1%, respectively. The baseline FUI was the global median value of 0.639 L fuel/kg catch with low and high values of 0.32 and 1.47 L fuel/kg catch, respectively. The baseline emissions of SLCFs were the average values for ECAs with low and high values given by the standard deviations (Table 1.3). We also consider a flat emission factor for BC, 0.35 g BC/kg fuel, as an alternative to the binned approach we used to estimate the BC emission factors given in Table 1.3. The baseline GWPs for SO_2, NOx, OC, and BC were the average values for each climate effect (direct and total) and time horizon (20 year and 100 year horizons) with high and low values given by the standard deviations (Table 1.2). For all scenarios, the FUI was the dominant source of uncertainty. Secondary sources of uncertainty were from the BC emission factors and the BC GWP.

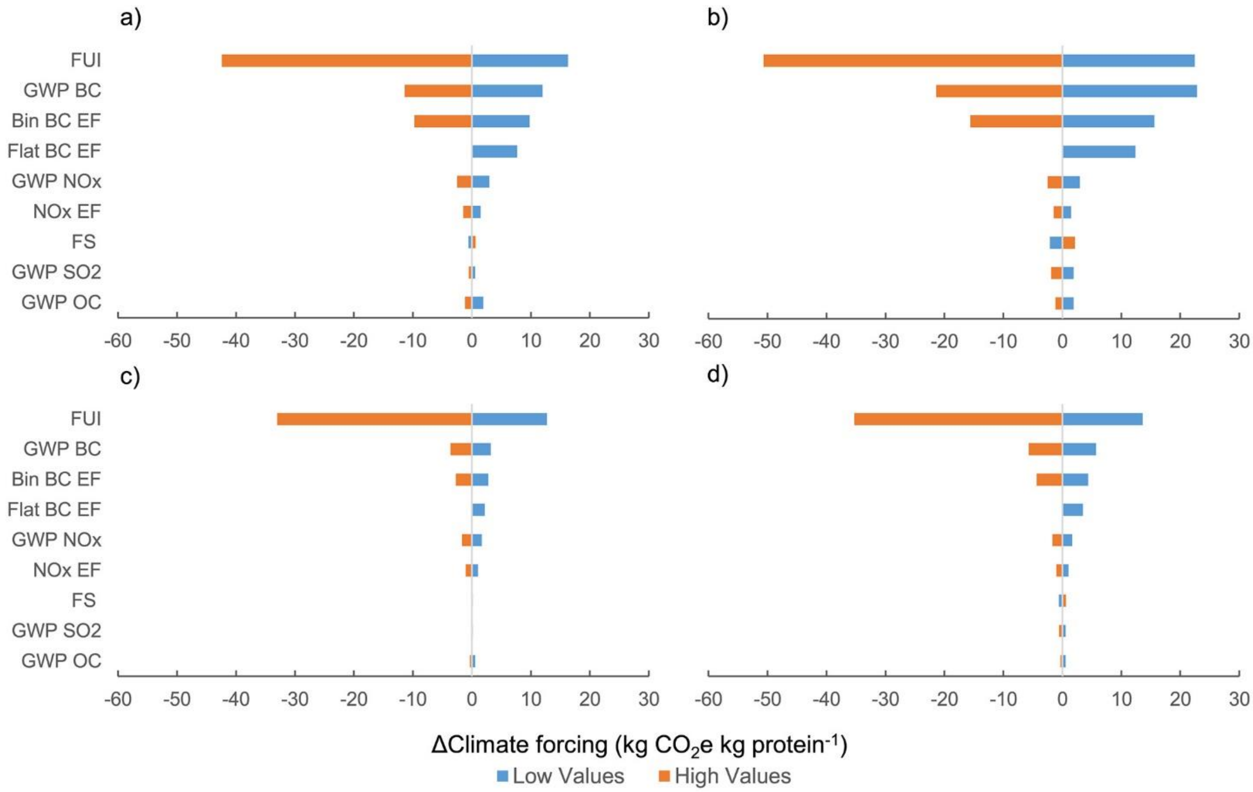

Figure 1.4: *Tornado plots of uncertainty in climate forcing estimates for direct effects (left), total effects (right), 20-yr horizons (top), and 100-yr horizons (bottom). Sensitivity is simulated for model inputs including global warming potential (GWP), emission factors (EF), fuel use intensity (FUI), and fuel sulfur content (FS). The centerline represents the baseline case.*

1.5. Discussion

Understanding fishing vessel emissions is timely as the International Maritime Organization is considering whether to uphold its decision to reduce international fuel sulfur limits from 3.5% to 0.5% in 2020. This discussion of Arctic emissions is also relevant considering the Arctic Council has proposed to develop a standardized way to measure BC and investigate potential control options. Although fuel sulfur laws were designed to reduce air pollution, they may have an unintended consequence of increasing net climate forcing for fishing and other maritime industries *[Fuglestvedt et al., 2009]*. With respect to the climate impacts of BC, the results of this analysis suggest that sulfur control regulation may not be the best mitigation approach.

It was also hypothesized that previously published climate impact assessments of food had not included SLCFs and may have understated climate forcing. For some emission factors and GWP estimates, the added net warming from SLCFs caused crustacean fisheries to have a similar climate forcing as beef, while pelagic fishery impacts were elevated to have a similar forcing as pork. It would appear that seafood harvested in regions with fuel sulfur control laws has a larger climate forcing than in regions that are not regulated. This work is important because consumers reward fisheries that use sustainable harvesting processes with the help of consumer advisory groups.

1.5.1. Model Uncertainties

It has been pointed out that using catch statistics (as we have in our global estimate) for emissions inventories could be understated by a factor of two or three, due to poor reporting

[Greer, 2014]. In addition to uncertainties related to global catch statistics, the climate forcing is particularly sensitive to FUI. As shown in Figure 4, at the low end of the FUI sensitivity range (0.32 L fuel/kg fish) the global median fishery climate forcing is 51% of the mean climate forcing, whereas at the high end of the FUI sensitivity range (1.5 L fuel/kg fish) the climate forcing is 230% of the mean climate forcing. The fuel consumption per kilogram of caught fish is reported to vary considerably as a function of fishing gear and vessel size, even when considering the same target species *[Thrane et al., 2009; Tyedmers, 2001; Parker and Tyedmers, 2015]*. The global vessel characterization and the global FUI that we used in this study may not be representative of fishing communities at the regional scale. Vessel sizes can range from 2 m boats used in subsistence fisheries to industrial fishing ships that exceed 130 m in length (FAO, Fisheries and Aquaculture topics. Fishing vessels: http://www.fao.org/fishery/topic/1616/en). The energy consumption increases as a function of vessel size because engine power increases with the size of the ship and larger fisheries substitute human power with mechanized fishing gears that require greater engine power *[Thrane et al., 2009]*. Larger vessels are also reported to exploit more distant fish resources than small vessels, which would then require a longer sailing distance to and from the catch area and thus greater fuel consumption *[Thrane et al., 2009]*.

The climate forcing of fisheries is also sensitive to the GWP of SLCFs, particularly BC. The substantial uncertainties in our estimate are, in part, due to the heterogeneous distributions and radiative forcing patterns that are dependent on the aerosol emission location *[Collins et al., 2013]*. The regional variability for BC is reported to be 30% to 40% for the direct effect, with the largest forcing typically found at low latitudes *[Bond et al., 2013]*. For the snow albedo effect the regional variation is much larger with higher values for high-latitude regions where the emitted BC is more likely to be deposited on snow surfaces. The snow albedo effect of BC ranges from practically zero for emissions in the tropics to values that reach 30% to 60% of the direct effect in the higher-latitude regions *[Bond et al., 2013]*. For all aerosols, model estimates of indirect effects have a much larger relative spread for indirect effects compared with direct effects. For example, the uncertainty estimate for the cloud albedo effect is double that of the aerosol direct effect *[Bond et al., 2013]*. While we used GWP estimates for a first approximation of the climate forcing from fisheries, future work using spatially explicit emissions inventories and climate models may be useful in reducing the uncertainty of these estimates.

Another substantial source of uncertainty in this model is the BC emission factor. Previous fishing emission estimates have used a flat BC emission factor of 0.35 g BC/kg fuel for Arctic inventories and 0.18 g/kg for global inventories that both originate from a small subset of the published ship emission data and are not specific to the engine types of fishing vessels. The binned BC emission factors used in this analysis (Table 3) are two or more times the previously applied BC emission factors. The climate forcing for global median fisheries using the flat 0.35 g/kg emission factor is 69% of the mean value of our binned approach (Figure 1.4). Due to bias in sampling of data points and methods used to sort the data into bins, an alternative to the binned approach that does not depend on load or fishing gears (described in equation 2) was considered, resulting in 0.92 and 0.86 g BC/kg fuel for low and high sulfur fuel, respectively. The hypothesis that the alternate BC emission factors for engines using MDO were less than or equal to the flat emission factor and that the flat BC emission factor was greater than or equal to the emission factor for the MSD engine using HFO was also tested. These hypotheses are rejected with high confidence (p values: 1×10^{-11}, $n = 51$; 5×10^{-6}, $n = 45$; 1×10^{-4}, $n = 12$; 0.06, $n = 30$) except the case of emissions for HSD using high sulfur MDO, 0.36 g BC/kg fuel, ($p = 0.45$, $n = 8$). Due to the similarity in values of the binned (described in equations 3-5 and presented in Table 1.3) to the alternative BC emission factors, it is likely that fishing vessels are better represented by the higher emission estimates of this study than the lower emission factors used in previous studies *[Sinha et al., 2003; Corbett et al., 2010a]*.

There are possible limitations to using plume sampling and test-rig data. Because only a small number of engines have been tested, there is a limited amount of in-use emissions data for MSD engines and an even smaller set of data specific to fishing boats *[Cappa et al., 2014; Buffaloe et al., 2014; Lack et al., 2008]*. In one plume-sampling study, the emissions for fishing vessels were reported although the data for this category consist of only one ship sampled multiple times, and the ship was a research fishing vessel *[Buffaloe et al., 2014]*. It should also be pointed out that although there is a large amount of ship-to-ship variability from the plume sampling ensemble studies, this data may not reflect the contribution of poorly functioning vessels with very high emissions. The fraction of such vessels and their emission factors are not well known which may result in an underestimation of inventories. Vessels in this category are likely to be more widespread in developing countries, but there is little data on the fraction of vessels with such high emissions *[Bond et al., 2013]*.

1.6. Conclusions

The emission estimates presented here advance the understanding of the fishing vessel contribution to global and regional emissions inventories. Emission uncertainties are on the order of 50% and could be reduced through plume intercept studies of fishing vessels that include measurement of emission factors under actual operating conditions (including the influence of engine load, ship size, engine type, and fuel quality) and atmospheric dilution conditions.

Furthermore, mapping the spatial distribution and temporal variability of these emissions and simulating their impacts with climate models could reduce the uncertainties in the regional climate response. Despite these uncertainties, the inventories of this study show significantly larger SLCF emissions than previous inventories. In particular, global BC had been underestimated by an order of magnitude. Emerging policies concerning global fuel sulfur reductions may result in net warming from fishing vessel emissions globally and in the Arctic. Considering the large contribution of emissions from fishing vessels compared to other ships in the Arctic, the climate sensitivity to BC in the Arctic, and the small number of studies dedicated to fishing vessels, fishing emissions studies may be an important focus area for further work.

2. Synergies and trade-offs between sustainable seafood practices and climate change

2.1. Chapter Summary

Food systems are a dominant sector for greenhouse gas (GHG) emissions, accounting for 10% to 32% of the global anthropogenic sources *[Heller and Keoleian, 2015; Eshel et al., 2014]*. Although seafood is a significant animal protein source for global human consumption, it is often overlooked in GHG emissions inventories. Here it is shown that the climate impact of some sustainable fishing practices—namely, selective fishing gears, improved fuel quality, and a proposed ban on high seas fishing—present trade-offs and synergies with conservation goals. The climate forcing was quantified from multiple long-lived (e.g. CO_2) and short-lived (e.g. black carbon) species due to emerging fishery practices for tuna caught by U.S. fleets, one of the most important capture fisheries by both volume and value. The approach integrates ship registry data, historical sulfur levels in fuels, gear-specific fishery fuel use data, historical gear-specific landings data, and a range of global warming potentials (GWPs). Skipjack tuna caught with purse-seine gear that has bycatch impacts also has a lower climate impact than many other protein sources with the exception of plants. Conversely, skipjack tuna caught with troll gear that mitigates bycatch has a higher climate impact than most other protein sources with the exception of beef. However, other gears that result in less bycatch could reduce climate forcing. Because environmental conservation is a central goal of climate change mitigation, climate policies must be designed to avoid these unintended consequences to fishery sustainability and enhance existing synergies.

2.2. Introduction

Explosive growth in certified sustainable seafood is driven by consumer demand and policy. While the benefits of sustainable fishing practices on conservation are well studied *[Myers and Worm, 2003; Worm et al., 2009; Beddington et al., 2007; Smith et al., 2010; Sampson et al., 2015; Costello et al., 2016]*, the implications of sustainable fishing practices for climate change are not.

Previous work generally focuses on the fishing industry's impact on conservation, rather than climate change. Key conservation issues are the status of the fish stock, the impact of the fishery on the ecosystem, and the performance of the fishery management system *[Myers and Worm, 2003; Worm et al., 2009; Beddington et al., 2007; Smith et al., 2010; Sampson et al., 2015; Costello et al., 2016]*. Fisheries have fully exploited more than half of the world's fish stocks, and before the advent of modern fisheries management for sustainability, commercial fishing resulted in the collapse of numerous fish populations *[Worm et al., 2009; Myers and Worm, 2003]*. Ecosystems are affected not only by the extraction of target species but also by the collateral damage that results from the extraction of non-target species or bycatch *[Gilman, 2011]*.

These conservation challenges have led to a fundamental shift in fisheries governance to more sustainable management practices. First, more selective fishing gears such as pole-and-line and trolling gears limit bycatch impacts to a greater degree than less selective gears such as longlines and purse-seines, which have an observed history of bycatch and impacts on protected marine mammals and endangered sea turtles *[Gilman, 2011]*. Second, the proposed closing of the high seas to fishing could enhance global fishery management *[Beddington et al., 2007]*. Third, increasingly stringent regulations on the sulfur content in marine fuels, though not often the focus of sustainable seafood advocates, is another important factor that is shaping the sustainability of seafood production *[Cullinane and Bergqvist, 2014]*.

The hypothesis that each of these three sustainable fishing practices could impact the climate forcing of seafood was tested. First, a trade-off between climate and conservation goals may exist with fleets that employ highly selective fishing gears that may require a higher rate of fuel consumption per quantity of fish caught than less selective gears *[Tyedmers and Parker, 2012]*. Second, a synergy between climate and conservation goals may exist by closing the high seas to fishing which may reduce the average traveling distance by fishing vessels. Third, a trade-off between goals may result from fuel sulfur content regulations, thereby diminishing the emissions of cooling species *[Westervelt et al., 2015]* which may in turn increase the climate impact of seafood. Because marine fuels have particularly high sulfur dioxide emissions *[Unger et al., 2010; von Schneidemesser et al., 2015]*, seafood may be an important sector for the assessment of a broader suite of climate forcing species than only CO_2 *[McKuin and Campbell, 2016]*. Furthermore, sulfur regulations on marine fuels require additional refinery processes, driving up emissions at the refinery *[Ma et al., 2012; Abella and Bergerson, 2012]*. Ignoring the integrated climate impacts of these three practices may lead to inaccurate estimates of the climate effect of seafood relative to other food choices.

To assess the climate impact of these three sustainable practices, the climate forcing associated with selected U.S. tuna fleets was modeled. The U.S. has undergone a resurgence in the last five years to have one of the largest tuna landings of any country in the world (~300,000 metric tons yr^{-1}). Furthermore, tuna landings from U.S. tuna fleets are an important supply of certified sustainable tuna, making up 24% of the fisheries with either a “certified” or “in assessment” status with the Marine Stewardship Council *[Marine Stewardship Council, 2016]*.

Fuel use consumption and fuel-specific GWPs of the selected fleets were combined to provide a first-order estimate of the climate forcing of tuna protein caught by U.S. fleets using two different time horizons for climate forcing (20-y and 100-y). To estimate the fuel consumption and emissions of the fleets, a bottom-up activity-based approach was used that has been previously employed in shipping inventories *[Moreno-Gutierrez et al., 2015]*. This activity-based approach combined main engine power, vessel performance data, and detailed catch and effort data that has been applied to fisheries research *[Tyedmers, 2001]*. An emissions analysis was conducted that accounts for long-lived climate forcing species (LLCF) including CO_2, methane (CH_4), nitrous oxide (N_2O), as well as short-lived climate forcing species (SLCF) including nitrogen oxides (NOx), black carbon (BC), organic carbon (OC), and sulfur dioxide (SO_2). Recently published plume-sampling data from an ensemble of ships, shipping and fishery databases, and a range of GWP estimates were used for this analysis *[Lack et al., 2008; Petzold et al., 2011; Cappa et al., 2014; Buffaloe et al., 2014]*. To evaluate the climate impact of high seas fishing, the climate impact of tuna protein for fleets that operate both within the U.S. EEZ and on the high seas were separately calculated. Furthermore, the climate forcing of tuna per unit protein was compared to other protein sources.

2.2.1. *Fisheries descriptions and key assumptions*

Seven different fleets were selected that represent a cross-section of the U.S. commercial tuna fleets employing different types of fishing gears, targeting different tuna species, and operating within different regions of the Pacific Ocean. Six fleets that operate within the Western Central Pacific Fisheries Commission Convention Area (WCPFC-CA) (conf. Fig. 1 in *[Williams and Terawasi, 2016]*) and one fleet that operates in the North Pacific along the coast of North America (conf. Fig. 1 in *[Childers and Pease, 2012]*). For comparisons of activities that take place exclusively on the high seas, international (all flagged vessels) pole-and-line and purse-seine fleets were also considered.

Here, information about each fishing fleet and key assumptions related to the hypotheses are provided 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. EEZ; and 3) assumptions regarding fuel quality in the various fishing territories.

2.2.1.1. *Purse seine fleets*

Skipjack is the principal species targeted by purse-seine fleets but these fleets also catch large quantities of other species of tuna and fish as bycatch. 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 *[NMFS, 2017p]*. Of particular concern is the catch of species that are overfished and experiencing overfishing including silky sharks, oceanic whitetip sharks, juvenile bigeye tuna, and juvenile yellowfin tuna *[Restrepo et al., 2017]*. There are also concerns related to the catch of mammals including dolphins which led to the passage of the Marine Mammal Protection Act.

These fleets operate within the exclusive economic zones (EEZ) of countries in the Western Pacific Ocean and on the high sea *[Williams and Terawasi, 2016]*. Fishing trips can last up to several months. During a trip, the vessels are active during the day and at night *[Walker et al., 2010; Langley, 2011]*. Furthermore, as defined by the vessel day scheme that sets limits on the effort of purse-seine vessels in the eight Pacific islands that are Parties to the Nauru Agreement (the Federated States of Micronesia, Kiribati, the Marshall Islands, Nauru, Palau, Papua New Guinea, the Solomon Islands and Tuvalu), a fishing day is defined as 24 hours *[Havice, 2013]*.

Purse-seine fleets fishing in the Western Pacific Ocean may use marine fuels with relatively high levels of sulfur for a number of reasons. First, these fleets fish the high seas and in the EEZs of countries that are not included in emission control areas *[IMO, 2015]*. Some of the larger vessels in these fleets have bunkering capacity and are thus capable of using the residuals of the distillates, called residual oil or heavy fuel oil. Given the fact that heavy fuel oil is significantly less expensive than higher quality fuel, these fleets may refuel with the less expensive heavy fuel oil when fishing in regions outside emission control areas *[Wang and Corbett, 2007]*. Second, the sulfur levels of distillate fuels in Pacific Island nations are not subject to the same fuel sulfur regulations as the continental U.S. and Hawaii *[e-CFR, 2015]*. Thus, even the vessels that do not have bunkering capacity are likely to use high sulfur distillates.

2.2.1.1.1. International purse-seine fleet.

Approximately 21 countries and 308 vessels participate in purse-seine fishing in the WCPFC-CA *[Williams and Terawasi, 2016]*. In the five year period between 2011 and 2015, the mean catch by international fleets is approximately 1.6 x10^6 metric tons (conf. Table A3 in *[Williams and Terawasi, 2016]*) of which approximately 15% is taken on the high sea.

2.2.1.1.2. U.S. purse-seine fleet.

Most of the tuna caught by U.S. purse-seine vessels is caught in the WCPFC-CA. Approximately 39 vessels participated in this fishery in 2015 *[NMFS, 2016a]*. In the five year period between 2011 and 2015, the mean catch of this fleet is roughly 2.5 x10^5 tons of tuna of which approximately 92% is taken outside the U.S. EEZ.

2.2.1.2. Pole-and-line fleet.

Skipjack is the principal species targeted by the pole-and-line fleet but this fleet also catches other species of fish as bycatch. This fleets carries live bait in tanks of circulating seawater. In some cases, the water in the bait tank is refrigerated in order to maintain a temperature similar to that of the water where the bait was captured thereby increasing the survival of the baitfish *[Joseph, 2003]*. Pole-and-line gear is considered highly selective because fish are caught one-at-a-time, there is little bycatch, and it is reported that there is a high survival rate of bycatch that is released alive *[Miller et al., 2017]*.

2.2.1.2.1. International pole-and-line fleet.

Approximately 7 countries and 122 vessels participate in pole-and-line fishing in the WCPFC-CA *[Williams and Terawasi, 2016]*, where the majority of the fleet is the Japanese pole-and-line fleet. In the five year period between 2011 and 2015, the mean catch by international fleets is approximately 2.8 $x10^5$ metric tons (conf. Fig. 31 in *[Williams and Terawasi, 2016]*) of which approximately 19% is taken on the high sea.

This fleet operates within the exclusive economic zones (EEZ) of countries in the WCPFC-CA region and on the high sea. Vessels equipped with freezers and sufficient hold capacity may stay at sea for three or four months *[Joseph, 2003]*. During a trip, the vessels are active during the day and at night. However, most of the activity taking place at night is related to catching live bait fish. According to one study, the fishing for the target species begins in the early morning and ends in the early evening *[Miller et al., 2017]*. It was assumed that the vessels in this fleet operate 12 hours per day.

The international pole-and-line fleets fishing in the WCPCF-CA are likely to use marine fuels with relatively high levels of sulfur. The sulfur levels of distillate fuels available in Pacific Island nations are not subject to the same fuel sulfur regulations as the continental U.S. and Hawaii *[e-CFR, 2015]*.

2.2.1.2.2. Hawaii pole-and-line fleet.

Approximately 2 vessels participated in this fishery in 2015 *[NMFS, 2016a]*. This fleet operates from major ports in Hawaii out to approximately 40 miles from the shore. However, fishing can occur in both state and federal waters. According to an older description, this fishery begins with bait seining at dawn followed by fishing until dusk *[Boggs and Ito, 1993]*. Thus, a 12 hour operating day was assumed for this study.

North Pacific surface methods fleet.

Albacore is the principal species targeted by the North Pacific surface-methods fleet and it is reported that there is little bycatch associated with this fleet (conf. 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 12 miles offshore Canadian waters *[NMFS, 2017ab]*. Likewise, Canadian fisherman have access to fish 12 miles offshore U.S. waters. Including Canadian vessels, approximately 565 vessels participated in this fishery in 2015 (conf. 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 EEZ of North America and on the high sea. In the five year period between 2011 and 2015, the mean catch by this fleet is approximately 12.4 x10^3 metric tons (conf. Table 1 in *[PFMC, 2016]*) of which approximately 0.8% is taken on the high sea. Although an older technical description of this fleet reported operating hours of 14-15 hours per day *[Dotson, 1980]*, it was assumed the operating characteristics of the albacore troll fishery in New Zealand are similar to those of the North Pacific troll fishery. In that fleet, the mean operating time is 12 hours *[Kendrick and Bentley, 2010]*.

Currently, this fleet operates almost exclusively within the emission control areas of Canada and the U.S. Thus, it was assumed that this fleet only uses ultra-low sulfur distillates as required by the Clean Air Act.

2.2.1.3. Hawaii troll fleet.

Commercial troll fisheries target wahoo, mahi-mahi, and large yellowfin tuna. Although troll gears are highly selective, there are concerns related to bycatch of striped marlin. Approximately 2,117 vessels participated in this fishery in 2015 *[NMFS, 2017h]*.

It is reported that pelagic trollers generally fish at an average distance of 5 to 8 miles from shore, with maximum distance of about 30 miles from shore *[NMFS, 2017h]*. According to an older report, most commercial pelagic trollers conduct operations as single-day trips lasting more than eight hours and some larger vessels engage in multi-day trips *[NMFS, 2000]*. However, due to a lack of recent data, it was assumed this fleet has the same effort hours as the American Samoa fleet—approximately 5 hours.

This fleet operates almost exclusively within the coastal region of Hawaii which is included in the North American emission control area. Thus, it was assumed this fleet only uses ultra-low sulfur distillates as required by the Clean Air Act.

2.2.1.4. American Samoa troll fleet.

Commercial troll fisheries target various species, including tuna, mahi-mahi, ono, and billfishes *[NMFS, 2017f]*. Although troll gears are highly selective, there are concerns related to bycatch of striped marlin. Approximately 13 vessels participated in this fishery in 2015 *[NMFS, 2017f]*.

In this fleet, fishing occurs in local nearshore or federal waters year-round, with trips lasting less than a day. It is reported that these vessels made approximately 132 trolling trips totaling 673 trolling hours, and thus the average trip duration is about 5 hours *[NMFS, 2017f]*..

It is likely this fleet uses high sulfur distillate fuels. Although the American Samoa is a U.S. territory, it is exempt from the stringent sulfur control laws that apply to the continental U.S. and Hawaii *[e-CFR, 2015]*.

2.2.1.5. Hawaii deep-set longline fleet.

Bigeye tuna is the principal species targeted by the Hawaii deep-set longline fleet. Longlines are considered less selective because a substantial amount of bycatch including endangered and threatened species (mammals, sea turtles, sharks, striped marlin, and seabirds) that are protected under federal law are caught along with the target species. Approximately 139 vessels participated in this fishery in *2015 [NMFS, 2017i]*.

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 sea. We estimated the vessel operation time by using the “soak time”, approximately 21 hours per day *[Bayless et al., 2017]*.

This fleet operates both inside and outside the emission control area. For fleet activity inside the EEZ of Hawaii, it was assumed that the vessels uses ultra-low sulfur distillates. However, vessels that engage in multi-day trips that take place outside the EEZ of Hawaii may refuel using high sulfur fuel because distillate fuels that are available in other Pacific Island nations are not subject to the same fuel sulfur regulations in effect for the continental U.S. and Hawaii *[e-CFR, 2015]*.

2.2.1.6. American Samoa longline fleet.

Albacore tuna is the principal species targeted by the American Samoa longline fleet. Longlines are considered less selective because a substantial amount of bycatch including endangered and threatened species (mammals, sea turtles, sharks, striped marlin, and seabirds) protected by federal law is caught along with the target species. Approximately 20 vessels participated in this fishery in *2015 [NMFS, 2017k]*.

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 sea. Effort hours were provided by logbooks for this fleet.

It is likely this fleet uses high sulfur distillate fuels. Although the American Samoa is a U.S. territory, it is exempt from the stringent sulfur control laws that apply to the continental U.S. and Hawaii *[e-CFR, 2015]*.

2.3. Methods

2.3.1. Fuel use intensity (FUI).

The FUI was estimated for two scenarios: 1) all seven U.S. fleets operating within their respective domains; 2) separate estimates of fleet fishing activity within the U.S. EEZ (five fleets) and fleet fishing activity outside the U.S. EEZ (three U.S. fleets and two international fleets) using the following equation:

$$FUI_{i,j,k,l,m} = \frac{FC_{i,j,k,l}}{M^{catch}_{i,j,k,l}} \cdot \frac{M^{catch}_{i,j,k,l,m}}{\sum_m M^{catch}_{i,j,j,k,l,m}} \quad (1)$$

where *FC* is the annual fuel consumption of each tuna fleet (liters of fuel per year), M^{catch} is the mass of tuna or pelagic species catch (in metric tons per year), *i* is the fishing region (Western Central Pacific Ocean convention area, American Samoa, Hawaii, and the North Pacific region of North America), *j* is the fishing gear (pole-and-line, troll, purse seine, surface methods, or longline), *k* is the fishing territory (inside or outside the U.S. exclusive economic zone), *l* is the year (1996-2015), and *m* is a specific species of tuna (albacore, bigeye, skipjack, and yellowfin). The subscript *k* applies to the scenario where the effort and catch was disaggregated between the high sea and the exclusive economic zone. In the case in which the effort and catch was not disaggregated between the EEZ and high sea, the *k* is omitted.

The following equation was used to estimate a bottom-up activity based methodology to calculate the mean fuel consumption of the fleets *[Tyedmers, 2001; Coello et al., 2015; Eyring et al., 2005; Smith et al., 2014]*:

$$FC_{i,j,k,l} = P_{i,j,k}^{M,avg} \cdot LF_{i,j,k}^{avg} \cdot t_{i,j,k,l}^{eff} \cdot \sum_n f_{l,n}^{FQ} \cdot \frac{SFOC_n}{\rho_n} \qquad (2)$$

where $P^{M,avg}$ is the fleet average main engine power (in kW), LF^{avg} is the average fleet load factor, t^{eff} is the fishing effort time (in days), f^{FQ} is the fraction of the fleet using a particular fuel type, *SFOC* is the specific fuel oil consumption (in grams per kilowatt hour), ρ is the density of the fuel type (in liters per gram), *i* is the fishing region (Western Central Pacific Ocean convention area, American Samoa, Hawaii, and the North Pacific region of North America), *j* is the fishing gear (pole-and-line, troll, purse seine, surface methods, or longline), *k* is the fishing territory (inside or outside the U.S. exclusive economic zone), and *l* is the year (1996-2015), and *n* is the fuel type (heavy fuel oil, marine diesel oil, marine gas oil, or ultra-low sulfur diesel).

The activity based methodology includes vessel registry data and fleet logbook data for fishing effort. The vessel registry data includes engine speed and fuel quality (Table A.8), and main engine power (Table A.9).

The following equation was used to calculate the engine load factor for each fleet :

$$LF_{i,j,k}^{avg} = L_{max} \cdot \left(\frac{v_{avg_{i,j,k}}}{v_{d_{i,j,k}}} \right)^3 \qquad (3)$$

where v_{acg} is the vessel's average speed, v_d is the vessel's design speed, L_{max} is the fraction of maximum engine power used at a vessel's design speed, *i* is the fishing region (Western Central Pacific Ocean convention area, American Samoa, Hawaii, and the North Pacific region of North America), *j* is the fishing gear (pole-and-line, troll, purse seine, surface methods, or longline), and *k* is the fishing territory (inside or outside the U.S. exclusive economic zone).

The fraction of maximum engine power used at a vessel design speed, 90%, was taken from *[Goldsworthy and Goldsworthy, 2015]*. The vessel average speed and vessel design speed was obtained from the Marine Traffic database *[Marine Traffic, 2017]* (Table A.10).

Fishing effort was obtained from the logbooks for each fleet operating within their respective domains (Table A.11), fleets operating in the U.S. EEZ (Table A.12), and fleets operating on the high sea (Table A.13). Catch statistics were also obtained for each fleet operating within their respective domains (Table A.14-A.20), for fleet fishing activity within the U.S. EEZ (Tables A.21 and A.22) and fleet fishing activity outside the U.S. EEZ (Tables A.23 and A.24). The specific fuel oil consumption (SFOC) data was obtained from *[ICF International, 2009]*. The SFOC is 213 and 203 g kWh^{-1} for HFO and distillates, respectively. Weighted averages of the fuel product densities of distillates and HFO were taken from the Petroleum Refinery Life Cycle Inventory Model (PRELIM) simulations (Table A.25) used in this study.

2.3.2. Fuel cycle phases.

2.3.2.1. Crude oil refinery climate forcing.

The following formula was used to estimate the relative contributions to each climate forcing constituent for the refinery process (CF^{ref}, in g CO_2e per liter of fuel) using the following formula:

$$CF_{n,o,p,q}^{ref} = EF^{GHG,ref} \cdot f_o^{alloc,ref} \cdot LHV_{n,p} \cdot \rho_{n,p} \cdot GWP_{o,q} \qquad (4)$$

where $EF^{GHG,ref}$ is the GHG emission factor for fuel refining (in g CO_2e per MJ fuel product), $f^{alloc,ref}$ is the fraction of each climate forcing constituent that can be allocated to the refining

GHG emission factor (in g pollutant per g CO_2e), *n* is the fuel type (ULSD, MGO, MDO, and HFO), *o* is the constituent (CO_2, CH_4, N_2O, NOx, SO_2, OC, and BC), *p* is the fuel sulfur level, and *q* is the time horizon (20-y or 100-y).

PRELIM was used to simulate the fuel product densities (Table A.26), lower heating values (Table A.27), and GHGs (Tables A.28-A.32) for this analysis *[Abella and Bergerson, 2012]*. In the simulations, 62 different oil field assays, two different refinery types (hydro-cracking and coking), and a variety of refinery configurations for each product slate were selected (Table A.33). To reflect differences of the conversion configuration, a mix of refinery processes and fuel blends were used 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 A.34). The mean values and 95% confidence intervals for the crude oil refinery GHG emission factors, fuel product lower heating values, fuel product densities (Table A.35), and GWPs (Table A.36) were used as inputs to Eq. 4.

2.3.2.2. Crude oil extraction climate forcing.

The following formula was used to estimate the relative contributions to each climate forcing constituent for crude oil extraction, CF^{ext} (in g CO_2e per liter of fuel) using the following formula:

$$CF^{ext}_{n,o,p,q} = EF^{GHG,ext} \cdot f^{alloc,ext}_{o} \cdot r^{feed}_{n} \cdot LHV_{n,p} \cdot \rho_{n,p} \cdot GWP_{o,q} \qquad (5)$$

where $EF^{GHG,ext}$ is the GHG emission factor for crude extraction (in g CO_2e per MJ crude oil), $f^{alloc,ext}$ is the fraction of each climate forcing constituent that can be allocated to the GHG emission factor (in g pollutant per g CO_2e), r^{feed} is the ratio of crude feed input to the fuel product output (in MJ crude per MJ fuel product), *LHV* is the lower heating value (in MJ per kg), ρ is the fuel density (in kilograms per liter), *GWP* is the global warming potential (in g CO_2e per g pollutant), *n* is the fuel type (ULSD, MGO, MDO, and HFO), *o* is the constituent (CO_2, CH_4, N_2O, NOx, SO_2, OC, and BC), *p* is the fuel sulfur level, and *q* is the time horizon (20-y or 100-y).

The crude extraction emissions were matched to the corresponding oil field assays used in the refinery emissions analysis. The inputs to Eq. 5 include the crude oil extraction emissions data from the literature and technical reports (Table A.37), calculated mean values and 95% confidence intervals for the crude oil extraction GHG emission factors (Table A.38) and GWP values (Table A.36), the ratio of crude feed input to the fuel product output obtained in PRELIM (Table A.35), and the crude oil GHG emissions allocated to each climate forcing constituent using the pump-to-well crude oil emission factor provided in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model *[Wang, 2011]*.

2.3.2.3. Vessel exhaust climate forcing.

The exhaust emissions, CF^{exh} (in grams CO_2e per liter), were calculated using the following formula:

$$CF^{exh}_{n,o,p,q,r} = EF^{exh}_{n,o,r} \cdot \rho_n \cdot GWP_{o,q} \tag{6}$$

where EF^{exh} is the exhaust emission factor (in g CO_2e per kg fuel), ρ is the fuel density (in kg per liter), *GWP* is the global warming potential (in g CO_2e per g pollutant), *n* is the fuel type (ULSD, MGO, MDO, and HFO), *o* is the constituent (CO_2, CH_4, N_2O, NOx, SO_2, OC, and BC), *p* is the fuel sulfur level, *q* is the time horizon (20-y or 100-y), and *r* is the engine type including medium-speed diesel (MSD) or high-speed diesel (HSD) engines.

To estimate the LLCF and NOx vessel-exhaust emissions of the U.S. tuna fleet the emission factors (Table A.39) and GWPs (Table A.40) were obtained in technical reports and the literature. The mean and 95% confidence intervals of recently published plume sampling studies were calculated for the estimates of BC: 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; Cappa et al., 2014]*. The remaining SLCF emissions, OC and SO_2, were estimated with Eqs. 7 and 8.

The sulfur dioxide (SO_2) exhaust emissions, EF^{exh,SO_2} (in gram SO_2 per kilogram fuel), are directly related to fuel sulfur *[Faloona, 2009; Lack and Corbett, 2012]* and were calculated using the following equation:

$$EF_{n,p}^{exh,SO_2} = f_n^S \cdot 2 \cdot f^{SO_2} \qquad (7)$$

where f^S is the fuel sulfur fraction (g S/kg fuel), 2 is the ratio of molecular weights of SO_2 to S, f^{SO2} is the fraction of fuel sulfur emitted as SO_2 (97.8%) *[ICF International, 2009]*, *n* is the fuel type (ULSD, MGO, MDO, and HFO), and *p* is the fuel sulfur level.

The emission factor for OC, EF^{OC} (in grams OC per kilogram fuel), was calculated using the following equation:

$$EF_r^{exh,OC} = EF_r^{exh,BC} \cdot \frac{POM}{1.2 \cdot BC} \quad (8)$$

where *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).

2.3.3. Total fuel-cycle climate forcing over time.

The total-fuel cycle climate forcing over time (1996-2015) by marine fuel type (distillates and HFO), fishing territory (U.S. EEZ and high sea) and engine type (MSD and HSD) on a 20-y and 100-y time horizon was calculated using the following formula:

$$CF_{k,l,q,r,s}^{tot,ts} = \sum_n \sum_p f_{k,l,n,p}^{FQ} \cdot CF_{n,p,q,r}^{tot,net} \quad (9)$$

where f^{FQ} is the fraction used to model the fuel quality (fuel sulfur level), $CF^{tot,net}$ (in g CO_2e per liter of fuel) is the net (sum of all climate forcing constituents) total fuel-cycle climate forcing, *k* is the fishing territory (inside or outside the U.S. exclusive economic zone), *l* is the year (1996-2015), *n* is the fuel type (ULSD, MGO, MDO, and HFO), *o* is the constituent (CO_2, CH_4, N_2O, NOx, SO_2, OC, and BC), *p* is the fuel sulfur level, *q* is the time horizon (20-y or 100-y), *r* is the engine type including medium-speed diesel (MSD) or high-speed diesel (HSD) engines, and *s* is the weighted mean of the fuel quality of marine fuels (distillates or HFO).

To construct historical (1996-2015) fuel sulfur levels for each fishing territory, data found in technical reports, the literature, and statistics from the U.S. Energy Information Administration

(Tables A.41 and A.42) was used. Weighting factors were used 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 A.43-A.46).

2.3.4. Climate forcing of tuna protein over time.

The protein-and-species-specific climate forcing of tuna over time (1996-2015) on 20-y and 100-y time horizons was calculated using Eqs. 10 and 11. Eq. 10 considers the scenario that is inclusive of all fishing territories:

$$CF_{i,j,l,m,q}^{t,prot} = \frac{\left[\sum_{k}^{2} M_{i,j,k,l}^{catch}\left(\sum_{r}^{2}\sum_{s}^{2} f_{k,l,r,s}^{char} \cdot CF_{k,l,q,r,s}^{tot,ts}\right)\right] \cdot FUI_{i,j,l,m}}{f^{yield} \cdot f^{prot}} \cdot \frac{1\ t\ fish}{10^3\ kg\ fish} \cdot \frac{1\ kg\ CO_2e}{10^3\ kg\ CO_2e} \qquad (10)$$

Eq. 11 considers the scenarios that are specific to fishing territories inside and outside the U.S. EEZ:

$$CF_{i,j,k,l,m,q}^{t,prot,terr} = \frac{\left(\sum_{r}^{2}\sum_{s}^{2} f_{k,l,r,s}^{char} \cdot CF_{k,l,q,r,s}^{tot,ts}\right) \cdot FUI_{i,j,k,l,m}}{f^{yield} \cdot f^{prot}} \cdot \frac{1\ t\ fish}{10^3\ kg\ fish} \cdot \frac{1\ kg\ CO_2e}{10^3\ kg\ CO_2e} \qquad (11)$$

where M^{catch} is the mass of tuna or pelagic species catch (in metric tons per year), f^{char} is the fuel and engine type characteristics of each fleet,), f^{yield} is the retail yield of landed tuna, f^{prot} is the fraction of the retail yield that is protein, *i* is the fishing region (Western Central Pacific Ocean convention area, American Samoa, Hawaii, and the North Pacific region of North America), *j* is the fishing gear (pole-and-line, troll, purse seine, surface methods, or longline), *k* is the fishing territory (inside or outside the U.S. exclusive economic zone), *l* is the year (1996-2015), *q* is the time horizon (20-y or 100-y), *r* is the engine type including medium-speed diesel (MSD) or high-speed diesel (HSD) engines, and *s* is the weighted mean of the is the weighted mean fuel quality of the marine fuels (distillates or HFO).

The inputs to Eqs. 10 and 11 include the results of the catch analysis, the results of the combined fuel quality and engine speed analysis (Table A.8), the results of the total fuel-cycle analysis, and the FUI analysis.

2.3.5. Comparison to other protein sources.

The climate forcing per unit tuna protein was compared to other protein sources using the following equation:

$$CF_t^{f,prot} = \sum_u \sum_v GHG_t^{prot,100-y} \cdot f_{t,u}^{alloc} \cdot f_{u,v}^{GHG,alloc} \cdot \frac{GWP_v^{20-y}}{GWP_v^{100-y}} \quad (12)$$

where $GHG^{prot,100\text{-}y}$ is the greenhouse gas emissions for a given protein source on a 100-y time horizon, f^{alloc} is the fraction of GHGs allocated to a particular farm activity, $f^{GHG,alloc}$ is the allocation of a farm activity to a GHG emission, $GWP^{20\text{-}y}$ is the global warming potential of a gas constituent on a 20-y time horizon, and $GWP^{100\text{-}y}$ 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 (CO_2, CH_4, and N_2O).

The inputs to Eq. 12--GHG emissions of farmed protein sources, the fraction of GHG emissions allocated to farming activities, and those allocated to each GHG constituent--are the results of literature review, statistical analyses, and calculations to normalize the emissions per unit protein (Tables A.47-A.52). To estimate the climate forcing on a 20-y time horizon, the global scale GWPs were used (Table A.36).

2.3.6. Construction of confidence intervals.

95% confidence intervals of the FUI, total fuel-cycle climate forcing, climate forcing of tuna protein, and farm-raised animal protein were constructed by calculating the standard error of the mean. The error was propagated for selected variables using the derivative method *[Bevington and Robinson, 2003]*. This method was applied to the fuel consumption, total-fuel cycle climate forcing, and the climate forcing of tuna protein. In the calculation of the fuel consumption (Eq. 2), the error was propagated for the main engine power, engine load factor, and fuel density variables. In the calculation of the total fuel-cycle climate forcing (Eqs. 4-6), the error was propagated for crude oil extraction emission factors, crude oil refining emission factors, the lower heating values, fuel densities, the emissions of BC, and the GWP of SLCF variables. In the calculation of the climate forcing of tuna protein (Eqs. 10 and 11), the error was propagated for the FUI and the total fuel-cycle climate forcing variables.

2.3.7. Hypothesis testing.

An independent-sample, single-tailed, unequal variance student t-test was used to test a one-sided hypothesis according to the following formula *[Ross, 2004]*:

$$H_0: \mu_x \leq \mu_y \;\; versus \; H_1: \mu_x > \mu_y; \text{ reject } H_0 \text{ if } T \geq t_{\alpha,n+m-2} \qquad (13)$$

where H_0 is the null hypothesis, H_1 is the alternative hypothesis, T is the student-t test value, $t_{\alpha,n+m-2}$ is the critical t-value, α is the significance level, n is the number of observations in the first sample, m is the number of samples in the second sample, μ_x is the population of the first sample, and μ_y is the population mean of the second sample.

The probability of a higher value of the t-statistic was calculated under the assumption that the samples are from populations with the same mean using the "T.TEST" function available in Microsoft Excel. Here, the probability is given that the t-test is greater than the critical t-value, and thus the null hypothesis (climate impact of tuna protein: caught with less selective gears is less than or equal to that caught with highly selective gears; that caught by vessels using high sulfur fuel is less than or equal to that caught by vessels using low sulfur fuel; and that caught in EEZs is less than or equal to that caught on the high sea) is rejected. In order to test that the sample inputs in the student t-tests have normal distributions, Kolmogorov–Smirnov statistics were computed.

2.4. Results

2.4.1. Fuel use intensity (FUI).

The results show wide variation in the fuel use intensity (FUI) with respect to gear types and species (Table 2.1, Figs. 2.5.1). Here, an emphasis was placed on skipjack and albacore because there are multiple fleets that target these species, allowing a comparison across practices. Among skipjack tuna in the Pacific, the FUIs of the Hawaii pole-and-line and American Samoa troll gears (519 ± 206 and 2354 ± 357 liters fuel / metric ton tuna, respectively; 5-y mean ± 95% confidence interval) are roughly 2 and 9 times larger than the U.S. purse-seine fleet (266 ± 23 liters fuel / metric ton tuna). In contrast, the FUI of the American Samoa longline fleet (798 ± 163 liters fuel / metric ton tuna) is 1.4 times higher than the FUI of North Pacific surface methods fleet (573 ± 83 liters fuel / metric ton tuna).

The FUIs of four fleets that operate on the high sea was also estimated and compared to three U.S. EEZ fleets that use the same gear types and target the same species (Fig. 2.5.2). Over time (1996-2015), with the exception of the U.S. EEZ (Hawaii) pole-and-line fleet, the FUIs of the fleets that operate on the high sea have a higher FUI than their counterparts that operate in the U.S. EEZ. The international purse-seine and U.S. purse-seine fleets operating on the high seas have FUIs (235 ±20 and 273 ±24 liters fuel / metric ton tuna, respectively) that are 1.5 and 1.8 times higher than the U.S. EEZ purse-seine fleet (124 ±14 liters fuel / metric ton tuna) (Fig. 2.5.2D).

Table 2.1: *Literature values of fuel use intensity (FUI) of tuna and pelagics and comparisons to this study by region or Ocean, primary tuna target and gear type.*

Region/Ocean	Primary Target	FUI (l fuel t tuna^{-1})	Source
		Purse-seine	
Pacific	Skipjack	349	*[Tyedmers and Parker, 2012]*
Pacific	Yellowfin	362	*[Tyedmers and Parker, 2012]*
Pacific	Skipjack/Yellowfin	527	*[Hospido et al., 2006]*
Pacific	Tuna	412	*[Wilson et al., 2009]*
Pacific	Skipjack	797	*[Avadi et al., 2015]*
Pacific	Skipjack	868	*[Avadi et al., 2015]*
	Small pelagics	71	*[Parker and Tyedmers, 2015]*
Pacific	Bigeye/Skipjack/Yellowfin	325 (± 28)[a]	This study, U.S. fleet
Pacific	Skipjack	266 (± 23)[b]	This study, U.S. fleet
		Troll	
	Large pelagics	1612	*[Parker and Tyedmers, 2015]*
Atlantic	Albacore/Skipjack	1107	*[Tyedmers and Parker, 2012]*
Atlantic	Bluefin/Albacore	1136	*[Basurko et al., 2013]*
Pacific	Skipjack/Yellowfin	3896 (± 590)[a,c]	This study, American Samoa fleet
Pacific	Skipjack	2354 (± 357)[b]	This study, American Samoa fleet
Pacific	Albacore/Bigeye/Yellowfin/Skipjack	1805 (± 713)[a,d]	This study, Hawaii fleet
Pacific	Yellowfin	1214 (± 480)[b]	This study, Hawaii fleet
Pacific	Albacore	573 (± 83)	This study, North Pacific fleet
		Pole-and-line	
Atlantic	Albacore	1485	*[Tyedmers and Parker, 2012]*
Atlantic	Bluefin/Albacore	1080	*[Basurko et al., 2013]*
Asia	Large pelagics	1925	*[Parker and Tyedmers, 2015]*
Europe	Large pelagics	1745	*[Parker and Tyedmers, 2015]*
Oceana	Large pelagics	1676	*[Parker and Tyedmers, 2015]*
North America	Large pelagics	1495	*[Parker and Tyedmers, 2015]*
Indian	Skipjack	356	*[Horne-Sparboth, T., Adam, M. S., Ziyad, 2015]*
Pacific	Skipjack/Yellowfin	579 (± 230)[a]	This study, Hawaii fleet
Pacific	Skipjack	519 (± 206)[b]	This study, Hawaii fleet
		Longline	
Pacific	Albacore	1135	*[Tyedmers and Parker, 2012]*
Pacific	Albacore	1915	*[Krampe, 2006]*
Pacific	Bluefin/Bigeye	3660	*[Krampe, 2006]*
Pacific	Tuna	1765	*[Wilson et al., 2009]*
Pacific	Albacore/Bigeye/Yellowfin/Skipjack	1057 (± 216)[a,e]	This study, American Samoa fleet
Pacific	Albacore	798 (± 163)[b]	This study, American Samoa fleet
Pacific	Albacore/Bigeye/Yellowfin/Skipjack	1938 (± 181)[a]	This study, Hawaii fleet
Pacific	Bigeye	1629 (± 152)[b]	This study, Hawaii fleet

[a]FUI estimate of all tuna species.

[b]FUI estimate of specific tuna species by mass allocation.

[c]FUI estimate of tuna by mass allocation of tuna relative to all pelagics; 5-y mean FUI and 95% confidence interval of all pelagics 4747 (± 719) l fuel / t tuna.

[d]FUI estimate of tuna by mass allocation of tuna relative to all pelagics; 5-y mean FUI and 95% confidence interval of all pelagics 3514 (± 1388) l fuel / t tuna.

[e]FUI estimate of tuna by mass allocation of tuna relative to all pelagics; 5-y mean FUI and 95% confidence interval of all pelagics 1113 (± 228) l fuel / t tuna.

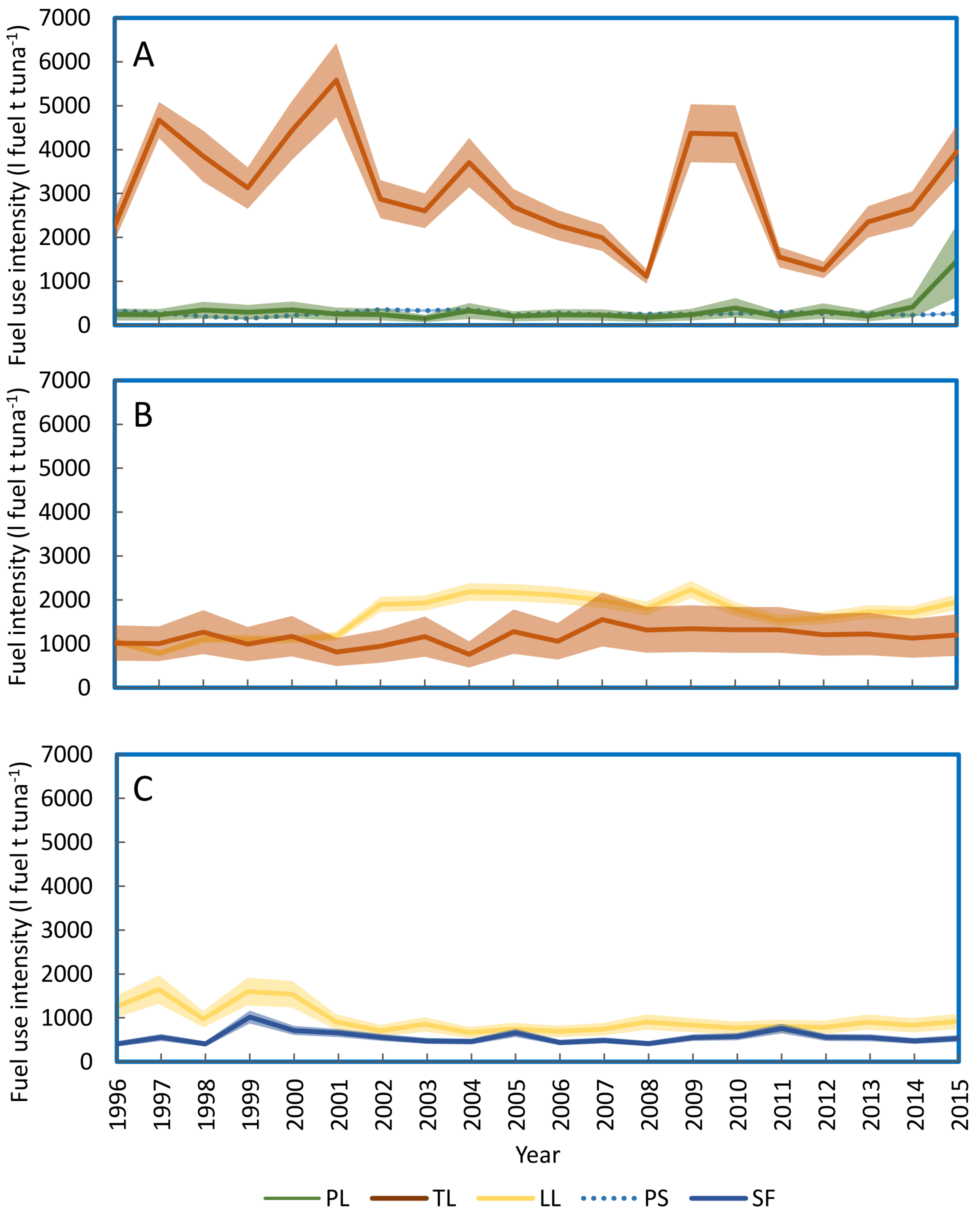

Figure 2.1: *Fuel use intensity (FUI) of five different fishing gears used to catch four different species of tuna in selected regions of the Pacific Ocean. The fishing gears include highly selective gears—pole and line (PL), troll (TL), and surface methods (SF) that include both TL and hook-and-line—and less selective gears—purse seine (PS) and longline (LL). The tuna species include skipjack (SKJ), albacore (ALB), big eye (BET), and yellowfin (YFT). The selected fishing regions include the Western and Central Pacific Fisheries Commission convention area (WCPFC-CA), American Samoa (AS), Hawaii (HI), and the North Pacific (NP) coastline of North America. (A) SKJ caught by the AS TL, HI PL, and U.S. PS fleets; (B) BET caught by the HI LL and YFT caught by the HI TL fleets; and (C) ALB caught by the AS LL and NP SF fleets. The shaded regions represent the 95% confidence interval.*

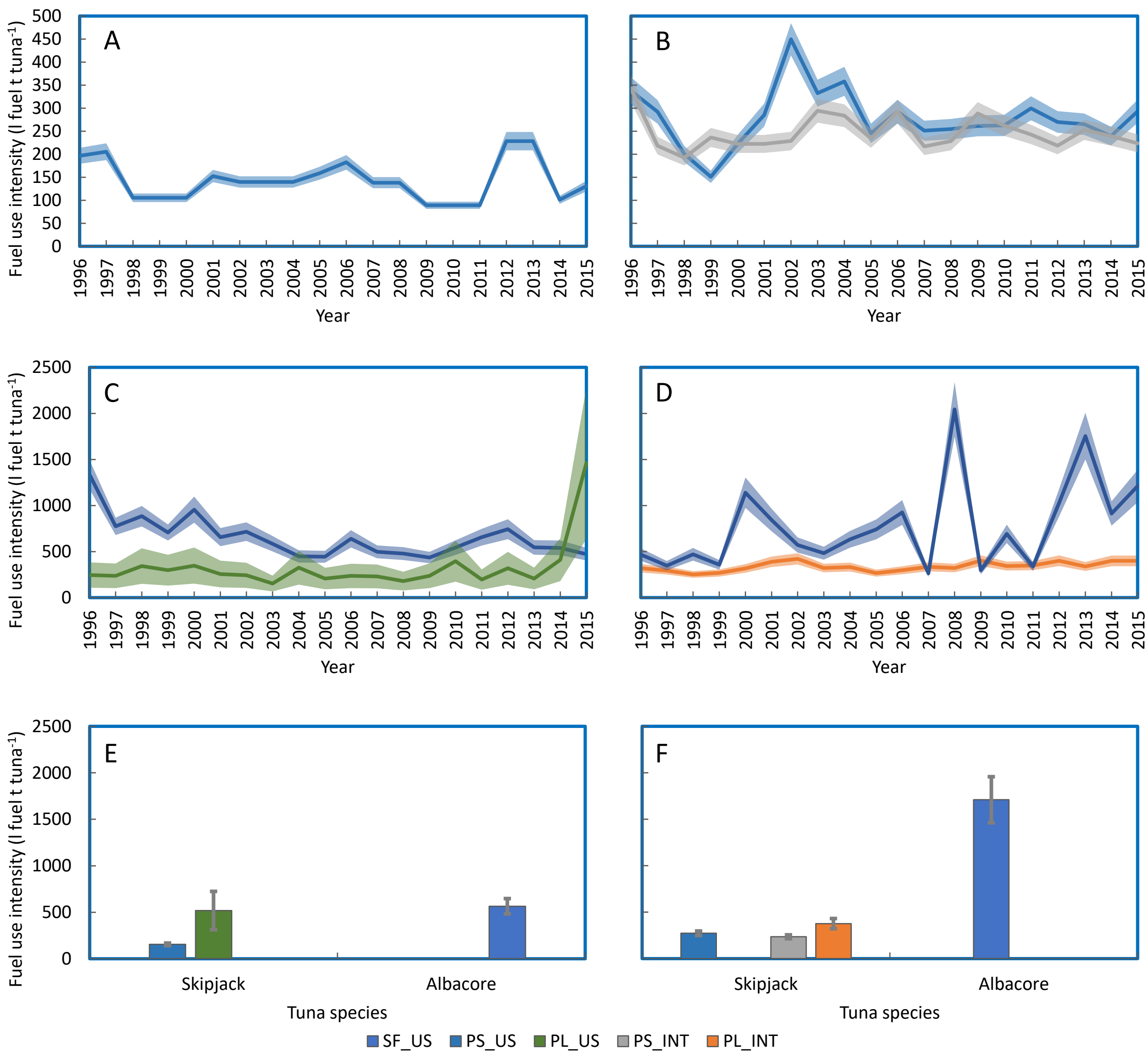

Figure 2.2: *Fuel use intensity (FUI) by gear type of fleets operating inside and outside the U.S. exclusive economic zone (EEZ). The fishing gear types include purse seine (PS), pole and line (PL), and surface methods (SF) which include PL and troll gears. Left panels (A,C,E): FUI of U.S. fleets operating in the U.S. EEZ. Right panels (B,D,F): FUI of U.S. fleets operating outside the U.S. EEZ. The international (INT) PL (PL_INT) and PS (PS_INT) FUIs represent activity by all flagged fleets operating only on the high sea whereas the U.S. fleets operate on the high sea and the EEZs of other countries outside the U.S. Top panels (A,B):FUIs of the U.S. PS (PS_US), and INT PS (PS_INT) fleets. Middle panels (C,D): U.S. PL, INT PL, and the North Pacific SF fleets. Bottom panels (E,F): Mean values (2011-2015). The error bars and shaded regions represent the 95% confidence interval.*

2.4.2. Fuel-specific climate forcing.

The fuel-specific climate forcing (g CO_2e / l fuel) of the individual contributions of the life-cycle phases of crude oil extraction, crude oil refining, and fuel combustion of four different marine fuels with varying fuel quality (levels of fuel sulfur) was quantified.

2.4.2.1. Crude oil extraction climate forcing.

The fuel-specific climate forcing of the crude oil extraction phase was dominated by CO_2 and CH_4 emissions (Fig. 2.5.3). The extraction emissions for a wide range of fuel types (ultra-low-sulfur diesel, marine gas oil, marine diesel oil, and heavy fuel oil) and fuel sulfur levels (0.0015 - 3.5% wt.) were relatively similar.

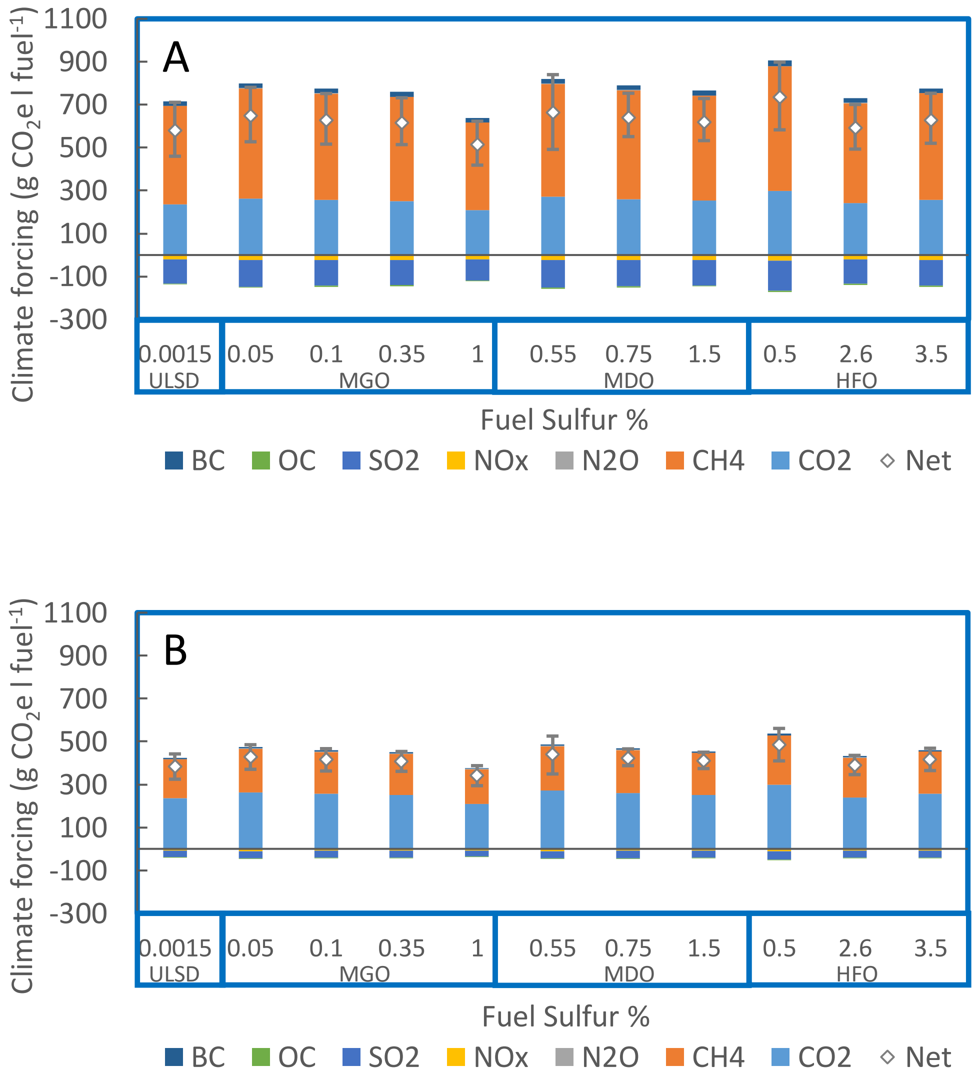

Figure 2.3: *Climate forcing for extraction of crude oil phase of the fuel cycle of ultra-low-sulfur diesel (ULSD), marine gas oil (MGO), marine diesel oil (MDO), and heavy fuel oil (HFO) with varying levels of fuel sulfur by chemical constituent. The chemical constituents include black carbon (BC), organic carbon (OC), sulfur dioxide (SO2), nitrogen oxides (NOx), nitrous oxide (N2O), methane (CH4), and carbon dioxide (CO2). Top panel: (A) 20-y time horizon. Bottom panel: (B) 100-y time horizon. The error bars represent the 95% confidence interval.*

2.4.2.2. Crude oil refining climate forcing.

The fuel-specific forcing of the crude oil refining phase was primarily associated with CO_2 emissions and was closely related to the fuel type and sulfur levels (Fig. 2.5.4). Climate forcing from refining activities were comparable in magnitude to oil extraction for more heavily processed fuels (ultra-low-sulfur diesel and low-sulfur marine gas oil) but an order of magnitude smaller for heavy fuel oil. For a given fuel type, decreasing sulfur content in the processed fuel required additional refinery processes that increased refinery climate forcing by up to 50%.

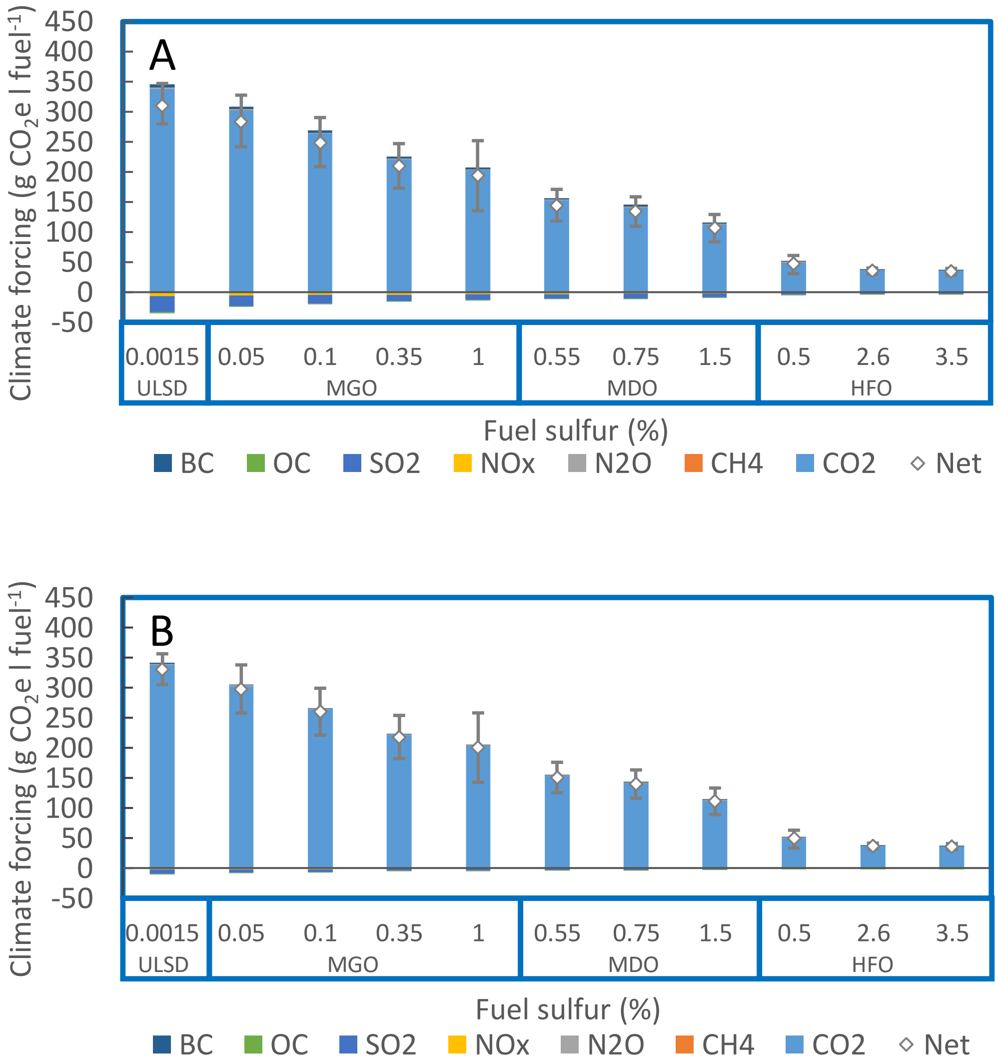

Figure 20.4: *Climate forcing for refinery phase of the fuel-cycle of ultra-low-sulfur diesel (ULSD), marine gas oil (MGO), marine diesel oil (MDO), and heavy fuel oil (HFO) with varying levels of fuel sulfur by chemical constituent. The chemical constituents include black carbon (BC), organic carbon (OC), sulfur dioxide (SO2), nitrogen oxides (NOx), nitrous oxide (N2O), methane (CH4), and carbon dioxide (CO2). Top panel: (A) 20-y time horizon. Bottom panel: (B) 100-y time horizon. The error bars represent the 95% confidence interval.*

2.4.2.3. Vessel-exhaust climate forcing.

While the crude oil extraction and crude oil refining phases consistently result in a positive climate forcing, the emissions from the fishing vessel-exhaust phase exhibit much greater variation (Fig. 2.5.5). The vessel-exhaust emissions of low sulfur fuels have positive climate forcing that is generally an order of magnitude larger than extraction and refining. However, for some high sulfur variants of marine diesel oil and heavy fuel oil, the climate forcing is close to zero or even negative, largely due to the offsetting climate effect of SO_2 emissions. For all fuel types, the dominant warming constituent is CO_2 followed by BC. The fuel-exhaust climate forcing of fishing vessels operating with medium-speed diesel (MSD) engines is as much as 3.7 and 1.2 times higher than fishing vessels operating with high-speed diesel (HSD) engines on a 20-y and 100-y time horizon, respectively. This can be attributed to the fact that HSD diesel engines are known to produce lower emissions of BC and OC pollutants than MSD diesel engines *[Lack et al., 2008; Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014]*.

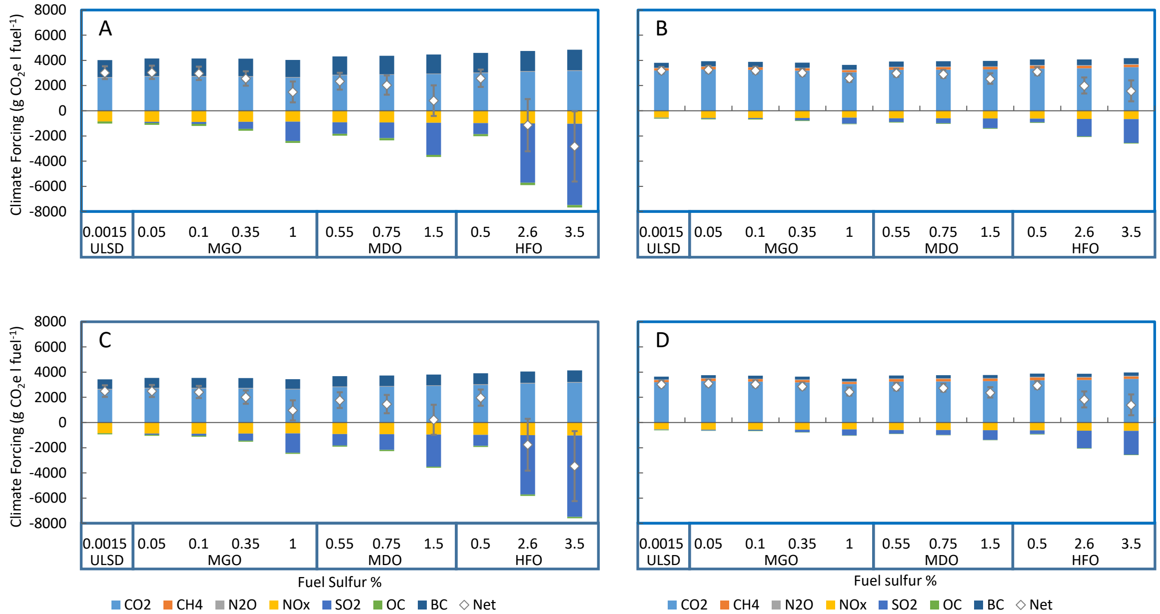

Figure 2.5: *Climate forcing of the vessel exhaust phase of the fuel-cycle of marine fuels by chemical constituent, marine fuel types, engine characteristics, and time horizons. The marine fuels include distillates and heavy fuel oil (HFO). The distillates include ultra-low sulfur diesel (ULSD), marine gas oil (MGO), and marine diesel oil (MDO). The chemical constituents include black carbon (BC), organic carbon (OC), sulfur dioxide (SO2), nitrogen oxides (NOx), nitrous oxide (N2O), methane (CH4), and carbon dioxide (CO2). The engine characteristics include medium-speed diesel (MSD) and high-speed diesel (HSD) engines. Top panels (A,B): total fuel-cycle climate forcing of medium speed diesel engines. Bottom panels (C,D): total fuel-cycle climate forcing of high speed diesel engines. Left panels (A,C): 20-y time horizon. Right panels (B,D): 100-y time horizon. The error bars represent the 95% confidence interval.*

2.4.2.4. Overall fuel-specific climate forcing.

The overall fuel-specific climate forcing from the combined impacts of crude oil extraction, crude oil refining, and fishing vessel fuel-exhaust emissions is closely related to fuel sulfur content (Fig. 2.5.6). Low sulfur marine fuels (fuel sulfur ≤ 0.1% wt.) emit nearly 4000 g CO_2e l $fuel^{-1}$, while higher sulfur fuels have a negative climate forcing (in the case of a 20-y time horizon) due to cooling constituents including SO_2 and OC (Fig. 2.5.6A-2.5.6D). In the case of a 100-y time horizon, the emissions of high sulfur marine fuels are roughly 50% lower than low sulfur marine fuels (Fig. 2.5.6E-2.5.6H). The total fuel-cycle climate forcing of fishing vessels operating with MSD engines is as much as 1.6 and 1.1 times higher than fishing vessels operating with HSD engines on a 20-y and 100-y time horizon, respectively (Figs. 2.5.6A, 2.5.6C, 2.5.6E, and 2.5.6G). The vessel fuel-exhaust phase is the largest component of the overall life-cycle climate forcing (Figs. 2.5.6B, 2.5.6D, 2.5.6F, and 2.5.6H). With the exception of higher sulfur fuels in the case of the 20-y time horizon (Figs. 2.5.6B and 2.5.6D), the other phases are responsible for at least 20% of the climate forcing.

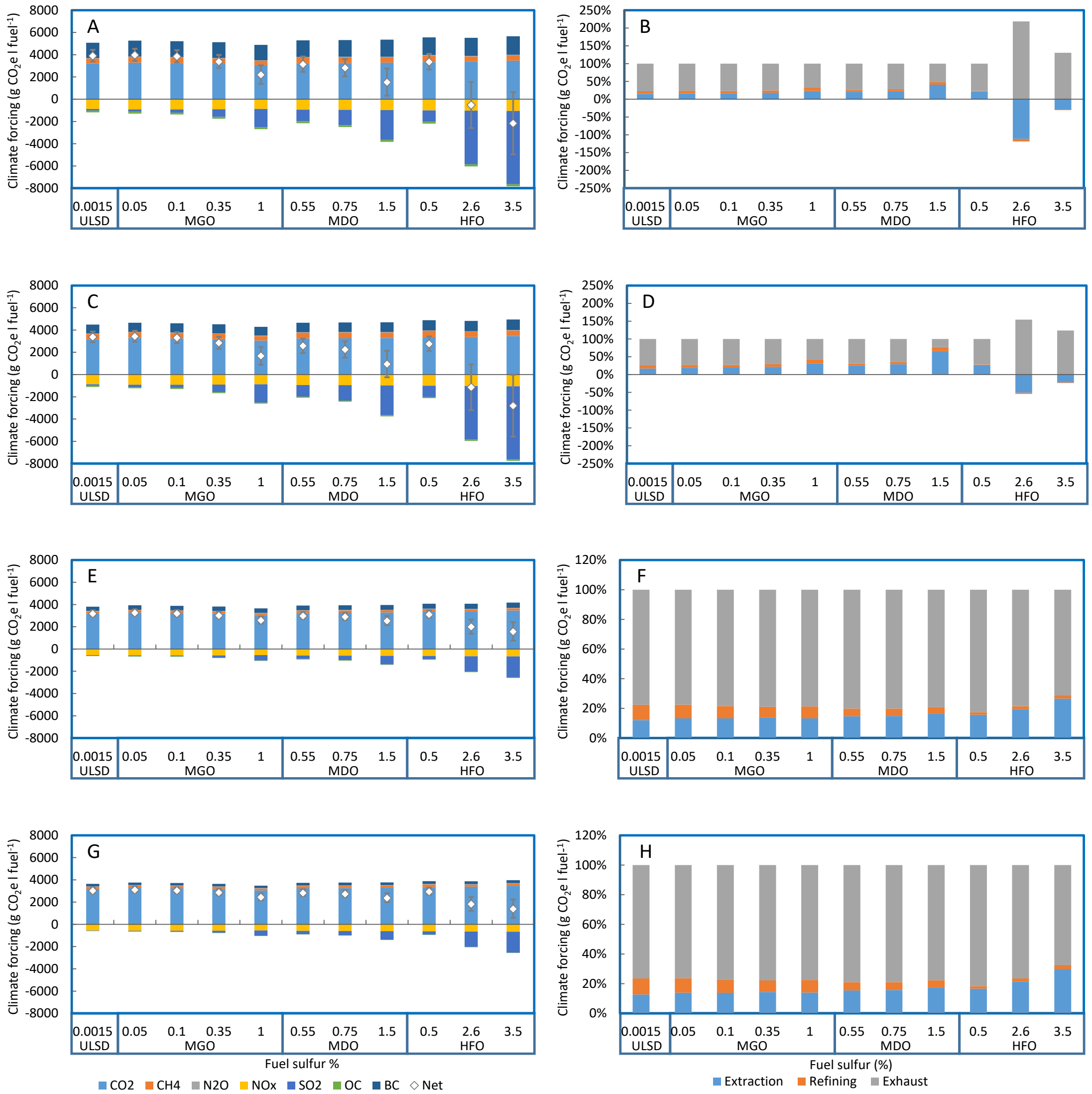

Figure 2.6: *Total fuel-cycle (crude oil extraction, crude refining, and vessel fuel-exhaust emission) climate forcing of marine fuels by chemical constituent , marine fuel type, and engine characteristics on 20-y and100-y time horizons. The marine fuels include distillates and heavy fuel oil (HFO). The distillates include ultra-low sulfur diesel (ULSD), marine gas oil (MGO), and marine diesel oil (MDO). The chemical constituents include black carbon (BC), organic carbon (OC), sulfur dioxide (SO2), nitrogen oxides (NOx), nitrous oxide (N2O), methane (CH4), and carbon dioxide (CO2). The engine characteristics include medium-speed diesel (MSD) and high-speed diesel (HSD) engines. Left panels (A,C): total fuel-cycle climate forcing by chemical constituent. Right panels (B,D): mean percent (%) contribution of each phase to the total fuel-cycle climate forcing. First and third rows (A,B,E,F): total-fuel climate forcing of MSD engines. Second and fourth rows (C,D,G,H): total fuel-cycle climate forcing of HSD engines. 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 error bars represent the 95% confidence interval.*

2.4.3. Total fuel-cycle climate forcing over time.

The mean total fuel-cycle climate forcing of fishing vessels over time (1996-2015) by engine type (medium-speed diesel and high-speed diesel), by marine fuel (distillates and heavy fuel oil), and by fishing territory (U.S. EEZ and high seas) was constructed on 20-y and 100-y time horizons (Figs. 2.5.7). Across the scenarios considered here, the trend is an increase in climate forcing over time due to the decrease in fuel sulfur. The progressive decreases in fuel sulfur are a result of the U.S. Environmental Protection Agency regulations under the authority of the Clean Air Act. In the case of fishing vessels operating with distillates, the increase in climate forcing over the 20-y time period is as much as 141% and 25% for the 20-y and 100-y time horizons, respectively (Figs. 2.5.7A, 2.5.7B, 2.5.7E and 2.5.7F). In the case of fishing vessels operating with heavy fuel oil, the climate forcing increased over the 20-y time series by as much as 250% and 28% for the 20-y and 100-y time horizons, respectively (Fig. 2.5.7C, 2.5.7D, 2.5.7G and 2.5.7H). The uncertainty for the 95% confidence intervals decreased over the 20-y time series due to a reduction in SO_2 emissions which has the highest uncertainty with respect to the GWP among the climate forcing constituents (Figs. 2.5.7C and 2.5.7D).

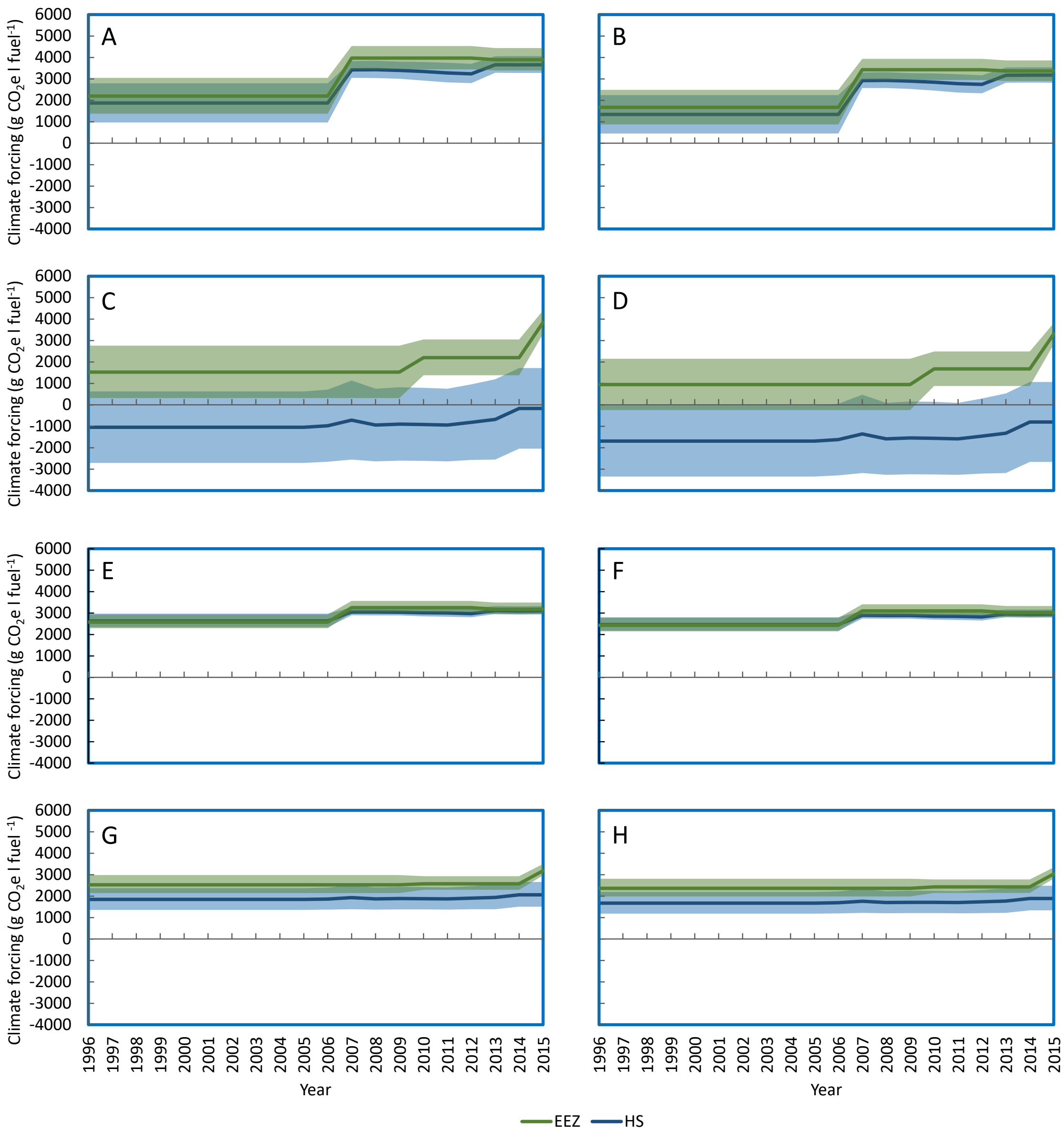

Figure 2.7: *Mean climate forcing associated with the total fuel-cycle (crude oil extraction, crude refining, and vessel fuel-exhaust emission) of marine fuels over time (1996-2015) on 20-y and 100-y time horizons by engine characteristics and fishing territories. The mean and CI values represent the 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 the high sea (HS). The engine characteristics include medium speed diesel (MSD) and high speed diesel (HSD) engines. Left panel (A,C): MSD engines. Right panel (B,D): HSD engines. First and third rows (A,B,E,F): Distillate fuels. Second and fourth rows (C,D,G,H): (A,B): 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.*

2.4.4. Climate forcing of tuna protein.

The FUIs and the total fuel-cycle climate forcing were combined to estimate the climate forcing of tuna protein over time on 20-y and 100-y time horizons. The climate forcing of the three proposed sustainability practices including selective gear, reduced fuel sulfur, and restricted high seas fishing were considered.

In the first case, fleets targeting the same species were considered and the climate impact of those using highly selective gears were compared to those using less selective gears (Fig. 2.5.8). It was found that the climate forcing of skipjack tuna protein caught by the fleets using highly selective gears was, in some cases, significantly higher (p values of 4.8×10^{-2} and 7.7×10^{-8} on a 20-y time horizon; and p values of 1.4×10^{-1} and 1.3×10^{-9} on a 100-y time horizon for the Hawaii pole-and-line and American Samoa troll fleets, respectively) than the U.S. purse-seine fleet (Table 2.2). In the case of albacore tuna protein, however, a consistent difference between the less selective and highly selective gears was not found.

In the second case, we compared the climate impact of tuna protein caught by fleets that operate in territories that allow the use of high sulfur marine fuels to the climate impact of tuna protein that is caught within the U.S. EEZ where the sulfur levels in fuel are strictly regulated, on 20-y and 100-y time horizons (Fig. 2.5.9). While several of the fleets that were considered for this analysis travel outside the U.S. EEZ (U.S. purse-seine, American Samoa longline, Hawaii longline, and North Pacific surface methods), only two operate in regions that have differing fuel quality (U.S. purse-seine and Hawaii longline). In both of these fleets, the climate forcing of tuna protein is higher in regions requiring low sulfur fuels than in regions that allow high sulfur fuels on a 20-y time horizon (Fig. 2.5.9A, 2.5.9C, and 2.5.9E). Only the U.S. purse-seine fleet has a significantly higher value on a 20-y time horizon (p values 2.2×10^{-3} and 1.3×10^{-1} on a 20-y time horizon; and 1.8×10^{-1} and 3.9×10^{-1} on a 100-y time horizon for the U.S. purse-seine and Hawaii longline, respectively) (Table 2.2). In this case, the higher level of significance can be explained by the higher levels of sulfur (and greater cooling effects) in the fuel mix used by the U.S. purse-seine fleet (approximately 15% HFO and 85% distillates), whereas the Hawaii longline fleet only uses distillates with lower levels of sulfur (Table A.8). For the 100-y time horizon, the low sulfur region had a similar climate forcing to the high sulfur region (Fig. 2.5.9B, 2.5.9D, and 2.5.9F).

In the third case, the climate forcing of the four fleets that operate on the high sea (the U.S. purse-seine, the international purse-seine which includes the U.S. PS fleet, the international pole-and-line fleet, and the North Pacific surface methods fleet) was compared to the climate forcing of the three fleets operating in the U.S. EEZ (U.S. purse-seine, Hawaii pole-and-line, and the North Pacific surface methods fleets) (Figs. 2.5.10, and 2.5.11). With the exception of the pole-and-line fleets, the climate forcing from fleets that operate on the high sea have a significantly higher impact than the fleets that operate in the U.S. EEZ.

Table 2.2: *Results of student t-tests by hypothesis and by fleets. Student t-tests are of the type independent-sample, single-tailed, and unequal variance. The sample data includes the 20-y (1996-2015) mean and standard deviations (Std. dev.) of the climate forcing of tuna protein (kg CO2e per kg tuna protein) categories by hypothesis and by fleet. Kolmogorov–Smirnov statistics (K-S stat.) confirm normal distributions.*

Hypothesis	Fleet	Mean	Std. dev.	K-S stat.[a]	Fleet	Mean	Std. Dev.	K-S stat.[a]	p-value[b]
20-y time horizon									
Gear type[c]	US PS[d,e]	6.1	2.1	0.21168	HI PL[f,g]	11	12	0.27864	4.8E-02
Gear type[c]	US PS[d,e]	6.1	2.1	0.21168	AS TL[f,h]	72	37	0.17771	7.7E-08
Gear type[c]	AS LL[d,i]	19	7.0	0.21269	NP SF[f,j]	16	6	0.11872	1.2E-01
Sulfur level[k]	US PS[d,e,l]	8.1	2.5	0.17081	US PS[d,e,m]	6.0	2.1	0.24647	2.2E-03
Sulfur level[k]	HI LL[d,l,n]	36	19	0.15030	HI LL[d,m,n]	43	22	0.14450	1.3E-01
Fishing territory[o]	Int PL[f,p,q]	9.7	3.9	0.17436	HI PL[f,g,r]	16	18	0.27864	7.2E-02
Fishing territory[o]	Int PS[d,p,s]	5.5	1.9	0.13107	U.S. PS[d,e,r]	4.3	1.9	0.15501	3.0E-02
Fishing territory[o]	U.S. PS[d,e,t]	6.1	2.2	0.20554	U.S. PS[d,e,r]	4.3	1.9	0.15501	3.6E-03
Fishing territory[o]	NP SF[f,j,p]	31	34	0.22550	NP SF[f,j,r]	18	5	0.07782	4.9E-02
100-ytime horizon									
Gear type[c]	US PS[d,e]	7.9	1.5	0.19336	HI PL[f,g]	10	10	0.27373	1.4E-01
Gear type[c]	US PS[d,e]	7.9	1.5	0.19336	AS TL[f,h]	88	34	0.11530	1.3E-09
Gear type[c]	AS LL[d,i]	26	8.0	0.14920	NP SF[f,j]	17	4	0.11209	5.4E-05
Sulfur level[k]	US PS[d,e,l]	8.2	1.6	0.16510	US PS[d,e,m]	7.8	1.4	0.17812	1.8E-01
Sulfur level[k]	HI LL[d,l,n]	46	14	0.18629	HI LL[d,m,n]	47	15	0.23007	3.9E-01
Fishing territory[o]	Int PL[f,p,q]	10	2.0	0.13299	HI PL[f,g,r]	10	10	0.27373	5.0E-01
Fishing territory[o]	Int PS[d,p,s]	7.2	1.1	0.07861	U.S. PS[d,e,r]	4.4	1.4	0.16022	3.0E-08
Fishing territory[o]	U.S. PS[d,e,t]	8.1	1.7	0.19886	U.S. PS[d,e,r]	4.4	1.4	0.16022	4.1E-09
Fishing territory[o]	NP SF[f,j,p]	30	28	0.20594	NP SF[f,j,r]	18	4	0.09101	4.5E-02

[a]K-S stat. used to confirm normal distributions. If critical value (α=0.05) is greater than 0.29407, then the distribution is normal.
[b]For p-values less than the critical value of 0.05, the null hypothesis is rejected, and thus statistically significant.
[c]Gear type hypothesis: selective gears (catching one fish at a time including pole and line, troll, and surface methods—which includes both hook-and-line and troll gears) have a higher climate impact than non-selective gears (including purse seine and longline).
[d]Non-Selective gear type.
[e]U.S. purse seine (PS) fleet.
[f]Selective gear type.
[g]Hawaii (HI) pole and line (PL).
[h]American Samoa (AS) troll (TL).
[i]American Samoa (AS) longline (LL).
[j]North Pacific (NP) surface methods (SF).
[k]Sulfur level hypothesis: fleets operating in regions that regulate the sulfur levels in marine fuels (EEZ of the continental U.S. and HI) have a higher climate impact than fleets operating in regions that are exempt from sulfur regulations (outside Emission Control Areas).
[l]High sulfur scenario; fleet activity in regions exempt from sulfur regulations.
[m]Low sulfur scenario; fleet activity in regions with strict sulfur regulations.
[n]Hawaii (HI) longline (LL).
[o]Fishing territory hypothesis: fleets operating outside the U.S. EEZ may have a higher climate impact than fleets operating on the high sea.
[p]Fleet activity on the high sea.
[q]International (Int) pole and line (PL).
[r]Fleet activity in the U.S. EEZ.
[s]International (Int) purse seine (PS).
[t]Fleet activity outside the U.S. which includes the high sea and in the EEZ of other countries.

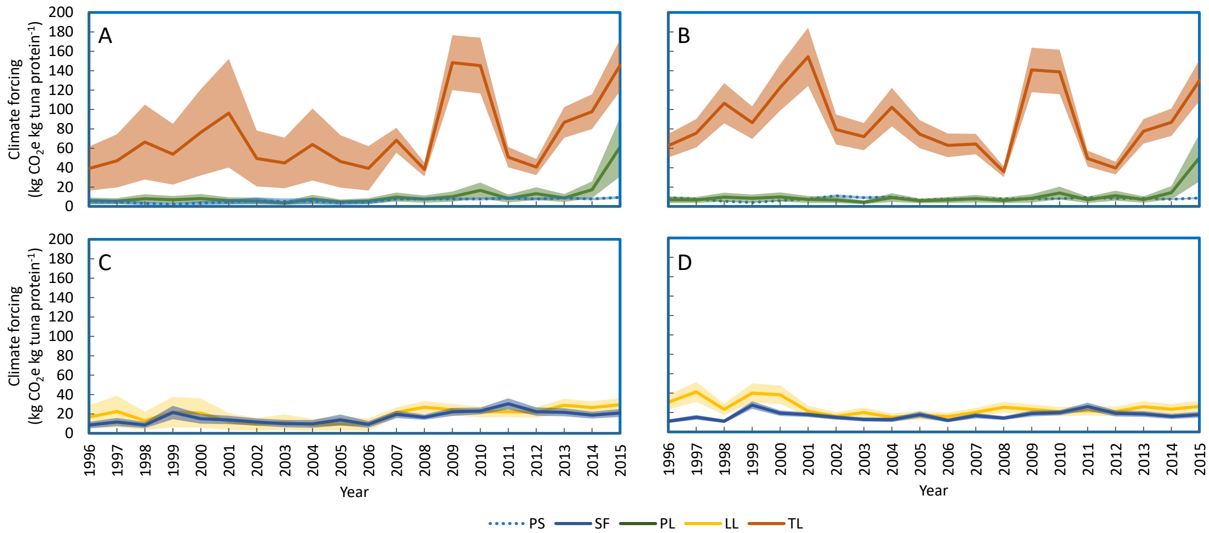

Figure 2.8: *Climate forcing of tuna protein over time (1996-2015) by species and fishing gear types on 20-y and 100-y time horizons. The tuna species include skipjack and albacore. The fishing gear types include highly selective gears—pole and line (PL), troll (TL), and surface methods (SF) that include both TL and hook-and-line gears—and less selective gears—purse-seine (PS) and longline (LL). Top panel (A,B): Skipjack caught by the American Samoa TL, Hawaii PL and the U.S. PS fleets. Bottom panel (C,D): Albacore caught by the American Samoa LL and the Northern acific SF fleets. Left panel (A,C): 20-y time horizon. Right panel (B,D): 100-y time horizon. The shaded regions represent the 95% confidence interval.*

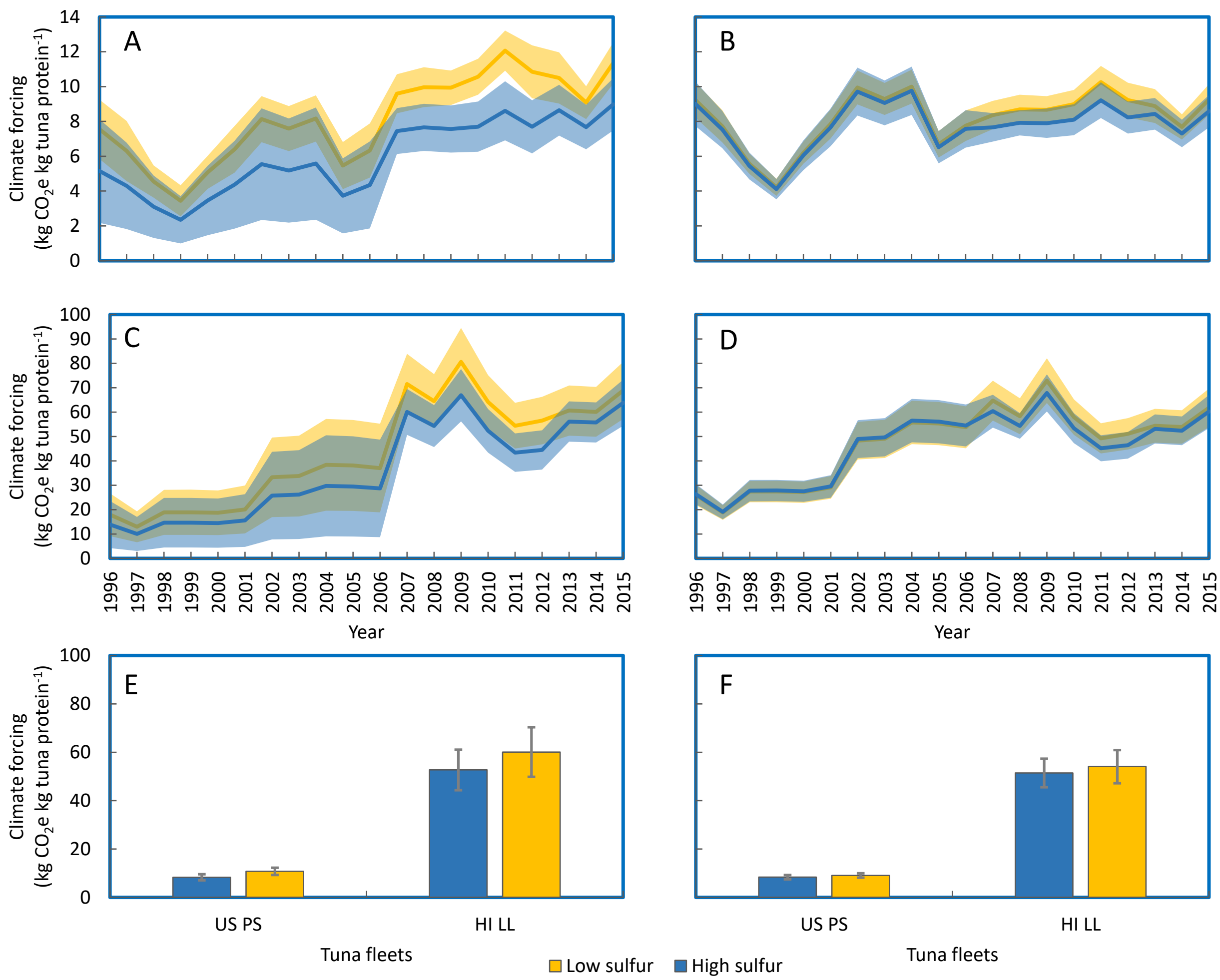

Figure 2.9: *Climate forcing of tuna protein comparison between fleet operations within regions that strictly regulate marine fuel quality (low sulfur) and fleet operations in regions that do not regulate marine fuel quality (high sulfur) on 20-y and 100-y time horizons. The selected fleets include the U.S. purse seine (PS) and Hawaii (HI) longline line (LL) fleets. Left panels (A,C,E): 20-y time horizon. Right panels (B,D,F): 100-y time horizon. Top row (A,B): U.S. PS fleet. Middle row (C,D): HI LL fleet. Bottom row (E,F): 5-y means (2011-2015). The shaded regions and the error bars represent the 95% confidence interval.*

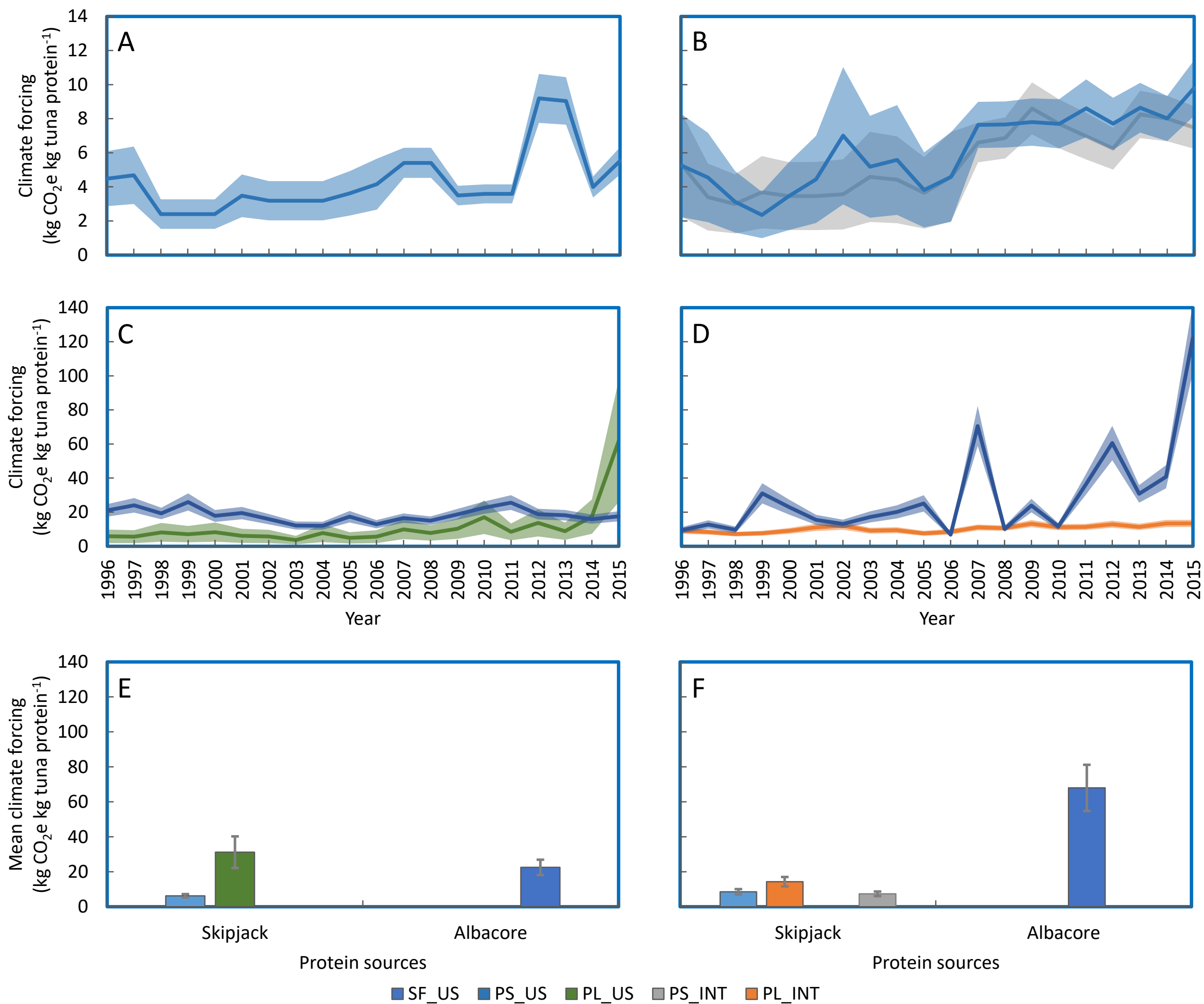

Figure 2.10: *Mean climate forcing of tuna protein over time (1996-2015) by gear type, and fishing territory on a 20-y time horizon. The fishing gear types include purse seine (PS), pole and line (PL), and surface methods (SF) which includes PL and troll gears. Left panels (A,C): FUI of U.S. fleets operating in the U.S. exclusive economic zone (EEZ). Right panels (B,D): FUI of U.S. fleets operating outside the U.S. EEZ. The international (INT) PL (PL_INT) and PS (PS_INT) FUIs represent activity by all flagged fleets operating only on the high sea whereas the U.S. fleets operate on the high sea and the EEZs of other countries outside the U.S. Top panels (A,B): FUIs of U.S. PS (PS_US), and INT PS (PS_INT) fleets. Middle panels (C,D): (C,D): U.S. PL, INT PL, and the North Pacific SF fleets. Bottom panels (E,F): Mean values (2011-2015). The error bars and shaded regions represent the 95% confidence interval.*

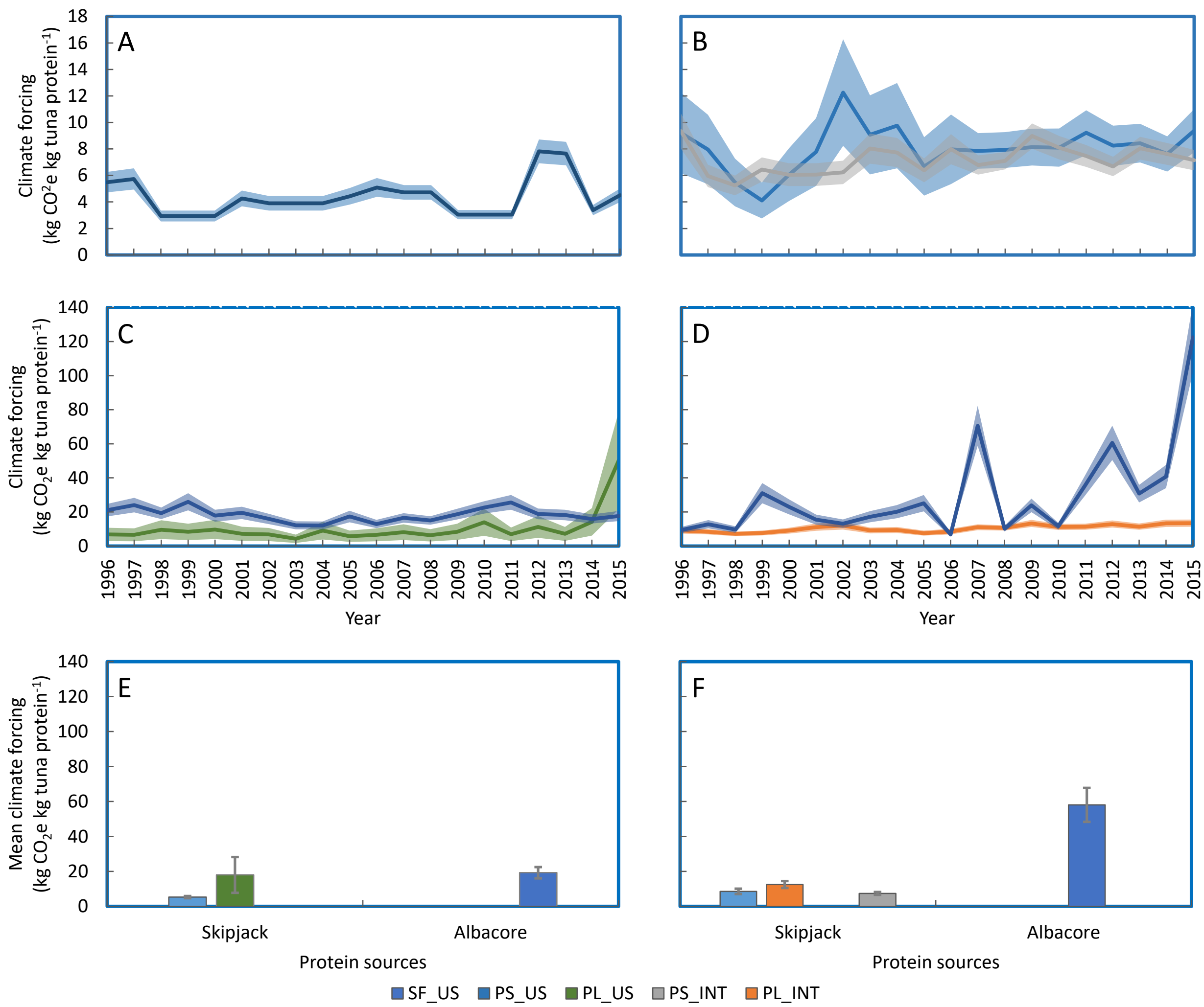

Figure 2.11: *Mean climate forcing of tuna protein over time (2007-2015) by gear type, and fishing territory on a 100-y time horizon. The fishing gear types include purse seine (PS), pole and line (PL), and surface methods (SF) which includes PL and troll gears. Left panels (A,C): FUI of U.S. fleets operating in the U.S. exclusive economic zone (EEZ). Right panels (B,D): FUI of U.S. fleets operating outside the U.S. EEZ. The international (INT) PL (PL_INT) and PS (PS_INT) FUIs represent activity by all flagged fleets operating only on the high sea whereas the U.S. fleets operate on the high sea and the EEZs of other countries outside the U.S. Top panels (A,B): FUIs of U.S. PS (PS_US), and INT PS (PS_INT) fleets. Middle panels (C,D): (C,D): U.S. PL, INT PL, and the North Pacific SF fleets. Bottom panels (E,F): Mean values (2011-2015). The error bars and shaded regions represent the 95% confidence interval.*

2.4.5. Comparisons of climate forcing among protein sources.

Here, the protein-specific climate forcing of tuna (the scenario of combined territory-specific—U.S. EEZ and outside U.S. EEZ—FUIs and total fuel-cycle climate forcing weighted by the relative amounts of catch inside and outside the U.S. EEZ) of seven different fleets was compared on 20-y and 100-y time horizons. Furthermore, the results of this analysis was compared with other sources of protein (Fig. 2.5.12).

Across both time horizons (20-y and 100-y), the mean (2011-2015) climate forcing of tuna protein and 95% confidence interval varies between 8.4 (±1.5) and 84 (±16) kg CO_2e / kg tuna protein for skipjack caught by the U.S. purse-seine fleet and American Samoa troll fleets, respectively. Within the skipjack species, the climate forcing of the three fleets that target this species varies widely on both time horizons (8.4 ±1.5, 22 ±11, and 84 ±16 kg CO_2e / kg tuna protein on a 20-y time horizon; 8.4 ± 0.9, 18 ±9, and 77 ±13 kg CO_2e / kg tuna protein on a100-y time horizon for the U.S purse-seine, Hawaii pole-and-line, and American Samoa troll fleets, respectively). The climate forcing of skipjack caught with highly selective gears is as much as 2.6 and 10 times higher (pole-and-line and troll gear, respectively) than the skipjack caught with the less selective gear (purse-seine). This this trend was not observed within the albacore species, however. The mean climate forcing of albacore tuna protein and 95% confidence interval is very similar on both time horizons (23 ± 4 and 26 ± 6 kg CO_2e / kg tuna protein on a 20-y time horizon; 20 ± 3 and 25 ± 5 kg CO_2e / kg tuna protein on a 100-y time horizon for the North Pacific surface methods and American Samoa longline fleets, respectively). As for the other tropical tunas, the climate forcing is 55 (±7) and 52 (±5) liters fuel / kg tuna protein for bigeye caught by the Hawaii longline fleet and 48 (±20) and

41 (±17) for yellowfin caught by the Hawaii troll fleet, on 20-y and 100-y time horizons, respectively.

To better understand the sustainability of tuna in the larger scope of food systems, the climate forcing of tuna protein for the selected fleets was compared and ranked (in order of low to high) with other sources of protein on 20-y and 100-y time horizons (Fig. 2.5.12). Compared to land-based protein sources, skipjack tuna protein caught by the U.S. purse-seine fleet has a significantly lower climate impact than most other protein sources with the exception of vegetable protein. Albacore tuna protein (caught by both the American Samoa longline and North Pacific surface methods fleets) and pole-and-line skipjack have a medium impact similar to that of chicken. In terms of medium-high impact, yellowfin tuna protein caught with troll gear has a similar impact to that of farmed shrimp and pork. As for the remaining tropical fleets (bigeye caught by the Hawaiian longline fleet and skipjack caught by the American Samoa troll fleet) the mean climate impact is significantly higher than most other protein sources except beef.

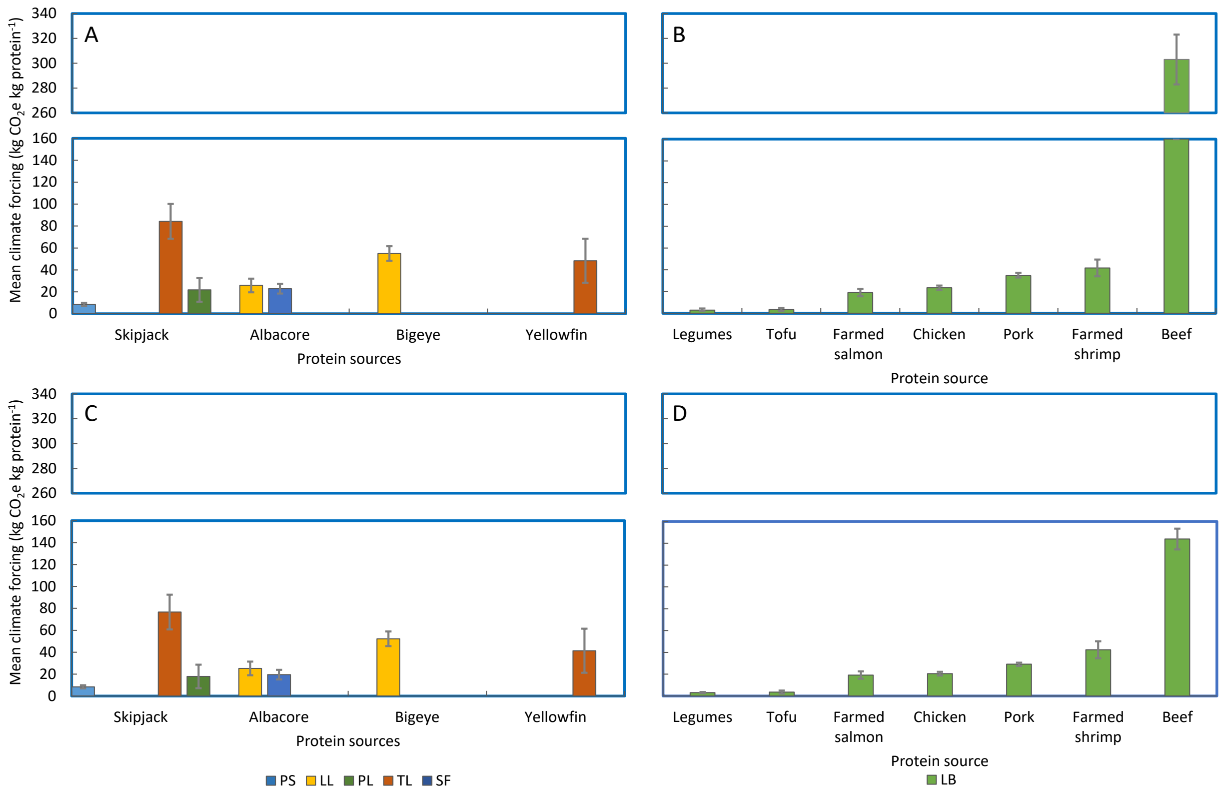

Figure 2.12: *Mean climate forcing of tuna and land-based tuna protein sources on 20-y and 100-y time horizons including several species of wild-caught tuna and various farmed sources. Left panels (A,C): Mean (2011-2015) climate forcing of wild-caught tuna categorized by species and fishing gear including purse seine (PS), longline (LL), pole and line (PL), troll (TL), and surface (SF) methods which includes both hook-and-line and TL. Right panels (B,D): Mean climate forcing of land-based (LB) protein sources for comparison. Top panels (A,B): 20-y time horizon. Bottom panels (C,D): 100-y time horizon. The error bars represent the 95% confidence interval.*

2.5. Discussion and conclusion.

This research highlights potential synergies and trade-offs between sustainable seafood practices and climate change.

With respect to polices aimed at improving air quality, a climate tradeoff was found. The climate forcing of tuna protein is significantly higher when it is caught by purse-seine fleets that operate in regions where sulfur levels in marine fuels are strictly regulated (such as the U.S. EEZ) than when it is caught by purse-seine fleets that refuel and operate in regions that are exempt from fuel quality standards. Although most skipjack tuna is currently caught in regions without strict fuel quality standards, these results have important implications for the future sustainability of seafood in the near term. The International Maritime Organization's Marine Environment Protection Committee set requirements which will see sulfur emissions fall from the current maximum of 3.5 percent of fuel content to 0.5 percent *[Smith et al., 2014]*. In addition to global fuel standards for heavy fuel oil, it is likely the sulfur levels in distillates will also be reduced as an increasing number of countries impose fuel quality standards that meet or exceed those of emission control areas *[Cullinane and Bergqvist, 2014]*.

With respect to the proposed ban of fishing on the high sea, a climate synergy was found. The climate forcing of tuna protein caught by purse-seine and the North Pacific surface methods fleets have a significantly higher climate forcing than the fleet operations in the U.S. EEZ, due to a higher effort to catch ratio. These results are in line with the suggestion made by other researchers— that vessels fishing the high seas may incur a higher cost per unit weight of fish than vessels fishing solely within EEZs *[Sumaila et al., 2015]*. However, it should be pointed out that only a small amount (roughly 15% and less than 2% over the last five years for the international purse-seine and the North Pacific surface methods fleets, respectively) of tuna is caught on the high seas compared to that caught in EEZs. Possible explanations for why fishermen would choose to fish the high seas at a greater cost include effort limits imposed in EEZs (such as the vessel day scheme) *[Havice, 2013]*, regional fidelity of tuna stocks situated on the high seas *[Sumaila et al., 2010; Squires et al., 2017]*, and fuel subsidies *[Sumaila et al., 2010; Sumaila et al., 2014]*.

With respect to fishing gear types, synergies and tradeoffs were found when the climate impact of tuna protein was compared with other sustainability indicators including stock status (Table 2.3) and protected species status (Table 2.4). In the case of the pole-and-line and North Pacific surface method fleets, climate synergies were found with respect to stock status and protected species interactions, whereas, climate tradeoffs were found in the case of the purse-seine and American Samoa troll fleets. In the case of the purse-seine fleet, the climate impact is low and the stock status of skipjack is not overfished and overfishing is not occurring, but there are concerns related to the bycatch of sharks and juvenile tunas. Although the stock status of skipjack is healthy, the climate impact of the American Samoa troll fleet is higher than the other fisheries that were considered in this study and there are concerns related to the bycatch of striped marlin. As for the Hawaii longline fishery, synergies and tradeoffs were not found but instead the relatively high climate impact gives weight to the evidence of the ecological indicators. In this case, overfishing is occurring for the bigeye stock, and there are concerns related to protected species interactions (mammals, sea turtles, sharks, and sea birds).

Although the climate impact is an important indicator for understanding seafood sustainability, there are some important considerations. First, the bycatch and protected species interactions of the highly selective pole-and-line and troll fleets are relatively unknown compared to the longline and purse-seine fleets, due to a lack of observer coverage *[Martin et al., 2015; Miller et al., 2017]*. Second, some highly selective fishing methods require a substantial quantity of baitfish which may not be sustainable if the tuna caught using these methods were to replace a significant amount of the fish currently caught with highly efficient methods that do not require bait such as purse-seine gear *[Gillett, 2011]*. Lastly, the evidence of climate trade-offs does not provide an argument for environmental destruction because this would confuse the narrow goal of climate mitigation with the broader goal of conservation. After all, ecosystem protection is a central goal of climate initiatives.

While these results do not support a case for harmful fishing practices, they do have implications for seafood and climate. First, continued development of sustainable seafood practices is warranted, particularly with respect to the energy efficiency of selective fishing gears. Second, the notion that natural resources can be conserved through greater consumption of sustainable seafood may not be justified. Seafood should clearly be harvested using sustainable practices but sustainable seafood may need to constitute a small portion of overall food consumption if the massive climate forcing of food systems is to be reduced. Third, climate policies must be designed to avoid the unintended consequences to fisheries and other natural resources that have energy intensive conservation practices. Mitigation and adaptation to global change should address broad goals in order to avoid environmental degradation that can result from narrower perspectives.

Table 2.3: *Stock status indicators by fleet and target species. The stock status indicators include the ratio of recent fishing mortality to that which will support the maximum sustainable yield (F_{recent}/F_{MSY}), the ratio of the average recent spawning biomass to the average spawning potential predicted to occur in the absence of fishing stock status ($SB_{recent}/SB_{F=0}$), overfishing status, and overfished status.*

Fleet	Species	F_{recent}/F_{MSY}[a]	$SB_{recent}/SB_{F=0}$[b]	Overfishing?[c]	Overfished?[d]
U.S. purse-seine	Skipjack[e]	0.45	0.58	No[f]	No[g]
International purse-seine	Skipjack[e]	0.45	0.58	No[f]	No[g]
Hawaii pole-and-line	Skipjack[e]	0.45	0.58	No[f]	No[g]
Hawaii longline	Bigeye[e]	0.83[h]	0.32[i]	Yes[j]	No[k]
Hawaii troll	Yellowfin[e]	0.74[l]	0.38[m]	No[n]	No[n]
American Samoa troll	Skipjack[e]	0.45	0.58	No[f]	No[g]
American Samoa longline	Albacore[e]	0.39[o]	0.40[p]	No[q]	No[q]
North Pacific surface methods	Albacore	0.61[r]	0.24[s]	No[t]	No[t]

[a]Maximum sustainable yield (MSY) is defined as the largest long-term average catch that can be taken from a stock under prevailing environmental and fishery conditions [USDC and NMFS, 2017].

[b]The average spawning biomass over the last 3 years for albacore and skipjack and 4 years for bigeye and yellowfin [Brouwer et al., 2017].

[c]Overfishing is defined as a stock that has a harvest rate higher than the rate that produces its MSY [USDC and NMFS, 2017].

[d]Overfished is a stock that has a population size that is too low and that jeopardizes the stock's ability to produce its MSY [USDC and NMFS, 2017].

[e]Conf. Table 3 [Brouwer et al., 2017].

[f]Across the reference case and the structural uncertainty grid F_{recent}/F_{MSY} varied between 0.38 (5% quantile) to 0.64 (95%quantile). This indicates that overfishing is not occurring for the WCPO skipjack tuna stock [Brouwer et al., 2017].

[g]Conf. Fig. 7 [Brouwer et al., 2017].

[h]23% probability that recent fishing mortality was above F_{MSY} [Brouwer et al., 2017].

[i]16% probability that the recent spawning biomass had breached the adopted limit reference point (LRP) [Brouwer et al., 2017].

[j]Bigeye is on NOAA's overfishing list [Brouwer et al., 2017].

[k]Conf. Pg. 60, "Both the sensitivity models (L2-184, 2014Reg) representing old growth/2017 regions and new growth/2014 regions, respectively, move into the overfishing region of the plot but do not reach an overfished state. The grid model (A0B1C0D0E1; old growth/2014 regions) progressively shifted into the overfishing region in the early 2000's and then progressed into the overfished state for the last decade of the assessment period." [McKechnie et al., 2017].

[l]4% probability that the recent fishing mortality was above F_{MSY} [Brouwer et al., 2017].

[m]8% probability (4 out of 48 models) that the recent spawning biomass had breached the adopted LRP [Brouwer et al., 2017].

[n]Conf. Pg. 44; "all models at the start of the assessment period were close to an $SB/SB_{F=0}$ of one and an F/F_{MSY} approaching zero, but each progressively tracked towards the overfishing and overfished definitions over the remaining period, with the Size50 model much closer to both $20\%SB_{F=0}$ and an F/F_{MSY} of 1 in final years than the Size10 model. The diagnostic case model never reaches $20\%SB_{F=0}$ or an F/F_{MSY} of 1" [Tremblay-Boyer et al., 2017].

[o]Recent levels of fishing mortality are lower than the level that will support the MSY, conf. Pg. 32 in [Harley et al., 2015].

[p]Recent levels of spawning potential are most likely above the level which will support the MSY and $20\%SB_{F=0}$, conf. Pg. 32 in [Harley et al., 2015].

[q]Overfishing is not occurring, but fishing mortality on adults is approaching the assumed level of natural mortality (conf. Figure 13). The SB_{MSY} is lower than the limit reference point (0.14 $SB_{F=0}$) due to the combination of the selectivity of the fisheries and maturity of the species [McKechnie et al., 2016].

[r]Conf. Table 5.4 in [Holmes et al., 2017].

[s]Conf. Fig. 5.15 (A) in [Holmes et al., 2017].

[t]North Pacific albacore stock is likely not overfished relative to the limit reference point adopted by the Western and Central Pacific Fisheries Commission (20%SSB current F=0) [Holmes et al., 2017].

***Table 2.4**: Marine Mammal Protection Act (MMPA) classification and listing of other species of concern. Other species of concern includes endangered or threatened sea turtles, endangered and or threatened sharks and rays, fish that are overfished and subject to overfishing, and seabirds.*

Fleet	MMPA classification[a]	Sea turtles	Sharks and rays	Fish	Seabirds
Purse-seine[b]	Category II[c,d]	Green[e,f,g,h]	Silky shark[i,j,k]	Striped marlin[l,m]	Unknown[n,o]
		Hawksbill[e,g,h,p]	Oceanic whitetip shark[q,r,s,t]	Juvenile tuna[u]	
			Whale sharks[v,w,x]		
			Rays[y,z]		
International pole-and-line	Category II[aa]			Juvenile tuna[u]	
Hawaii pole-and-line	Category III[ab]			Juvenile tuna[u]	
Hawaii longline	Category I[ac,ad]	Loggerhead[ae,af]	Silky shark[i,ag]	Striped marlin[l,ah]	Albatrosses[ai,aj]
		Leatherback[ak,al]	Oceanic whitetip shark[q,r,am]		Other seabirds[ai,an]
		Olive Ridley[ao,ap]			
		Green turtle[f,aq]			
Hawaii troll	Category III[ar]			Striped marlin[l,as]	
American Samoa troll	Category III[at]			Striped marlin[l,as]	
American Samoa longline	Category II[au]	Green turtle[f,av]	Silky shark[i,ag]	Striped marlin[l,ah]	Albatrosses[ai,aj]
		Leatherback[ak,aw]	Oceanic whitetip shark[q,r,am]		Other seabirds[ai,an]
		Olive Ridley[ao,ax]			
North Pacific surface methods	Category III[ay]				

[a]Three categories according to the level of incidental mortality or serious injury of marine mammals: category I is frequent incidental mortality or serious injury of marine mammals; category II is the occasional incidental mortality or serious injury of marine mammals; and category III is the remote likelihood of / no known incidental mortality or serious injury of marine mammals [NMFS, 2017l]

[b]Purse seining is a non-selective fishing method that captures everything that it surrounds, including protected species [NMFS, 2017p].

[c]Purse seines can easily encircle marine mammals along with target species as the net is set; historically, dolphin pods were even used as a natural cue visually leading purse seiners toward areas of abundant schooling fish (called "setting on dolphins"), a technique no longer employed in the U.S.; once the netting has been set, encircled marine mammals cannot escape and can become entangled, injured, or stressed. Even with quick retrieval, marine mammals' sensitive bodies and internal organs cannot usually withstand the weight of the catch or the impact of being placed on the vessel. In U.S. fisheries, species most commonly captured include bottlenose dolphins and humpback whales [NMFS, 2017p].

[d]Category II due to the lack of specific information on marine mammal abundance and interactions with the fishery on the high seas [NMFS, 2017j].

[e]Sea turtles can be captured by a purse seine as it is set and then become entangled in the net mesh as it is hauled in. Entangled turtles may sustain injuries to their flippers and shells due to the force of the net as it is hauled; in a large catch, turtles risk being crushed under the sheer weight of the tow. Captured turtles can be released alive if they are quickly retrieved and removed from the net [NMFS, 2017p].

[f]Green turtles are listed as threatened [NMFS, 2017o].

[g]On average, roughly 25% of the U.S. fleet has been observed from 1998 through 2004 and only 10 interactions with sea turtles have been observed. These interactions involved at least two species (green and hawksbill), and may have involved others [NMFS, 2006].

[h]Sea turtles are caught in very small numbers (from a few tens up to a couple of hundreds of individuals per year in every ocean) by purse seiners and most of them (> 90%) are released alive relatively easily. The mortality of turtles due to being captured by the seine can be considered negligible [Restrepo et al., 2017].

[i]Silky shark is overfished and overfishing is occurring [Justel-Rubio and Restrepo, 2015] .

[j]44012 silky sharks taken (5-y mean) by the Western Pacific Ocean purse-seine fleet [Restrepo et al., 2017].

[k]Estimated post-capture survival of about 20% in purse-seine fisheries [Justel-Rubio and Restrepo, 2015].

[l]Striped marlin is overfished and overfishing is occurring [Justel-Rubio and Restrepo, 2015].

[m]Total catch of billfish by tropical tuna purse seine fisheries worldwide is negligible in comparison to catches by longline fleets, which capture billfish both as target species and as bycatch [Restrepo et al., 2017].

[n]Seabirds are not usually caught by purse-seine fisheries, or any other non-shallow fisheries, although there are indications that coastal purse-seine vessels impact shearwater species [Justel-Rubio and Restrepo, 2015].

[o]Very few records of seabird bycatch in the Western Central Pacific Ocean purse-seine fishery [Peatman et al., 2017].

[p]Hawksbill turtles are endangered [NMFS, 2017n].

[q]Oceanic whitetip shark is threatened [NMFS, 2017b].

[r]Oceanic whitetip shark is overfished and overfishing is occurring [Justel-Rubio and Restrepo, 2015].

[s]490 white-tip sharks taken (5-y mean) by the Western Pacific Ocean purse-seine fleet [Restrepo et al., 2017].

[t]Estimates of post-release survival are not available for purse-seine fisheries [Justel-Rubio and Restrepo, 2015].

[u]Concerns that large numbers of small bigeye and yellowfin are caught in association with FAD sets, and how this contributes to overfishing of some bigeye and yellowfin stocks. Bigeye and yellowfin tuna are caught by many tuna fisheries and gear types. Large mature individuals are targeted by longline fisheries while smaller fish (typically juveniles) are caught by purse seine, pole-and-line and hand-line fisheries [Restrepo et al., 2017].

[v]Although interaction rates are low, any level of fishing mortality is of concern due to their life history and ecological significance [Restrepo et al., 2017].

[w]The WCPFC observer database recorded whale shark encounters in 155 of 88,084 observed sets (2008-2012 average) for a set encounter rate of 0.94% [Restrepo et al., 2017].

[x]Recent studies have suggested whale sharks released from purse seine gear using best practices have a high rate of survival, but further studies are needed [Restrepo et al., 2017].

[y]Giant manta rays are threatened [NMFS, 2017a].

[z]Rays are rarely captured in tuna purse seine gear, generally less than 0.1% by weight and therefore considerably less than shark catch [Restrepo et al., 2017].

[aa]The handline/pole and line components are classified as Category II due to the lack of specific information on marine mammal abundance and interactions with fisheries on the high seas [NMFS, 2017j].

[ab]There are no known incidental mortalities or serious injuries of marine mammals in this fishery, and there is a remote likelihood of marine mammal interactions because the gear is actively fished and the method is selective, targeting schools of tuna using barbless hooks [NMFS, 2017g].

[ac]Marine mammals are often entangled or hooked in longline gear; pilot whales and false killer whales are known to steal bait and or target catch from longlines and can thus be hooked in the mouth or entangled in the lines; Risso's dolphins, bottlenose dolphins, and several species of whales have also been documented as longline bycatch; Injuries from these interactions can include lacerations, puncture wounds, exhaustion, and drowning [NMFS, 2017m].

[ad]Classification due to mortality and serious injury of false killer whales (HI pelagic stock); this fishery exceeds 50% of the stock's Potential Biological Removal level [NMFS, 2017e].

[f]13 (5-y mean) Loggerhead turtles caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[ag]180335 (2007-2009) catch of silky sharks for the Western Central Pacific Ocean [Justel-Rubio and Restrepo, 2015].

[ah]3296 metric tons (2010-2013) of striped Marlin for the Western Central Pacific Ocean [Justel-Rubio and Restrepo, 2015].

[ai]Seabirds incidental mortality caused by longline fishing operations happens primarily during line setting, when foraging birds are attracted to the bait, become hooked or entangled, and are then dragged underwater and drown. They may also be hooked during line hauling [Justel-Rubio and Restrepo, 2015].

[aj]360 (5-y mean) albatrosses caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[ak]Leatherback turtles are endangered[NMFS, 2016b].

[al]27 (5-y mean) leatherhead turtles caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[am]98340 (2009) catch of Oceanic whitetip sharks for the Western Central Pacific Ocean [Justel-Rubio and Restrepo, 2015].

[an]23 (5-y mean) "other seabirds" caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[ao]Olive Ridley turtles are threatened or endangered [NMFS, 2017c].

[ap]36 (5-y mean) Olive Ridley turtles caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[aq]6 (5-y mean) Green turtles caught by the Hawaii longline fleet; not clear if released alive or dead [NMFS, 2016a].

[ar]Category listing in [NMFS, 2017h].

[as]14 metric tons (2010-2013) of striped Marlin for the Western Central Pacific Ocean [Justel-Rubio and Restrepo, 2015].

[at]Category listing in [NMFS, 2017f].

[au]Category listing in [NMFS, 2017k].

[av]American Samoa longline fishery interacted with an average of 24 green sea turtles (22 estimated mortalities) annually within the action area between (2006-2015) [NMFS, 2015].

[aw]American Samoa longline fishery is estimated to have interacted with an average of 9 leatherback sea turtles (6 estimated mortalities) annually within the action area between 2011and June 30, 2015 [NMFS, 2015].

[ax]American Samoa longline fishery is estimated to have interacted with an average of 6 olive ridley sea turtles (2 estimated mortalities) annually within the action area between 2011 and June 30, 2015 [NMFS, 2015].

[ay]Conf. Table 1: WA/OR/CA albacore surface pole-and-line/troll [NMFS, 2017d].

3. Climate forcing of battered-and-breaded fillets and crab-flavored sticks from Alaskan pollock

3.1. Chapter summary

The food sector is a significant contributor to global emissions and climate forcing. Compared with land-based food production systems, relatively little is known about the climate impact of seafood products. Previous studies have placed an emphasis on fishing activities, overlooking the contribution of the processing phase in the seafood supply-chain. Furthermore, other studies have ignored the contribution of short-lived climate forcing pollutants which can cause both warming and cooling. Here, the climate impact of two Alaskan pollock seafood products was evaluated by combining GWPs and emission inventories constructed from the literature. A holistic assessment was made including all stages in the supply-chain up to the retail display case, and a suite of pollutants in addition to greenhouse gases were considered. This study found that the processing stage contributed up to 1.6 times the climate impact of the fishing phase of the seafood supply-chain. Thus, for highly fuel efficient fisheries, such as the pollock catcher/processor fleet, the contribution of the processing stage of the seafood supply-chain should not be ignored. Furthermore, the inclusion of short-lived climate forcing pollutants may be important to include in life-cycle assessments of seafood. In this study, the contribution from SLCF cooling species (sulfur and nitrogen oxides) offset a significant portion of the climate forcing from warming species. The estimates that include only greenhouse gases are as much as 1.7 times higher than the cases that include SLCFs, suggesting that the exclusion of SLCFs could result in overestimates of the climate forcing of seafood. A full accounting of the supply-chain and of the impact of the pollutants emitted by food production systems may be important for climate change mitigation strategies in the near term.

3.2. Introduction

The last decade has seen increasing interest in the climate impacts of food *[Vermeulen et al., 2012; Godfray et al., 2010; Foley et al., 2011]*. Greenhouse gas emissions from agriculture form one of the largest sectors contributing to climate change *[Heller and Keoleian, 2015; Eshel et al., 2014]*. Life-cycle studies reveal that different food choices of consumers can have a very wide range of climate forcing *[Heller and Keoleian, 2015; Hallström et al., 2015]*. Understanding the emissions associated with food is therefore critical for mitigating climate change and informing consumer behavior *[Bajželj et al., 2014; Girod et al., 2014]*.

While much has been learned about the emissions from land-based food sources, robust quantifications of seafood life-cycle emissions are relatively sparse *[Nijdam et al., 2012; Clune et al., 2017]*. The limited information on seafood life-cycle emissions in part reflects the need for improved input data. Previous studies have found that the life-cycle emissions are dominated by fuel combustion during fishing *[Thrane, 2004; Guttormsdóttir, 2009; Svanes et al., 2011; Buchspies et al., 2011; Vázquez-Rowe et al., 2013]*, but the number of published studies is small relative to the diversity of fishing methods and species targeted *[Jafarzadeh et al., 2016; Parker et al., 2015]*. Given the limited number of studies and the assumption that fuel consumption is most important in the seafood-supply chain, researchers may be overlooking the importance of processes upstream of fishing activities

A further limitation of previous seafood emission studies is the focus on a narrow group of pollutants. Most efforts to quantify the climate impact of seafood have focused on CO_2 emissions *[Tyedmers and Parker, 2012]*. While CO_2 is the most important global greenhouse gas for most economic sectors, recent work revealed that the climate impact of the fishing activities can have large effects from species other than CO_2 *[McKuin and Campbell, 2016]*. In particular, ignoring the cooling effects of sulfur dioxide can lead to overestimates in the climate forcing of fishing activities. *[McKuin and Campbell, 2016]*. However, that study did not investigate activities upstream of the fishing phase of the seafood-supply chain. Thus, the impact of short-lived climate forcing (SLCF) pollutants on processes upstream of fishing activities is largely unknown.

Given these challenges and the increasing importance of understanding seafood emissions, a life-cycle study of Alaskan walleye pollock (hereafter, pollock) fishery was studied. The Alaskan pollock fishery in the eastern Bering Sea is globally important both in terms of volume and economic value of landings *[Fissel et al., 2016]*. Historically, fillets have been the dominant product produced from pollock. However, due to market forces there has been a recent surge in surimi produced from pollock *[Fissel et al., 2016]*. Although, the life-cycle impact of white-fish (cod, haddock, and hake) fillet products has been studied *[Guttormsdóttir, 2009; Svanes et al., 2011; Winther et al., 2009; Blonk et al., 2008; Sonesson et al., 2010; Buchspies et al., 2011; Fulton, 2010; The Co-operative Group, 2010; Iribarren et al., 2010; Vázquez-Rowe et al., 2012;*

Vázquez-Rowe et al., 2011; Sund, 2009; Vázquez-Rowe et al., 2013], a life-cycle assessment of surimi products has not been conducted. Thus, the climate impact of a shift in production away from fillets and an increase in production in surimi products is uncertain.

To this end, a first-order estimate of the climate forcing of frozen battered-and-breaded fillets and crab-flavored sticks (e.g. imitation crab produced from pollock surimi) for the retail market was developed on 20-y and 100-y time horizons. A broad range of climate forcing species (CO_2, sulfur dioxide, black carbon, nitrogen oxides) and life-cycle stages was evaluated for domestic and top importers of Alaskan pollock fillet and surimi products. The relative importance of these diverse life-cycle stages and the potential to systematically evaluate the climate impact of alternative food sources was evaluated.

3.3. Methods

To estimate the climate forcing of frozen battered-and-breaded fillets and crab-flavored sticks for domestic and export retail markets, a range of GWPs from the literature was applied to the emission inventories of the seafood supply-chain. The emission inventories were developed by constructing an inventory of material and energy inputs from technical reports and the literature and by applying emission factors found in life-cycle assessment software

The material and energy used in the supply chain depends on the product form, location of the secondary processor and the location of the final retail market (Fig. 3.1).

Alaskan pollock (and a small amount of bycatch) is caught by the catcher/processor fleet using pelagic trawl gears. Whole pollock is processed on-board the catcher/processor into several fresh and frozen products including whole fish, headed and gutted fish, frozen fillet blocks, frozen surimi blocks, minced fish, fish meal, and fish oil, among others. In the case of the two products considered in this study, the processing on board the fishing vessel is an intermediary step that is followed by additional processing at a separate location. In the case of frozen pollock fillet blocks, the top markets include Germany, the U.S., and the Netherlands (Fig. 3.1A). In the case of frozen pollock surimi blocks, the top markets include Japan, South Korea, and the U.S (Fig. 3.1B).

The products are transported by various modes, depending on the market, to the processing plant. At the processing plant the products are transformed into frozen battered-and-breaded fillets or crab-flavored sticks. After processing, the products are transported to a wholesale storage facility. From the wholesale storage facility, the products are transported to the retailer.

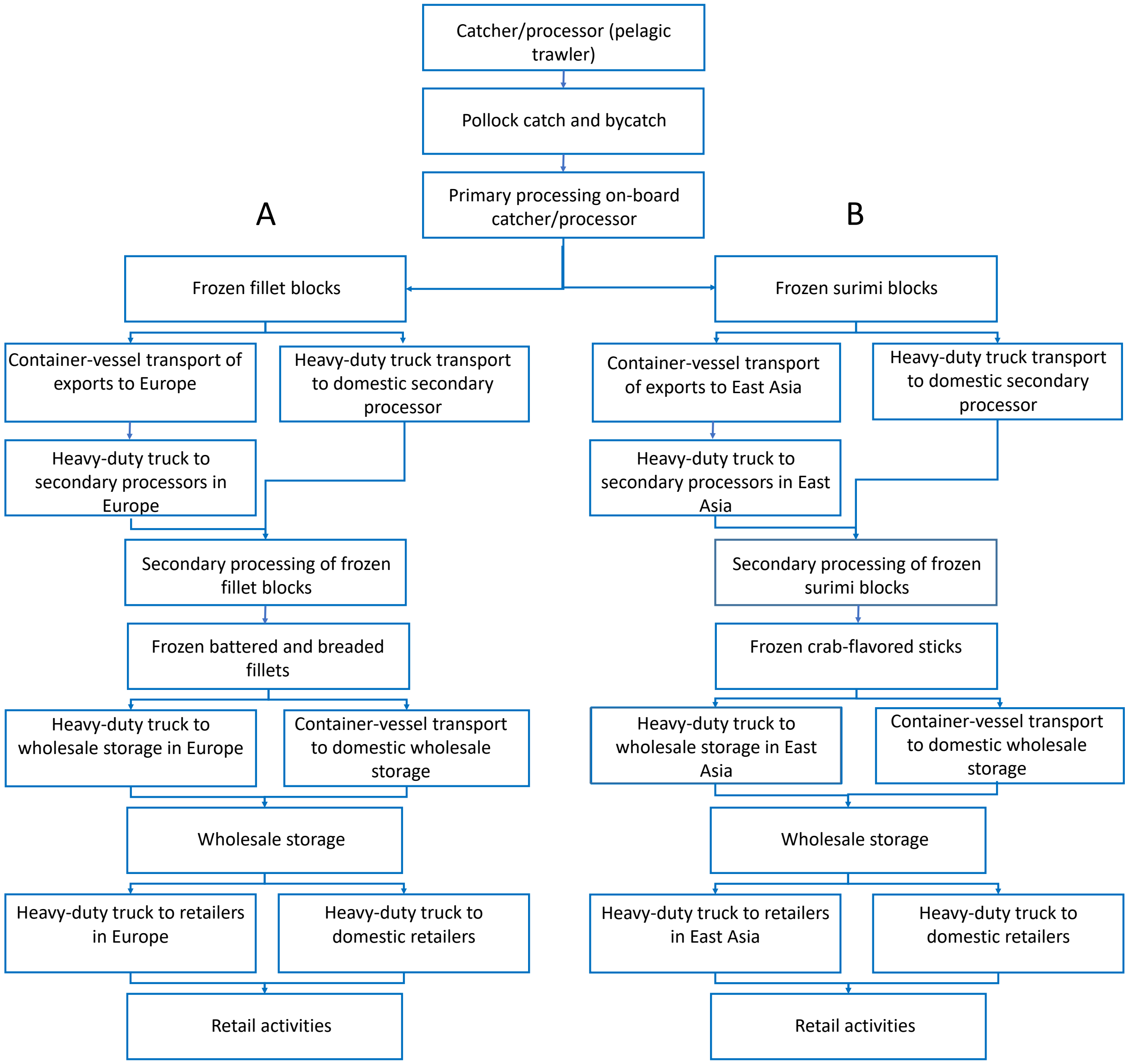

Figure 3.1: *Overview of supply chain of two Alaskan pollock products for domestic and export retail markets. (A): Frozen battered-and-breaded fillets for domestic and European export retail markets. (B): Crab-flavored stick for domestic and South-east Asian export retail markets.*

3.3.1. Fishing vessel characterization

The Eastern Bering Sea catcher/processor fleet targeting pollock was characterized with respect to the number of active fishing vessels, the fuel quality, and fishing gear types using data available from the Alaska Department of Fish and Game (ADFG), NOAA, and Sea-web vessel databases. The characterization of the fishing vessels also included the engine power, engine speed, and whether the vessels have refrigerated holds (Table A.53). The fishing vessels operate within the U.S. exclusive economic zone (EEZ) and as such, are subject to fuel-sulfur control laws. Small harbor and ocean-going vessels (category 1 and 2 engines) must use ultra-low sulfur diesel (ULSD) with a fuel sulfur level of 0.0015 (% wt.) whereas larger ocean-going vessels are permitted to use marine gas oil (MGO) with a fuel sulfur level of 0.1 (% wt.). Main engine power was used to estimate vessel categories (Table A.54).

3.3.2. Material and energy consumption

3.3.2.1. Fishing activities

The inventory of materials and energy used in the fishing phase of the seafood supply-chain was based on technical reports and the literature. Energy is consumed directly in the form of fuel used during fishing, landing, and hoteling activities of the fishing vessel at the port. Materials and indirect energies (embodied in the materials) are consumed in the manufacture and maintenance of the fishing vessels and fishing gears. The material inputs include lubricating oil, cooling agent for air conditioning, metals, paints (anti-fouling paints and top-side paints), and fishing gears.

The estimates of fuel consumption were based on vessel fuel survey conducted by NOAA (Table A.55) *[Fissel et al., 2016]*.

The annual lubricating oil consumption the fleet was estimated by applying the annual requirement of 14,000 kg of lubricating oil for a freezer trawler vessel *[Ziegler et al., 2015]* to the number of active vessels in the fleet.

The annual coolant for air conditioning supplied to each fleet was estimated by applying the initial charge of air conditioning is 150 kg of R-404a per fishing vessel and an a leakage rate of 30% per year *[Smith et al., 2014]* to the number of active vessels in the fleet.

The mass of metals used in the manufacture and maintenance of the fishing vessels components (M^{VC}, in metric tons) was estimated using the following equation:

$$M_{j,k,l}^{VC} = f_{j,k}^{mat} \cdot \sum_l LSW_l \qquad (1)$$

where f^{mat} is the fraction of material (steel, copper wire, or aluminum), *LSW* is the light ship weight (in metric tons),), *j* is the component (hull or other structural elements), *k* is the material of the component (steel, copper wire, and aluminum), and *l* is the individual vessel.

A linear relationship between the holding capacity and vessel width was used to estimate the *LSW*, using the following formula:

$$LSW = -263.81 + 0.57 \cdot HC + 43.7 \cdot L^{beam} \quad (2)$$

where *HC* is the holding capacity in cubic meters and L^{beam} is the vessel beam length (width) in meters. The holding capacity was estimated by converting the gross tons to cubic meters (2.83 cubic meters per gross ton) (conversion factor information—100 ft^3 per gross ton--obtained from http://www.themaritimesite.com/a-guide-to-understanding-ship-weight-and-tonnage-measurements/).

Following *[Fréon et al., 2014]*, approximately 80 % of the light ship weight (LSW) was assumed to correspond to the mass of the steel hull (including the frame, steel sheets, deck, etc.). The remaining 20 % of the LSW value corresponds to the mass of other structural elements and, propulsion. The composition of the other structural elements and propulsion was assumed to be: 43 % as steel, 33 % as copper wire (mostly coil) and 24 % as aluminium. A maintenance factor was added based on *[Tyedmers, 2000]*, which assumed 25% of the original material and energy inputs would be used over the lifetime of that vessel for maintenance. Although the lifetime of trawlers can vary between between 30-50 years *[Ziegler et al., 2015]*, in this study a lifetime of 30 years was assumed which is consistent with other seafood life-cycle assessments *[Fulton, 2010; Parker and Tyedmers, 2012; Ziegler et al., 2015]*.

The mass of the main engine of each vessel was assumed to be 125 metric tons *[Parker and Tyedmers, 2012]* and composed as follows: 65 % cast iron, 34 % chrome steel and 1 % white metal alloys (aluminium alloy 2024, $AlCuMg_2$) *[Fréon et al., 2014]*. The main engine lifetime has been estimated to be 15 years *[Fréon et al., 2014]*.

The paint consumption (anti-fouling for the hull, and top-side paints) was also estimated. The volume of anti-fouling substances, V^{af} (in liters), was estimating using the following formula:

$$V^{af} = \sum_j A_j^{hull} \cdot V^{s,af} \quad (3)$$

where A^{hull} is the area of the hull, $V^{s,af}$ is the specific volume of the anti-fouling substance (liters per square meter), and *j* is the individual vessel in the fleet. We estimated the area of the hull, A^{hull} (in square meters), using the following formula (estimate from Jamestown Distributors of Interlux anti-fouling paint available at: https://www.jamestowndistributors.com/userportal/document.do?docId=331):

$$A^{hull} = 0.85 \cdot LOA \cdot L^{beam} \quad (4)$$

where *LOA* is the length overall (in meters).

It was assumed steel vessels would require three types of paint for the top-side: primer, two-part polyurethane, and enamel paint. The volume, *V* (in liters), of top-side paint required using a linear relationship based on the length of the vessel using the following equations (Interlux product distributor paint volume estimates available at: http://www.yachtpaint.com/usa/diy/ask-the-experts/how-much-topside-paint-do-i-need.aspx):

$$V_i^{primer} = 0.653 \sum_j (LOA_j - 2.082) \quad (5)$$

$$V_i^{polyurethane} = 0.963 \sum_j (LOA_j - 3.028) \quad (6)$$

$$V_i^{enamel} = 1.15 \sum_j (LOA_j - 3.312) \quad (7)$$

For anti-fouling estimates, one liter of paint covers between 8.7 – 9.8 m^2 of hull area (Jamestown Distributors of Interlux anti-fouling paint available at: https://www.jamestowndistributors.com/userportal/document.do?docId=331). It has been estimated that the vessels are painted every two years *[Ziegler et al., 2015]*.

The mass and material composition of the pelagic trawl gear was obtained from the literature (Table A.56).

The annual catch of pollock and bycatch at the individual vessel-level was obtained from Pollock Conservation Cooperative and High Sea Catcher's Cooperative reports (Table A.57).

3.3.2.2. Primary processing

The primary processing phase of the seafood supply-chain includes on-board production of intermediary products and storage of the product at a wholesaler. The inventory of materials and energy used is based on the literature *[Fulton, 2010; Schau et al., 2009; Winther et al., 2009]*. Energy is consumed directly in the form of fuel used during processing of the fish on-board the fishing vessel and electricity for freezing the product. Material and indirect energy (embodied in the materials) is consumed in the manufacture of cooling agents for refrigerants, and the manufacture of packaging materials.

The estimates of primary processing fuel consumption is based on the literature. It has been reported that factory trawlers use approximately 5-7% of the on-board fuel use for processing

[Eyjólfsdóttir et al., 2003; Sund, 2009; Schau et al., 2009]. For this analysis, a mean value of 6% of the on-board fuel for processing was used.

The annual coolant charge for the on-board freezer holds was estimated as a product of the mass of 210 kg of R-134a per vessel and a leakage rate of 30% per year *[Smith et al., 2014]*.

The estimate of material consumption for packaging the frozen fillet and surimi blocks is based on survey results that were reported in the literature *[Fulton, 2010]*. According to the survey results in that study, 15.66 kg of cardboard carton, 10.3 kg of liner (83% cardboard and 17% wax), and 0.18 kg packaging film (LLDPE) are required for every metric ton of catch.

The initial charge of coolants such as R-404a and R-134a for the freezer storage systems was based on values found in the literature *[Bovea et al., 2007; Blowers and Lownsbury, 2010; Cascini et al., 2016]*. For this study however, it was assumed ammonia has a similar initial charge requirement as other commonly used refrigerants. In the literature, the lifetime of freezer storage varies between 10-15 years *[Bovea et al., 2007; Blowers and Lownsbury, 2010; Cascini et al., 2016]*. For this study, a mean value of 11.7 years was used. The initial charge as a function of volume varies between 0.04 to 0.44 kg m^{-3} depending on the freezer type. For this study, a specific annual initial charge of 0.012 kg m^{-3} y^{-1} was used. The required storage volume for each product was estimated as a function of the mass of the frozen products and the mass per unit volume of the packaged products (available at: http://www.ppsf.com/ecom_img/original-7-16-ss_pollock.pdf). The freezer storage time for frozen cod varies between 30 and 90 days *[Winther et al., 2009]*. For this study, a mean freezer storage time of 60 days was used.

The energy consumption of freezer storage is based on the literature *[Winther et al., 2009]*. In that study, a specific energy consumption of 2.6 kJ kg^{-1} d^{-1} was reported.

The annual production (2012-2015) of pollock products that were processed on-board the catcher/processor vessels was obtained from a technical report (Table A.51) *[Fissel et al., 2016]*.

3.3.2.3. Transportation inputs

The transportation inputs include two modes, either heavy-duty truck or container vessel, or a combination of the two. The key inputs associated with both modes of transportation include fuel to power the engines (and in the case of the container vessel, the auxiliary engine), fuel for the freezer duty-cycle of the temperature-controlled container, and the coolant charge for the temperature-controlled container.

The container vessel fuel consumption and emission factors were obtained from GREET's Marine Plug-in module. The characteristics of the container vessel include a 37.5 MW main engine, an 8.3 MW auxiliary engine, and a 40.4-kiloton payload. The engine load and fuel consumption factors vary based on the activity. In cruise and reduced speed zone modes, the engine load factor is 0.6, whereas in hotel mode, the engine load factor is 0.2. The distance traveled within emission control areas was also estimated to reflect the different fuel qualities used within each zone. Within emission control areas, the container vessels use marine gas oil (MGO) with a fuel sulfur level of 0.1 % (percent wt.). Outside emission control areas, the container vessels use heavy fuel oil (HFO) with an average fuel sulfur level of 2.4 % (percent wt.). For the cruise activity, an average speed of 18 knots with a fuel consumption of 3.98×10^{-3}

kg t^{-1} km^{-1} was assumed. For the reduced speed zone activity, an average speed of 12 knots with a fuel consumption of 3.60 x 10^{-3} kg t^{-1} km^{-1} was assumed. Following GREET, approximately 233 km of an international trip will be within a reduced speed zone. Furthermore, 44 hours is spent in hotel activity mode with a fuel consumption factor of 413.4 kg h^{-1}.

The amount of fuel consumed by the heavy-duty truck was estimated by using fuel consumption factors obtained from GREET's Well-to-Wheel Vehicle Editor. For this analysis, a short-haul heavy-duty truck with a payload of approximately 24 tons that operates with ultra-low sulfur diesel (ULSD) was used. For this vehicle, the fuel consumption factor is 1.51 x 10^{-2} kg ULSD t^{-1} km^{-1}. It was assumed that trips undertaken by heavy-duty truck make a return trip with half the payload.

In addition to fuel consumption for the main and auxiliary engines of the container vessel and the motive of the heavy-duty truck, fuel is consumed for the freezer duty-cycle of the temperature-controlled container. The fuel consumed by the temperature-controlled container on-board the container vessel is approximately 19% of the fuel consumption of the main and auxiliary engines *[Fitzgerald et al., 2011]*. The fuel consumed by the temperature-controlled container on-board the heavy duty truck is approximately 3 liters fuel per hour *[Tassou et al., 2009]*.

The coolant for the temperature-controlled container and air conditioning in the cabin was also estimated. The annual coolant charge of the air conditioning in the cabin of the container vessel is 150 kg R-404a with a loss rate of 30% *[Smith et al., 2014]*. The annual coolant charge of the temperature-controlled container is 6 kg R-404a per container with a loss rate of 15%, *[Smith et al., 2014]*.

3.3.2.3.1. Mass of products to secondary processors.

The gross shipping mass included the pallets and containers. In addition, the disposition of the quantities of the products to retail locations was estimated.

The gross mass of the twenty-foot equivalent (TEU) containers was multiplied by the number of TEU containers to estimate the shipping mass. The maximum payload of a twenty-foot equivalent unit (TEU) container is 22 metric tons and the mass of each TEU is approximately 2 metric tons (http://freightfilter.com/full-container-load-fcl-guide/) giving a gross mass of the TEU of 24 metric tons. The total number of TEUs was estimated by dividing the total mass of the product (including packaging and pallets) by the TEU payload. The gross mass of the pallets was estimated as the product of the number of pallets by the mass of each pallet. The mass of each pallet is approximately 18 kg (https://greenwaypsllc.com/pallet-weight/). The total number of pallets was estimated by dividing the mass of the product (with packaging) by the payload of the pallet. The maximum payload of a pallet is 1,180 kg (http://www.fao.org/docrep/003/r1076e/R1076E05.htm).

The disposition of the product to each retail location was estimated from technical reports *[Fissel et al., 2016]* and the U.S. Foreign Trade Commerical Fisheries Statistics database available from NOAA NMFS (https://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/) (Tables A.58 and A.59).

3.3.2.3.2. Distance of products to secondary processors

For the German market, packaged frozen fillet blocks are transported a distance of 11,997 km by container vessel from the Port of Dutch Harbor to the Port of Hamburg (https://sea-distances.org/). Approximately 10,727 km of the trip occurs outside emission control areas. For 11,764 and 233 kilometers of the trip the container vessel operates in cruise and reduced speed zone modes, respectively. Furthermore, the duration of the container vessel trip is 339, 10, and 44 hours in cruise, reduced speed zone, and hotel modes, respectively. From the Port of Hamburg, the temperature-controlled containers are shipped by the heavy-duty truck a distance of 184.6 km (average distance between the port and two major seafood processors; the major processors are located in the cities of Bremerhaven and Riepe), one-way. The total duration of the trip, one-way, is 1.8 hours.

For the Netherlands market, packaged frozen fillet blocks are transported a distance of 11,908 km by container vessel from the Port of Dutch Harbor to the Port of Rotterdam (http://distances.com/distances/dutch%20harbor/rotterdam). Approximately 10,648 km of the trip occurs outside emission control areas. For 11,764 and 233 kilometers of the trip, the container vessel operates in cruise and reduced speed zone modes, respectively. Furthermore, the duration of the container vessel trip is 381, 10.5, and 44 hours in cruise, reduced speed zone, and hotel modes, respectively. From the Port of Rotterdam, the temperature-controlled containers are shipped by the heavy-duty truck a distance of 113.6 km (average distance between the port and two major seafood processors; the major processors are located in the cities of Ijmuiden and Urk), one-way. The total duration of the trip, one-way, is 1.2 hours.

For the Japanese market, packaged frozen surimi blocks are transported a mean distance of 4,864 km (an average of the distances to Kushiro--3,936 km, Nagoya--5,093 km, and Imbari--5,556 km) by container vessel. Approximately 4,494 km of the trip occurs outside emission control areas. For 4,261 and 233 kilometers of the trip, the container vessel operates in cruise and reduced speed zone modes, respectively. Furthermore, the duration of the container vessel trip is 139, 10.5, and 44 hours in cruise, reduced speed zone, and hotel modes, respectively. From the Port, the temperature controlled containers are shipped by the heavy-duty truck a distance of 8 km (average distance between the port and three major seafood processors; the major processor locations are in the cities of Mitoyo, Kushiro, and Nagoya), one-way. The total duration of the trip, one-way, is 0.23 hours.

For the South Korean market, packaged frozen surimi blocks are transported a mean distance of 5.515 km from the Port of Dutch Harbor to the Port of Busan by container vessel. Approximately 5,145 km of the trip occurs outside emission control areas. For 5,282 and 233 kilometers of the trip the container vessel operates in cruise and reduced speed zone modes, respectively. Furthermore, the duration of the container vessel trip is 159, 10.5, and 44 hours in cruise, reduced speed zone, and hotel modes, respectively. From the Port of Busan, the temperature controlled containers are shipped by the heavy-duty truck a distance of 8 km, one-way. The total duration of the trip one-way is 0.23 hours.

For the U.S. market, it is assumed that packaged frozen fillet blocks and packaged frozen surimi blocks are processed in the same location. Each product is transported a distance of 16.9 km by heavy-duty truck from the point of landing to an on-shore processor. The distance was estimated using the U.S. Census Bureau Commodity Flow Public Use Microdata dataset for the year 2012 (available at: https://www.census.gov/econ/cfs/pums.html). Several filters were applied: export data was excluded; refrigerated truck shipments originating from Alaska and destined for Alaska was selected; "meat, poultry, fish, seafood, and their preparations" commodities in the standard classifications of transported goods was selected; and the following North American industry classification systems: "grocery and related product merchant wholesalers" and "food manufacturing" were selected. Assuming an average traveling speed of 72.4 km h^{-1}, the total duration of the trip is 0.23 hours.

3.3.2.4. Secondary processing

In the case of frozen battered-and-breaded fillets, the inventory of materials and energy was obtained from a study that considered an identical product, but different white-fish (Patagonian grenadier) as the raw material for the product *[Vázquez-Rowe et al., 2013]*. It was assumed that pollock would be interchangeable with Patagonian grenadier.

In the case of frozen crab-flavored sticks, the inventory of ingredients was obtained from the literature *[Hur et al., 2011]*. The electricity demand for processing crab-flavored sticks was estimated by using the formulas in *[Sanjuán et al., 2014]*, and the power labels and loading rates found in equipment sales brochures of surimi processing equipment (http://www.ube-yanagiya.com/html/products/surimi%20products/surimi.html).

3.3.2.5. Transportation to wholesale and retail markets

In the case of packaged frozen battered-and-breaded fillets exported to European retail markets and in the case of packaged frozen crab-flavored sticks exported to Japan, it is was assumed that the product would be transported 1,500 km in a heavy-duty truck *[Pretty et al., 2005]*. Assuming an average traveling speed of 155.4 km h^{-1}, the total duration of the one-way trip is 4.8 hours.

In the case of packaged frozen crab-flavored sticks exported to South Korea, a shorter distance of 121 km was assumed due to the smaller length of the national roadways compared to the other countries that import pollock products. Assuming an average traveling speed of 155.4 km h^{-1}, the total duration of the one-way trip is 0.8 hours.

In the case of products destined for the U.S. retail markets, the products are transported a distance of 3,160 km by container vessel from the Port of Dutch Harbor to the Port of Seattle (https://sea-distances.org/). It was assumed the trip occurs entirely within emission control areas. For 2,927 and 233 kilometers of the trip, the container vessel operates in cruise and reduced speed zone modes, respectively. Furthermore, the duration of the container vessel trip is 87.8, 10.5, and 44 hours in cruise, reduced speed zone, and hotel modes, respectively. From the Port of Seattle, the heavy-duty truck carrying the temperature-controlled containers travel a distance of 2,341 km, one-way. This distance was estimated using the U.S. Census Bureau Commodity Flow Public Use Microdata dataset for the year 2012 (available at: https://www.census.gov/econ/cfs/pums.html). Several filters were applied: export data was excluded; refrigerated truck shipments originating from Seattle and destined for various regions throughout the U.S. was selected; "meat, poultry, fish, seafood, and their preparations" commodities in the standard classifications of transported goods was selected; and the following

North American industry classification systems: “grocery and related product merchant wholesalers” and “food manufacturing” were selected. Assuming an average traveling speed of 155.4 km h^{-1}, the total duration of the one-way trip is 15.1 hours.

3.3.2.6. Retail activities

Material and energy is consumed while the product is being stored at a wholesale distribution center, while the product is being stored at the retail store prior to display, and during the time it is on display at the retail store.

The annual initial charge for the freezer (wholesale distribution storage, retail storage, and retail display freezer) of 0.012 kg m^{-3} y^{-1} was applied to the estimated volumes of each product.

In the case of frozen battered-and-breaded fillets, energy consumption of freezer storage (wholesale, retail, and display case) was 2.6 kJ kg^{-1} d^{-1}.

In the case of crab-flavored sticks, it was assumed that after the product arrives at the retail location, it is allowed to thaw and stored in a refrigerated case which requires 10 kWh $m^{-2}d^{-1}$ *[Hoang et al., 2016]*.

For all products, it was assumed that ancillary operations (lights, air conditioning, etc.) would require 800 kWh m^{-2} y^{-1} *[Tassou et al., 2011]*.

It was assumed that the storage time and time spent in retail display cases would be the same for all products: storage time of 7 days at a wholesale distribution center, a storage time of 10 days at the retail store prior to retail display, and 10 days in the retail display freezer *[Ziegler, 2002]*.

3.3.3. Emission factors

3.3.3.1. Direct vehicle exhaust emission factors

The direct emissions factors of vehicle exhaust were assembled for fishing vessel, container vessel, and heavy duty truck transportation.

Well-mixed GHGs (CO_2, CH_4 and N_2O) and NOx of the fishing fleet and the container vessel were obtained from a technical report, and from GREET's marine plug-in module. The remaining SLCF emissions (including SO_2, BC, and OC) of the fishing fleet and container vessel were calculated.

The SO_2 emissions, $EF^{exh,SO2}$ (g SO_2 / kg fuel), of the fishing fleet and the container vessel were calcuated using the following equation:

$$EF_j^{exh,SO_2} = f_j^S \cdot 2 \cdot f^{SO_2} \qquad (8)$$

where f^S is the fuel sulfur fraction (g S per kg fuel), 2 is the ratio of molecular weights of SO_2 to S, f^{SO2} is the fraction of fuel sulfur emitted as SO_2 (97.8%), and j is the fuel sulfur fraction *[ICF International, 2009]*. The SO_2 emissions depend on the fuel quality used by the fleet. For the Alaskan pollock catcher/processor pelagic trawl fleet, approximately 23% of the fleet is classified as a Category 2 engine operating with ULSD (fuel sulfur 0.0015% wt.) and the remainder is classified as Category 3 engine operating with MGO (fuel sulfur 0.1% wt.). The emissions from the container vessel depend on a number of factors including vessel activity mode (reduced-speed zone, cruise, or hoteling) and fuel quality. When the vessel is traveling in an emission control area, the vessel is required to use MGO with a fuel sulfur level of 0.1 (% wt.). Outside of emission control areas the vessel uses HFO with an average sulfur level of 2.4 (% wt.).

The emissions of black carbon (BC) and organic carbon (OC) depend on the fleet engine speed. For the Alaskan pollock catcher/processor pelagic trawl fleet, the Sea-web database was searched for International Maritime Organization numbers and vessel names to estimate the vessel engine speed. The search returned only result, with a vessel speed of 900 rpm. Because the engine speeds were not available for all of the vessels in the fleet, it was assumed the fleet is comprised of medium-speed diesel (MSD) engines, which is consistent with what other studies have found for fishing fleets *[Lack et al., 2008]*. In the case of the container vessel, a slow-speed diesel (SSD) engine was assumed *[Lack et al., 2008]*. The BC emission factors exhaust emissions were taken from plume sampling studies of in-use vessels *[Lack et al., 2008; Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014]*. The mean and 95% confidence intervals 0.41 (± 0.27), 0.85 (± 0.14), 0.48 (± 0.16) g BC kg fuel^{-1} for slow-speed diesel (SSD), medium-speed diesel (MSD), and high-speed diesel (HSD) engines, respectively *[Lack et al., 2008; Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014]*.

The emission factor for organic carbon (OC), $EF^{exh,OC}$ (g OC / kg fuel), was calculated using the following equation:

$$EF_k^{exh,OC} = EF_k^{exh,BC} \cdot \frac{POM}{1.2 \cdot BC} \qquad (9)$$

where $EF^{exh,BC}$ is the emission factor of black carbon (BC), *POM* is particulate organic matter which is120% of the OC, the ratio of *POM* to *BC* is 1.4 *[Petzold et al., 2011; Fuglestvedt et al., 2010]* and *k* is the engine type. The engine type is either slow speed diesel (SSD), medium speed diesel (MSD), or high speed diesel (HSD). For our calculations we use a density of 825 (±0.7) and 840 (±7.3) grams per liter for ULSD and MGO, respectively.

In the computation of heavy-duty truck emissions, emissions factors were obtained from GREET's Well-to-Wheel Vehicle Editor.

3.3.3.2. Indirect emissions factors

Indirect emission factors were assembled for the energy sources, and materials used throughout the seafood supply-chain. Multiple sources for the indirect emission factors were used including the literature, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (v.1.3.0.12842), and Simapro (v.7.2). Because BC emissions were unavailable in Simapro, BC emission factors were estimated from the PM 2.5 emissions using a technical report *[Cai, 2014]*.

*3.3.4. Global warming potential*s

The global warming potentials (GWPs) on a 20-y and a 100-y time horizon used in this analysis were obtained from the literature. A boot-strap analysis was conducted on the GWPs of SLCFs to estimate the uncertainty.

3.4. Results

3.4.1. Material and energy flow

The inventory of the material and energy flows of the two products for five retail destinations are presented in Tables 3.1-3.10.

3.4.2. Emission factor results

The results of the direct emission factor analysis (vessel exhaust of the fishing vessels, container vessels and heavy-duty trucks) are presented in Tables (3.11-3.14). The results of the indirect emissions factor analysis are categorized by non-ingredient results (Table 3.15) and ingredient results (Table 3.16).

3.4.3. Global warming potential results

The results of the GWP analysis are presented in Table 3.17.

Table 3.1: *Inventory of material and energy flows of the fishing phase of the seafood supply chain for the pollock fleet.*

Inventory item	Amount	Units
Direct inputs		
Fuel consumption in fishing operations[a]	6.32 (± 0.20) x 10^7	liters
Marine lubricating oil	2.07 (± 0.13) x 10^5	kilograms
Refrigerant HFC-404a	6.64 (± 0.43) x 10^2	kilograms
Steel for vessel construction and maintenance	4.56 (± 0.30) x 10^6	kilograms
Copper wire for vessel construction and maintenance	3.40 (± 0.22) x 10^5	kilograms
Aluminum for vessel construction and maintenance	2.47 (± 0.16) x 10^5	kilograms
Cast iron for main engine construction	7.99 (± 0.52) x 10^4	kilograms
Chrome steel for main engine construction	4.18 (± 0.27) x 10^4	kilograms
Aluminum alloy for main engine construction	1.23 (± 0.08) x 10^3	kilograms
Anti-fouling paint	8.79 (± 0.57) x 10^2	liters
Primer paint	3.97 (± 0.26) x 10^2	liters
Polyurethane paint	5.87 (± 0.38) x 10^2	liters
Enamel paint	7.03 (± 0.46) x 10^2	liters
Steel for fishing gear	5.79 (± 10) x 10^2	kilograms
Nylon for fishing gear	7.73 (± 0.13) x 10^2	kilograms
Lead for fishing gear	5.02 (± 0.09) x 10^3	kilograms
Polyethylene for fishing gear	7.73 (± 0.13) x 10^2	kilograms
Direct outputs		
Whole live-weight pollock	4.43 (± 0.14) x 10^5	tons
By-catch	3.99 (± 1.23) x 10^4	tons

[a]Fuel consumption: 23% ultra-low sulfur diesel; 77% marine gas oil.
[b]6% of total fuel consumption is allocated to processing; fuel consumption from fuel log data allocated to fishing activities by applying a factor of 0.94.

Table 3.2: *Inventory of material and energy flows of the primary processing phase of the seafood supply chain for the pollock catcher/processor fleet.*

Inventory item	Amount	Units
Direct inputs		
Fuel consumption in on-board processing[a]	4.06 (± 0.13) x 10^6	liters
Refrigerant HFC-134a for on-board freezing	1.23 (± 0.60) x 10^3	kilograms
Cardboard	4.39 (± 0.51) x 10^6	kilograms
Packaging film (LLDPE)	5.05 (± 0.58) x 10^4	kilograms
Liner (83% cardboard and 17% wax)	2.89 (± 0.33) x 10^6	kilograms
Refrigerant NH_3 for freezer storage	5.88 (± 0.63) x 10^2	kilograms
Energy consumption for freezer storage	3.91 (± 0.42) x 10^{10}	kilojoules
Direct outputs		
Whole fish	3.86 (± 3.8) x 10^5	kilograms
Headed & gutted	3.24 (± 0.58) x 10^7	kilograms
Roe	1.06 (± 0.15) x 10^7	kilograms
Fillet	9.20 (± 0.73) x 10^7	kilograms
Surimi	8.27 (± 0.86) x 10^7	kilograms
Mince	2.23 (± 0.21) x 10^7	kilograms
Meal	2.26 (± 0.68) x 10^7	kilograms
Other	1.38 (± 0.33) x 10^7	kilograms

Table 3.3: *Transportation inputs of frozen Alaskan pollock fillet blocks for three different port destinations.*

Item	Units	Japan	South Korea	United States
Inputs				
Frozen fillet blocks	kg	3.32 (± 0.50) x 10^{7}	2.66 (± 0.40) x 10^{7}	7.99 (± 0.12) x 10^{6}
Packaging	kg	8.69 (± 1.30) x 10^{5}	6.95 (± 1.04) x 10^{5}	2.09 (± 0.31) x 10^{5}
Pallets	kg	5.31 (± 0.79) x 10^{5}	4.25 (± 0.63) x 10^{5}	1.28 (± 0.19) x 10^{5}
Container	kg	3.15 (± 0.47) x 10^{6}	2.52 (± 0.38) x 10^{6}	7.57(± 0.11) x 10^{2}
Gross shipping mass	kg	3.78 (± 0.56) x 10^{7}	3.02 (± 0.45) x 10^{7}	8.33 (± 0.12) x 10^{6}
Container vessel from Dutch Harbor to secondary processor				
HFO fuel consumption of main and auxilary engines	kg	6.74 (± 1.01) x 10^{5}	6.18 (± 0.92) x 10^{5}	
HFO fuel consumption for freezer duty	kg	1.28 (± 0.19) x 10^{5}	1.17 (± 0.18. x 10^{5}	
MGO fuel consumption of main and auxilary engines	kg	9.04 (± 0.81) x 10^{4}	7.96 (± 0.65) x 10^{4}	
MGO fuel consumption for freezer duty	kg	1.72 (± 0.15) x 10^{4}	1.51 (± 0.12) x 10^{4}	
Coolant for vessel air conditioning (R-404a)	kg	6.77 (± 1.01) x 10^{-1}	4.70 (± 0.70 x 10^{-1}	
Coolant for container (R-134a)	kg	6.15 (± 0.92) x 10^{1}	5.41 (± 0.81) x 10^{1}	
Heavy duty truck transportation from port to secondary processor				
ULSD fuel consumption of truck main engine	kg	4.70 (± 0.70) x 10^{3}	1.89 (± 0.35) x 10^{3}	2.41 (± 0.36) x 10^{3}
ULSD fuel consumption of freezer duty	kg	1.40 (± 0.50) x 10^{7}	1.09 (± 0.16) x 10^{3}	3.28 (± 0.49) x 10^{2}
Coolant for container (R-134a)	kg	5.79 (± 0.20) x 10^{-2}	4.53 (± 0.68) x 10^{-2}	1.36 (± 0.20) x 10^{-2}
Outputs				
Frozen fillet blocks	kg	3.32 (± 0.50) x 10^{7}	2.66 (± 0.40) x 10^{7}	7.99 (± 0.12) x 10^{6}
Packaging	kg	8.69 (± 1.30) x 10^{5}	6.95 (± 1.04) x 10^{5}	2.09 (± 0.31) x 10^{5}

Table 3.4: *Transportation inputs of frozen Alaskan surimi fillet blocks for three different port destinations.*

Item	Units	Japan	South Korea	United States
Inputs				
Frozen fillet blocks	kg	3.32 (± 0.50) x 10^7	2.66 (± 0.40) x 10^7	7.99 (± 0.12) x 10^6
Packaging	kg	8.69 (± 1.30) x 10^5	6.95 (± 1.04) x 10^5	2.09 (± 0.31) x 10^5
Pallets	kg	5.31 (± 0.79) x 10^5	4.25 (± 0.63) x 10^5	1.28 (± 0.19) x 10^5
Container	kg	3.15 (± 0.47) x 10^6	2.52 (± 0.38) x 10^6	7.57(± 0.11) x 10^2
Gross shipping mass	kg	3.78 (± 0.56) x 10^7	3.02 (± 0.45) x 10^7	8.33 (± 0.12) x 10^6
Container vessel from Dutch Harbor to secondary processor				
HFO fuel consumption of main and auxilary engines	kg	6.74 (± 1.01) x 10^5	6.18 (± 0.92) x 10^5	
HFO fuel consumption for freezer duty	kg	1.28 (± 0.19) x 10^5	1.17 (± 0.18. x 10^5	
MGO fuel consumption of main and auxilary engines	kg	9.04 (± 0.81) x 10^4	7.96 (± 0.65) x 10^4	
MGO fuel consumption for freezer duty	kg	1.72 (± 0.15) x 10^4	1.51 (± 0.12) x 10^4	
Coolant for vessel air conditioning (R-404a)	kg	6.77 (± 1.01) x 10^{-1}	4.70 (± 0.70 x 10^{-1}	
Coolant for container (R-134a)	kg	6.15 (± 0.92) x 10^1	5.41 (± 0.81) x 10^1	
Heavy duty truck transportation from port to secondary processor				
ULSD fuel consumption of truck main engine	kg	4.70 (± 0.70) x 10^3	1.89 (± 0.35) x 10^3	2.41 (± 0.36) x 10^3
ULSD fuel consumption of freezer duty	kg	1.40 (± 0.50) x 10^7	1.09 (± 0.16) x 10^3	3.28 (± 0.49) x 10^2
Coolant for container (R-134a)	kg	5.79 (± 0.20) x 10^{-2}	4.53 (± 0.68) x 10^{-2}	1.36 (± 0.20) x 10^{-2}
Outputs				
Frozen fillet blocks	kg	3.32 (± 0.50) x 10^7	2.66 (± 0.40) x 10^7	7.99 (± 0.12) x 10^6
Packaging	kg	8.69 (± 1.30) x 10^5	6.95 (± 1.04) x 10^5	2.09 (± 0.31) x 10^5

Table 3.5: *Secondary processing material and energy flows of frozen Alaskan pollock battered-and-breaded fillets Vázquez-Rowe et al. (2013)*

Item	Amount	Units
Inputs		
Frozen fillet blocks	9.20 (± 0.73) x 10^{7}	kg
Packaging	7.33 (± 0.85) x 10^{6}	kg
Reception		
Lubricating oil (pallet jack and forklift)	6.32 (± 0.28) x 10^{2}	kg
Electricity (pallet jack and forklift)	1.84 (± 0.08) x 10^{4}	kWh
Unwrapping		
Lubricating oil (forklift)	4.08 (± 0.18) x 10^{2}	kg
Electricity (forklift)	1.72 (± 0.08) x 10^{4}	kWh
Block cutting		
Lubricating oil (band-saw)	4.03 (± 0.18) x 10^{2}	kg
Electricity (band-saw)	4.77 (± 0.21) x 10^{6}	kWh
Battering of filets		
Wheat-mix batter	1.15 (± 0.10) x 10^{7}	kg
Tap water for battering process	2.66 (± 0.21) x 10^{7}	kg
Electricity for mixing batter	1.87 (± 0.15) x 10^{3}	kWh
Breadcrumb application		
Breadcrumbs	4.20 (± 0.17) x 10^{7}	kg
Electricity for coating machine	9.40 (± 0.75) x 10^{2}	kWh
Industrial frying		
Sunflower oil	9.40 (± 0.75) x 10^{2}	kg
Electricity for oil sprinkler	9.40 (± 0.75) x 10^{2}	kWh
Freezing		
Electricity for freezing	9.40 (± 0.75) x 10^{2}	kWh
Packaging		
Cardboard	4.70 (± 0.37) x 10^{6}	kg
Polyethylene	3.33 (± 0.47) x 10^{5}	kg
Retractable polyolefin	4.69 (± 0.67) x 10^{5}	kg
Electricity for packaging	1.10 (± 0.09) x 10^{7}	kWh
Ancillary operations at the processing plant		
Damaged fish blocks	8.28 (± 0.66) x 10^{6}	kg
Fishsticks	1.65 (± 0.13) x 10^{8}	kg
Fishstick packaging	1.65 (± 0.14) x 10^{7}	kg
Excess breadcrumbs	2.52 (± 0.10) x 10^{6}	kg
Excess batter	2.18 (± 0.17) x 10^{3}	L

Table 3.6: *Secondary processing material and energy flows of frozen Alaskan pollock crab-flavored sticks.*

Item	Units	Amount
Inputs		
Frozen surimi blocks	kg	8.27 (± 0.86) x 10^7
Packaging	kg	2.16 (± 0.23) x 10^6
Reception		
Lubricating oil (pallet jack and forklift)	kg	5.59 (± 0.62) x 10^2
Electricity (pallet jack and forklift)	kWh	1.74 (± 0.18) x 10^4
Unwrapping		
Lubricating oil (forklift)	kg	3.84 (± 0.40) x 10^2
Electricity (forklift)	kWh	1.62 (± 0.17) x 10^4
Block cutting		
Lubricating oil (band-saw)	kg	3.80 (± 0.40) x 10^2
Electricity (band-saw)	kWh	4.49 (± 0.47) x 10^6
Crab-flavored stick production		
Electricity for kamaboko production	kWh	1.25 (± 0.13) x 10^7
Wheat starch	kg	4.13 (± 0.43) x 10^6
Potato starch	kg	4.13 (± 0.43) x 10^6
Sugar	kg	2.19 (± 0.23) x 10^6
Salt	kg	2.02 (± 0.21) x 10^6
Crab extract	kg	1.83 (± 0.19) x 10^6
Kelp extract	kg	6.26 (± 0.65) x 10^5
Albumen	kg	6.24 (± 0.67) x 10^5
Calcium carbonate	kg	1.03 (± 0.11) x 10^6
Crab flavor	kg	4.54 (± 0.47) x 10^5
Soybean oil	kg	5.17 (± 0.54) x 10^4
Phosphate	kg	3.13 (± 0.33 x 10^5
Seasoning mix	kg	3.40 (± 0.35) x 10^6
Red colorant	kg	4.70 (± 0.49) x 10^4
Distilled water	kg	5.17 (± 0.54) x 10^7
Freezing		
Electricity for freezing	kWh	1.86 (± 0.19) x 10^7
Packaging		
Cardboard	kg	4.43 (± 0.46) x 10^6
Polyethylene	kg	3.13 (± 0.33) x 10^5
Retractable polyolefin	kg	4.42 (± 0.50) x 10^5
Electricity for packaging	kWh	1.04 (± 0.11) x 10^7
Ancillary operations at the processing plant		
Ammonia (NH_3)	kg	6.02 (± 1.18)
Detergents	kg	2.20 (± 0.43) x 10^2
Bleach	kg	1.61 (± 0.32) x 10^2
Caustic soda	kg	2.26 (± 0.44) x 10^4
Electricity	kWh	5.14 (± 0.66) x 10^7
Outputs		
Packaging for frozen surimi blocks	kg	2.16 (± 0.23) x 10^6
Crab-flavored sticks	kg	1.56 (± 0.16) x 10^8
Crab-flavored stick packaging	kg	4.74 (± 0.49) x 10^6

Table 3.7: *Transportation inputs for frozen Alaskan pollock battered-and-breaded fillets for three different retail markets***.**

Description	Units	Germany	Netherlands	United States
Transportation to retail distribution center				
Inputs				

Frozen battered-and-breaded fillets	kg	7.25 (± 0.58) x 10^{7}	3.03 (± 0.24) x 10^{7}	6.25 (± 0.50) x 10^{7}
Packaging	kg	6.03 (± 0.48) x 10^{6}	2.52 (± 0.20) x 10^{6}	5.20 (± 0.41) x 10^{6}
Pallets	kg	1.22 (± 0.01) x 10^{6}	5.11 (± 0.03) x 10^{5}	1.05 (± 0.01) x 10^{6}
Container	kg	7.25 (± 0.59) x 10^{6}	3.03 (± 0.02) x 10^{6}	6.25 (± 0.50) x 10^{6}
Gross shipping mass	kg	8.69 (± 0.63) x 10^{7}	3.64 (± 0.26) x 10^{7}	7.50 (± 0.54) x 10^{7}
Heavy duty truck transportation				
ULSD consumption of main engine	kg	1.47 (± 0.11) x 10^{6}	6.15 (± 0.44) x 10^{5}	
ULSD consumption of refrigerated container freezer duty	kg	6.49 (± 0.05) x 10^{4}	2.72 (± 0.01) x 10^{4}	
Coolant (R-404a) initial charge for refrigerated container	kg	2.70 (± 0.02)	1.13 (± 0.01)	
Container vessel transportation				
MGO fuel consumption of main and auxilary engines	kg			9.55 (± 0.12) x 10^{5}
MGO fuel consumption of refrigerated container freezer duty	kg			1.81 (± 0.02) x 10^{5}
Coolant (R-404a) initial charge for vessel air conditioning	kg			7.14 (± 0.07) x 10^{-1}
Coolant (R-404a) initial charge for refrigerated container	kg			4.46 (± 0.04) x 10^{1}
Transportation to retail stores				
ULSD consumption of main engine	kg	1.47 (± 0.11) x 10^{6}	6.15 (± 0.44) x 10^{5}	3.96 (± 0.29) x 10^{6}
ULSD consumption of refrigerated container freezer duty	kg	6.49 (± 0.05) x 10^{4}	2.72 (± 0.01) x 10^{4}	1.75 (± 0.34) x 10^{5}
Coolant (R-404a) initial charge for refrigerated container	kg	2.70 (± 0.02)	1.13 (± 0.01)	4.84 (± 0.04)

Table 3.8: *Transportation inputs for crab-flavored sticks for three different retail markets.*

Description	Units	Japan	South Korea	United States
Transportation to retail distribution center				
Inputs				
Crab-flavored sticks	kg	$7.63 (\pm 0.79) \times 10^{7}$	$6.10 (\pm 0.63) \times 10^{7}$	$1.83 (\pm 0.19) \times 10^{7}$
Packaging	kg	$8.48 (\pm 0.88) \times 10^{6}$	$6.78 (\pm 0.71) \times 10^{6}$	$2.04 (\pm 0.21) \times 10^{6}$
Pallets	kg	$1.32 (\pm 0.14) \times 10^{6}$	$1.06 (\pm 0.11) \times 10^{6}$	$3.18 (\pm 0.33) \times 10^{5}$
Container	kg	$7.83 (\pm 0.81) \times 10^{6}$	$6.26 (\pm 0.65) \times 10^{6}$	$1.88 (\pm 0.20) \times 10^{6}$
Gross shipping mass	kg	$9.39 (\pm 0.98) \times 10^{7}$	$7.51 (\pm 0.78) \times 10^{7}$	$2.26 (\pm 0.24) \times 10^{7}$
Heavy duty truck transportation				
ULSD consumption of main engine	kg	$1.59 (\pm 0.17) \times 10^{6}$	$2.05 (\pm 0.21) \times 10^{5}$	
ULSD consumption of refrigerated container freezer duty	kg	$7.01 (\pm 0.73) \times 10^{4}$	$9.03 (\pm 0.94) \times 10^{3}$	
Coolant (R-404a) initial charge for refrigerated container	kg	2.91 (± 0.30)	$3.75 (\pm 0.39) \times 10^{-1}$	
Container vessel transportation				
MGO fuel consumption of main and auxilary engines	kg			$3.00 (\pm 0.48) \times 10^{5}$
MGO fuel consumption of refrigerated container freezer duty	kg			$1.98 (\pm 0.77) \times 10^{5}$
Coolant (R-404a) initial charge for vessel air conditioning	kg			$7.14 (\pm 0.07) \times 10^{-1}$
Coolant (R-404a) initial charge for refrigerated container	kg			$1.34 (\pm 0.14) \times 10^{1}$
Transportation to retail stores				
ULSD consumption of main engine	kg	$1.59 (\pm 0.17) \times 10^{6}$	$2.05 (\pm 0.21) \times 10^{5}$	$1.19 (\pm 0.12) \times 10^{6}$
ULSD consumption of refrigerated container freezer duty	kg	$7.01 (\pm 0.73) \times 10^{4}$	$9.03 (\pm 0.94) \times 10^{3}$	$1.69 (\pm 0.18) \times 10^{4}$
Coolant (R-404a) initial charge for refrigerated container	kg	2.91 (± 0.30)	$3.75 (\pm 0.39) \times 10^{-1}$	1.46 (± 0.15)

Table 3.9: *Material and energy flows of Alaskan frozen battered-and-breaded pollock fillets during the retail phase of the seafood supply-chain for three different retail markets.*

Description		Germany	Netherlands	United States
Frozen battered-and-breaded fillets	kg	7.25 (± 0.73) x 10^7	3.03 (± 0.30) x 10^7	6.25 (± 0.62) x 10^7
Packaging for frozen fish sticks	kg	6.03 (± 0.60) x 10^6	2.52 (± 0.25) x 10^6	5.20 (± 0.52) x 10^6
Storage at retail distribution center				
Electricity for freezer storage (7 days)	MJ	1.47 (± 0.15) x 10^6	6.07 (± 0.61) x 10^5	1.25 (± 0.13) x 10^6
Coolant (NH_3) initial charge for retail distribution storage freezer	kg	2.21 (± 0.22) x 10^1	9.26 (± 0.93)	1.91 (± 0.19) x 10^1
Retail store				
Electricity for freezer storage (10 days)	MJ	2.07 (± 0.21) x 10^6	8.67 (± 0.87) x 10^5	1.79 (± 0.18) x 10^6
Coolant (R-404a) initial charge for retail freezer storage	kg	3.16 (± 0.32) x 10^1	1.32 (± 0.13) x 10^1	2.73 (± 0.27) x 10^1
Electricity for retail freezer (10 days)	MJ	2.07 (± 0.21) x 10^6	8.67 (± 0.87) x 10^5	1.79 (± 0.18) x 10^6
Coolant (R-404a) initial charge for retail display freezer	kg	3.16 (± 0.32) x 10^1	1.32 (± 0.13) x 10^1	2.73 (± 0.28) x 10^1
Electricity for retail ancillary operations	MJ	8.07 (± 0.81) x 10^6	1.86 (± 0.19) x 10^6	6.61 (± 0.66) x 10^6
Outputs				
Frozen fish sticks	kg	7.25 (± 0.73) x 10^7	3.03 (± 0.30) x 10^7	6.25 (± 0.63) x 10^7
Packaging for frozen fish sticks	kg	6.03 (± 0.60) x 10^6	2.52 (± 0.23) x 10^6	5.20 (± 0.52) x 10^6

Table 3.10: Material and energy flows of Alaskan frozen crab-flavored stick during the retail phase of the seafood supply-chain for three different retail markets.

Description	Units	Japan	South Korea	United States
Inputs				
Frozen crab-flavored sticks	kg	7.63 (± 0.79) x 10^7	6.10 (± 0.63) x 10^7	1.83 (± 0.19) x 10^7
Packaging for crab-flavored fish sticks	kg	8.48 (± 0.88) x 10^6	6.78 (± 0.71) x 10^6	2.04 (± 0.21) x 10^6
Storage at retail distribution center				
Electricity for freezer storage (7 days)	MJ	1.57 (± 0.16) x 10^5	1.25 (± 0.13) x 10^6	3.77 (± 0.39) x 10^5
Coolant (NH_3) initial charge for retail distribution storage freezer	kg	2.39 (± 0.25) x 10^1	1.91 (± 0.20) x 10^1	5.75 (± 0.60)
Retail store				
Electricity for freezer storage (10 days)	MJ	8.27 (± 0.86) x 10^5	6.61 (± 0.69) x 10^5	1.99 (± 0.21) x 10^5
Coolant (R-404a) initial charge for retail freezer storage	kg	3.42 (± 0.34) x 10^1	2.73 (± 0.28 x 10^1	8.22 (± 0.85)
Electricity for retail freezer (10 days)	MJ	8.27 (± 0.86) x 10^5	6.61 (± 0.69) x 10^5	1.99 (± 0.21) x 10^5
Coolant (R-404a) initial charge for retail display freezer	kg	3.42 (± 0.36) x 10^1	2.73 (± 0.28 x 10^1	8.22 (± 0.85)
Electricity for retail ancillary operations	MJ	3.19 (± 0.18) x 10^7	2.19 (± 0.23) x 10^7	5.26 (± 0.55) x 10^6
Outputs				
Frozen crab-flavored sticks	kg	7.63 (± 0.79) x 10^7	6.10 (± 0.63) x 10^7	1.83 (± 0.19) x 10^7
Packaging for crab-flavored fish sticks	kg	8.48 (± 0.88) x 10^6	6.78 (± 0.71) x 10^6	2.04 (± 0.21) x 10^6

Table 3.11: *Fishing vessel emission factors for long-lived climate forcing pollutants (CO_2, CH_4, and N_2O), nitrogen oxides (NOx), and sulfur dioxide (SO_2) for ultra-low sulfur diesel (ULSD) and marine gas oil (MGO).*

Fuel type	Fuel sulfur (% wt.)	Emission factor pollutants (g/kg fuel)				
		CO_2	CH_4	N_2O	NOx	SO2
ULSD	0.0015	3,183	0.03	0.16	52	0.03
MGO	0.1	3,183	0.02	0.15	52	1.96

Table 3.12: *Emission factors of black carbon (BC) and organic carbon (OC) pollutants as a function of engine speed : slow speed diesel (SSD), medium speed diesel (MSD), or high speed diesel (HSD).*

	Emission factor pollutants (g/kg fuel)	
Engine type	BC	OC
SSD	0.41 (± 0.27)	0.48 (± 0.32)
MSD	0.85 (± 0.14)	0.99 (± 0.16)
HSD	0.48 (± 0.16)	0.56 (± 0.18)

Table 3.13: *Container vessel emission factors by trip segment and fuel type [Wang, 2011].*

Trip segment	CO_2	CH_4	N_2O	NOx[a]	SOx[b]	BC	POC
RSZ[c,d]							
HFO[e]	1.14×10^{-2}	9.04×10^{-8}	5.65×10^{-7}	2.91×10^{-4}	1.94×10^{-4}	1.48×10^{-6}	1.73×10^{-6}
MGO[f]	1.26×10^{-2}	1.21×10^{-7}	6.30×10^{-7}	3.26×10^{-4}	2.15×10^{-4}	1.63×10^{-6}	1.91×10^{-6}
Cruise[d,g]							
HFO[e]	1.14×10^{-2}	9.04×10^{-8}	5.65×10^{-7}	2.91×10^{-4}	1.94×10^{-4}	1.48×10^{-6}	1.73×10^{-6}
MGO[f]	1.26×10^{-2}	1.21×10^{-7}	6.30×10^{-7}	3.26×10^{-4}	2.15×10^{-4}	1.63×10^{-6}	1.91×10^{-6}
Hotel[h]							
MGO[f]	1.31×10^{3}	7.28×10^{-3}	5.65×10^{-2}	2.68×10^{1}	2.23×10^{1}	1.69×10^{-1}	1.98×10^{-1}

[a] NOx as nitrogen dioxide (NO_2).
[b] SOx as sulfur dioxide (SO_2).
[c] Reduced speed zone (RSZ); container vessel speed 12 knots.
[d] Emission factor given in units kilograms of pollutant per ton-kilometer.
[e] Heavy fuel oil (HFO) with a fuel sulfur level of 2.4 (% wt.).
[f] Marine gas oil (MGO) with a fuel sulfur level of 0.1 (% wt.).
[g] Cruise zone; container vessel speed 18 knots.
[h] Emission factor given in units kilograms of pollutant per hour.

Table 3.14: *Heavy-truck emission factors. Emission factors given in kilograms of pollutant per ton-kilometer [Wang, 2011].*

Fuel type	CO_2	CH_4	N_2O	NOx[a]	SOx[b]	BC	OC
ULSD[c]	4.62E-02	1.82E-06	7.45E-08	4.30E-05	4.42E-07	7.94E-08	1.40E-07

[a]NOx as nitrogen dioxide (NO_2).

[b]SOx as sulfur dioxide (SO_2).

[c]Ultra-low sulfur diesel (ULSD) with a fuel sulfur level of 0.0015 (% wt.).

Table 3.15: *Indirect emission factors of non-ingredient material and energy sources.*

Inventory Item	CO_2 (kg)	CH_4 (g)	N_2O (mg)	NOx (g)	SOx (g)	BC (mg)	POC (mg)	CF_4 (mg)	C_2F_6 (mg)
ULSD[a](1kg)	0.69	6.49	9.88	1.78	0.92	16.2	33.3		
MGO[b] (1kg)	0.63	6.97	8.87	1.79	0.89	16.4	33.4		
HFO[c] (1kg)	0.29	5.6	3.4	1.2	0.66	23	12		
Lubricant oil[d,e] (1kg)	3.13	3.59	62.2	6.64	20.3	41.5	45.9		
R-134a[f,g] (1kg)	95.4	212	2405	33.3	32.8	143	259		
R-404a[h](1kg)	148	329	3731	51.6	50.8	221	401		
Steeld,[i] (1kg)	3.66	6.26	42.1	4.31	13.8	24.6	52.9		
Copper wired(1kg)	3.08	5.43	57.1	7.82	150	100	80.2		
Aluminumd,[j] (1kg)	2.7	5.58	56.2	3.08	8.27	25.3	50.5	18.9	2.61
Cast iron[d,k] (1kg)	0.91	4.57	16.7	1.79	3.48	9	22.4		
Chrome[d,l] (1kg)	4.5	7.15	66.1	6.72	12.4	41.1	80.4		
Anti-fouling paint[f,m] (1kg)	1.45	40.7	17.1	4.33	3.95	13.9	21.2		
Primer paint[d,n] (1kg)	5.82	20.1	180	8.97	11.9	65	120		
Polyurethane paint[d,o] (1kg)	2.97	19	91.7	5.75	17.8	57.2	67.1		
Enamel paint[f,p] (1kg)	2.57	8.36	34.3	6.08	7.07	33.5	59.6		
Nylon[f,q] (1kg)	8.7	13.8	105	23	18.5	75.4	122		
Lead[d,r] (1kg)	0.52	2.47	5.12	0.82	13.1	2.37	5.79		
Polyethylene[d,s] (1kg)	2.94	15.9	74.4	5.36	13.2	53.8	65.4		
Poly-steel[d,t] (1kg)	2.47	20.5	83.8	4.42	16.9	35.5	58.3		
Polypropylene[d] (1kg)	1.83	24.7	86.6	3.72	24.3	25.5	43.1		
Carton[f,u] (1kg)	1.16	1.9	15	2.7	2.4	9.9	17		
Plastic bag[f,v] (1kg)	2.26	12.2	57.1	4.13	10.1	41.3	50.3		
Liner (1kg)[f,w]	0.8	1.15	16.3	2.3	2.19	7.93	12.3		

[a]Ultra-low sulfur diesel with 0.0015 (% wt.) fuel sulfur.
[b]Marine gas oil with 0.1 (% wt.) fuel sulfur.
[c]Heavy fuel oil with 2.6 (% wt.) fuel sulfur.
[d]The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Argonne National Lab v.1.3.0.12842.
[e]'Engine oil'.
fGHG emissions obtained from Simapro v.7.2 using IPCC 2007 GWP 100a v.1.02 method; energy carrier contributions identified using Cumulative Energy Demand v.1.07 method; energy carriers allocated to individual pollutants using GREET.
[g]'Trichloroethylene' and 'tetrachloroethylene' energy carrier information was substituted for 'unspecified organics' in Simapro due to lack of data.
[h]Data for R-404a was unavailable; GHG emissions were obtained from Cascini et al. (2016); energy carrier and pollutant allocations were made using the data for R-134a.
[i]'Average steel'; 26% recycled and 73.6% virgin.
[j]Average cast aluminum'; 85% recycled and 15% virgin.
[k]'Final iron product'; 85% cast iron and 15% forged iron.
[l]'Chromium steel 18/8, at plant/RER U'.
[m]We base our ingredient list on an anti-fouling bottom paint for steel hulls with a formula of 45% copper oxide ('Copper oxide, at plant/RER U') and 55% intert materials; for the inert materials we assume 'Alkyd resin, long oil, 70% in white spirit, at plant/RER U'.
[n]'Liquid epoxy resin'.
[o]'Polyurethane flexible foam'
[p]'Alkyd paint, white, 60% in solvent, at plant/RER U'.
[q]'Nylon 6 E'.
[r]'Mix: average lead'; 73% recycled and 27% virgin.
[s]'Polyethylene terephthalate resin'.
[t]'High-impact polystyrene resin'.
[u]'Packaging, corrugated board, mixed fibre, single wall, at plant/CH U'.
[v]'Packaging film, LDPE, at plant/RER U'.
[w]'Kraft paper, unbleached, at plant/RER S; Paraffin, at plant/RER U'.

Table 3.16: *Indirect emission factors of ingredient materials.*

Inventory Item	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	NOx (kg)	SOx (kg)	BC (kg)	OC (kg)
Wheat-mix batter[a,b] (1kg)	1.11E+00	2.40E-03	1.49E-05	2.01E-03	2.50E-03	1.40E-03	1.67E-05
Tap water[a] (1kg)	3.00E-04	4.40E-07	4.30E-09	5.60E-07	8.60E-07	2.80E-09	5.20E-09
Breadcrumbs[a,b] (1kg)	1.01E+00	2.53E-03	1.46E-05	1.81E-03	2.26E-03	4.24E-04	1.50E-05
Sunflower oil[a,b] (1kg)	2.59E+00	3.59E-03	2.93E-05	8.08E-03	6.34E-03	2.39E-05	3.53E-05
Wheat starch[a,b] (1 kg)d	1.88E+00	3.67E-03	2.42E-05	4.45E-03	3.99E-03	1.69E-05	2.80E-05
Potato starch[a] (1 kg)	4.44E-01	8.92E-04	8.31E-04	5.68E-04	7.68E-04	5.25E-05	4.99E-05
Sugar[a] (1 kg)	2.84E-01	5.77E-04	6.92E-04	1.33E-03	4.19E-04	8.11E-05	3.44E-05
Salt[a] (1 kg)	3.03E+00	4.63E-03	4.43E-05	5.02E-03	8.44E-03	2.78E-05	5.30E-05
Crab extract[a] (1 kg)	4.92E+00	1.86E-02	4.81E-03	1.87E-02	1.27E-02	2.41E-03	2.17E-03
Crab flavoring[a](1 kg)	1.77E+00	6.69E-03	1.73E-03	6.72E-03	4.56E-03	8.66E-04	7.78E-04
Carrageenan[a] (1 kg)	5.89E-01	2.23E-03	5.75E-04	2.24E-03	1.52E-03	2.89E-04	2.59E-04
Kelp extract[a] (1 kg)	6.18E-01	2.34E-03	6.04E-04	2.35E-03	1.60E-03	3.03E-04	2.72E-04
Albumen[a] (1 kg)	6.25E-01	1.85E-03	4.30E-03	3.36E-03	3.47E-04	9.13E-05	1.10E-04
Calcium carbonate[c] (1 kg)	1.30E-02	2.70E-05	8.15E-08	3.44E-05	6.33E-06	2.60E-07	2.80E-07
Soybean oil[a] (1 kg)	3.58E-01	5.59E-04	1.82E-03	2.21E-03	1.21E-03	6.80E-05	4.63E-05
Phosphate[c] (1 kg)	1.42E+00	3.35E-03	2.59E-05	4.78E-03	4.97E-02	4.56E-05	1.00E-04
Seasoning mix[a] (1 kg)	5.11E-01	1.94E-03	4.99E-04	1.94E-03	1.32E-03	2.51E-04	2.25E-04
Red colorant[a] (1 kg)	5.89E-01	2.23E-03	5.75E-04	2.24E-03	1.52E-03	2.89E-04	2.59E-04
Distilled water[a](1 kg)	7.45E-04	1.24E-06	2.28E-08	1.62E-06	2.40E-06	1.62E-08	4.43E-08
Retractable polyethylene[c,d]	3.20E+00	2.64E-02	2.50E-04	5.25E-03	1.78E-02	4.05E-05	6.14E-05
NH3 (1 kg)[a]	2.21E+00	8.95E-03	4.51E-05	2.29E-03	8.00E-04	1.58E-05	3.69E-05
Detergents (1 kg)[a,e]	1.16E+00	1.93E-03	1.47E-05	2.73E-03	2.42E-03	9.90E-06	1.70E-05
Bleach (1 kg)[a,f]	2.26E+00	1.22E-02	5.71E-05	4.13E-03	1.01E-02	4.13E-05	5.03E-05
Caustic soda (1 kg)[c,g]	7.98E-01	1.15E-03	1.63E-05	2.30E-03	2.19E-03	7.93E-06	1.23E-05

[a]GHG emissions obtained from Simapro v.7.2 using IPCC 2007 GWP 100a v.1.02 method
[b] Vázquez-Rowe et al. (2013)
[c]The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Argonne National Lab v.1.3.0.12842.
[d]'Adhesives'.
[e]'Soap, at plant/RER U'.
[f]'Sodium hypochlorite, 15% in H2O, at plant/RER U'.
[g]'Sodium hydroxide'

***Table 3.17**: Global warming potentials (GWPs).*

GWP	CO_2[a]	CH_4[a]	N_2O[a]	NOx[b,c,d,e]	SO_2[b,d,e]	OC[b,d,g]	BC[b,d,h]	CF_4[i]	C_2F_6[i]
20-y	1	86	268	-20 [-28,-12]	-95 [-135,-55]	-187 [-213, -133]	1,936 [1,540, 2,391]	4,400	6,200
100-y	1	34	298	-13 [-17, -6.2]	27 [-39, -16]	-54 [-61, -38]	545 [435, 665]	6,500	9,200

[a]Values include carbon-climate feedback taken from [Myhre et al., 2013]
[b]Mean values and 95% confidence intervals constructed using bootstrap analysis methods described in [Orloff and Bloom, 2014].
[c]Given as NO_2.
[d]Direct effects (aerosol-radiation interaction)
[e]Mean global values (n=4) taken from [Fuglestvedt et al., 2010].
[f]Mean global values (n=3) taken from [Fuglestvedt et al., 2010].
[g]Mean global values (n=3) taken from [Fuglestvedt et al., 2010; Bond et al., 2011; Collins et al., 2013].
[h]Mean global values (n=5) taken from [Fuglestvedt et al., 2010; Bond et al., 2011; Collins et al., 2013; Bond et al., 2013; Aamaas et al., 2015].
[i]Values taken from UNFCCC, available at: http://unfccc.int/ghg_data/items/3825.php

3.4.4. *Climate impact along the supply-chain.*

The climate impact results of two different Alaskan pollock products (frozen battered-and breaded-fillets and crab-flavored sticks) for five different retail markets were disaggregated by supply-chain step (fishing, intermediary processing, transport to processor, secondary processing, transport to distribution centers, and retail activities) on 20-y and 100-y time horizons (Fig. 3.2). Particular emphasis was placed on a comparison of the processing contribution of the two seafood products (Fig. 3.3).

Across all time horizons and seafood products, the mean climate forcing (and 95% confidence intervals in parentheses) varies between 0.90 (± 0.17) and 1.55 (± 0.16) kg CO_2e per kg product, in the case of crab-flavored sticks in the South Korean retail market on a 20-y time horizon and battered-and-breaded fillets in the U.S. retail market on a 100-y time horizon, respectively (Fig. 3.2). Owing to the larger GWP potentials of the cooling SLCFs, the mean results on a 100-y time horizon are as much as 1.3 times higher than the estimates on a 20-y time horizon.

Examination of the results disaggregated by supply-chain step indicate that, for certain pollock products, the upstream processing (transformation of primary products—frozen fillet blocks into frozen battered-and-breaded fillets or frozen surimi blocks into frozen crab-flavored sticks) can contribute as much to the overall climate impact as the fishing phase (Fig. 3.2). In the case of crab-flavored sticks, the secondary processing phase of the seafood-supply chain (0.41 ±0.05 and 0.53±0.06 kg CO_2e per kg product) contribute 0.93 and 1.3 times the climate impact of the fishing phase (0.40 ±0.13 and 0.44 ±0.13 kg CO_2e kg per kg product) on 20-y and 100-y time horizons, respectively (Fig. 3.2A and 3.2C). In the case of battered-and-breaded fillets, the secondary processing phase of the seafood-supply chain (0.51 ±0.09 and 0.66 ±0.07 kg CO_2e per kg product) contributes 1.1 and 1.6 times the climate impact of the fishing phase (0.44 ±0.13 and 0.42 ±0.13 kg CO_2e kg CO2e per kg product), on 20-y and 100-y time horizons, respectively (Fig. 3.2B and 3.2D).

Given the importance of the processing stage in the pollock supply-chain and the objective to compare the climate impact of increasing the supply of processed surimi-type products over frozen fillet-type products, the results of this stage were examined in greater detail (Fig. 3.3). Product formation (the embodied energy in product ingredients and electricity for production processes) makes the largest contribution to the overall climate forcing associated with processing. For crab-flavored sticks, the mean climate forcing of product formation is 0.25 (±0.05) and 0.29 (±0.03) kg CO_2e per kg product on 20-y and 100-y time horizons, respectively. Approximately 70% of the climate impact of product formation is attributed to product ingredients, with the remainder attributed to electricity consumption. For battered-and-breaded fillets, the mean climate forcing of product formation is 0.33 (±0.07) and 0.42 (±0.04) kg CO_2e per kg product on 20-y and 100-y time horizons, respectively. In this case, roughly 90% of the climate impact of product formation is attributed to product ingredients and the remainder is attributed to electricity consumption. The climate impact of the product formation of battered-and-breaded fillets is more than 1.3 times higher than the climate impact of the product formation of crab-flavored sticks. Although the climate impact of electricity consumption is lower for battered-and-breaded fillets than crab-flavored sticks, the ingredient burden is greater.

This can be explained by the greater consumption of wheat ingredients for both batter and breading of the fillet product. As for the other processing activities, ancillary operations (electricity and embodied energy in the chemicals used by the processing facility such as bleach and detergents) and packaging, the climate impact is very similar between products. Ancillary operations contributes 0.11 (±0.05) and 0.15 (±0.02) kg CO_2e per kg product (in both cases) on 20-y and 100-y time horizons, respectively. Packaging contributes roughly 0.06 (±0.01) and 0.08 (±0.01) kg CO_2e per product (in both cases) on 20-y and 100-y time horizons, respectively.

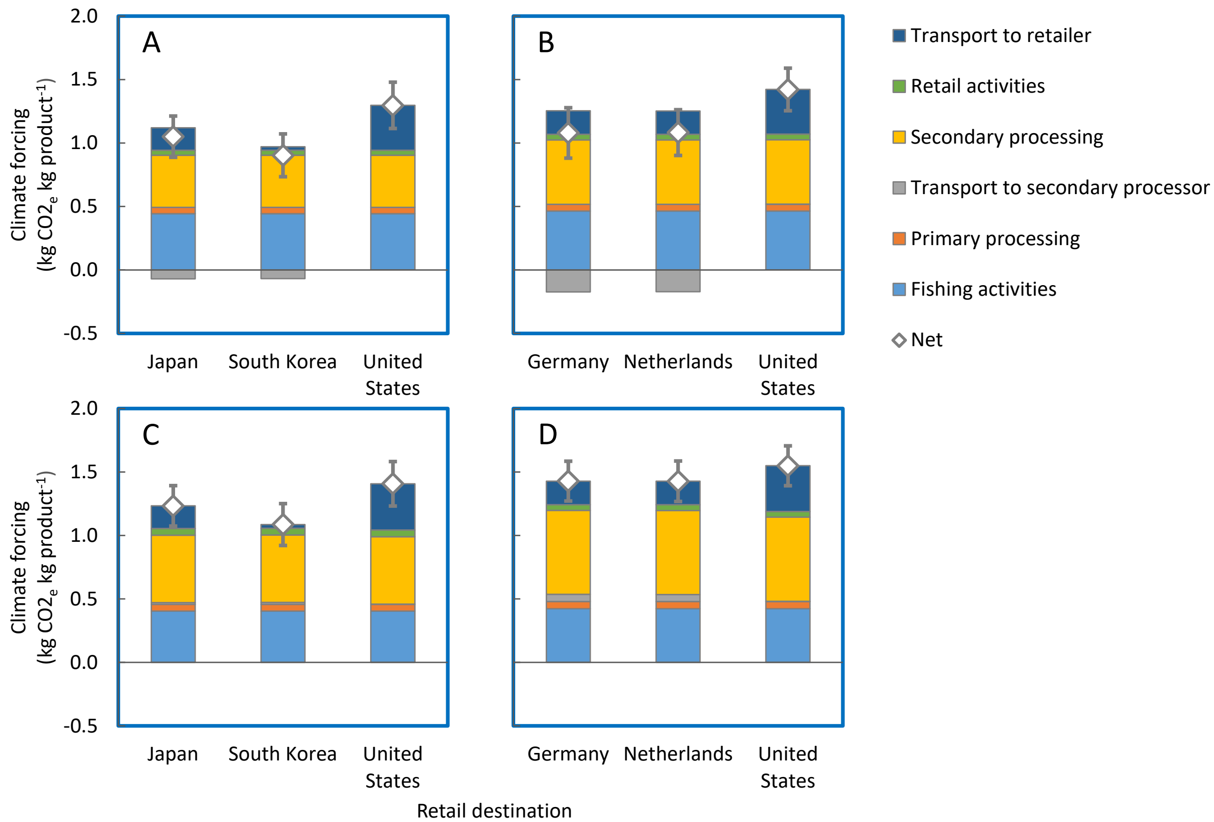

Figure 3.2: *Climate impact of two different Alaskan pollock products destined for five different markets categorized by stage in the seafood supply chain (fishing activities, primary processing, transport to secondary processor, secondary processor, transport to retailer, and retail activities) on 20-y and 100-y time horizons. Left panel (A,C): Refrigerated crab-flavored sticks for three retail markets including Japan, South Korea, and the United States. Right panel (B,D): Frozen battered-and-breaded fillets for three retail markets including Germany, the Netherlands, and the United States. Top panel (A,B): 20-y time horizon. Bottom panel (C,D): 100-y time horizon. The error bars represent the 95% confidence interval.*

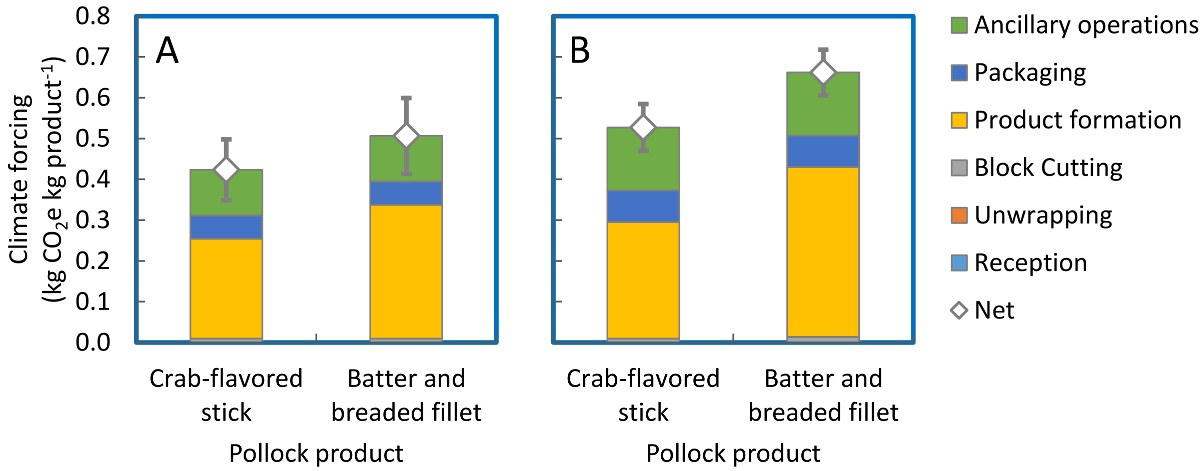

Figure 3.3: *Climate forcing associated with the secondary processing of two Alaskan pollock products by processing activity. Left panel (A): 20-y time horizon. Right panel (B): 100-y time horizon. The error bars represent the 95% confidence interval.*

3.4.5. Impact of including short-lived climate forcing pollutants.

The impact of the individual pollutants on the climate forcing of seafood products was evaluated by chemical constituent (baseline) and a scenario that considers only GHGs on 20-y and 100-y time horizons. Comparisons at the chemical constituent level were made between the two products (battered-and-breaded fillets and crab-flavored sticks), between exported and domestic products, and between scenarios (baseline including SLCFs to a scenario that includes only GHGs--CO_2, CH_4, and N_2O) (Figs. 3.4 and 3.5).

First, the dominant chemical constituents of the two scenarios were examined. CO_2 is the dominant chemical constituent for all products (varies between 1.04 and 1.56 kg CO_2e kg product, for crab-flavored sticks for the South Korean retail market and battered-and-breaded fillets for the domestic market, respectively) and scenarios (Figs. 3.4 and 3.5). However, other chemical constituents have strong warming effects on the climate impact of the two seafood products. On a 20-y time horizon, BC is the second largest warming chemical constituent in the case of crab-flavored sticks (contributes between 13-15% of total warming species--defined as the sum of CO_2, CH_4, N_2O, BC, R-134a, R-404a, CF_4, and C_2F_6; mean total warming species varies between 1.48 and 1.88 kg CO_2e per kg product for the South Korean market and the domestic market, respectively) whereas in the case of battered-and-breaded fillets the contribution of BC to the total warming species is nearly equivalent to CH_4 (contributing 11% and 12% of total warming for BC and CH_4, respectively; mean total warming species totals 2.04 kg CO_2e per kg product for all retail locations). On a 100-y time horizon, the effect of BC is smaller (contributing between 4 and 6% of total warming species—1.76 and 1.23 for crab-flavored sticks for the South Korean market and battered-and-breaded fillets for the domestic market, respectively) and almost equal to the amount contributed by CH_4 (between 5 and 6% of total warming species for crab-flavored sticks for the South Korean market and battered-and-breaded fillets for the domestic market, respectively) (Figs. 3.5A and 3.5C). SO_2 is the dominant species of the cooling chemical constituents (including SO_2, NOx, and OC) on both time horizons (Figs. 3.4A, 3.4C, 3.5A, and 3.5C). On a 20-y time horizon, the contribution of SO_2 varies between 65 and 77% of the mean total cooling species (-0.57 and -0.96 kg CO_2e per kg product, for crab-flavored stick for the domestic market and battered-and-breaded fillets for export markets, respectively). On a 100-y time horizon, the contribution of SO_2 varies between 55 and 69% (-0.18 and -0.29 kg CO_2e per kg product, for crab-flavored stick for the domestic market and battered-and-breaded fillets for export markets, respectively). In the cases that consider only GHGs, CH_4 is second in order of importance followed by N_2O on both time horizons (Figs. 3.4B, 3.4D, 3.5B, and 3.5D).

An analysis of the individual processes of the seafood supply-chain at the chemical constituent level may help to identify where SLCFs have the most significant impact in the seafood supply-chain. Disaggregated by individual processes, the fishing phase is the dominant source BC emissions in the seafood supply-chain across products and time horizons (contributing between 62 and 80% of the mean total climate forcing of BC, 0.25 and 0.20 kg CO_2e per kg product, on a 20-y time horizon for domestic crab-flavored sticks and domestic battered-and-breaded fillets, respectively; contributing between 59 and 74% of the mean total GWP of BC, 0.07 and 0.06 kg CO_2e per kg product, on a 100-y time horizon for domestic crab-flavored sticks and domestic battered-and-breaded fillets, respectively). Secondary processing is second in order of importance (22-25%) of BC emissions in the case of crab-flavored sticks on both time horizons. In the case of battered-and-breaded fillets, transport (~15 %) and processing activities (~10%) are important sources of BC for the export markets on both time horizons. For domestic battered-and-breaded fillets, retail (~10%) and processing activities (~10%) are important contributions on both time horizons.

Considering the primary cooling SLCF constituent by supply-chain activity, processing activities make an important contribution to the overall source (contributing between 43 and 74% of the mean total GWP of SO_2, -0.73 and -0.42 kg CO_2e per kg product, on a 20-y time horizon for battered-and-breaded fillets, for the export and domestic markets, respectively; contributing between 42 and 73% of the mean total climate forcing of SO_2, -0.20 and -0.12 kg CO_2e per kg product, on a 100-y time horizon for the export and domestic markets, respectively). Transportation makes up roughly 30 and 40% of the SO_2 emissions in the case of exported crab-flavored sticks and battered-and-breaded fillets on both time horizons, respectively. Fishing activities are also important sources of SO_2, contributing between 13-15% for domestic markets and between 8-12% for export markets.

Comparing the estimates of the exported products to the domestic products in the baseline scenario, reveals that the climate impact of the exported products is generally lower than the domestic products. The exported products undergo transoceanic shipping, which results in higher amounts of cooling species than the domestic products. Although domestic products are also shipped by container vessel, it is likely the short shipping route (from Port of Dutch Harbor to

Port of Seattle) would take place within emission control areas where the sulfur in marine fuels is regulated (0.1 % sulfur in fuel by % wt.) whereas the exported products are shipped in container vessels outside emission control areas where the sulfur in marine fuels is an order of magnitude higher (global average is ~2.4% sulfur by % wt.).

For battered-and-breaded fillets in the scenario that only includes GHGs, the climate impact is very similar regardless of the retail distribution location or time horizon (Figs. 3.4B and 3.5B). The first explanation is that although the exported products travel a greater overall distance, the product shipped by container vessel is in an unfinished form with a smaller shipping mass. The domestic product is shipped a shorter distance but in a finished product form and thus with a greater shipping mass. Second, it is was assumed that the domestic products travel a greater distance to the retail markets than the exported products. Unlike battered-and-breaded fillets, the climate impact of the exported and domestic crab-flavored sticks have similar trends in both the baseline scenario and the scenario that only considers GHGs (Figs. 3.4C, 3.4D, 3.5C, and 3.5D).

Lastly, the climate impact of the baseline case was compared to the climate impact of the scenario that considers only GHGs. For battered-and-breaded fillets on a 20-y time horizon, the climate impact of the scenario considering only GHGs (1.8 ±0.1 kg CO_2e per kg product for all retail markets) is 1.7 and 1.3 times higher than the baseline scenarios (1.1 ±0.2 and 1.4 ±0.2 kg CO_2e per kg product for the export and domestic markets, respectively). On a 100-y time horizon, the climate impact of battered-and-breaded fillets considering only GHGs (1.7 ±0.1 kg CO_2e per kg product for all markets) is roughly 1.2 and 1.1 higher than the baseline scenario

(1.4 ±0.2 and 1.6 ±0.2 kg CO_2e per kg product for the export and domestic markets, respectively). For crab-flavored sticks on a 20-y time horizon, the climate impact of the scenario considering only GHGs (1.4 ±0.1, 1.3 ±0.1, and 1.6 ±0.2 kg CO_2e per kg product) is 1.3, 1.4, and 1.2 times higher than the baseline scenario for the Japanese, South Korean, and domestic markets, respectively (1.1 ±0.2, 0.9 ±0.2, and 1.3 ±0.2 kg CO_2e per kg product). On a 100-y time horizon, the climate impact of crab-flavored sticks considering only GHGs (1.3 ±0.1, 1.2 ±0.1, and 1.5 ±0.2 kg CO_2e per kg product for the Japanese, South Korean, and U.S. markets, respectively) is roughly 1.1 times higher than the baseline scenario for all markets (1.2 ±0.2, 1.1 ±0.2, and 1.4 ±0.2 kg CO_2e per kg product for the Japanese, South Korean, and U.S. markets, respectively).

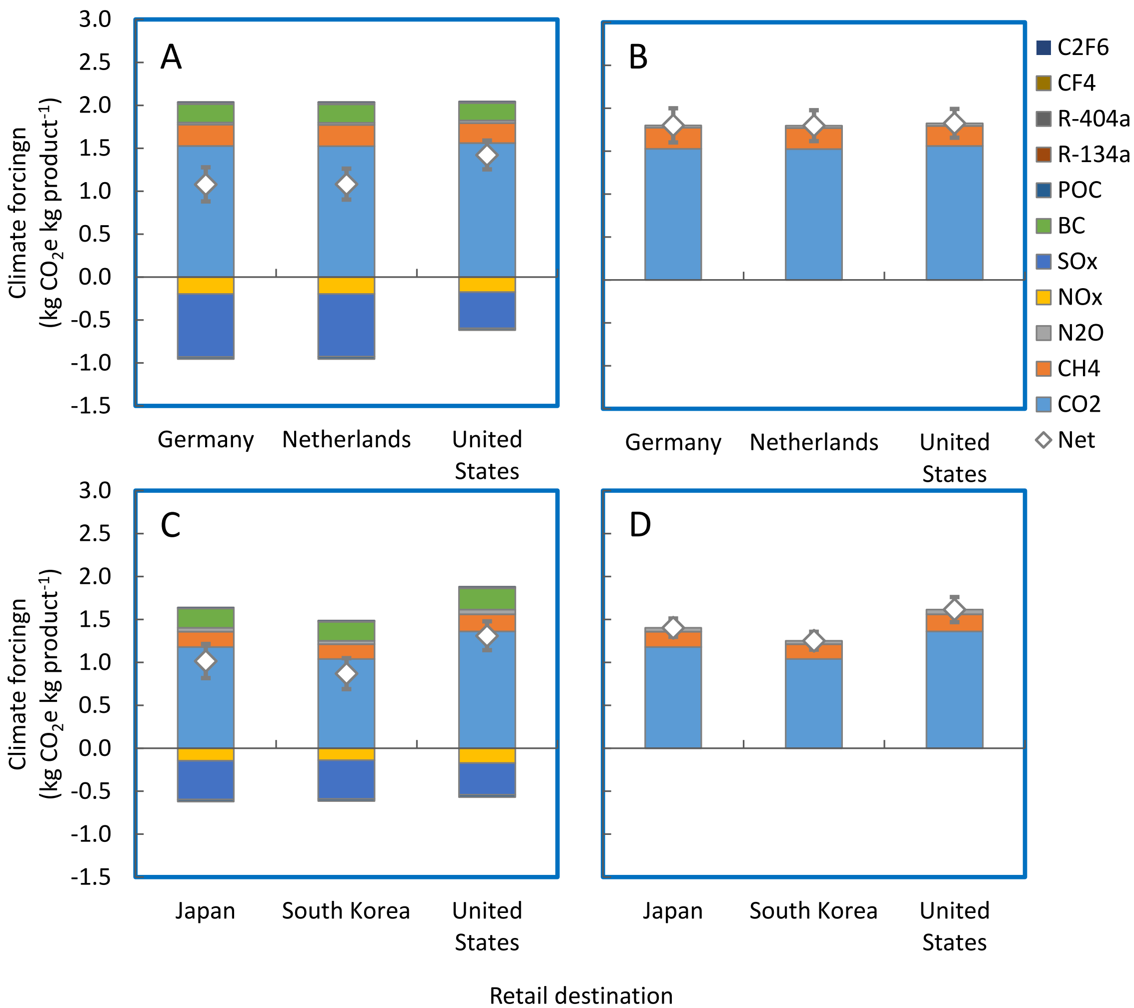

Figure 3.4: *Climate forcing of two different Alaskan pollock products for five different retail markets by chemical constituent on a 20-y time horizon. Top panels (A,B): Frozen battered-and-breaded fillets. Bottom panels (C,D): Refrigerated crab-flavored sticks. Left panels (A,C): Analysis including a suite of greenhouse gases and short-lived climate forcing pollutants. Right panels (B,D): Analysis including only the three primary greenhouse gases (CO_2, CH_4, and N_2O). The error bars represent the 95% confidence interval.*

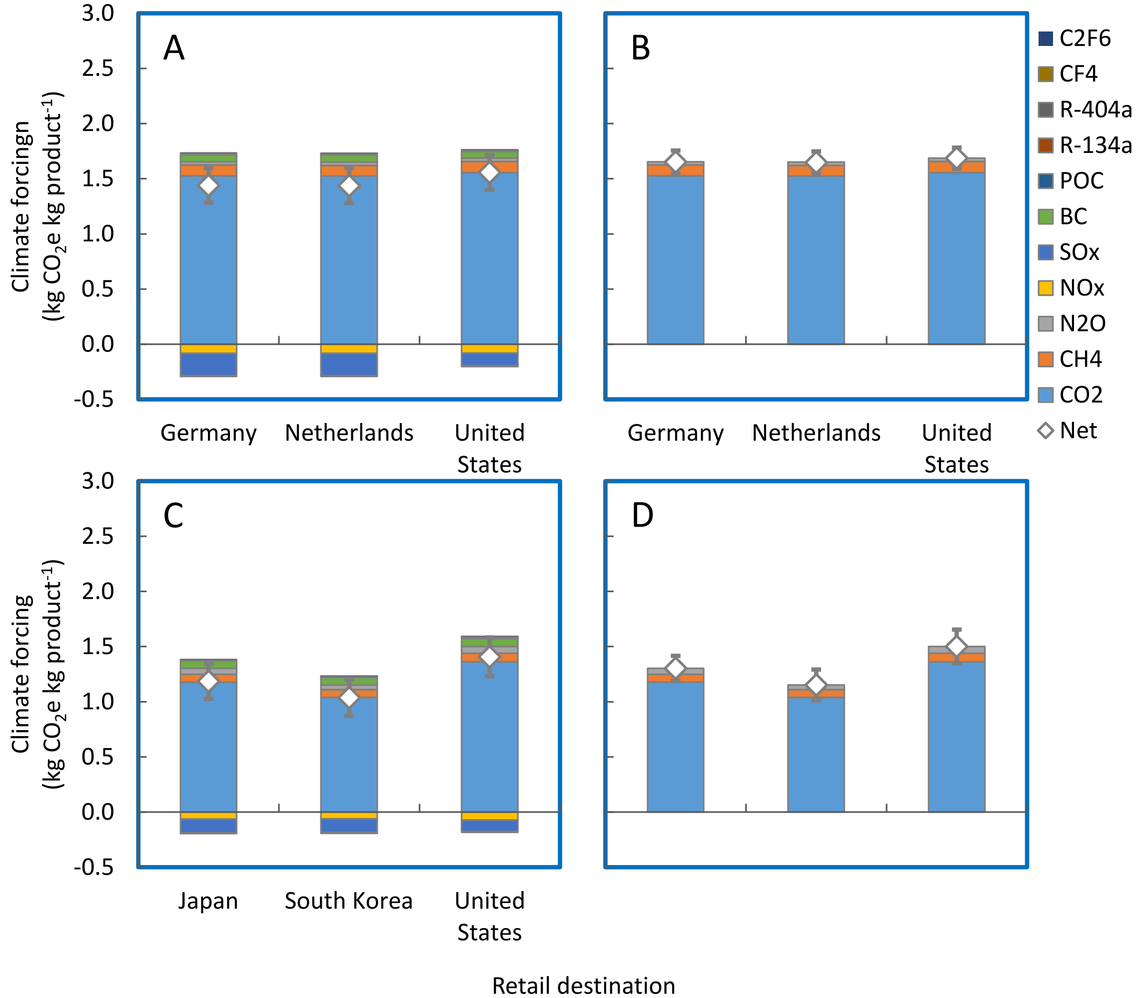

Figure 3.5: *Climate forcing of two different Alaskan pollock products for five different retail markets by chemical constituent on a 100-y time horizon. Top panels (A,B): Frozen battered-and-breaded fillets. Bottom panels (C,D): Refrigerated crab-flavored sticks. Left panels (A,C): Analysis including a suite of greenhouse gases and short-lived climate forcing pollutants. Right panels (B,D): Analysis including only the three primary greenhouse gases (CO_2, CH_4, and N_2O). The error bars represent the 95% confidence interval.*

3.5. Discussion

This research highlights the importance of processing inputs in seafood LCAs, compares the climate impact of two different Alaskan pollock products, and evaluates the importance of SLCF pollutants on the climate impact of the seafood supply-chain. Furthermore, the results of this study were compared to other studies.

Although direct comparisons are difficult to make due to differences in fish species, fishing methods, product forms, LCA boundaries, and allocation methods—the results of this study fall within the wide range of values (0.70 – 14.2 kg CO2e per kg product) found in other studies of white-fish (Tables 3.18-3.20). However, the studies that are most similar to this research include those of pollock products *[Blonk et al., 2008; Sund, 2009; Fulton, 2010]* and those of breaded white-fish products *[Sund, 2009; Vázquez-Rowe et al., 2013]*. The climate forcing values of pollock products in this study are in reasonable agreement with other studies, which vary between 1.1 and 1.6 kg CO_2e per kg of product (Table 3.20). In the case of breaded white-fish fillets, the values found in other studies vary between 1.2 and 3.4 kg CO_2e per kg of product (Table 3.20). For frozen battered-and-breaded fillets on a 100-y time horizon, the climate forcing estimates of this study are between 1.1 and 1.4 times higher than the estimates of breaded pollock fillets reported by Sund (2009). On the other hand, the values of battered-and-breaded pollock fillets of this study are roughly half the estimate of the breaded cod fillets reported by Sund (2009). A lack of detail related to the processing material and energy flows in Sund (2009), however, make it difficult to explain the reason for the differences between studies. The GWP of battered-and-breaded Patagonian grenadier fillets reported by Vázquez-Rowe et al. (2013) is between 1.3 and 1.5 times higher than the estimate of battered-and-breaded Alaskan pollock fillets in this study, on a 100-y time horizon.

Because the material and energy flows of processing the frozen Alaskan pollock fillet blocks into frozen battered-and-breaded fillets of this study were adapted from Vázquez-Rowe et al. (2013), a more detailed comparison between the two studies may be warranted. Despite the smaller system boundary of Vázquez-Rowe et al. (2013) (which includes the seafood supply-chain steps up to the production facility gate), it is reported that the fishing phase makes up approximately 70% of the total climate burden and that processing and ingredients makes up the remainder. In this study, however, processing and fishing activities are nearly equivalent in terms of the climate burden. The lower apportionment of the total climate burden to the fishing phase in this study can be explained by the higher fuel efficiency of the Alaskan pollock catcher/processor pelagic-trawl fleet, 152 (±36) liters of fuel per ton of fish, compared with the fuel efficiency of the Patagonian grenadier bottom-trawl fleet, reported to be 469 liters of fuel per ton of fish. Second, unlike Vázquez-Rowe et al. (2013), our study did not include the co-products of fish feed from broken fillet blocks. Furthermore, other important co-products for Alaskan pollock may include fish oil that could be used to offset the fuel for fishing and/or processing the whole fish into intermediary products *[Yuvaraj et al., 2016]*.

The finding of a lower climate impact of crab-flavored sticks compared with battered-and-breaded fillets suggests there may be a climate benefit associated with a shift in production from fillet products to surimi products. However, before drawing inferences it is important to point out study limitations. First, this study would benefit from a statistical analysis to better understand the significance of the results. Second, the analysis of processing the crab-flavored sticks in this study relied on literature values for the ingredients, and power labels and loading rates found in equipment sales brochures. The inputs for the battered-and-breaded fillets, however, relied on a detailed inventory from the literature in which the values were obtained from an industrial plant. Thus, the analysis of crab-flavored sticks in this study could be improved by obtaining a more detailed inventory of data directly from industrial processors.

The climate impact of the products in the scenario that includes only GHGs is significantly higher than the products that include SLCFs in the analysis. Particularly, in the exported products that are globally distributed by container vessels. This suggests that including SLCFs throughout the seafood supply-chain may be important for understanding the sustainability of seafood.

Table 3.18: *Literature review of the GWPs of cod products.*

Product description	GHGs (kg CO2e kg product^{-1})	Data source
Frozen cod fillet, longline	1.58	[Guttormsdóttir, 2009]
Frozen cod fillet, trawl fishing	5.14	[Guttormsdóttir, 2009]
Frozen cod, wetpack	2.20	[Svanes et al., 2011]
Chilled cod loins	4.40	[Svanes et al., 2011]
Cod burger	1.80	[Svanes et al., 2011]
Fresh gutted cod	3.62	[Winther et al., 2009]
Fresh cod fillet to Oslo	2.36	[Winther et al., 2009]
Fresh cod fillet to Paris	2.51	[Winther et al., 2009]
Frozen cod fillet to Paris	2.51	[Winther et al., 2009]
Frozen cod fillets to Paris via China	3.78	[Winther et al., 2009]
Salted cod to Lisbon	2.20	[Winther et al., 2009]
"Clipfish" cod to Lisbon	2.26	[Winther et al., 2009]
Cod, product not specified	3.36	[Blonk et al., 2008]
Cod, product not specified	4.30	[Sonesson et al., 2010]
Cod, product not specified	4.80	[Sonesson et al., 2010]
Cod fillet	5.30	[Buchspies et al., 2011]
Frozen cod fillets	5.38	[Ziegler and Hansson, 2003]
Frozen cod fillets	0.70	[Fulton, 2010]
Fresh cod fillets, air transport	2.60	[Fulton, 2010]

Table 3.19: *Literature review of the GWPs of various white-fish including saithe, haddock, and hake.*

Product description	GHGs (kg CO2e kg product^{-1})	Data source
Frozen saithe fillets to Berlin	2.56	[Winther et al., 2009]
Frozen haddock fillets to London	3.72	[Winther et al., 2009]
Fresh gutted haddock fillets to London	3.84	[Winther et al., 2009]
Haddock fillets	2.80	[The Co-operative Group, 2010]
Haddock fillets	3.10	[The Co-operative Group, 2010]
Landed hake	6.88	[Iribarren et al., 2010]
Landed hake	9.77	[Vázquez-Rowe et al., 2012]
Landed hake	14.15	[Vázquez-Rowe et al., 2012]
Hake hillet	7.25	[Vázquez-Rowe et al., 2011]
Hake hillet	11.03	[Vázquez-Rowe et al., 2011]
Landed hake, Senegal	11.61	[Vázquez-Rowe et al., 2012]

Table 3.20: *Literature review of the GWP of pollock products, GWP of breaded white-fish, and comparisons to this study. The values in parenthesis represent the 95% confidence interval.*

Product description	**GWP (kg CO2e kg product^{-1})**	**Data source**
Pollock products		
Pollock, product not specified	1.60	[Blonk et al., 2008]
Frozen Alaskan pollock fillets	1.10	[Fulton, 2010]
Frozen battered-and-breaded white-fish fillets		
Frozen breaded cod fillet	3.40	[Sund, 2009]
Frozen breaded and battered Patagonian grenadier	2.21	[Vázquez-Rowe et al., 2013]
Frozen breaded Alaskan pollock fillet	1.20	[Sund, 2009]
Frozen battered-and-breaded fillets, GHGs only		
Domestic production, 100-y time horizon	1.69 (± 0.14)	This study
Exports to Germany, 100-y time horizon	1.65 (± 0.14)	This study
Exports to the Netherlands, 100-y time horizon	1.65 (± 0.14)	This study
Domestic production, 20-y time horizon	1.80 (± 0.15)	This study
Exports to Germany, 20-y time horizon	1.80 (± 0.15)	This study
Exports to the Netherlands, 20-y time horizon	1.82 (± 0.15)	This study
Frozen battered-and-breaded fillets, baseline		
Domestic production,100-y time horizon	1.44 (± 0.21)	This study
Exports to Germany, 100-y time horizon	1.44 (± 0.21)	This study
Exports to the Netherlands,100-y time horizon	1.56 (± 0.21)	This study
Domestic production, 20-y time horizon	1.08 (± 0.23)	This study
Exports to Germany, 20-y time horizon	1.08 (± 0.21)	This study
Exports to the Netherlands,20-y time horizon	1.42 (± 0.20)	This study
Crab-flavored sticks, GHGs only		
Domestic production, 100-y time horizon	1.30 (± 0.15)	This study
Exports to Japan, 100-y time horizon	1.15 (± 0.17)	This study
Exports to South Korea, 100-y time horizon	1.50 (± 0.18)	This study
Domestic production, 20-y time horizon	1.40 (± 0.14)	This study
Exports to Japan, 20-y time horizon	1.25 (± 0.14)	This study
Exports to South Korea, 20-y time horizon	1.61 (± 0.17)	This study
Crab-flavored sticks, baseline		
Domestic production, 100-y time horizon	1.18 (± 0.21)	This study
Exports to Japan, 100-y time horizon	1.04 (± 0.21)	This study
Exports to South Korea, 100-y time horizon	1.41(± 0.22)	This study
Domestic production,20-y time horizon	1.02 (± 0.20)	This study
Exports to Japan, 20-y time horizon	0.87 (± 0.20)	This study
Exports to the South Korea,20-y time horizon	1.31 (± 0.21)	This study

3.6. Conclusions

An accurate accounting of the climate impact of food systems is a necessary first step in prioritizing emission mitigation strategies. For products derived from highly fuel efficient fisheries, the upstream processing of seafood products is important and should not be ignored in seafood LCAs.

There is a growing consensus among policy-makers and scientists that efforts to address climate change should not be limited to reductions of CO_2 but should be complemented by mitigation of SLCFs in the near term [Smith and Mizrahi, 2013; Rogelj et al., 2014]. Thus, climate accounting of food production systems should not ignore the contribution of SLCFs. This study found that for products shipped by container vessels, the cooling from sulfur oxides resulting from the combustion of marine fuels have a significant effect on the climate impact of seafood.

Furthermore, there may be important policy implications for the future sustainability of seafood in the near term. The current maximum sulfur content of marine fuels, of 3.5 percent set by the International Maritime Organization's Marine Environmental Protection Committee, will be capped at 0.5 percent by 2020 *[Smith et al., 2014]*. As a result of this policy, the cooling effect of sulfur oxides may be diminished and increase the climate impact of food that is shipped on trans-oceanic voyages.

REFERENCES

AAFA (2017), American Albacore Fishing Association Vessel Roster.

Aamaas, B., T.K. Berntsen, J.S. Fuglestvedt, K.P. Shine and N. Bellouin (2015), Multimodel emission metrics for regional emissions of short lived climate forcers, Atmospheric Chemistry and Physics Discussions., 15(18), 26089-26130, doi: 10.5194/acpd-15-26089-2015.

Abella, J.P., and J.A. Bergerson (2012), Model to Investigate Energy and Greenhouse Gas Emissions Implications of Refining Petroleum: Impacts of Crude Quality and Refinery Configuration, Environ.Sci.Technol., 46(24), 13037-13047, doi: 10.1021/es3018682.

ABS (2015), Fuel Switching Advisory, 2015, ABS.

Aliabadi, A.A., R.M. Staebler and S. Sharma (2015), Air quality monitoring in communities of the Canadian Arctic during the high shipping season with a focus on local and marine pollution, Atmospheric Chemistry and Physics., 15(5), 2651-2673, doi: 10.5194/acp-15-2651-2015.

Avadi, A., C. Bolanos, I. Sandoval and C. Ycaza (2015), Life cycle assessment of Ecuadorian processed tuna, International Journal of Life Cycle Assessment., 20(10), 1415-1428, doi: 10.1007/s11367-015-0943-2.

Bajželj, B., K.S. Richards, J.M. Allwood, P. Smith, J.S. Dennis, E. Curmi and C.A. Gilligan (2014), Importance of food-demand management for climate mitigation, Nature Climate Change., 4(10), 924, doi: 10.1038/nclimate2353.

Baker, L.H., W.J. Collins, D.J.L. Olivié, R. Cherian, Ø Hodnebrog, G. Myhre, J. Quaas and B.H. Samset (2015), Climate responses to anthropogenic emissions of short-lived climate pollutants, Atmospheric Chemistry and Physics Discussions., 15(3), 3823-3862, doi: 10.5194/acpd-15-3823-2015.

Baruthio, A., and et al. (2008), Environmental assessment of Filipino fish/prawn polyculture using Life Cycle Assessment, Proc. of the 6th Int. Conf. on LCA in the Agri-Food Sector.

Basurko, O.C., G. Gabiña and Z. Uriondo (2013), Energy performance of fishing vessels and potential savings, J.Clean.Prod., 54, 30-40, doi: //dx.doi.org/10.1016/j.jclepro.2013.05.024.

Bayless, A.R., E.M. Oleson, S. Baumann-Pickering, A.E. Simonis, J. Marchetti, S. Martin and S.M. Wiggins (2017), Acoustically monitoring the Hawai‘i longline fishery for interactions with false killer whales, Fisheries Research., 190, 122-131, doi: 10.1016/j.fishres.2017.02.006.

Beddington, J.R., D.J. Agnew and C.W. Clark (2007), Current Problems in the Management of Marine Fisheries, Science., 316(5832), 1713-1716, doi: 10.1126/science.1137362.

Bevington, P.R., and D.K. Robinson (2003), Data reduction and error analysis for the physical sciences edited by D. Bruflodt, McGraw-Hill, Boston.

Blonk, H., A. Kool, B. Luske and S. de Waart (2008), Environmental effects of protein-rich food products in the Netherlands: consequences of animal protein substitutes, Blonk Milieuadvies and the Dutch Vegetarian Association, Netherlands.

Blowers, P., and J.M. Lownsbury (2010), Carbon dioxide emission implications if hydrofluorocarbons are regulated: a refrigeration case study, Environmental science & technology., 44(5), 1526.

Boggs, C., and R. Ito (1993), Hawaii's Pelagic Fisheries, Marine Fisheries Review., 55(2), 69-82.

Boggs, C.H., and B.S. Kikkawa (1993), The development and decline of Hawaii's skipjack tuna fishery, Marine Fisheries Review., 55(2), 61.

Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Kaercher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren and C.S. Zender (2013), Bounding the role of black carbon in the climate system: A scientific assessment, Journal of Geophysical Research-Atmospheres., 118(11), 5380-5552, doi: 10.1002/jgrd.50171.

Bond, T.C., C. Zarzycki, M.G. Flanner and D.M. Koch (2011), Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse, Atmospheric Chemistry and Physics., 11(4), 1505-1525, doi: 10.5194/acp-11-1505-2011.

Boucher, O., and M.S. Reddy (2008), Climate trade-off between black carbon and carbon dioxide emissions, Energy Policy., 36(1), 193-200, doi: 10.1016/j.enpol.2007.08.039.

Bovea, M., R. Cabello and D. Querol (2007), Comparative life cycle assessment of commonly used refrigerants in commercial refrigeration systems, Int J Life Cycle Assess., 12(5), 299-307, doi: 10.1065/lca2007.06.346.

Brandt, A.R., Y. Sun and K. Vafi (2015), Uncertainty in Regional-Average Petroleum GHG Intensities: Countering Information Gaps with Targeted Data Gathering, Environ.Sci.Technol., 49(1), 679-686, doi: 10.1021/es505376t.

Brouwer, S., G. Pilling, J. Hampton, P. Williams, S. McKechnie and L. Tremblay-Boyer (2017), The Western and Central Pacific tuna fishery: 2016 overview and status of stocks, Tuna Fisheries Assessment Report No. 17, SPC, Noumea, Cedex, New Caledonia.

Browse, J., K.S. Carslaw, A. Schmidt and J.J. Corbett (2013), Impact of future Arctic shipping on high-latitude black carbon deposition, Geophys. Res. Lett., 40, 4459-4463, doi: 10.1002/grl.50876.

Buchspies, B., S. Tölle and N. Jungbluth (2011), Life Cycle Assessment of High-Sea Fish and Salmon Aquaculture, ESU-services Ltd.

Buffaloe, G.M., D.A. Lack, E.J. Williams, D. Coffman, K.L. Hayden, B.M. Lerner, S.-. Li, I. Nuaaman, P. Massoli, T.B. Onasch, P.K. Quinn and C.D. Cappa (2014), Black carbon emissions from in-use ships: a California regional assessment, Atmospheric Chemistry and Physics., 14(4), 1881-1896, doi: 10.5194/acp-14-1881-2014.

Cai, H. (2014), Estimation of Emission Factors and Particulate Black Carbon and Organic Carbon from Stationary, Mobile, and Non-point Sources in the United States for Incorporation into GREET, EE Office of Vehicle Technologies, United States.

Cao, L., J.S. Diana, G.A. Keoleian and Q. Lai (2011), Life Cycle Assessment of Chinese Shrimp Farming Systems Targeted for Export and Domestic Sales, Environ.Sci.Technol., 45(15), 6531-6538, doi: 10.1021/es104058z.

Cappa, C.D., E.J. Williams, D.A. Lack, G.M. Buffaloe, D. Coffman, K.L. Hayden, S.C. Herndon, B.M. Lerner, S.-. Li, P. Massoli, R. McLaren, I. Nuaaman, T.B. Onasch and P.K. Quinn (2014), A case study into the measurement of ship emissions from plume intercepts of the NOAA ship Miller Freeman, Atmospheric Chemistry and Physics., 14(3), 1337-1352, doi: 10.5194/acp-14-1337-2014.

Cascini, A., M. Gamberi, C. Mora, M. Rosano and M. Bortolini (2016), Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations, Journal of Cleaner Production., 112, 3998-4011, doi: 10.1016/j.jclepro.2015.08.075.

Childers, J., and A. Pease (2012), Summary of the 2009 and 2010 U.S.A North and South Pacific albacore pole-and-line fisheries, Administrative report LJ-12-02, La Jolla, CA.

Clune, S., E. Crossin and K. Verghese (2017), Systematic review of greenhouse gas emissions for different fresh food categories, Journal of Cleaner Production., 140, 766-783, doi: 10.1016/j.jclepro.2016.04.082.

Coello, J., I. Williams, D.A. Hudson and S. Kemp (2015), An AIS-based approach to calculate atmospheric emissions from the UK fishing fleet, Atmos.Environ., 114, 1-7, doi: //dx.doi.org/10.1016/j.atmosenv.2015.05.011.

Collins, W.J., M.M. Fry, H. Yu, J.S. Fuglestvedt, D.T. Shindell and J.J. West (2013), Global and regional temperature-change potentials for near-term climate forcers, Atmospheric Chemistry and Physics., 13(5), 2471-2485, doi: 10.5194/acp-13-2471-2013.

Corbett, J.J., and H.W. Koehler (2003), Updated emissions from ocean shipping, Journal of Geophysical Research-Atmospheres., 108(D20), 4650, doi: 10.1029/2003JD003751.

Corbett, J.J., D.A. Lack, J.J. Winebrake, S. Harder, J.A. Silberman and M. Gold (2010a), Arctic shipping emissions inventories and future scenarios, Atmospheric Chemistry and Physics., 10(19), 9689-9704, doi: 10.5194/acp-10-9689-2010.

Corbett, J.J., J.J. Winebrake and E.H. Green (2010b), An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping, Carbon Management., 1(2), 207-225, doi: 10.4155/CMT.10.27.

Costello, C., D. Ovando, T. Clavelle, C.K. Strauss, R. Hilborn, M.C. Melnychuk, T.A. Branch, S.D. Gaines, C.S. Szuwalski, R.B. Cabral, D.N. Rader and A. Leland (2016), Global fishery prospects under contrasting management regimes, Proceedings of the National Academy of Sciences., 113(18), 5125-5129, doi: 10.1073/pnas.1520420113.

COWI, E3-M Lab and Exergia (2014), Study on actual GHG data for diesel, petrol, kerosene and natural gas, European Commission, DG Ener, Brussels.

Cullinane, K., and R. Bergqvist (2014), Emission Control Areas and Their Impact on Maritime Transport, Transportation Research: Part D: Transport and Environment., 28, 1-5, doi: 10.1016/j.trd.2013.12.004.

d'Orbcastel, E.R., J. Blancheton and J. Aubin (2009), Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment, Aquacult.Eng., 40(3), 113-119, doi: //dx.doi.org/10.1016/j.aquaeng.2008.12.002.

Dalsøren, S.B., M.S. Eide, Ø Endresen, A. Mjelde, G. Gravir and I.S.A. Isaksen (2009), Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports, Atmospheric Chemistry and Physics., 9(6), 2171-2194.

Dotson, R.C. (1980), Fishing methods and equipment of the U.S. west coast albacore fleet.

Duffy, J. (2015), Staff Report: Calculating Carbon Intensity Values of Crude Oil Supplied to California Refineries, California Environmental Protection Agency Air Resources Board, Sacramento, California.

e-CFR (2015), Electronic Code of Federal Regulations, U.S. Federal Government, Part 80-Regulation of fuels and additives, §80.608 What requirements apply to diesel fuel and ECA marine fuel for use in the Territories?, 2017(September, 30,).

EIA (2017a), U.S. Department of Energy, Energy Information Administration (EIA), Distillate Fuel Oil and Kerosene Sales by End Use, 2017(April 9,).

EIA (2017b), U.S. Department of Energy, Energy Information Administration (EIA), Suppy and Disposition.

Endresen, Ø, E. Sørgård, H.L. Behrens, P.O. Brett and I.S.A. Isaksen (2007), A historical reconstruction of ships' fuel consumption and emissions, Journal of Geophysical Research-Atmospheres., 112(D12), D12301, doi: 10.1029/2006JD007630.

Endresen, Ø, E. Sørgård, J.K. Sundet, S.B. Dalsøren, I.S.A. Isaksen, T.F. Berglen and G. Gravir (2003), Emission from international sea transportation and environmental impact, Journal of Geophysical Research: Atmospheres., 108(D17), n/a, doi: 10.1029/2002JD002898.

Energy and Environmental Analysis, Inc (2000), Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data, Rep. EPA420-R-00-002, United States Environmental Protection Agency, Washington D.C.

Eshel, G., A. Shepon, T. Makov and R. Milo (2014), Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States, Proceedings of the National Academy of Sciences., 111(33), 11996-12001, doi: 10.1073/pnas.1402183111.

Eyjólfsdóttir, H., H. Jónsdóttir, E. Yngvadóttir and B. Skuladóttir (2003), Environmental effects of fish on the consumer dish - life cycle assessment of Icelandic frozen cod products, Skýrsla ITÍ/ IceTec report 0305/HTD05.

Eyring, V., I.S.A. Isaksen, T. Berntsen, W.J. Collins, J.J. Corbett, Ø Endresen, R.G. Grainger, J. Moldanova, H. Schlager and D.S. Stevenson (2010), Transport impacts on atmosphere and climate: Shipping, Atmos.Environ., 44(37), 4735-4771, doi: //dx.doi.org/10.1016/j.atmosenv.2009.04.059.

Eyring, V., H.W. Kohler, J. van Aardenne and A. Lauer (2005), Emissions from international shipping: 1. The last 50 years, Journal of Geophysical Research-Part D-Atmospheres., 110(D17), 12 pp., doi: 10.1029/2004JD005619.

Eyring, V., D.S. Stevenson, A. Lauer, F.J. Dentener, T. Butler, W.J. Collins, K. Ellingsen, M. Gauss, D.A. Hauglustaine, I.S.A. Isaksen, M.G. Lawrence, A. Richter, J.M. Rodriguez, M. Sanderson, S.E. Strahan, K. Sudo, S. Szopa, van Noije, T P C and O. Wild (2007), Multi-model simulations of the impact of international shipping on Atmospheric Chemistry and Climate in 2000 and 2030, Atmospheric Chemistry and Physics., 7(3), 757-780, doi: 10.5194/acp-7-757-2007.

Faloona, I. (2009), Sulfur processing in the marine atmospheric boundary layer: A review and critical assessment of modeling uncertainties, Atmos.Environ., 43(18), 2841-2854, doi: 10.1016/j.atmosenv.2009.02.043.

FAO (2015a), Fisheries and aquaculture software. FishStatJ - software for fishery statistical time series. In: *FAO Fisheries and Aquaculture Department* [online]. Rome. Updated 23 June 2015. [Cited 24 November 2015]. http://www.fao.org/fishery/statistics/software/fishstatj/en.

FAO (2015b), Food and Agriculture Organization of the United Nations. Fisheries and Aquaculture Department, Fisheries Technology, Fish Capture Technology, World fishing fleet, 2015(3/10).

Farmery, A., C. Gardner, B.S. Green, S. Jennings and R. Watson (2015), Life cycle assessment of wild capture prawns: expanding sustainability considerations in the Australian Northern Prawn Fishery, J.Clean.Prod., 87, 96-104, doi: //dx.doi.org/10.1016/j.jclepro.2014.10.063.

Fissel, B., M. Dalton, R. Felthoven, B. Garber-Yonts, A. Haynie, S. Kasperski, J. Lee, D. Lew, A. Santos, C. Seung and K. Sparks (2016), Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area: Economic status of the groundfish fisheries off Alaska, 2015. Economic and Social Sciences Research Program, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA.

Fitzgerald, W.B., O.J.A. Howitt, I.J. Smith and A. Hume (2011), Energy use of integral refrigerated containers in maritime transportation, Energy Policy., 39(4), 1885-1896, doi: 10.1016/j.enpol.2010.12.015.

Flanner, M.G. (2013), Arctic climate sensitivity to local black carbon, Journal of Geophysical Research-Atmospheres., 118(4), 1840-1851, doi: 10.1002/jgrd.50176.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman and D.P.M. Zaks (2011), Solutions for a cultivated planet, Nature., 478(7369), 337-342, doi: 10.1038/nature10452.

Fréon, P., A. Avadí, R. Vinatea Chavez and F. Iriarte Ahón (2014), Life cycle assessment of the Peruvian industrial anchoveta fleet: boundary setting in life cycle inventory analyses of complex and plural means of production, Int J Life Cycle Assess., 19(5), 1068-1086, doi: 10.1007/s11367-014-0716-3.

Fuglestvedt, J.S., K.P. Shine, T. Berntsen, J. Cook, D.S. Lee, A. Stenke, R.B. Skeie, G.J.M. Velders and I.A. Waitz (2010), Transport impacts on atmosphere and climate: Metrics, Atmos.Environ., 44(37), 4648-4677, doi: 10.1016/j.atmosenv.2009.04.044.

Fuglestvedt, J., T. Berntsen, V. Eyring, I. Isaksen, D.S. Lee and R. Sausen (2009), Shipping Emissions: From Cooling to Warming of Climate—and Reducing Impacts on Health, Environ.Sci.Technol., 43(24), 9057-9062, doi: 10.1021/es901944r.

Fuglestvedt, J., T. Berntsen, G. Myhre, K. Rypdal and R.B. Skeie (2008), Climate forcing from the transport sectors, Proceedings of the National Academy of Sciences., 105(2), 454-458, doi: 10.1073/pnas.0702958104.

Fulton, S. (2010), Fish and Fuel: Life cycle greenhouse gas emissions associated with Icelandic cod, Alaskan pollock, and Alaskan pink salmon fillets delivered to the United Kingdom.

Geagla, A., W. Brown and J. Powell (2015), Energy Information Administration. With increased regulation, continued decline in residual fuel oil demand is expected, 2016(June 15,).

Gillett, R.D. (1986), Observer trip on U.S. purse-seine vessels-1984, Tuna and Billfish Assessment Programme, Technical report no. 15, South Pacific Commission, Noumea, New Caledonia.

Gillett, R., M. McCoy and D.G. Itano (2002), Status of the United States Western Pacific Tuna Purse Seine Fleet and Factors Affecting Its Future, SOEST 02-01, JIMA Contribution 02-344, University of Hawaii at Monoa, Monoa, Hawaii.

Gillett, R. (2011), Replacing purse seining with pole-and-line fishing in the central and Western Pacific: Some aspects of the baitfish requirements, Marine Policy., 35(2), 148-154, doi: 10.1016/j.marpol.2010.08.013.

Gilman, E.L. (2011), Bycatch governance and best practice mitigation technology in global tuna fisheries, Mar.Policy., 35(5), 590-609, doi: 10.1016/j.marpol.2011.01.021.

Girod, B., D.P. van Vuuren and E.G. Hertwich (2014), Climate policy through changing consumption choices: Options and obstacles for reducing greenhouse gas emissions, Global Environmental Change., 25(March 2014), 5-15, doi: 10.1016/j.gloenvcha.2014.01.004.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas and C. Toulmin (2010), Food Security: The Challenge of Feeding 9 Billion People, Science., 327(5967), 812-818, doi: 10.1126/science.1185383.

Goldsworthy, L., and B. Goldsworthy (2015), Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – An Australian case study, Environmental Modelling & Software., 63, 45-60, doi: //dx.doi.org/10.1016/j.envsoft.2014.09.009.

Gordon, D., A. Brandt, J. Bergerson and J. Koomey (2015), Know Your Oil: Creating a Global Oil-Climate Index, Carnegie Endowment for International Peace.

Greer, K. (2014), Considering the 'effort factor' in fisheries: a methodology for reconstructing global fishing effort and CO_2 emissions, 1950-2010 [Masters of Science Thesis], The University of British Columbia, Vancouver.

Guttormsdóttir, A. (2009), Life cycle assessment on Icelandic cod product based on two different fishing methods: Environmental impacts from fisheries.

Hallström, E., A. Carlsson-Kanyama and P. Börjesson (2015), Environmental impact of dietary change: a systematic review, Journal of Cleaner Production., 91, 1-11, doi: //dx.doi.org/10.1016/j.jclepro.2014.12.008.

Harley, S.J., N. Davies, L. Tremblay-Boyer, J. Hampton and S. McKechnie (2015), Scientific Committee Eleventh Regular Session: Stock assessment for South Pacific albacore tuna, WCPFC-SC11-2015/SA-WP-06, Western and Central Pacific Fisheries Commission, Pohnpei, Federated States of Micronesia.

Havice, E. (2013), Rights-based management in the Western and Central Pacific Ocean tuna fishery: Economic and environmental change under the Vessel Day Scheme, Marine Policy., 42, 259-267, doi: 10.1016/j.marpol.2013.03.003.

Head, M., M. Sevenster and H. Croezen (2011), Life cycle impacts of protein: rich foods for Superwijzer; 70 p, CE Delft, Delft.

Heller, M.C., and G.A. Keoleian (2015), Greenhouse Gas Emission Estimates of US Dietary Choices and Food Loss, J.Ind.Ecol., 19(3), 391-401, doi: 10.1111/jiec.12174.

Hoang, H.M., T. Brown, E. Indergard, D. Leducq and G. Alvarez (2016), Life cycle assessment of salmon cold chains: comparison between chilling and superchilling technologies, Journal of Cleaner Production., 126, 363-372, doi: 10.1016/j.jclepro.2016.03.049.

Holmes, C.D., M.J. Prather and G.C.M. Vinken (2014), The climate impact of ship NO$_x$ emissions: an improved estimate accounting for plume chemistry, Atmospheric Chemistry and Physics., 14(13), 6801-6812, doi: 10.5194/acp-14-6801-2014.

Holmes, J., C. Minte-Vera, C. Chen, D. Ochi, D. Itano, D. Tommasi, H. Kiyofuji, H. Ijima, H. Lee, K. Piner, O. Sakai, S. Teo, A. Zhang and Z. Geng (2017), Albacore Working Group of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean. Scientific Committee Thirteenth Regular Session: Stock assessment of albacore in the North Pacific Ocean in 2017, WCPFC-SC13-2017/SA-WP-09, Western and Central Pacific Fisheries Commission, Rarotonga, Cook Islands.

Horne-Sparboth, T., Adam, M. S., Ziyad (2015), A socio-economic assessment of the tuna fisheries in the Maldives, IPNLF Technical Report 5. International Pole and Line Foundation, London 44 pages.

Hospido, A., M.E. Vazquez, A. Cuevas, G. Feijoo and M.T. Moreira (2006), Environmental assessment of canned tuna manufacture with a life-cycle perspective, Resources Conservation and Recycling., 47(1), 56-72, doi: 10.1016/j.resconrec.2005.10.003.

Hur, S.J., Y.J. Choi, B.D. Choi, B.G. Kim and S.K. Jin (2011), Quality characteristics of imitation crab sticks made from Alaska Pollack and spent laying hen meat, LWT - Food Science and Technology., 44(6), 1482-1489, doi: 10.1016/j.lwt.2011.02.013.

ICCT, and DieselNet (2016), U.S. Fuels: Diesel and Gasoline, 2016(June 15,).

ICF Consulting (1999), In-use marine diesel fuel, Rep. EPA 420-R-99-027, United States Environmental Protection Agency, Washington D.C.

ICF International (2009), Current methodologies in preparing mobile source port-related emissions inventories: Final report prepared for the US EPA, United States Environmental Protection Agency, Washington D.C.

IMO (2015), International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Regulation 14 - Sulfur oxides MEPC.209(603).

Inter-American Tropical Tuna Commission, (IATTC) (2017), IATTC Vessel Search, 2017(December 18,).

Iqbal, A., I.A. Khalil, N. Ateeq and M. Sayyar Khan (2006), Nutritional quality of important food legumes, Food Chem., 97(2), 331-335, doi: //dx.doi.org/10.1016/j.foodchem.2005.05.011.

Iribarren, D., I. Vázquez-Rowe, A. Hospido, M.T. Moreira and G. Feijoo (2010), Estimation of the carbon footprint of the Galician fishing activity (NW Spain), Sci.Total Environ., 408(22), 5284-5294, doi: //dx.doi.org/10.1016/j.scitotenv.2010.07.082.

Jafarzadeh, S., H. Ellingsen and S.A. Aanondsen (2016), Energy efficiency of Norwegian fisheries from 2003 to 2012, Journal of Cleaner Production., 112, 3616-3630, doi: //dx.doi.org/10.1016/j.jclepro.2015.06.114.

Jonell, M., and P.J.G. Henriksson (2015), Mangrove–shrimp farms in Vietnam—Comparing organic and conventional systems using life cycle assessment, Aquaculture., 447, 66-75, doi: //dx.doi.org/10.1016/j.aquaculture.2014.11.001.

Joseph, J. (2003), Managing fishing capacity of the world tuna fleet, The tuna fishing vessels of the world, Food and Agriculture Organization Fisheries, Cicular. No. 982., Food and Agriculture Organization, Rome.

Justel-Rubio, A., and V. Restrepo (2015), Preliminary study of the relative fishery impacts on non-tuna species caught in tuna fisheries. ISSF Technical Report 2015-02., International Seafood Sustainability Foundation, Washington D.C., USA.

Katajajuuri, J., J. Grönroos and K. Usva (2008), Environmental Impacts and Related Options for Improving the Chicken Meat Supply Chain. 6th International Conference on LCA in the Agri-Food Sector, Zurich.

Kendrick, T.H., and N. Bentley (2010), Indices of albacore abundance from the west coast troll fishery, 1989–90 to 2007–08, New Zealand Fisheries Assessment Report 2010/45.

Krampe, P. (2006), Rising fuel prices and its impact on the tuna industry, Tuna 2006 – Ninth Infofish World Tuna Trade Conference, Bangkok.

Lack, D.A., and J.J. Corbett (2012), Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing, Atmospheric Chemistry and Physics., 12(9), 3985-4000, doi: 10.5194/acp-12-3985-2012.

Lack, D.A., C.D. Cappa, J. Langridge, R. Bahreini, G. Buffaloe, C. Brock, K. Cerully, D. Coffman, K. Hayden, J. Holloway, B. Lerner, P. Massoli, S. Li, R. McLaren, A.M. Middlebrook, R. Moore, A. Nenes, I. Nuaaman, T.B. Onasch, J. Peischl, A. Perring, P.K. Quinn, T. Ryerson, J.P. Schwartz, R. Spackman, S.C. Wofsy, D. Worsnop, B. Xiang and E. Williams (2011), Impact of Fuel Quality Regulation and Speed Reductions on Shipping Emissions: Implications for Climate and Air Quality, Environ.Sci.Technol., 45(20), 9052-9060, doi: 10.1021/es2013424.

Lack, D.A., J.J. Corbett, T. Onasch, B. Lerner, P. Massoli, P.K. Quinn, T.S. Bates, D.S. Covert, D. Coffman, B. Sierau, S. Herndon, J. Allan, T. Baynard, E. Lovejoy, A.R. Ravishankara and E. Williams (2009), Particulate emissions from commercial shipping: Chemical, physical, and optical properties, Journal of Geophysical Research: Atmospheres., 114(D7), n/a, doi: 10.1029/2008JD011300.

Lack, D., B. Lerner, C. Granier, T. Baynard, E. Lovejoy, P. Massoli, A.R. Ravishankara and E. Williams (2008), Light absorbing carbon emissions from commercial shipping, Geophys.Res.Lett., 35(13), L13815, doi: 10.1029/2008GL033906.

Langley, A. (2011), Scientific Committee Seventh Regular Session: A preliminary analysis of VMS data from the equatorial purse-seine fleet - the potential application of VMS data in the analysis of purse-seine catch and effort data, WCPFC-SC7-2011/SA-SP-07, Pohnpei, Federated States of Micronesia.

Laso, J., I. Vázquez-Rowe, M. Margallo, R. Crujeiras, A. Irabien and R. Aldaco (2018), Life cycle assessment of European anchovy (Engraulis encrasicolus) landed by purse seine vessels in northern Spain, The International Journal of Life Cycle Assessment., 23(5), 1107-1125, doi: 10.1007/s11367-017-1318-7.

Lauer, A., V. Eyring, J. Hendricks, P. Joeckel and U. Lohmann (2007), Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget, Atmospheric Chemistry and Physics., 7(19), 5061-5079.

Liu, Y., T.W. Rosten, K. Henriksen, E.S. Hognes, S. Summerfelt and B. Vinci (2016), Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater, Aquacult.Eng., 71, 1-12, doi: //dx.doi.org/10.1016/j.aquaeng.2016.01.001.

Ma, H., K. Steernberg, X. Riera-Palou and N. Tait (2012), Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry, Transportation Research Part D: Transport and Environment., 17(4), 301-308, doi: //dx.doi.org/10.1016/j.trd.2012.01.005.

Marine Stewardship Council (2016), Marine Stewardship Council:
Global Impacts Report 2016, London, UK. 64 pp
ISSN 2052-8876.

Marine Traffic (2017), Marine Traffic Vessel Search.

Martin, S.L., S.M. Stohs and J.E. Moore (2015), Bayesian inference and assessment for rare-event bycatch in marine fisheries: a drift gillnet fishery case study, Ecological Applications., 25(2), 416-429, doi: 10.1890/14-0059.1.

Mathwave Data Analysis and Simulation (2015), Mathwave Data Analysis and Simulation. EasyFit Distribution Fitting Software for Excel, Version 5.6.

McCarthy, D., A. Matopoulos and P. Davies (2015), Life cycle assessment in the food supply chain: a case study, International Journal of Logistics Research and Applications., 18(2), 140-154, doi: 10.1080/13675567.2014.997197.

McGrath, K.P., N.L. Pelletier and P.H. Tyedmers (2015), Life Cycle Assessment of a Novel Closed-Containment Salmon Aquaculture Technology, Environ.Sci.Technol., 49(9), 5628-5636, doi: 10.1021/es5051138.

McKechnie, S., J. Hampton, G.M. Pilling and N. Davies (2016), Scientific Committee Twelfth Regular Session: Stock assessment of skipjack tuna in the Western and Central Pacific Ocean, WCPFC-SC12-2016/SA-WP-04, Western and Central Pacific Fisheries Commission, Bali, Indonesia.

McKechnie, S., G. Pilling and J. Hampton (2017), Stock assessment of bigeye tuna in the Western and Central Pacific Ocean, WCPFC-SC13-2017/SA-WP-05, Western Central and Pacific Fisheries Commission, Rarotonga, Cook Islands.

McKuin, B., and J.E. Campbell (2016), Emissions and climate forcing from global and Arctic fishing vessels, Journal of Geophysical Research: Atmospheres., 121(4), 1844-1858, doi: 10.1002/2015JD023747.

Mestl, T., G. Løvoll, E. Stensrud and A. Le Breton (2013), The Doubtful Environmental Benefit of Reduced Maximum Sulfur Limit in International Shipping Fuel, Environ.Sci.Technol., 47(12), 6098-6101, doi: 10.1021/es4009954.

Miller, K.I., I. Nadheeh, A.R. Jauharee, R.C. Anderson and M.S. Adam (2017), Bycatch in the Maldivian pole-and-line tuna fishery, PLoS One., 12(5), e0177391, doi: 10.1371/journal.pone.0177391.

Min, S., Y. Yu and S.S. Martin (2005), Effect of Soybean Varieties and Growing Locations on the Physical and Chemical Properties of Soymilk and Tofu, J.Food Sci., 70(1), C21, doi: 10.1111/j.1365-2621.2005.tb09026.x.

Mjelde, A., K. Martinsen, M. Eide and Ø Endresen (2014), Environmental accounting for Arctic shipping – A framework building on ship tracking data from satellites, Mar.Pollut.Bull., 87(1–2), 22-28, doi: //dx.doi.org/10.1016/j.marpolbul.2014.07.013.

Moreno-Gutierrez, J., F. Calderay, N. Saborido, M. Boile, R.R. Valero and V. Duran-Grados (2015), Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods, Energy., 86, 603-616, doi: 10.1016/j.energy.2015.04.083.

Mueller, L., G. Jakobi, H. Czech, B. Stengel, J. Orasche, J.M. Arteaga-Salas, E. Karg, M. Elsasser, O. Sippula, T. Streibel, J.G. Slowik, A.S.H. Prevot, J. Jokiniemi, R. Rabe, H. Harndorf, B. Michalke, J. Schnelle-Kreis and R. Zimmermann (2015), Characteristics and temporal evolution of particulate emissions from a ship diesel engine, Appl.Energy., 155, 204-217, doi: //dx.doi.org/10.1016/j.apenergy.2015.05.115.

Mungkung, R. (2005), Shrimp aquaculture in Thailand: application of life cycle assessment to support sustainable development, ProQuest Dissertations Publishing.

Myers, R.A., and B. Worm (2003), Rapid worldwide depletion of predatory fish communities, Nature., 423(6937), 280-283.

Myhre, G., D. Shindell, F.-. Breon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang (2013), Anthropogenic and Natural Radiative Forcing in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Quin, G. -K Plattner, et al, Cambridge University Press, Cambridge and New York.

Myhre, G., J.S. Fuglestvedt, T.K. Berntsen and M.T. Lund (2011), Mitigation of short-lived heating components may lead to unwanted long-term consequences, Atmos.Environ., 45(33), 6103-6106, doi: 10.1016/j.atmosenv.2011.08.009.

Nijdam, D., T. Rood and H. Westhoek (2012), The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes, Food Policy., 37(6), 760-770, doi: //dx.doi.org/10.1016/j.foodpol.2012.08.002.

NMFS (2017a), National Marine Fisheries Science, NOAA, Giant Manta Ray:, Conservation and Management, 2018(February 10,).

NMFS (2017b), National Marine Fisheries Science, NOAA, Oceanic Whitetip Shark: Conservation and Management, 2018(February 10,).

NMFS (2017c), National Marine Fisheries Science, NOAA. Protected Species Status, Olive Ridley Turtle (Lepidochelys olivacea), 2018(February 10,).

NMFS (2017d), National Marine Fisheries Service, NOAA, Current classification on the protected resources list of fisheries, WA/OR/CA albacore surface hook and line/troll, 2018(February 10,).

NMFS (2017e), National Marine Fisheries Service, NOAA, Current classification on the protected resources list of fisheries: Hawaii Deep-set longline fishery, 2018(February 10,).

NMFS (2017f), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries, American Samoa troll, 2018(February 10,).

NMFS (2017g), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries, Hawaii Aku Boat, pole-and-line fishery, 2018(February 10,).

NMFS (2017h), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries, Hawaii troll, 2018(February 10,).

NMFS (2017i), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries, Hawaiian deep-set longline fishery, 2018(February 10,).

NMFS (2017j), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries, High Seas Pacific Highly Migratory Species Fisheries, 2018(February 10,).

NMFS (2017k), National Marine Fisheries Service, NOAA, Current classification on the protected species list of fisheries: American Samoa longline.

NMFS (2017l), National Marine Fisheries Service, NOAA, Marine Mammal Protection Act list of fisheries, 2018(February 10,).

NMFS (2017m), National Marine Fisheries Service, NOAA, Pelagic Longlines: Fishing Gear and Risks to Protected Species, 2018(February 10,).

NMFS (2017n), National Marine Fisheries Service, NOAA, Protect Species Status, sea turtles, Hawksbill Turtle (Eretmochelys imbricata), 2018(February 10,).

NMFS (2017o), National Marine Fisheries Service, NOAA, Protected Species Status, sea turtles, Green Turtle (Chelonia mydas) , 2018(February 10,).

NMFS (2017p), National Marine Fisheries Service, NOAA, Purse Seine: Fishing Gear and Risks to Protected Species, 2017(September, 30,).

NMFS (2017q), National Marine Fisheries Service, Pacific Island Fisheries Science Center, NOAA, Hawaii Aku Boat Landings (1987-2015), 2017(September, 30,).

NMFS (2017r), National Marine Fisheries Service, Pacific Island Fisheries Science Center, NOAA. Hawaii Aku Boat Fishery Activity (1987-2015), 2017(September, 30,).

NMFS (2017s), National Marine Fisheries Service, Pacific Island Fisheries Science Center, NOAA. Hawaii MHI Troll Landings of yellowfin, skipjack, bigeye, and albacore tuna (1987-2015), 2017(September, 30,).

NMFS (2017t), National Marine Fisheries Service, Pacific Island Fisheries Science Center, NOAA. Hawaii Troll Landings of Blue Marlin, Striped Marlin, and Other Billfish (1987-2015), 2017(September, 30,).

NMFS (2017u), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, American Samoa Annual Trolling Trip-Hours and Pounds per Trip-Hour.

NMFS (2017v), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, American Samoa Pelagic Plan Team Report Graphs, 2017(December 1).

NMFS (2017w), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Annual American Samoa Longline Set-Hours for all Pelagics from Creel Survey Data and Logbook Data, 2017(September, 30,).

NMFS (2017x), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Hawaii Longline Landings of Bigeye, Yellowfin, and Albacore Tuna, 2017(September, 30,).

NMFS (2017y), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Hawaii Longline Trips by Type (1991-2015), 2017(September, 30,).

NMFS (2017z), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Hawaii Troll Landings of Mahimahi and Wahoo, 2017(September, 30,).

NMFS (2017aa), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Main Hawaiian Islands Troll Numbers of Fishers and Days Fished (1987-2015), 2017(September, 30,).

NMFS (2017ab), National Marine Fisheries Service, West Coast Region, NOAA, Highly Migratory Species, Pacific Albacore., 2017(September, 30,).

NMFS (2016a), National Marine Fisheries Service, NOAA, 2016 Annual Report to the Western and Central Pacific Fisheries Commission United States of America.

NMFS (2016b), National Marine Fisheries Service, NOAA, Protected Species Status, sea turtles, Leatherback Turtle (Dermochelys coriacea), 2018(February 10,).

NMFS (2015), National Marine Fisheries Service, Pacific Islands Fisheries Science Center, NOAA, Biological opinion and conference opinion: Continued operation of the American Samoa longline fishery.

NMFS (2006), National Marine Fisheries Service, NOAA, Biological opinion and incidental take statement of the U.S. Western and Central Pacific purse-seine fishery as authorized by the South Pacific Tuna Act and the High Seas Fishing Compliance Act.

NMFS (2000), National Marine Fisheries Service, NOAA, Environmental Impact Statement, Hawaii troll fisheries.

Notteboom, T., E. Delhaye and K. Vanherele (2010), Analysis of the Consequences of Low Sulphur Fuel Requirements, European Community Shipowners Association, Leuven.

Ødemark, K., S.B. Dalsøren, B.H. Samset, T.K. Berntsen, J.S. Fuglestvedt and G. Myhre (2012), Short-lived climate forcers from current shipping and petroleum activities in the Arctic, Atmospheric Chemistry and Physics., 12(4), 1979-1993, doi: 10.5194/acp-12-1979-2012.

Orloff, J., and J. Bloom (2014), MIT Open Courseware: Bootstrap confidence intervals. Web accessed July 15, 2016. Available at: http://ocw.mit.edu/courses/mathematics/18-05-introduction-to-probability-and-statistics-spring-2014/readings/MIT18_05S14_Reading24.pdf.

Parker, R.W.R., K. Hartmann, B.S. Green, C. Gardner and R.A. Watson (2015), Environmental and economic dimensions of fuel use in Australian fisheries, J.Clean.Prod., 87, 78-86, doi: 10.1016/j.jclepro.2014.09.081.

Parker, R.W.R., and P.H. Tyedmers (2015), Fuel consumption of global fishing fleets: current understanding and knowledge gaps, Fish Fish., 16(4), 684-696, doi: 10.1111/faf.12087.

Parker, R.W.R., and P.H. Tyedmers (2012), Life Cycle Environmental Impacts of Three Products Derived from Wild-Caught Antarctic Krill (Euphausia superba), Environ.Sci.Technol., 46(9), 4958-4965, doi: 10.1021/es2040703.

Peatman, T., V. Allain, S. Caillot, P. Williams and N. Smith (2017), Scientific Committee Thirteenth Regular Session: Summary of purse-seine fishery bycatch at a regional scale, 2003-2016, WCPFC-SC13-2017/ST-WP-05, Western and Central Pacific Fisheries Commission, Rarotonga, Cook Islands.

Pelletier, N., and P. Tyedmers (2007), Feeding farmed salmon: Is organic better?, Aquaculture., 272(1–4), 399-416, doi: //dx.doi.org/10.1016/j.aquaculture.2007.06.024.

Pelletier, N., and P. Tyedmers (2010), Forecasting potential global environmental costs of livestock production 20002050, Proceedings of the National Academy of Sciences., 107(43), 18371-18374, doi: 10.1073/pnas.1004659107.

Pelletier, N., and P. Tyedmers (2008), Life Cycle Considerations for Improving Sustainability Assessments in Seafood Awareness Campaigns, Environ.Manage., 42(5), 918-931, doi: 10.1007/s00267-008-9148-9.

Pelletier, N., P. Tyedmers, U. Sonesson, A. Scholz, F. Ziegler, A. Flysjo, S. Kruse, B. Cancino and H. Silverman (2009), Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems, Environ.Sci.Technol., 43(23), 8730-8736, doi: 10.1021/es9010114.

Peters, G.P., B. Aamaas, M.T. Lund, C. Solli and J.S. Fuglestvedt (2011), Alternative "Global Warming" Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data, Environ.Sci.Technol., 45(20), 8633-8641, doi: 10.1021/es200627s.

Petzold, A., E. Weingartner, I. Hasselbach, P. Lauer, C. Kurok and F. Fleischer (2010), Physical Properties, Chemical Composition, and Cloud Forming Potential of Particulate Emissions from a Marine Diesel Engine at Various Load Conditions, Environ.Sci.Technol., 44(10), 3800-3805, doi: 10.1021/es903681z.

Petzold, A., P. Lauer, U. Fritsche, J. Hasselbach, M. Lichtenstern, H. Schlager and F. Fleischer (2011), Operation of Marine Diesel Engines on Biogenic Fuels: Modification of Emissions and Resulting Climate Effects, Environ.Sci.Technol., 45(24), 10394-10400, doi: 10.1021/es2021439.

PFMC (2017a), Pacific Fishery Management Council, Current HMS SAFE Report, U.S.-Canada Albacore Treaty Data Exchange.

PFMC (2017b), Pacific Fishery Management Council, Distribution of Canadian and U.S. Albacore Troll and Pole-and-Line Fleet Fishing Effort in the North Pacific Ocean, 2017(September, 30,).

PFMC (2016), Pacific Fishery Management Council, Current HMS SAFE Report, U.S.-Canada Albacore Treaty Data Exchange, 2017(September, 30,).

Platts Bunkerworld (2016), Market Review, Global, Bunker Bulletin., 1-25.

Pretty, J.N., A.S. Ball, T. Lang and J.I.L. Morison (2005), Farm costs and food miles: An assessment of the full cost of the UK weekly food basket, Food Policy., 30(1), 1-19, doi: 10.1016/j.foodpol.2005.02.001.

Quinn, P.K., T.S. Bates, E. Baum, N. Doubleday, A.M. Fiore, M. Flanner, A. Fridlind, T.J. Garrett, D. Koch, S. Menon, D. Shindell, A. Stohl and S.G. Warren (2008), Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, Atmospheric Chemistry and Physics., 8(6), 1723-1735, doi: 10.5194/acp-8-1723-2008.

Restrepo, V., L. Dagorn, D. Itano, A. Justel-Rubio, F. Forget and G. Moreno (2017), A Summary of Bycatch Issues and ISSF Mitigation Activities To Date in Purse-Seine Fisheries, with Emphasis on FADs, lSSF Technical Report 2017-06, International Seafood Sustainability Foundation, Washington D.C.

Rogelj, J., M. Schaeffer, M. Meinshausen, D. Shindell, W. Hare, Z. Klimont, G. Velders, M. Amann and H.J. Schellnhuber (2014), Disentangling the effects of CO_2 and short-lived climate forcer mitigation, Proceedings of the National Academy of Sciences., 111(46), 16325-16330, doi: 10.1073/pnas.1415631111.

Ross, S.M. (2004), Introduction to probability and statistics for engineers and scientists , Elsevier, Amsterdam.

Sampson, G.S., J.N. Sanchirico, C.A. Roheim, S.R. Bush, J.E. Taylor, E.H. Allison, J.L. Anderson, N.C. Ban, R. Fujita, S. Jupiter and J.R. Wilson (2015), Secure sustainable seafood from developing countries, Science., 348(6234), 504-6, doi: 10.1126/science.aaa4639.

Sanjuán, N., F. Stoessel and S. Hellweg (2014), Closing data gaps for LCA of food products: estimating the energy demand of food processing, Environ.Sci.Technol., 48(2), 1132.

Santos, A.A.O., J. Aubin, M.S. Corson, W.C. Valenti and A.F.M. Camargo (2015), Comparing environmental impacts of native and introduced freshwater prawn farming in Brazil and the influence of better effluent management using LCA, Aquaculture., 444, 151-159, doi: //dx.doi.org/10.1016/j.aquaculture.2015.03.006.

Schau, E.M., H. Ellingsen, A. Endal and S.A. Aanondsen (2009), Energy consumption in the Norwegian fisheries, J.Clean.Prod., 17(3), 325-334, doi: //dx.doi.org/10.1016/j.jclepro.2008.08.015.

Shindell, D.T., G. Faluvegi, D.M. Koch, G.A. Schmidt, N. Unger and S.E. Bauer (2009), Improved Attribution of Climate Forcing to Emissions, Science., 326(5953), 716-718, doi: 10.1126/science.1174760.

Shindell, D., and G. Faluvegi (2009), Climate response to regional radiative forcing during the twentieth century, Nature Geosci., 2(4), 294-300.

Sinha, P., P.V. Hobbs, R.J. Yokelson, T.J. Christian, T.W. Kirchstetter and R. Bruintjes (2003), Emissions of trace gases and particles from two ships in the southern Atlantic Ocean, Atmos.Environ., 37(15), 2139-2148, doi: //dx.doi.org/10.1016/S1352-2310(03)00080-3.

Smetana, S., A. Mathys, A. Knoch and V. Heinz (2015), Meat alternatives: life cycle assessment of most known meat substitutes, The International Journal of Life Cycle Assessment., 20(9), 1254-1267, doi: 10.1007/s11367-015-0931-6.

Smith, M.D., C.A. Roheim, L.B. Crowder, B.S. Halpern, M. Turnipseed, J.L. Anderson, F. Asche, L. Bourillon, A.G. Guttormsen, A. Khan, L.A. Liguori, A. McNevin, M.I. O'Connor, D. Squires, P. Tyedmers, C. Brownstein, K. Carden, D.H. Klinger, R. Sagarin and K.A. Selkoe (2010), Sustainability and Global Seafood, Science., 327(5967), 784-786, doi: 10.1126/science.1185345.

Smith, S.J., J. van Aardenne, Z. Klimont, R.J. Andres, A. Volke and S. Delgado Arias (2011), Anthropogenic sulfur dioxide emissions: 1850–2005, Atmos.Chem.Phys., 11(3), 1101-1116, doi: 10.5194/acp-11-1101-2011.

Smith, S.J., and A. Mizrahi (2013), Near-term climate mitigation by short-lived forcers, Proc.Natl.Acad.Sci.U.S.A., 110(35), 14202-14206, doi: 10.1073/pnas.1308470110.

Smith, T.W.P., J.P. Jalkanen, B.A. Anderson, J.J. Corbett, J. Faber, S. Hanayama, E. O'Keeffe, S. Parker, L. Johansson, L. Aldous, C. Raucci, M. Traut, S. Ettinger, D. Nelissen, D.S. Lee, S.

Ng, A. Agrawal, J.J. Winebrake, M. Hoen, S. Chesworth and A. Pandey (2014), Third International Maritime Organization (IMO) GHG Study 2014, Rep. MEPC 67/INF.3, International Maritime Organization, London.

Sonesson, U., J. Davis and F. Ziegler (2010), Food production and emissions of greenhouse gases : an overview of the climate impact of different product groups.

Squires, D., M. Maunder, R. Allen, P. Andersen, K. Astorkiza, D. Butterworth, G. Caballero, R. Clarke, H. Ellefsen, P. Guillotreau, J. Hampton, R. Hannesson, E. Havice, M. Helvey, S. Herrick, K. Hoydal, V. Maharaj, R. Metzner, I. Mosqueira, A. Parma, I. Prieto-Bowen, V. Restrepo, S.F. Sidique, S.I. Steinsham, E. Thunberg, I. Valle and N. Vestergaard (2017), Effort rights-based management, Fish and Fisheries., 18(3), 440-465, doi: 10.1111/faf.12185.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales and C. de Haan (2006), Livestock's long shadow: environmental issues and options, Food and Agricultural Organization of the United Nations, Rome.

Sumaila, U.R., V.W.Y. Lam, D.D. Miller, L. Teh, R.A. Watson, D. Zeller, W.W.L. Cheung, I.M. Cote, A.D. Rogers, C. Roberts, E. Sala and D. Pauly (2015), Winners and losers in a world where the high seas is closed to fishing., Scientific reports., 5, 8481, doi: 10.1038/srep08481.

Sumaila, U., A. Dyck and A. Baske (2014), Subsidies to tuna fisheries in the Western Central Pacific Ocean, Marine Policy., 43, 288-294, doi: 10.1016/j.marpol.2013.06.012.

Sumaila, U.R., A. Khan, L. Teh, R. Watson, P. Tyedmers and D. Pauly (2010), Subsidies to high seas bottom trawl fleets and the sustainability of deep-sea demersal fish stocks, Marine Policy., 34(3), 495-497, doi: 10.1016/j.marpol.2009.10.004.

Sun, W. (2009), Life Cycle Assessment of Indoor Recirculating Shrimp Aquaculture System.

Sund, V. (2009), Environmental assessment of northeast arctic cod caught by long-lines and Alaska pollock caught by pelagic trawls.

Svanes, E., M. Vold and O. Hanssen (2011), Environmental assessment of cod (Gadus morhua) from autoline fisheries, Int J Life Cycle Assess., 16(7), 611-624, doi: 10.1007/s11367-011-0298-2.

Tassou, S.A., G. De-Lille and Y.T. Ge (2009), Food transport refrigeration – Approaches to reduce energy consumption and environmental impacts of road transport, Applied Thermal Engineering., 29(8), 1467-1477, doi: //dx.doi.org/10.1016/j.applthermaleng.2008.06.027.

Tassou, S.A., Y. Ge, A. Hadawey and D. Marriott (2011), Energy consumption and conservation in food retailing, Applied Thermal Engineering., 31(2), 147-156, doi: 10.1016/j.applthermaleng.2010.08.023.

Teah, Y.H., Y. Fukushima and M. Onuki (2015), Experiential Knowledge Complements an LCA-Based Decision Support Framework, Sustainability., 7(9), doi: 10.3390/su70912386.

The Arctic Council (2009), Arctic Marine Shipping Assessment 2009 Report, The Arctic Council.

The Co-operative Group (2010), The Co-operative Group Sustainability Report., The Co-operative Group Limited., Manchester.

Thrane, M. (2004), Energy Consumption in the Danish Fishery: Identification of Key Factors, Journal of Industrial Ecology., 8(1-2), 223-239, doi: 10.1162/1088198041269427.

Thrane, M., F. Ziegler and U. Sonesson (2009), Eco-labelling of wild-caught seafood products, J.Clean.Prod., 17(3), 416-423, doi: //dx.doi.org/10.1016/j.jclepro.2008.08.007.

Tidwell, J. and S. Coyle (2011), Post-Harvest Handling of Freshwater Prawns, Southern Regional Aquaculture Center.

Tormodsgard, Y. (2015), Facts 2014: The Norwegian Petroleum Sector, Norwegian Ministry of Petroleum and Energy, Norway.

Tremblay-Boyer, L., S. McKechnie, G. Pilling and J. Hampton (2017), Stock assessment of yellowfin tuna in the Western and Central Pacific Ocean, WCPFC-SC13-2017/SA-WP-06, Western and Central Pacific Fisheries Commission, Rarotonga, Cook Islands.

Trozzi, C. (2010), Emission estimate methodology for maritime navigation, Techne Consulting, Rome.

Tyedmers, P. (2001), Energy consumed by North Atlantic fisheries, in , edited by D. Zeller, R. Watson and D. Pauly. , pp. 12-34, Fisheries Centre, University of British Columbia, Vancouver.

Tyedmers, P.H., R. Watson and D. Pauly (2005), Fueling global fishing fleets, Ambio., 34(8), 635-638, doi: FGFF]2.0.CO;2.

Tyedmers, P., and R. Parker (2012), Fuel consumption and greenhouse gas emissions from global tuna fisheries: A preliminary assessment. ISSF Technical Report No. 2012-03., International Seafood Sustainability Foundation, McLean, Virginia, USA.

Tyedmers, P. (2000), Salmon and sustainability : the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry.

Unger, N., T.C. Bond, J.S. Wang, D.M. Koch, S. Menon, D.T. Shindell and S. Bauer (2010), Attribution of climate forcing to economic sectors, Proceedings of the National Academy of Sciences., 107(8), 3382-3387, doi: 10.1073/pnas.0906548107.

USDC, and NMFS (2017), U.S. Department of Commerce and National Marine Fisheries Service, NOAA, Status of Stocks 2016, Annual Report to Congress on the Status of U.S. Fisheries, 2017 ASI 2164-35.

Vázquez-Rowe, I., M.T. Moreira and G. Feijoo (2011), Life Cycle Assessment of fresh hake fillets captured by the Galician fleet in the Northern Stock, Fisheries Research., 110(1), 128-135, doi: 10.1016/j.fishres.2011.03.022.

Vázquez-Rowe, I., M. Moreira and G. Feijoo (2012), Inclusion of discard assessment indicators in fisheries life cycle assessment studies. Expanding the use of fishery-specific impact categories, Int J Life Cycle Assess., 17(5), 535-549, doi: 10.1007/s11367-012-0395-x.

Vázquez-Rowe, I., P. Villanueva-Rey, J. Mallo, De la Cerda, Juan José, M.T. Moreira and G. Feijoo (2013), Carbon footprint of a multi-ingredient seafood product from a business-to-business perspective, J.Clean.Prod., 44, 200-210, doi: //doi.org/10.1016/j.jclepro.2012.11.049.

Vergé, X.P.C., D. Maxime, J.A. Dyer, R.L. Desjardins, Y. Arcand and A. Vanderzaag (2013), Carbon footprint of Canadian dairy products: Calculations and issues, J.Dairy Sci., 96(9), 6091-6104, doi: //dx.doi.org/10.3168/jds.2013-6563.

Vermeulen, S.J., B.M. Campbell and J.S.I. Ingram (2012), Climate Change and Food Systems, Annual Review of Environment and Resources., 37(1), 195-222, doi: 10.1146/annurev-environ-020411-130608.

von Schneidemesser, E., P.S. Monks, J.D. Allan, L. Bruhwiler, P. Forster, D. Fowler, A. Lauer, W.T. Morgan, P. Paasonen, M. Righi, K. Sindelarova and M.A. Sutton (2015), Chemistry and the Linkages between Air Quality and Climate Change, Chem.Rev., 115(10), 3856-3897, doi: 10.1021/acs.chemrev.5b00089.

Walker, E., D. Gaertner, P. Gaspar and N. Bez (2010), Fishing activity of tuna purse seiners estimated from VMS data and validated by observers' data, Collective Volume of Scientific Papers, ICCAT., 65(6), 2376-2391.

Wang, C., and J.J. Corbett (2007), The Costs and Benefits of Reducing SO2 Emissions from Ships in the US West Coastal Waters, Transportation Research: Part D: Transport and Environment., 12(8), 577-588, doi: 10.1016/j.trd.2007.08.003.

Wang, H., and R. Minjares (2013), Global emissions of marine black carbon: critical review and revised assessment, Transportation Research Board of the National Academies, Washington D.C.

Wang, M. (2011), The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Software: GREET 1, 2011.

WCPFC (2017a), Western and Central Pacific Fisheries Commission, Public Domain Aggregated Catch/Effort Data, 2017(November 1,).

WCPFC (2017b), Western and Central Pacific Fisheries Commission, Record of Fishing Vessels, 2017(December 1).

WCPFC (2017c), Western and Central Pacific Fisheries Commission, Yearbook 2016, 2017(September, 30,).

WCPFC (2006), Western and Central Pacific Fisheries Commission, Pelagic Fisheries of the Western Pacific Region, 2005 Annual Report.

Westervelt, D.M., L.W. Horowitz, V. Naik, J.-. Golaz and D.L. Mauzerall (2015), Radiative forcing and climate response to projected 21st century aerosol decreases, Atmos.Chem.Phys., 15(22), 12681-12703, doi: 10.5194/acp-15-12681-2015.

Williams, P., and P. Terawasi (2016), Scientific Committee Twelfth Regular Session: Overview of tuna fisheries in the Western and Central Pacific Ocean, including economic conditions - 2015, WCPFC-SC12-2016/GN WP-1, Bali, Indonesia.

Wilson, J., McCoy and M. (2009), Study of the impact of energy price fluctuations on fisheries in the Pacific with emphasis on the tuna industry, Energy costs and fishing, World Bank.

Winther, M., J.H. Christensen, M.S. Plejdrup, E.S. Ravn, O.F. Eriksson and H.O. Kristensen (2014), Emission inventories for ships in the arctic based on satellite sampled AIS data, Atmos.Environ., 91, 1-14, doi: 10.1016/j.atmosenv.2014.03.006.

Winther, U., F. Ziegler, E.S. Hognes, A. Emanuelsson, V. Sund and H. Ellingsen (2009), Carbon footprint and energy use of Norwegian seafood products, SINTEF Fisheries and Aquaculture.

Worm, B., R. Hilborn, J.K. Baum, T.A. Branch, J.S. Collie, C. Costello, M.J. Fogarty, E.A. Fulton, J.A. Hutchings, S. Jennings, O.P. Jensen, H.K. Lotze, P.M. Mace, T.R. McClanahan, C. Minto, S.R. Palumbi, A.M. Parma, D. Ricard, A.A. Rosenberg, R. Watson and D. Zeller (2009), Rebuilding Global Fisheries, Science., 325(5940), 578-585, doi: 10.1126/science.1173146.

Yuvaraj, D., B. Bharathiraja, J. Rithika, S. Dhanasree, V. Ezhilarasi, A. Lavanya and R. Praveenkumar (2016), Production of biofuels from fish wastes: an overview, Biofuels., 1-7, doi: 10.1080/17597269.2016.1231951.

Ziegler, F., E.A. Groen, S. Hornborg, E.A.M. Bokkers, K.M. Karlsen and d. Boer I.J.M (2015), Assessing broad life cycle impacts of daily onboard decision-making, annual strategic planning, and fisheries management in a northeast Atlantic trawl fishery, The International Journal of Life Cycle Assessment., doi: 10.1007/s11367-015-0898-3.

Ziegler, F., and P.A. Hansson (2003), Emissions from fuel combustion in Swedish cod fishery, J.Clean.Prod., 11(3), 303-314, doi: 10.1016/S0959-6526(02)00050-1.

Ziegler, F. (2002), Environmental assessment of a Swedish, frozen cod product with a life-cycle perspective.

Ziegler, F., U. Winther, E.S. Hognes, A. Emanuelsson, V. Sund and H. Ellingsen (2013), The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market, J.Ind.Ecol., 17(1), 103-116, doi: 10.1111/j.1530-9290.2012.00485.x.

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Table A.1: *Mean and standard errors for BC emission factors of plume and test-rig studies , $EF^{BC}_{j,k,l}$, (g BC / kg fuel).*

Fuel Type	MSD	HSD
Fs (% wt.), l = 1= 0.051 ±0.050		
MDO[a]	0.97 (± 0.14)	0.51 (± 0.10)
HFO	Δ	Δ
Fs (% wt.), l = 2= 0.590 ±0.309		
MDO[b]	0.97 (± 0.09)	0.36 (± 0.083)
HFO[c]	0.14 (± 0.05)	Δ

[a] n=45 for MSD; n=30 for HSD [Petzold et al., 2011; Buffaloe et al., 2014; Cappa et al., 2014]
[b] n=51 for MSD; n=8 for HSD [Lack et al., 2008]
[c] n=12 [Petzold et al., 2010; Petzold et al., 2011]
[Δ] Fishing not conducted under these conditions.

Table A.2: *Fraction of global catch for different gear* , f_{m}^{C} [a].

Trawl	Gillnet
0.62	0.38

[a] [Ziegler and Hansson, 2003]

Table A.3: *BC emission factor as a function of gear and sulfur level ,* $EF^{BC}_{l,m}$ *(g BC / kg fuel), for gear m and fuel sulfur level l.*

F_S (% wt.)	Gear	
	Trawl	Gillnet
0.051 (±0.050)	0.94	0.78
0.590 (±0.309)	0.78	0.93

Table A.4: *Fraction of global fishing fleet vessel characteristics: engine type, fuel type, and sulfure level;* $f^{Char}_{j,k,l}$ *, engine type j, fuel type k, and fuel sulfur level l*[a].

	Engine Type	
Fuel Type	MSD	HSD
Fs, l = 0.051% ±0.050%		
MDO	0.88	0.12
HFO	Δ	Δ
Fs, l = 0.590% ± 0.309%		
MDO	0.84	0.12
HFO	0.04	Δ

[a] [Trozzi, 2010]
[Δ] Fishing not conducted under these conditions.

Table A.5: *BC emission factors as a function of engine type, fuel type, and sulfur level ; $EF^{BC}_{j,k,l,m}$ (g BC / kg fuel) for engine type j, fuel type k, gear type m, and fuel sulfur level l.*

	Engine Type	
Fuel Type	MSD	HSD
m=1 (trawl) and l =1(0.051%)		
MDO	1.02 (± 0.68)	0.38 (± 0.22)
HFO	Δ	Δ
m=2 (gillnet) and l =1(0.051%)		
MDO	0.85 (± 0.79)	0.28 (± 0.16)
HFO	Δ	Δ
m=1 (trawl) and l =2 (0.590%)		
MDO	0.88 (± 0.57)	0.29 (± 0.08)
HFO	0.08	Δ
m=2 (gillnet) and l =2 (0.590%)		
MDO	1.04 (± 0.35)	0.30 (± 0.05)
HFO	0.31	Δ

[Δ] Fishing not conducted under these conditions.

Table A.6: *Fraction of fishing time as a function of engine load and gear ; ($f^{t}_{i,m}$) as a function of engine load (i) and gear (m)*[a].

Load	Gear	
	Trawl	Gillnet
0-20%	0	0.6
20-40%	0.3	0
40-60%	0	0
60-80%	0.5	0.3
80-100%	0.2	0.1

[a] [Ziegler and Hansson, 2003]

Table A.7: *BC emission factors as a function of engine load, engine type, fuel type, and fuel sulfur level ; $EF^{BC}_{i,j,k,l}$ (g BC / kg fuel) as a function of engine load (i), engine type (j), fuel type (k) and fuel sulfur level (l) calculated from statistical analysis of published data*[a].

	Engine Type	
Load	MSD	HSD
Fuel type = MDO; Fuel sulfur = 0.051% ±0.050[b]		
0-20%	0.91 (± 1.00)	0.20 (± 0.10)
20-40%	1.63 (± 1.15)	0.31 (± 0.16)
40-60%	0.54 (± 0.75)	0.21 (± 0.12)
60-80%	0.79 (± 0.45)	0.43 (± 0.25)
80-100%	0.67 (± 0.54)	0.35 (± 0.22)
Fuel type = MDO; Fuel sulfur = 0.590 ± 0.309[c]		
0-20%	1.13 (± 0.22)	0.28
20-40%	0.90 (± 0.67)	0.19
40-60%	0.92 (± 0.65)	0.53
60-80%	1.20 (± 0.74)	0.40 (± 0.14)
80-100%	0.06	0.16 (± 0.04)
Fuel type = HFO; Fuel sulfur = 0.590 ± 0.309[d]		
0-20%	0.48	Δ
20-40%	0.16	Δ
40-60%	0.07	Δ
60-80%	0.05	Δ
80-100%	0.05	Δ

[a] Mean ± s.d., n = 10,000 Monte Carlo simulations. Literature data are reported in Table 1 of the manuscript.
[b] Weighted fuel sulfur level reported here, from emissions at Fs (% wt.) ≤0.10
[c] Weighted fuel sulfur level reported here, from emissions at Fs (% wt.) 0.4 ±0.6
[d] Weighted fuel sulfur level reported here, from emissions at Fs (% wt.) 2.2
[Δ] Fishing not conducted under these conditions

Table A.8: *Fuel quality data and engine speed of selected commercial tuna fleets operating in the Pacific Ocean categorized by fishing region, fleet flag, target tuna species, and fraction (f) and number (n) of vessels using distillates, heavy fuel oil (HFO), medium-speed diesel (MSD) engines, and high-speed diesel (HSD) engines. The fuel quality and engine speed data was obtained from the IHS sea-web ship registry database.*

Fleet region	Flag	Fleet gear	Target Tuna Species	f Distillates	n Distillate Vessels	f HFO	n HFO Vessels	f MSD	n MSD Vessels	f HSD	n HSD Vessels
WCPFC-CA[a]	All	PS[b,c]	Skipjack	0.85	242	0.15	45	1	207	0	8
WCPFC-CA[a]	U.S.	PS[b,c]	Skipjack	0.85	12	0.15	2	1	14	0	0
WCPFC-CA[a]	All	PL[d,e]	Skipjack	1	58	0	1	1	33	0	0
HI	U.S.	PL[d,e,f]	Skipjack	1[g]	0	0	0	1[h]	0	0	0
AS[i]	U.S.	TL[j]	Skipjack	1[g]	3	0	0	0.5	1	0.5	1
AS[i]	U.S.	LL[k]	Albacore	1[g]	1	0	0	0	0	1	1
HI[l]	U.S.	TL[j,m]	Yellowfin	1[g]	0	0	0	0.5	0	0.5	0
HI[l]	U.S.	LL[k]	Big Eye	1[g]	8	0	0	0	0	1	5
NP[n]	U.S.	SF[m,o]	Albacore	1[g]	6	0	0	0.5	0	0.5	0

[a]Western Central Pacific Fisheries Commission convention area (WCPFC-CA).
[b]Purse seine (PS).
[c]To simplify our analysis, we used an average of the "All" (f Distillates: 0.84; f HFO: 0.16) and "U.S." (f Distillates: 0.86; f HFO: 0.14) flagged vessels.
[d]Pole and line (PL).
[e]To simplify our analysis, we rounded the "All" (f Distillates: 0.98; f HFO: 0.02) fraction of distillates up to 1
[f]We rounded the "All" (f MSD: 0.96; f HSD: 0.4) up to 1.
[g]Due to limited data, we assume all vessels in this fleet use distillates.
[h]Due to limited data, we assume the U.S. fleet has the same engine speed characteristics as the "All" flagged vessels.
[i]American Samoa (AS).
[j]Troll (TL).
[k]Longline (LL).
[l]Hawaii (HI).
[m]Due to limited data, we assume the engine speed is the same as the AS TL fleet.
[n]North Pacific (NP).
[o]Surface methods (SF) include troll and pole and line fishing gear.

Table A.9: *Mean engine power of selected commercial tuna fleets operating in the Pacific Ocean organized by fishing region, fleet flag, and target tuna species. The value in parenthesis represents the uncertainty (95% confidence intervals).*

Fleet region	Flag	Fleet gear	Target Tuna Species	Mean engine power (kW)	n Vessels
North Pacific[b]	U.S.	Surface methods[a]	Albacore	303 (± 33)	48
WCPFC-CA[c,d]	All	Purse Seine	Skipjack	1757 (± 97)[e]	595
WCPFC-CA[c,d]	U.S.	Purse Seine	Skipjack	2721 (± 159)[f]	35
WCPFC-CA[c,d]	All	Purse Seine	Skipjack	2591 (± 87)[g]	358
WCPFC-CA[c,d]	All	Pole and Line	Skipjack	790 (± 93)[g]	90
Hawaii[c]	U.S.	Pole and Line	Skipjack	232 (± 123)[f]	4
WCPFC-CA[c,d]	All	Pole and Line	Skipjack	1518 (± 134)[g]	20
Hawaii[c]	U.S.	Troll	Yellowfin	322 (± 95)	8
Hawaii[c]	U.S.	Longline	Big Eye	363 (± 20)	131
American Samoa[c]	U.S.	Troll	Skipjack	376 (± 47)	31
American Samoa[c]	U.S.	Longline	Albacore	332 (± 52)	10

[a]Surface methods include troll and pole-and-line fishing gear.
[b][AAFA, 2017; Inter-American Tropical Tuna Commission, (IATTC), 2017]
[c][WCPFC, 2017b]
[d]Western Central Pacific Fisheries Commission convention area.
[e]Main engine power used in the scenarios that include all fishing territories.
[f]Main engine power used in the U.S. exclusive economic zone fishing territory.
[g]Main engine power used on the high sea fishing territory; ocean going vessels with main engine power greater than 1000 kW.

Table A.10: *Mean load factor of selected commercial tuna fleets operating in the Pacific Ocean organized by fishing region, fleet flag, and target tuna species. The value in parenthesis represents the uncertainty (95% confidence intervals).*

Fleet region	Flag	Fleet gear	Target Tuna Species	Mean Load Factor	n Vessels
North Pacific	U.S.	Surface methods[a]	Albacore	0.59 (± 0.06)	13
WCPFC-CA[b]	All	Purse Seine	Skipjack	0.68 (± 0.01)	318
WCPFC-CA[b]	U.S.	Purse Seine	Skipjack	0.64 (± 0.04)	35
WCPFC-CA[b]	All	Pole and Line	Skipjack	0.60 (± 0.03)	89
Hawaii	U.S.	Pole and Line	Skipjack	0.60 (± 0.12)	9
Hawaii	U.S.	Troll	Yellowfin	0.54 (± 0.14)	5
Hawaii	U.S.	Longline	Big Eye	0.60 (± 0.03)	95
American Samoa	U.S.	Troll	Skipjack	0.60 (± 0.05)	26
American Samoa	U.S.	Longline	Albacore	0.60 (± 0.08)	10

[a]Surface methods include troll and pole-and-line fishing gear.
[b]Western Central Pacific Fisheries Commission convention area.

***Table A.11:** Annual fishing effort of selected commercial tuna fleets operating within respective domains. The annual fishing effort given in hours by fleet region and gear type including: the U.S. purse seine (PS), the Hawaii (HI) pole and line (PL), the HI troll (TL), the HI longline (LL), the American Samoa (AS) LL, the AS TL, and the North Pacific (NP) surface methods (SF)—which includes both PL and TL gears.*

Year	US PS[a,b,c,d,e]	HI PL[f,g,h]	HI TL[i,j,k,l]	HI LL[a,m,n]	AS LL[a,o]	AS TL[p]	NP SF[a,q,r,s]
1996	168828	6360	156200	151537	6366	4442	165804
1997	178759	6480	155040	171574	18334	3144	191136
1998	155586	4092	147030	175028	16112	1405	142824
1999	122483	5592	158975	178713	27420	1981	248304
2000	119172	3480	138980	187464	36973	1149	167040
2001	125793	3612	136355	227306	81291	1655	178980
2002	139034	3216	129270	267609	127023	1362	142752
2003	112552	3156	140140	279815	118408	1044	161280
2004	102621	3180	152000	306760	94076	1204	149712
2005	76138	3240	148570	321499	86331	862	134076
2006	59586	2244	145405	308832	104334	884	132264
2007	66207	2196	146255	318044	123288	723	132972
2008	172138	1848	149685	306990	99178	808	111660
2009	201931	1740	147825	282118	103897	424	155796
2010	192000	696	146515	271293	95633	308	154140
2011	188690	1032	145625	286954	81143	711	176124
2012	208552	528	151415	300542	89011	389	180324
2013	198621	660	133335	305838	72096	673	155076
2014	205241	312	134420	299851	55847	1063	145656
2015	175448	708	124870	318966	56048	1144	140808

[a]Fleet engages in multi-day trips [Joseph, 2003; Gillett, 1986; Gillett et al., 2002].
[b]According to vessel monitoring systems data; the fleet operates day and night [Walker et al., 2010; Langley, 2011].
[c]According to the vessel day scheme, a fishing day is defined as 24 hours [Havice, 2013].
[d]Effort (in days) was multiplied by 24 hours.
[e]Effort (in days) obtained from Western Central Pacific Fisheries Commission report [Williams and Terawasi, 2016].
[f]"Fishing trips seldom last longer than a day, and most vessels return to port each night." [Boggs and Kikkawa, 1993; WCPFC, 2006].
[g]Fleet engages in day trips; we multiplied effort days by 12 hours operating time per day.
[h]Effort (in days) obtained from [NMFS, 2017r].
[i]Fishing can occur in both state and federal waters year-round, with trips typically lasting less than a day, although larger vessels may make multi-day trips [NMFS, 2017h].
[j]Due to a lack of data, we assume the trip hours of the Hawaii troll fleet are similar to the American Samoa troll fleet ~5 hours.
[k]Effort (in days) was multiplied by 5 hours.
[l]Effort (in days) obtained from [NMFS, 2017aa].
[m]We assume the effort hours are the same as the "soak time", reported to average 21 hours [Bayless et al., 2017].
[n]Effort (in hours) was calculated by multiplying the number of trips [NMFS, 2017y] by the average number of trips per day (11.0 ±0.6) obtained from [65].
[o]Effort (in hours) obtained from [NMFS, 2017w].
[p]Effort (in hours) obtained from [NMFS, 2017u].
[q]Fleet engages in multi-day trips but "fishing takes place during the day; at night, the vessels cease such activity" [Basurko et al., 2013].
[r]Effort (in days) was multiplied by 12 hours operating time per day.
[s]Effort (in days) obtained from [PFMC, 2017b].

Table A.12: *Disaggregated annual fishing effort of selected fleets operating in the U.S. exclusive economic zone (EEZ). The fishing effort is given in hours by fleet region and gear type. The selected fleets include the U.S. purse seine (PS), the Hawaii (HI) pole and line (PL), and the North Pacific (NP) surface methods (SF)—which includes both PL and troll gears.*

Year	U.S. PS[a,b]	HI PL[c,d]	NP SF[c,e]
1996	4835	6360	43056
1997	24034	6480	61080
1998	1001	4092	36816
1999	0	5592	153996
2000	0	3480	107400
2001	2296	3612	112260
2002	21524	3216	100128
2003	0	3156	132540
2004	0	3180	135504
2005	4140	3240	123108
2006	5250	2244	119748
2007	2707	2196	130176
2008	0	1848	99288
2009	3562	1740	147168
2010	0	696	130608
2011	0	1032	164832
2012	2824	528	175764
2013	0	660	149652
2014	9972	6360	144540
2015	14043	6480	138876

[a]Fleet engages in multi-day trips; we multiplied effort days by 24 hours operating time per day.
[b]We obtained geo-referenced (5x5 grid cells) effort (in days) and aggregated by month; we used ArcMap (v. 10.5.1) to clip the gridded effort data to a U.S. EEZ territory shapefile.
[c]Fleet engages in day trips; we multiplied effort days by 12 hours operating time per day.
[d]Effort (in days) obtained from [NMFS, 2017r].
[e]Effort (in days) obtained from [PFMC, 2017b].

***Table A.13:** Disaggregated **a**nnual fishing effort of selected fleets operating on the high sea. The fishing effort given in hours by fleet region and gear type. The fleets include the U.S. purse seine (PS), the International (Int) PS, the INT pole and line (PL), and the North Pacific (NP) surface methods (SF)—which includes both PL and troll gears.*

Year	U.S. PS[a,b]	Int PS[b,c,d]	Int PL[c,d,e]	NP SF[e,f]
1996	163993	73957	71112	122748
1997	154724	160273	91452	130056
1998	154585	127305	69768	106008
1999	122483	202903	82812	94308
2000	119172	164086	86796	59640
2001	123497	202507	96576	66720
2002	117510	233394	98676	42624
2003	112552	107777	111156	28740
2004	102621	149276	83904	14208
2005	71998	169157	103872	10968
2006	54336	118675	83760	12516
2007	63500	168646	80772	2796
2008	172138	162074	74052	12372
2009	198369	178513	58608	8628
2010	192000	157496	83352	23532
2011	188690	131468	70860	11292
2012	205727	170347	81456	4560
2013	198621	180660	62580	5424
2014	195269	271924	51540	1116
2015	161405	209409	51540	1932

[a]The effort is the difference between total effort by U.S. flagged vessels and the effort within the U.S. EEZ.
[b]We multiplied effort days by 24 hours operating time per day.
[c]To estimate the high seas effort, we took the difference between the total effort and the effort that falls within an EEZ; to estimate the effort within the boundary of an EEZ, we used ArcMap (v. 10.5.1) to clip the geo-referenced (5x5 grid cells) effort data to a World EEZ territory shape-file.
[d]Gridded effort data was obtained from [WCPFC, 2017a].
[e]We multiplied effort days by 12 hours operating time per day.
[f]Effort (in days) obtained from [PFMC, 2017b].

Table A.14: *Annual catch (in metric tons) of the U.S. purse seine fleet [a].*

Year	Bigeye	Skipjack	Yellowfin	Totals
1996	8360	109561	31483	149404
1997	14595	80382	49105	144082
1998	16135	97922	60571	174628
1999	20615	102733	59137	182485
2000	8333	73229	43653	125215
2001	7710	74994	33154	115858
2002	3777	93381	23457	120615
2003	4653	56596	26207	87456
2004	6404	39724	21291	67419
2005	5807	58467	21898	86172
2006	4548	54651	9246	68445
2007	5354	69927	13455	88736
2008	6692	155553	47079	209324
2009	8928	239179	33482	281589
2010	7930	197894	39700	245524
2011	11533	157462	34244	203239
2012	8553	209249	41958	259760
2013	12779	207284	34285	254348
2014	10140	262676	40188	313004
2015	5460	208243	24461	238164

[a]Catch data obtained from [WCPFC, 2017c].

Table A.15: *Annual catch (in metric tons) of the Hawaii pole and line fleet [a].*

Year	Skipjack	Yellowfin	Other tuna	Mahimahi	All species	All tuna
1996	836	0.9	0.0	0.0	836	836
1997	881	0.0	0.0	2.3	883	881
1998	382	1.4	0.0	0.0	383	383
1999	586	9.5	0.0	0.0	595	595
2000	320	0.8	0.5	0.4	321	321
2001	448	2.0	0.3	0.3	451	451
2002	420	2.5	0.9	0.4	424	424
2003	586	33	4.5	1.2	625	623
2004	279	17	0.5	1.0	298	297
2005	353	68	1.2	0.4	423	422
2006	294	2.9	3.2	0.1	300	300
2007	272	23	1.2	0.2	296	296
2008	292	22	3.6	0.6	319	319
2009	213	16	0.6	0.8	230	230
2010	44	7.0	0.0	0.4	52	51
2011	159	9.4	0.1	1.3	169	168
2012	43	5.9	0.1	0.5	50	49
2013	104	1.5	0.2	0.2	106	106
2014	25	0.1	0.0	0.1	26	26
2015	12	1.9	0.1	0.3	14	14

[a]Data obtained from [NMFS, 2017q].

Table A.16: *Annual catch (in metric tons) pelagics by the Hawaii troll fleet.*

Year	YF[a,d]	SKJ[a,e]	BE[a,f]	ALB[a,g]	OT[a,h]	BM[b,i]	SM[b,j]	OBF[b,k]	SF[b,l]	MM[c,m]	ONO[c,n]	MP[c,o]	Total tuna	Total pelagics
1996	321	192	1.8	2.3	2.7	401	54	17	0.5	205	158	3.2	520	1358
1997	323	171	2.7	3.2	2.7	369	38	16	0.5	235	205	2.3	502	1368
1998	288	126	2.3	1.8	4.5	239	26	19	0.5	210	200	2.7	423	1121
1999	312	157	3.2	39	3.2	288	28	32	0.5	247	253	2.7	515	1367
2000	305	82	6.8	2.3	2.8	192	14	22	2.2	357	175	3.1	399	1163
2001	246	98	11	6.0	2.2	276	42	34	1.6	289	234	2.8	362	1242
2002	225	91	39	4.3	2.7	199	29	10	1.2	315	157	2.0	362	1076
2003	332	108	37	4.6	12	177	29	17	0.4	281	226	1.5	493	1224
2004	313	112	149	3.5	20	164	34	21	0.2	529	187	1.6	597	1533
2005	322	87	85	6.4	6.9	180	20	16	0.5	270	189	1.8	508	1185
2006	268	100	70	0.7	5.3	145	21	13	0.4	342	208	1.4	444	1175
2007	469	87	63	3.3	5.1	120	13	10	0.8	309	206	1.2	628	1288
2008	427	156	75	1.4	3.7	176	13	13	0.5	254	227	1.9	663	1349
2009	437	138	59	3.3	5.9	164	10	8	0.4	315	199	1.6	643	1342
2010	400	96	118	2.0	11	133	5.4	12	0.3	305	206	2.5	626	1291
2011	443	127	112	3.8	3.5	189	16	16	0.4	301	141	2.7	689	1354
2012	593	108	155	3.1	11	126	11	15	0.6	451	193	2.6	871	1670
2013	489	149	148	1.7	3.8	128	8.1	15	0.7	290	180	1.5	791	1414
2014	555	78	143	3.2	12	144	12	12	1.2	408	211	2.3	791	1582
2015	492	96	59	2.0	15	179	11	17	0.9	329	189	2.1	663	1391

[a]Tuna catch; data obtained from [NMFS, 2017s].
[b]Billfish catch; data obtained from: billfish [NMFS, 2017t].
[c]"Other pelagics" catch obtained from [NMFS, 2017z].
[d]Yellowfin (YF).
[e]Skipjack (SKJ).
[f]Bigeye (BE).
[g]Albacore (ALB).
[h]Other (OT) species.
[i]Blue marlin (BM).
[j]Striped marlin (SM).
[k]Other billfish (OBF).
[l]Swordfish (SF).
[m]Mahi mahi (MM)
[n]Wahoo or ono (ONO).
[o]Miscellaneous pelagics (MP).

Table A.17: *Annual catch (in metric tons) of tuna by the Hawaii longline fleet [a].*

Year	Bigeye	Yellowfin	Albacore	Skipjack	Bluefin	Total
1996	1787	630	1182	41	22	3662
1997	2449	1141	1645	106	24	5364
1998	3226	722	1111	76	16	5152
1999	2719	473	1474	99	10	4776
2000	2647	1205	898	100	3.2	4853
2001	2355	1033	1271	206	0.9	4867
2002	4392	561	519	128	0.5	5601
2003	3593	823	526	198	0.0	5141
2004	4336	711	360	137	0.5	5544
2005	4980	737	300	89	0.5	6106
2006	4427	962	262	72	0.0	5723
2007	5780	830	251	91	0.0	6952
2008	5855	900	367	119	0.0	7240
2009	4727	508	208	135	0.5	5578
2010	5435	574	418	150	0.0	6577
2011	5545	955	710	209	0.0	7418
2012	5833	887	674	246	0.5	7641
2013	6486	753	317	226	0.5	7783
2014	6970	672	202	187	0.5	8031
2015	8580	1.9	0.5	0.5	0.0	8583

[a]Data obtained from [NMFS, 2017x].

Table A.18: *Annual catch (in metric tons) of tuna by the American Samoa troll fleet [a].*

Year	Mahimahi	Wahoo	Marlin	Sailfish	Skipjack	Yellowfin	All tuna	All pelagics
1996	2.3	2.0	3.6	0.7	24	17	41	49
1997	1.6	0.9	2.4	0.0	14	9.8	24	29
1998	0.4	0.2	0.7	0.1	6.7	3.1	9.8	11
1999	1.0	0.3	0.3	0.1	16	5.2	21	23
2000	0.0	0.1	0.3	0.0	7.4	2.2	9.5	9.9
2001	0.4	0.3	0.0	0.0	6.8	2.8	9.6	10
2002	0.3	0.2	0.0	0.0	5.2	5.6	11	11
2003	0.7	0.3	0.6	0.0	8.8	3.2	12	14
2004	0.2	0.2	0.0	0.0	9.4	2.7	12	13
2005	0.1	0.4	0.1	0.1	4.9	3.4	8.3	9.0
2006	0.5	0.3	0.0	0.0	5.9	4.1	10	11
2007	0.3	0.4	0.1	0.0	5.6	4.1	9.7	10
2008	0.4	0.1	0.0	0.1	7.4	9.1	17	17
2009	0.1	0.0	0.0	0.0	1.3	1.3	2.5	2.6
2010	0.0	0.0	0.0	0.0	0.9	0.9	1.9	1.9
2011	0.3	0.0	0.0	0.0	9.0	5.6	15	15
2012	0.1	0.3	0.0	0.0	4.4	3.8	8.2	8.6
2013	0.1	0.5	0.0	0.0	3.8	3.2	7.1	7.7
2014	0.9	0.5	0.9	0.1	5.9	3.0	8.9	11
2015	0.4	0.2	0.8	0.6	3.1	1.8	4.9	7.0

[a]Data obtained from https://www.pifsc.noaa.gov/wpacfin/as/Pages/as_data_6.php.

Table A.19: *Annual catch (in metric tons) of tuna by the American Samoa longline fleet [a].*

Year	Yellowfin	Skipjack	Bigeye	Albacore	Wahoo	Mahimahi	Blue Marlin	Sailfish	Swordfish	Total tuna	Total pelagics
1996	12	0.2	3.9	86	1.6	2.4	10	1.4	0.4	102	118
1997	22	1.2	4.0	313	7.2	15	15	3.1	0.3	340	380
1998	42	18	10	446	18	15	21	3.3	1.7	517	576
1999	63	25	8.7	337	22	16	16	3.4	1.0	434	493
2000	86	15	22	632	21	19	27	1.0	0.9	755	825
2001	188	68	75	3230	52	39	17	2.5	5.9	3560	3677
2002	481	244	198	5946	165	38	41	3.1	15	6870	7131
2003	497	120	243	3943	196	37	12	2.8	15	4803	5065
2004	889	235	228	2486	215	19	5.6	2.1	9.2	3838	4090
2005	522	142	133	2916	221	24	23	2.2	7.5	3713	3991
2006	497	213	201	4178	286	22	27	5.9	37	5090	5469
2007	633	166	231	5190	198	14	39	1.0	13	6220	6485
2008	340	163	12	3552	136	13	35	0.9	6.8	4068	4259
2009	393	156	160	3926	139	17	42	1.9	13	4636	4847
2010	443	114	176	3954	131	8.2	45	1.5	11	4686	4883
2011	546	112	178	2334	128	10	39	3.7	13	3171	3365
2012	376	289	174	3200	85	10	37	1.5	14	4039	4187
2013	422	65	85	2127	90	19	31	1.8	11	2700	2852
2014	423	110	78	1391	71	10	26	1.5	10	2003	2121
2015	317	87	69	1577	63	5.0	23	1.6	7.8	2050	2149

[a]Data obtained from [NMFS, 2017v].

Table A.20: *Annual catch (in metric tons) of albacore tuna by the North Pacific surface methods (including pole and line and troll gears) fleet [a].*

Year	**Catch in EEZ[b]**	**Catch on high seas**	**Total Catch**
1996	2307	14655	16962
1997	2865	11460	14325
1998	2159	12330	14489
1999	6689	3431	10120
2000	6780	2934	9714
2001	6503	4846	11349
2002	7096	3661	10757
2003	12263	1883	14147
2004	12678	795	13473
2005	7996	492	8487
2006	10477	2070	12547
2007	11848	60	11908
2008	9938	1823	11761
2009	11797	543	12340
2010	8673	3027	11701
2011	9666	477	10143
2012	14036	113	14149
2013	12051	259	12310
2014	13329	40	13369
2015	11535	23	11558

[a]Data obtained from [PFMC, 2017a].

[b]Catch inside the U.S. and Canada exclusive economic zone (EEZ).

Table A.21: *Annual catch (in metric tons) of the U.S. purse seine fleet in the U.S. exclusive economic zones (EEZ)* [a,b].

Year	Skipjack	Yellowfin	Bigeye	Other	Total tuna
1996	5443	1702	170	0.0	7315
1997	14185	9984	1583	3.0	25755
1998	1213	862	73	0.0	2147
1999	0.0	0.0	0.0	0.0	0.0
2000	0.0	0.0	0.0	0.0	0.0
2001	2221	934	500	0.0	3655
2002	14504	14621	757	0.0	29882
2003	0.0	0.0	0.0	0.0	0.0
2004	0.0	0.0	0.0	0.0	0.0
2005	2734	2036	566	0.1	5337
2006	8020	948	637	0.7	9606
2007	2603	1736	176	0.0	4515
2008	0.0	0.0	0.0	0.0	0.0
2009	8511	2975	173	1.4	11661
2010	0.0	0.0	0.0	0.0	0.0
2011	0.0	0.0	0.0	0.0	0.0
2012	3378	552	156	0.6	4086
2013	0.0	0.0	0.0	0.0	0.0
2014	10123	9148	716	0.7	19987
2015	29792	5022	961	3.4	35778

[a]We obtained geo-referenced (5x5 grid cells) effort (in days) and aggregated by month; we used ArcMap (v. 10.5.1) to clip the gridded effort data to a U.S. EEZ territory shapefile.
[b]Geo-referenced (5x5 grid cells) catch (in metric tons) obtained from [WCPFC, 2017a].

Table A.22: *Annual catch (in metric tons) of the U.S. purse seine fleet outside the U.S. exclusive economic zones (EEZ)* [a],.

Year	Bigeye	Skipjack	Yellowfin	Total tuna
1996	8190	104118	29781	142089
1997	13012	66197	39121	118330
1998	16062	96709	59709	172481
1999	20615	102733	59137	182485
2000	8333	73229	43653	125215
2001	7210	72773	32220	112203
2002	3020	78877	8836	90733
2003	4653	56596	26207	87456
2004	6404	39724	21291	67419
2005	5241	55733	19862	80835
2006	3911	46631	8298	58840
2007	5178	67324	11719	84221
2008	6692	155553	47079	209324
2009	8755	230668	30507	269929
2010	7930	197894	39700	245524
2011	11533	157462	34244	203239
2012	8397	205871	41406	255674
2013	12779	207284	34285	254348
2014	9424	252553	31040	293017
2015	4499	178451	19439	202390

[a]The catch is the difference between the total catch by U.S. flagged vessels and the catch within the U.S. EEZ.

Table A.23: *Annual catch (in metric tons) of the international purse seine fleet on the high sea* [a,b].

Year	Skipjack	Yellowfin	Bigeye	Other tuna	Total tuna
1996	603199	172045	38714	2074	816032
1997	520622	292984	71675	6578	891859
1998	739368	378085	68289	1297	1187038
1999	657035	292752	57011	18012	1024810
2000	702292	303514	38556	15423	1059785
2001	717765	293083	45406	2960	1059214
2002	920366	252731	55986	5922	1235004
2003	878356	303361	37637	922	1220275
2004	921006	297001	60650	3739	1282397
2005	972416	343191	51577	8672	1375857
2006	1074566	286370	51362	5150	1417448
2007	1199016	310360	39070	2395	1550841
2008	1131861	397945	42085	8430	1580321
2009	1318053	289478	46163	5646	1659340
2010	1217818	322124	42988	2941	1585871
2011	1066696	281931	55377	224209	1628213
2012	1314907	357439	51265	167908	1891519
2013	1378238	324430	55401	142917	1900986
2014	1543815	340182	57295	123241	2064533
2015	1308410	283305	43725	157423	1792862

[a]To estimate the high seas catch, we took the difference between the total catch and the catch that falls within an EEZ; to estimate the catch within the boundary of an EEZ, we used ArcMap (v. 10.5.1) to clip the geo-referenced (5x5 ridded catch data to a World EEZ territory shapefile.
[b]Geo-referenced (5x5 grid cells) catch data was obtained from [WCPFC, 2017a].

Table A.24: *Annual catch (in metric tons) of the international pole and line fleet on the high sea* [a,b].

Year	Skipjack	Yellowfin	Other tuna	Total tuna
1996	33566	194	40	39945
1997	48468	177	127	56618
1998	45600	186	95	51874
1999	50519	100	41	57691
2000	41917	93	22	49426
2001	34106	107	19	42440
2002	29989	248	53	38679
2003	52845	134	2.3	62397
2004	37418	252	0.2	44868
2005	63775	126	0.7	72730
2006	43782	229	0.1	51166
2007	38448	163	3.4	45518
2008	37305	137	0.0	43770
2009	20664	220	0.0	25951
2010	38292	245	1.9	45622
2011	31542	302	3.7	37890
2012	29760	101	0.0	36795
2013	29455	76	3.0	34895
2014	18688	72	0.0	23206
2015[c]	18688	72	0.0	23206

[a]To estimate the high seas catch, we took the difference between the total catch and the catch that falls within an EEZ; to estimate the catch within the boundary of an EEZ, we used ArcMap (v. 10.5.1) to clip the geo-referenced (5x5 gridded catch data to a World EEZ territory shapefile.
[b]Geo-referenced (5x5 grid cells) catch data was obtained from [WCPFC, 2017a].
[c]Due to lack of data, data was copied from 2014.

Table A.25: *Mean density of marine fuels including distillates and heavy fuel oil (HFO) over the last 20 years. The mean values are the results of PRELIM simulations [Abella and Bergerson, 2012]. The value in parenthesis represents the uncertainty (95% confidence intervals).*

Year	Mean distillate density (g l fuel $^{-1}$)	Mean HFO 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)

***Table A.26**: PRELIM fuel product density results for ultra-low-sulfur diesel (ULSD), fuel oil, and bunker fuel [Abella and Bergerson, 2012].*

Region	Oil Field	ULSD Density (kg/m3)	Fuel Oil Density (kg/m3)	Bunker Fuel Density (kg/m3)
U.S.	Alaskan North Slope Exxon	825	825	959
Canada	Albian Heavy Synthetic	837	845	1,010
Canada	Albian Residual	827	829	1,010
Angola	Girassol_Exxon	822	818	941
Angola	Girassol_Statoil	824	822	969
Angola	Kuito_BP	827	828	1,039
Azerbaijan	Azeri Light_Chevron	825	872	908
Azerbaijan	Azeri Light_Exxon	825	879	870
Azerbaijan	Azeri Light_Statoil	825	879	923
U.S.	Belridge_Knovel	823	822	1,010
Nigeria	Bonny Light_Chevron	825	905	824
Canada	Bow River	828	831	1,010
Brazil	Frade_Chevron	824	824	1,010
Brazil	Lula	822	818	955
Brazil	Polvo	831	836	1,010
U.K.	Brent_BP	825	893	911
U.K.	Brent_Chevron	825	884	915
U.K.	Brent_Exxon	820	808	938
Canada	Hibernia_Chevron	822	818	1,000
Canada	Hibernia_Exxon	821	808	911
Canada	Hibernia_Statoil	825	889	940
China	Bozhong	826	826	1,010
Canada	Cold Lake (Dilbit)	829	833	1,010
Norway	Ekofisk_Chevron	825	882	929
Norway	Ekofisk_Statoil	825	882	937
U.K.	Forties_BP	824	823	954
U.K.	Forties_Chevron	820	812	996
U.K.	Forties_Statoil	824	824	996
Venezuela	Hamaca_Knovel	824	822	1,061
Canada	High Sour Edmonton	825	824	1,024
Canada	Husky Synthetic	825	895	929
Indonesia	Duri_Chevron	822	820	1,010
Indonesia	Tanggeh	825	897	904
Iraq	Basra	827	828	977
Kuwait	Eocene	823	823	1,010
Kuwait	Ratawi_Chevron	826	828	1,029
Canada	Lloyd Blend	828	830	1,010
Canada	Lloyd Kerrobert	830	834	1,010
U.S.	Mars_BP	826	828	964
Canada	Midale	827	829	1,055
U.S.	Midway Sunset	828	831	1,003
Nigeria	Agbami_Chevron	825	859	927
Nigeria	Agbami_Statoil	825	886	995
Nigeria	Bonga	826	830	941
Nigeria	Erha	825	899	911
Nigeria	Escravos	825	905	932
Nigeria	Pennington_Chevron	825	906	936
Nigeria	Qua Iboe	825	884	919
Denmark	North Sea Dansk_Statoil	825	908	930
Norway	North Sea Skarv	825	890	928
Russia	Sokol	825	897	904
Canada	Seal Heavy	828	831	1,010
Canada	Smiley-Coleville	829	832	1,010
Canada	Suncor Synthetic A	825	910	942
Canada	Syncrude Synthetic	827	831	997
Kazakhstan	Tengiz_Chevron	821	811	966
U.S.	Thunderhorse_BP	825	824	958
U.S.	Thunder Horse_Exxon	821	811	971
UAE	Murban	823	820	955
Canada	Wabasca	829	833	1,010
Canada	Western Canada Blend	827	828	1,010
Canada	Western Canada Select	828	831	1,010

Table A.27: *PRELIM lower heating value (LHV) results for ultra-low-sulfur diesel (ULSD), fuel oil, and bunker fuel [Abella and Bergerson, 2012]*.

Region	Oil Field	ULSD LHV (MJ/kg)	Fuel Oil LHV (MJ/kg)	Bunker Fuel LHV (MJ/kg)
U.S.	Alaskan North Slope Exxon	41.29	41.29	39.39
Canada	Albian Heavy Synthetic	41.13	41.02	38.6
Canada	Albian Residual	41.27	41.24	38.6
Angola	Girassol_Exxon	41.33	41.39	39.67
Angola	Girassol_Statoil	41.31	41.33	39.24
Angola	Kuito_BP	41.27	41.25	38.13
Azerbaijan	Azeri Light_Chevron	41.29	40.66	40.15
Azerbaijan	Azeri Light_Exxon	41.29	40.56	40.68
Azerbaijan	Azeri Light_Statoil	41.29	40.56	39.94
U.S.	Belridge_Knovel	41.32	41.34	38.6
Nigeria	Bonny Light_Chevron	41.29	40.19	41.3
Canada	Bow River	41.25	41.22	38.6
Brazil	Frade_Chevron	41.3	41.3	38.6
Brazil	Lula	41.33	41.38	39.46
Brazil	Polvo	41.21	41.15	38.6
U.K.	Brent_BP	41.29	40.37	40.11
U.K.	Brent_Chevron	41.29	40.5	40.05
U.K.	Brent_Exxon	41.36	41.51	39.72
Canada	Hibernia_Chevron	41.33	41.39	38.76
Canada	Hibernia_Exxon	41.35	41.51	40.11
Canada	Hibernia_Statoil	41.29	40.43	39.67
China	Bozhong	41.28	41.27	38.6
Canada	Cold Lake (Dilbit)	41.23	41.19	38.6
Norway	Ekofisk_Chevron	41.29	40.52	39.84
Norway	Ekofisk_Statoil	41.29	40.52	39.73
U.K.	Forties_BP	41.3	41.32	39.47
U.K.	Forties_Chevron	41.36	41.46	38.82
U.K.	Forties_Statoil	41.3	41.31	38.83
Venezuela	Hamaca_Knovel	41.31	41.33	37.77
Canada	High Sour Edmonton	41.3	41.31	38.37
Canada	Husky Synthetic	41.29	40.33	39.85
Indonesia	Duri_Chevron	41.34	41.36	38.6
Indonesia	Tanggeh	41.29	40.31	40.2
Iraq	Basra	41.27	41.25	39.12
Kuwait	Eocene	41.31	41.32	38.6
Kuwait	Ratawi_Chevron	41.27	41.25	38.29
Canada	Lloyd Blend	41.25	41.22	38.6
Canada	Lloyd Kerrobert	41.22	41.17	38.6
U.S.	Mars_BP	41.28	41.26	39.32
Canada	Midale	41.27	41.23	37.86
U.S.	Midway Sunset	41.26	41.21	38.71
Nigeria	Agbami_Chevron	41.29	40.83	39.87
Nigeria	Agbami_Statoil	41.29	40.43	38.84
Nigeria	Bonga	41.29	41.23	39.66
Nigeria	Erha	41.29	40.28	40.11
Nigeria	Escravos	41.29	40.19	39.8
Nigeria	Pennington_Chevron	41.29	40.18	39.74
Nigeria	Qua Iboe	41.29	40.49	39.99
Denmark	North Sea Dansk_Statoil	41.29	40.15	39.83
Norway	North Sea Skarv	41.29	40.41	39.85
Russia	Sokol	41.29	40.31	40.2
Canada	Seal Heavy	41.25	41.22	38.6

Canada	Smiley-Coleville	41.24	41.2	38.6
Canada	Suncor Synthetic A	41.29	40.12	39.66
Canada	Syncrude Synthetic	41.26	41.21	38.8
Kazakhstan	Tengiz_Chevron	41.35	41.48	39.28
U.S.	Thunderhorse_BP	41.3	41.3	39.41
U.S.	Thunder Horse_Exxon	41.35	41.47	39.21
UAE	Murban	41.31	41.36	39.46
Canada	Wabasca	41.23	41.19	38.6
Canada	Western Canada Blend	41.27	41.25	38.6
Canada	Western Canada Select	41.25	41.22	38.6

Table A.28: *PRELIM ultra-low-sulfur diesel (USLD) GHG emissions (100-y time horizon). The fuel sulfur level is 0.0011%. Crude oil refinery results for four different configurations [Abella and Bergerson, 2012].*

Region	Oil Field	Hydro-skimming[a] (g CO2e/MJ)	Medium[b] (g CO2e/MJ)	Deep - Coke (g CO2e/MJ)	Deep - Hydrocracking (g CO2e/MJ)
Alaska	Alaskan North Slope Exxon	2.03	7.07	12.23	15.20
Canada	Albian Heavy Synthetic	3.61	17.02	17.89	22.13
Canada	Albian Residual	2.75	9.40	14.82	17.37
Angola	Girassol_Exxon	2.69	7.75	11.53	14.29
Angola	Girassol_Statoil	2.85	7.27	12.44	15.34
Angola	Kuito_BP	1.93	10.23	22.10	22.10
Azerbaijan	Azeri Light_Chevron	2.15	4.76	6.83	9.34
Azerbaijan	Azeri Light_Exxon	2.87	7.32	12.54	15.48
Azerbaijan	Azeri Light_Statoil	2.73	8.27	10.38	12.31
U.S.	Belridge_Knovel	4.66	13.71	20.36	28.45
Nigeria	Bonny Light_Chevron	3.57	9.03	10.38	11.76
Canada	Bow River	5.27	12.89	15.01	19.07
Brazil	Frade_Chevron	1.86	11.47	19.95	23.27
Brazil	Lula	2.14	11.64	11.54	13.32
Brazil	Polvo	7.61	16.25	18.71	22.66
U.K.	Brent_BP	2.49	7.68	10.52	11.67
U.K.	Brent_Chevron	2.10	9.61	8.47	11.26
U.K.	Brent_Exxon	2.54	7.51	12.98	16.09
Canada	Hibernia_Chevron	2.67	6.98	12.56	15.54
Canada	Hibernia_Exxon	2.03	6.82	12.96	16.13
Canada	Hibernia_Statoil	2.76	10.18	12.81	15.11
China	Bozhong	2.02	10.71	13.97	19.72
Canada	Cold Lake (Dilbit)	4.38	13.59	17.30	20.90
Norway	Ekofisk_Chevron	2.02	6.77	11.29	15.57
Norway	Ekofisk_Statoil	2.67	8.63	11.66	13.04
U.K.	Forties_BP	2.64	8.74	10.87	12.79
U.K.	Forties_Chevron	2.08	6.08	9.78	13.99
U.K.	Forties_Statoil	2.81	8.59	11.55	12.86
Venezuela	Hamaca_Knovel	2.08	4.29	5.04	10.00
Canada	High Sour Edmonton	2.54	6.72	9.81	12.77
Canada	Husky Synthetic	2.69	8.18	8.43	8.57
Indonesia	Duri_Chevron	1.93	11.96	19.81	24.97
Indonesia	Tanggeh	2.40	4.56	5.37	5.71
Iraq	Basra	3.50	8.97	12.87	15.67
Kuwait	Eocene	3.23	12.47	20.08	23.61
Kuwait	Ratawi_Chevron	1.53	9.85	15.94	21.99
Canada	Lloyd Blend	5.38	13.33	17.41	20.64
Canada	Lloyd Kerrobert	4.97	13.84	17.38	20.34
U.S.	Mars_BP	2.78	8.85	12.52	16.22
Canada	Midale	2.87	8.65	11.76	14.60
U.S.	Midway Sunset	3.86	11.91	18.72	24.00
Nigeria	Agbami_Chevron	2.18	4.40	6.30	8.66
Nigeria	Agbami_Statoil	2.50	5.44	5.82	6.53
Nigeria	Bonga	2.37	3.33	8.31	9.62
Nigeria	Erha	2.44	11.08	15.07	17.03
Nigeria	Escravos	2.79	7.15	11.34	13.37
Nigeria	Pennington_Chevron	2.50	5.40	6.61	9.82
Nigeria	Qua Iboe	2.47	2.77	6.84	8.49
Denmark	North Sea Dansk_Statoil	2.58	7.07	12.31	15.66
Norway	North Sea Skarv	2.68	6.80	8.61	9.88
Russia	Sokol	2.42	6.49	12.22	12.84
Canada	Seal Heavy	3.89	13.26	18.49	21.85
Canada	Smiley-Coleville	5.93	13.42	17.09	20.10

Canada	Suncor Synthetic A	2.21	8.11	8.25	8.32
Canada	Syncrude Synthetic	2.18	9.16	10.23	9.76
Kazakhstan	Tengiz_Chevron	2.15	5.13	8.52	8.52
U.S.	Thunderhorse_BP	2.55	9.27	11.93	15.06
U.S.	Thunder Horse_Exxon	2.04	5.51	13.72	14.50
UAE	Murban	2.52	5.97	6.61	9.82
Canada	Wabasca	5.76	12.50	15.26	19.40
Canada	Western Canada Blend	3.59	11.53	14.61	18.83
Canada	Western Canada Select	4.96	12.77	15.40	19.87

[a]Results are the same for hydro-cracking and coking refineries.

[b]Coking refinery results.

***Table A.29**: PRELIM fuel oil GHG emissions (100-y time horizon); hydro-skimming configuration refinery results [Abella and Bergerson, 2012].*

Region	Oil Field	Fs%	GWP (g CO2e/MJ)
Nigeria	Agbami_Chevron	0.06	0.81
Canada	Husky Synthetic Blend	0.09	0.82
Nigeria	Qua Iboe_Exxon	0.13	0.76
Nigeria	Agbami_Statoil	0.14	0.72
Azerbaijan	Azeri Light_Chevron	0.14	0.84
Azerbaijan	Azeri Light_Statoil	0.14	0.85
Nigeria	Pennington_Chevron	0.15	0.83
Azerbaijan	Azeri Light_Exxon	0.15	0.94
Canada	Syncrude Synthetic	0.16	0.80
Indonesia	Duri_Chevron	0.16	1.85
China	Bozhong_Chevron	0.18	1.29
Nigeria	Erha_Exxon	0.18	0.80
Nigeria	Escravos_Chevron	0.19	0.92
Nigeria	Bonny Light_Chevron	0.21	0.80
Norway	Ekofisk_Chevron	0.22	0.89
U.S.	Belridge_Knovel	0.22	1.27
Canada	Suncor Synth A	0.23	0.77
Denmark	North Sea Dansk Statoil	0.25	0.91
Nigeria	Bonga_Exxon	0.25	0.77
Norway	Ekofisk_Statoil	0.26	0.80
Angola	Girassol_Exxon	0.28	0.95
Brazil	Lula	0.30	0.87
Angola	Girassol_Statoil	0.30	0.89
Indonesia	Tanngeh_BP	0.38	0.69
Russia	Sokol_Exxon	0.38	0.80
U.K.	Brent_Chevron	0.39	0.80
Canada	Hibernia_Exxon	0.41	0.91
Venezuela	Hamaca_Knovel	0.42	0.85
U.K.	Brent_ Exxon	0.42	0.86
Canada	Hibernia_Chevron	0.42	0.96
Norway	North Sea_BP	0.43	0.79
Canada	Hibernia_Statoil	0.47	0.83
U.K.	Brent_BP	0.49	0.81
U.K.	Forties_Chevron	0.49	0.85
Brazil	Frade_Chevron	0.52	1.28
Canada	Albian Synthetic Blend	0.54	0.92
Angola	Kuito_BP	0.56	1.17
U.S.	Thunderhorse_Exxon	0.72	0.88
U.S.	Thunderhorse_BP	0.75	0.83
U.S.	Alaskan North Slope_Exxon	0.85	0.87
U.S.	Midway Sunset	0.90	1.03
Brazil	Polvo	0.96	1.01
Kazakhstan	Tengiz_Chevron	0.98	0.78
U.K.	Forties_BP	1.00	0.78
U.K.	Forties_Statoil	1.00	0.78
Canada	High Sour Edmonton	1.20	0.82
UAE	Murban_BP	1.22	0.79
U.S.	Mars_BP	1.62	0.89
Canada	Albian Heavy Synthetic	1.64	0.99
Canada	Western Canada Blend	1.69	0.99
Canada	Western Canada Select	1.99	1.00

Canada	Bow River	2.00	0.97
Canada	Lloyd Kerrobert	2.09	1.00
Canada	Lloyd Blend	2.19	1.02
Canada	Midale	2.26	0.86
Canada	Smiley Coleville	2.28	0.99
Canada	Cold Lake	2.61	0.99
Iraq	Basra_BP	2.81	0.88
Kuwait	Eocene_Chevron	2.92	1.40
Kuwait	Ratawi_Chevron	3.02	1.10
Canada	Wabasca	3.15	0.96
Canada	Seal Heavy	3.54	0.97

***Table A.30**: PRELIM fuel oil GHG emissions (100-y time horizon); medium conversion configuration refinery results [Abella and Bergerson, 2012].*

Region	Oil Field	Fs%	GWP (g CO2e/MJ)
Nigeria	Agbami_Chevron	0.00013	5.09
Kazakhstan	Tengiz_Chevron	0.00017	7.79
Canada	Husky Synthetic Blend	0.00022	12.78
Nigeria	Qua Iboe_Exxon	0.00022	7.02
Nigeria	Agbami_Statoil	0.00023	5.44
Azerbaijan	Azeri Light_Chevron	0.00025	7.57
Nigeria	Pennington_Chevron	0.00025	7.51
Azerbaijan	Azeri Light_Statoil	0.00025	12.04
Canada	Albian Heavy Synthetic	0.00026	18.58
Indonesia	Duri_Chevron	0.00027	13.70
Azerbaijan	Azeri Light_Exxon	0.00028	10.66
China	Bozhong_Chevron	0.00031	11.84
Nigeria	Escravos	0.00034	9.78
Nigeria	Bonny Light_Chevron	0.00035	10.29
Canada	Syncrude Synthetic	0.00036	12.39
Nigeria	Bonga	0.00038	9.26
Nigeria	Erha_Exxon	0.00039	20.89
Norway	Ekofisk_Chevron	0.00041	8.31
Denmark	North Sea Dansk_Statoil	0.00042	8.83
Canada	Suncor Synthetic A	0.00043	11.94
Norway	Ekofisk_Statoil	0.00045	12.07
U.S.	Belridge_Knovel	0.00048	15.36
Brazil	Lula	0.00049	13.11
Angola	Girassol_Exxon	0.00051	11.54
Angola	Girassol_Statoil	0.00053	12.73
Indonesia	Tanngeh_BP	0.00067	7.41
Russia	Sokol	0.00070	10.95
Norway	North Sea Skarv	0.00073	9.89
U.K.	Brent_Chevron	0.00073	7.60
Canada	Hibernia_Exxon	0.00075	10.78
U.K.	Brent_Exxon	0.00078	9.84
U.K.	Brent_BP	0.00082	10.25
Canada	Hibernia_Statoil	0.00083	12.20
Canada	Hibernia_Chevron	0.00086	8.52
Brazil	Frade_Chevron	0.00093	13.19
Angola	Kuito_BP	0.00100	12.23
Venezuela	Hamaca_Knovel	0.00110	4.10
U.K.	Forties_Chevron	0.00112	8.58
U.S.	Thunderhorse_BP	0.00122	10.66
U.S.	Thunder Horse_Exxon	0.00130	9.24
Canada	Albian Residual	0.00138	13.07
Brazil	Polvo	0.00139	18.22
Alaska	Alaskan North Slope Exxon	0.00149	9.31
U.S.	Midway Sunset	0.00152	13.70
U.K.	Forties_BP	0.00162	10.92
U.K.	Forties_Statoil	0.00172	12.17
UAE	Murban	0.00189	8.60
Canada	High Sour Edmonton	0.00213	8.65
U.S.	Mars_BP	0.00260	10.78
Canada	Western Canada Blend	0.00316	13.04

Canada	Bow River	0.00334	14.06
Canada	Western Canada Select	0.00350	14.22
Canada	Lloyd Kerrobert	0.00357	15.79
Canada	Midale	0.00370	11.49
Canada	Smiley-Coleville	0.00374	14.76
Canada	Lloyd Blend	0.00390	14.51
Canada	Cold Lake (Dilbit)	0.00437	14.71
Iraq	Basra_BP	0.00458	11.47
Canada	Wabasca	0.00490	13.42
Kuwait	Ratawi_Chevron	0.00521	11.74
Kuwait	Eocene	0.00537	13.54
Canada	Seal Heavy	0.00572	14.18

Table A.31: *PRELIM bunker fuel GHG emissions (100-y time horizon); hydro-skimming configuration refinery results [Abella and Bergerson, 2012].*

Region	Oil Field	Fs%	GWP (g CO2e/MJ)
Nigeria	Agbami_Chevron	0.21	0.56
Canada	Husky Synthetic Blend	0.22	0.62
Indonesia	Duri_Chevron	0.26	0.30
Azerbaijan	Azeri Light_Statoil	0.27	0.53
Nigeria	Pennington_Chevron	0.28	0.53
U.S.	Belridge_Knovel	0.29	0.36
Azerbaijan	Azeri Light_Chevron	0.30	0.55
Nigeria	Agbami_Statoil	0.33	0.65
China	Bozhong_Chevron	0.35	0.37
Azerbaijan	Azeri Light_Exxon	0.35	0.48
Nigeria	Qua Iboe_Exxon	0.36	0.60
Canada	Syncrude Synthetic	0.36	0.60
Nigeria	Escravos	0.38	0.47
Nigeria	Erha_Exxon	0.41	0.56
Brazil	Lula	0.43	0.51
Canada	Suncor Synthetic A	0.43	0.63
Angola	Girassol_Exxon	0.49	0.47
Norway	Ekofisk_Statoil	0.51	0.53
Nigeria	Bonny Light_Chevron	0.52	0.35
Denmark	North Sea Dansk_Statoil	0.52	0.46
Nigeria	Bonga_Exxon	0.54	0.62
Norway	Ekofisk_Chevron	0.57	0.46
Angola	Girassol_Statoil	0.58	0.49
U.K.	Brent_BP	0.64	0.54
Norway	North Sea Skarv	0.81	0.55
U.K.	Brent_Chevron	0.85	0.53
Indonesia	Tanngeh_BP	0.87	0.63
Russia	Sokol_Exxon	0.87	0.54
Canada	Hibernia_Chevron	0.91	0.44
Canada	Hibernia_Statoil	0.92	0.51
Brazil	Frade_Chevron	0.98	0.35
Angola	Kuito_BP	1.12	0.37
U.K.	Brent_Exxon	1.12	0.50
Canada	Hibernia_Exxon	1.13	0.48
Brazil	Polvo	1.23	0.42
U.S.	Thunderhorse_BP	1.24	0.51
U.S.	Thunderhorse_Exxon	1.37	0.49
Alaska	Alaskan North Slope Exxon	1.50	0.48
U.K.	Forties_BP	1.63	0.54
Kazakhstan	Tengiz_Chevron	1.65	0.53
U.K.	Forties_Chevron	1.76	0.50
UAE	Murban	1.79	0.56
U.S.	Midway Sunset	1.80	0.42

U.K.	Forties_Statoil	1.86	0.54
U.S.	Mars_BP	2.46	0.47
Canada	High Sour Edmonston	2.69	0.52
Canada	Albian Heavy Synthetic	3.06	0.41
Venezuela	Hamaca	3.66	0.51
Canada	Midale	3.92	0.50
Canada	Bow River	3.96	0.45
Canada	Smiley-Coleville	4.25	0.44
Iraq	Basra_BP	4.36	0.48
Canada	Lloyd Kerrobert	4.77	0.43
Canada	Western Canadian Select	4.97	0.43
Canada	Western Canadian Blend	5.06	0.43
Canada	Lloyd Blend	5.40	0.43
Canada	Wabasca	5.52	0.44
Canada	Cold Lake	5.68	0.43
Canada	Albian Residual	6.01	0.46
Kuwait	Eocene	6.27	0.32
Kuwait	Ratawi	6.89	0.39
Canada	Seal Heavy	7.47	0.42

Table A.32: *PRELIM bunker fuel GHG emissions (100-y time horizon); medium conversion configuration refinery results [Abella and Bergerson, 2012].*

Region	Oil Field	Fs%	GWP (g CO2e/MJ)
Canada	Suncor Synthetic A	0.03	9.21
Canada	Husky Synthetic Crude Blend	0.04	6.61
U.S.	Belridge_Knovel	0.09	0.80
Canada	Suncrude Synthetic	0.17	6.81
Indonesia	Duri_Chevron	0.27	0.74
Nigeria	Agbami_Chevron	0.27	1.89
Azerbaijan	Azeri Light_Statoil	0.29	1.86
Nigeria	Pennington_Chevron	0.33	2.18
Brazil	Lula	0.34	3.34
Azerbaijan	Azeri Light_Chevron	0.34	1.78
Nigeria	Qua Iboe_Exxon	0.36	0.88
China	Bozhong_Chevron	0.37	1.19
Azerbaijan	Azeri Light_Exxon	0.39	1.28
Nigeria	Erha_Exxon	0.40	2.03
Nigeria	Escravos	0.40	1.47
Nigeria	Agbami_Statoil	0.41	3.34
Nigeria	Bonny Light_Chevron	0.45	2.38
Angola	Girassol_Exxon	0.49	1.38
U.K.	Brent_BP	0.50	1.77
Nigeria	Bonga_Exxon	0.56	0.95
Norway	Ekofisk_Statoil	0.57	1.67
Angola	Girassol_Statoil	0.62	1.50
Denmark	North Sea Dansk_Statoil	0.62	1.25
Norway	Ekofisk_Chevron	0.67	1.34
Norway	North Sea Skarv	0.93	2.12
U.K.	Brent_Chevron	0.94	1.56
Angola	Kuito_BP	0.94	1.19
Canada	Hibernia_Chevron	0.95	1.18
Russia	Sokol_Exxon	0.97	1.33
Canada	Hibernia_Statoil	1.00	1.60
Brazil	Frade_Chevron	1.02	0.96
Indonesia	Tanngeh_BP	1.14	2.32
Brazil	Polvo	1.22	1.53
U.S.	Thunderhorse_BP	1.28	1.58
U.K.	Brent_Exxon	1.29	1.27
Canada	Hibernia_Exxon	1.30	1.15
U.S.	Thunderhorse_Exxon	1.41	1.18
Alaska	Alaskan North Slope Exxon	1.53	1.17
Kazakhstan	Tengiz_Chevron	1.65	1.91
Forties_BP	Forties_BP	1.71	1.76
UAE	Murban	1.81	2.02
U.S.	Midway Sunset	1.96	0.75
U.K.	Forties_Statoil	2.00	1.69
U.K.	Forties_Chevron	2.18	1.41
U.S.	Mars_BP	2.57	1.27
Canada	High Sour Edmonston	3.10	1.48
Canada	Albian Heavy Synthetic	3.44	2.09
Canada	Midale	4.26	1.58
Canada	Bow River	4.40	1.63
Iraq	Basra_BP	4.46	1.38
Canada	Smiley-Coleville	4.61	1.51
Venezuela	Hamaca	5.27	1.48
Canada	Lloyd Kerrobert	5.39	1.56
Canada	Western Canadian Select	5.70	1.44

Canada	Western Canadian Blend	5.95	1.40
Canada	Wabasca	6.02	1.43
Canada	Lloyd Blend	6.17	1.41
Canada	Cold Lake	6.35	1.42
Kuwait	Eocene	6.63	0.84
Canada	Albian Residual	7.21	1.24
Kuwait	Ratawi	7.40	0.83
Canada	Seal Heavy	8.21	1.22

Table A.33*: Selected fuel refinery configurations for each product slate : hydro-skimming, medium and deep conversion. The medium and deep conversion configurations include fluid catalytic cracking (FCC) and gas oil hydrocracking and fractionation (GO-HC) processes [Abella and Bergerson, 2012].*

Fuel Product	Hydro-Skimming	Medium (FCC + GO-HC)	Deep (FCC + GO-HC)
Bunker fuel[a]	X	X	
Fuel oil[b]	X	X	
Ultra-low-sulfur diesel[c]	X	X	X

[a]We used the "bunker fuel" product slate to estimate the refinery emissions for residual oil or heavy fuel oil (HFO).
[b]We used the "fuel oil" product slate to estimate the refinery emissions for marine gas oil (MGO, and a blend of the "bunker fuel" and "fuel oil" product slates to estimate the refinery emissions for marine diesel oil (MDO).
[c]Ultra-low sulfur-diesel (ULSD) is a commonly used in certain engines operating within emission control areas.

Table A.34: *Selected PRELIM simulation values for ultra-low sulfur diesel (ULSD), marine gas oil (MGO), marine diesel oil (MDO), and heavy fuel oil (HFO) for varying fuel sulfur levels [a].*

Fuel Type	Fs%	Selected Values
ULSD[b]	0.0011	Table S5: (n=248)
MGO[c]	0.05	Table S7: (n=62); Table S6: Fs% < 0.30 (n=22)
MGO[c]	0.1	Table S7: (n=62);Table S6: Fs% < 0.52 (n=35)
MGO[c]	0.35	Table S7: (n=62);Table S6: Fs% < 0.52 (n=57)
MGO[c]	1	Table S7: Fs% > 0.0014 (n=20); Table S6: Fs% > 0.54 (n=27)
MDO[d]	0.2	Table S7: (n=62); Table S6: Fs% < 0.98 (n=43); Table S8: Fs% <0.56 (n=19; Table S9: Fs% < 0.52 (n=19)
MDO[d]	0.55	Table S6: (n=62); Table S7: (n=62);Table S8: Fs% < 1.80 (n=40); Table S9: Fs% < 1.80 (n=40)
MDO[d]	0.75	Table S6: (n=62); Table S7:(n=62); Table S8: Fs% < 4.60 (n=50); Table S9: Fs% <4.25 (n=50)
MDO[d]	1.5	Table S6: Fs% > 0.30 (n=40); Table S7: Fs% > 0.00045 (n=39); Table S8 (n=62); Table S9(n=62)
HFO[e]	0.5	Table S10: Fs% <1 (n=31); Table S11: Fs% < 1 (n=31)
HFO[e]	2.6	Table S10: Fs% > 0.40 (n=47); Table S11: Fs% > 0.43 (n=47)
HFO[e]	3.5	Table S10: Fs% > 1 (n=32); Table S11: Fs% > 1 (n=32)
HFO[e]	4.5	Table S10: Fs% > 1.8 (n=22); Table S11: Fs% > 1.7 (n=22)

[a]An oil field assay may appear more than once in a data set for three reasons: 1) an oil field has more than one producer (BP, Chevron, Exxon, Statoil, etc.), 2) more than one refinery configuration was used for each product, and 3) in the case of MDO, a blend of different fuels and refinery configurations was used.
[b]ULSD is commonly used in certain engines operating within emission control areas.
[c]We used the "fuel oil" product slate to estimate the refinery emissions for MGO.
[d]We used a blend of the "bunker fuel" and "fuel oil" product slates to estimate the refinery emissions for MDO.
[e]We used the "bunker fuel" product slate to estimate the refinery emissions for residual oil or HFO.

Table A.35: *Mean value and 95% confidence intervals for refinery greenhouse gas (GHG) emissions, lower heating values (LHV), and densities of four different fuels with varying fuel sulfur levels.*

Fs%	GHGs (g CO2e/MJ crude)	Crude feed input[b] (MJ crude/MJ fuel)	LHV[c] (MJ / kg)	Density[c] (g / liter)
Ultra-low-sulfur diesel (ULSD)				
0.0015	9.99 [9.24, 10.72]	0.99	41.0 (± 0.0)	825.0 (± 0.7)
Marine gas oil (MGO)				
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 (MDO)				
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 (HFO)				
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 and 95% confidence intervals constructed using bootstrap analysis methods described in [Orloff and Bloom, 2014].
[b]Crude feed input values were obtained from PRELIM [Abella and Bergerson, 2012].
[c]Confidence interval calculated using the following formula: $\mu \pm 1.96\times\sigma/n^{0.5}$ where μ is the mean, σ is the standard deviation, and n is the number of observations.

Table A.36: *Global warming potentials (GWP) used in the crude oil extraction, crude oil refinery, and farmed animal protein climate forcing analysis (g CO2e g pollutant-1). The values in brackets represent the 95% confidence interval.*

GWP	CO_2[a]	CH_4[a]	N_2O[a]	NOx[b,c,d,e]	SO_2[b,d,f]	OC[b,d,g]	BC[b,d,h]
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]Values include carbon-climate feedback taken from [Myhre et al., 2013]
[b]Mean values and 95% confidence intervals constructed using bootstrap analysis methods described in [Orloff and Bloom, 2014].
[c]Given as NO_2.
[d]Direct effects (aerosol-radiation interaction)
[e]Mean global values (n=4) taken from [Shindell et al., 2009], [Fuglestvedt et al., 2010], four regions [Collins et al., 2013], and [Aamaas et al., 2015].
[f]Mean global values (n=3) taken from [Shindell et al., 2009; Fuglestvedt et al., 2010; Aamaas et al., 2015].
[g]Mean global values (n=3) taken from [Bond et al., 2011], four regions [Collins et al., 2013], and [Fuglestvedt et al., 2010].
[h]Mean global values (n=5) taken 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 A.37: *Crude oil extraction GHG emissions literature review results (100-y time horizon).*

Region	Oil Field	GWP ($g\ CO_2e/MJ$)	Source
U.S.	Alaskan North Slope	16.57	[Brandt et al., 2015]
Canada	Albian Heavy Synthetic	20.52	[Duffy, 2015]
Canada	Albian Residual	20.52	[Duffy, 2015]
Angola	Girassol	6.12	[Brandt et al., 2015]
Azerbaijan	Azeri Light	8.25	[Duffy, 2015]
U.S.	Belridge	14.46	[Brandt et al., 2015]
Nigeria	Bonny	31.28	[Brandt et al., 2015]
Canada	Bow River	9.27	[Duffy, 2015]
Brazil	Frade	3.12	[Brandt et al., 2015]
Brazil	Lula	5.01	[Brandt et al., 2015]
Brazil	Polvo	6.39	[Duffy, 2015]
U.K.	Brent	14.22	[Brandt et al., 2015]
Canada	Hibernia	5.29	[Gordon et al., 2015]
China	Bozhong	43.29	[Brandt et al., 2015]
Canada	Cold Lake (Dilbit)	19.64	[Duffy, 2015]
Norway	Ekofisk	3.03	[Brandt et al., 2015]
U.K.	Forties	8.74	[Brandt et al., 2015]
Venezuela	Hamaca	25.91	[Brandt et al., 2015]
Canada	High Sour Edmonton	8.27	[Duffy, 2015]
Canada	Husky Synthetic	36.62	[Duffy, 2015]
Indonesia	Duri	20.48	[Brandt et al., 2015]
Indonesia	Tanggeh	20.48	[Brandt et al., 2015]
Iraq	Basra	13.08	[Duffy, 2015]
Kuwait	Eocene	7.48	[Duffy, 2015]
Kuwait	Ratawi	4.72	[Brandt et al., 2015]
Canada	Lloyd Blend	9.27	[Duffy, 2015]
Canada	Lloyd Kerrobert	8.27	[Duffy, 2015]
U.S.	Mars	4.24	[Brandt et al., 2015]
Canada	Midale	8.98	[Brandt et al., 2015]
U.S.	Midway Sunset	27.32	[Brandt et al., 2015]
Nigeria	Agbami	8.20	[Brandt et al., 2015]
Nigeria	Bonga	6.44	[Duffy, 2015]
Nigeria	Erha	10.50	[Duffy, 2015]
Nigeria	Escravos	20.52	[Duffy, 2015]
Nigeria	Pennington Chevron	21.69	[Duffy, 2015]
Nigeria	Qua Iboe	15.25	[Duffy, 2015]
Denmark	North Sea Dansk	2.48	[COWI et al., 2014]
Norway	Norway North Sea Skarv	3.28	[Tormodsgard, 2015]
Russia	Sokol	10.51	[Duffy, 2015]
Canada	Seal Heavy	9.27	[Duffy, 2015]
Canada	Smiley-Coleville	9.27	[Duffy, 2015]
Canada	Suncor Synthetic A (SCO)	24.16	[Duffy, 2015]
Canada	Syncrude Synthetic (SCO)	21.44	[Duffy, 2015]
Kazakhstan	Tengiz	4.44	[Brandt et al., 2015]
U.S.	Thunderhorse	4.92	[Brandt et al., 2015]
UAE	Murban	9.92	[Duffy, 2015]
Canada	Wabasca	6.79	[Duffy, 2015]
Canada	Western Canada Blend	4.01	[Duffy, 2015]
Canada	Western Canada Select	19.31	[Duffy, 2015]

***Table A.38**: Mean values and 95% confidence interval results for crude oil extraction greenhouse gas (GHG) emissions.*

Fs%	GHGs[a] (g CO2e/MJ crude)
Ultra-low-sulfur diesel (ULSD)	
0.0015	12.0 [9.8, 14.1]
Marine gas oil (MGO)	
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 (MDO)	
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 (HFO)	
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 values and 95% confidence intervals constructed using bootstrap analysis methods described in [Orloff and Bloom, 2014].

Table A.39: *Exhaust emission factors for long-lived climate forcers (LLCFs) and nitrogen oxides (NOx) by fuel type as given in [ICF International, 2009].*

Fuel type	Emission factor pollutants (g/kg fuel)			
	CO_2	CH_4	N_2O	NOx
HFO	3,183	0.03	0.16	52
MDO	3,183	0.02	0.15	52
MGO	3,183	0.02	0.15	52

Table A.40: *Global warming potentials (GWP) used in the vessel exhaust climate forcing analysis (g CO2e g pollutant^{-1}).*

GWP	CO_2[a]	CH_4[a]	N_2O[a]	NOx[b,c,d,e]	SO_2[b,d,f]	OC[b,d,g]	BC[b,d,h]
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]Values include carbon-climate feedback; values given in [Myhre et al., 2013].
[b]Mean values and 95% confidence intervals constructed using bootstrap analysis methods described in [Orloff and Bloom, 2014].
[c]Given as NO_2.
[d]Direct effects (aerosol-radiation interaction)
[e]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], [Fuglestvedt et al., 2008] as given in [Fuglestvedt et al., 2010], and four regions [Collins et al., 2013].
[f]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]
[g]Mean global values (n=3) taken from [Bond et al., 2011], four regions [Collins et al., 2013], and [Fuglestvedt et al., 2010].
[h]Mean global values (n=5) taken 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 A.41: *Historical fuel sulfur levels of marine fuels used by ocean going vessels operating in the high sea over time (1995-2015).*

Year	HFO	MDO	MGO	Weighted Average Distillates	Source
1995	2.90	1.5	1.00	1.3	[Smith et al., 2011]
1996	2.90	1.5	1.00	1.3	[Smith et al., 2011]
1997	2.90	1.5	1.00	1.3	[Smith et al., 2011]
1998	2.90	1.5	1.00	1.3	[Smith et al., 2011]
1999	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2000	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2001	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2002	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2003	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2004	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2005	2.90	1.5	1.00	1.3	[Smith et al., 2011]
2006	2.86	1.5	1.00	1.3	[Mestl et al., 2013][a]
2007	2.72	1.1	0.35	0.35	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2008	2.84	1.1	0.35	0.34	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2009	2.82	1.2	0.35	0.37	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2010	2.83	1.2	0.35	0.38	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2011	2.84	1.3	0.17	0.43	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2012	2.77	1.2	0.11	0.43	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2013	2.70	1.3	0.07	0.17	[Mestl et al., 2013; EIA, 2017a; EIA, 2017b][a,b,c]
2014	2.40	1.3	0.07	0.14	[ABS, 2015; EIA, 2017b; EIA, 2017a][a,b,c]
2015	2.40	1.3	0.07	0.16	[Platts Bunkerworld, 2016; EIA, 2017b; EIA, 2017a][a]

[a]Global averages assumed for fuel sulfur levels of heavy fuel oil (HFO).
[b]Fuel sulfur regulations begin to affect non-road diesel in 2007. We assume fuel sulfur levels of distillates follow distillate sales trends in the U.S. For marine diesel oil (MDO), we used U.S. commercial sales data for U.S. distillate No. 4. Because MDO is a blend of marine gas oil and residual oil, we weighted this by low, medium, and high sulfur residual oil finished products statistics.
[c]For marine gas oil (MGO), we used U.S. commercial sales data for U.S. fuel oil No. 2.

Table A.42: *Historical fuel sulfur levels of marine fuels used by vessels operating in the U.S. EEZ over time (1995-2015) [Geagla et al., 2015; ICCT and DieselNet, 2016].*

Year	HFO[a,b]	MDO[a,b]	MGO[a,c]
1995	1.50	1.50	1.00
1996	1.50	1.50	1.00
1997	1.50	1.50	1.00
1998	1.50	1.50	1.00
1999	1.50	1.50	1.00
2000	1.50	1.50	1.00
2001	1.50	1.50	1.00
2002	1.50	1.50	1.00
2003	1.50	1.50	1.00
2004	1.50	1.50	1.00
2005	1.50	1.50	1.00
2006	1.50	1.50	1.00
2007	1.50	1.50	0.05
2008	1.50	1.50	0.05
2009	1.50	1.50	0.05
2010	1.00	1.00	0.05
2011	1.00	1.00	0.05
2012	1.00	1.00	0.05
2013	1.00	1.00	0.0015
2014	1.00	1.00	0.0015
2015	0.10	0.10	0.0015

[a]The maximum allowable fuel sulfur levels were used in our estimates.
[b]Heavy fuel oil (HFO) and Marine diesel oil (MDO) values applied to vessels with category 3 engines.
[c]Marine gas oil (MGO) values applied to vessels with category 1 and 2 engines.

Table A.43: *Weighting factors used to construct the mean net total fuel-cycle calculations of ocean going vessels using heavy fuel oil in high seas fishing territories over time.*

Year	f^{FQ}, 3.5%	f^{FQ} 2.6%	f^{FQ} 0.5%
1995	0.33	0.67	
1996	0.33	0.67	
1997	0.33	0.67	
1998	0.33	0.67	
1999	0.33	0.67	
2000	0.33	0.67	
2001	0.33	0.67	
2002	0.33	0.67	
2003	0.33	0.67	
2004	0.33	0.67	
2005	0.33	0.67	
2006	0.29	0.71	
2007	0.13	0.87	
2008	0.27	0.73	
2009	0.24	0.76	
2010	0.25	0.75	
2011	0.27	0.73	
2012	0.19	0.81	
2013	0.11	0.89	
2014		0.905	0.085
2015		0.905	0.085

Table A.44: *Weighting factors used to construct the mean net total fuel-cycle climate forcing calculations of marine vessels using distillates in the high seas over time.*

Year	f^{FQ} 1.5%[a]	f^{FQ} 0.75%[a]	f^{FQ} 0.55%[a]	f^{FQ} 0.35%[b]	f^{FQ} 0.1%[c]	f^{FQ} 0.05%[d]	f^{FQ} 0.0015%[e]
1995	0.73	0.27					
1996	0.73	0.27					
1997	0.73	0.27					
1998	0.73	0.27					
1999	0.73	0.27					
2000	0.73	0.27					
2001	0.73	0.27					
2002	0.73	0.27					
2003	0.73	0.27					
2004	0.73	0.27					
2005	0.73	0.27					
2006	0.73	0.27					
2007	0.05	0.03	0.01	0.63	0.15	0.13	
2008	0.04	0.02	0.01	0.65	0.09	0.18	
2009	0.06	0.03	0.01	0.65	0.10	0.15	
2010	0.07	0.02	0.01	0.71	0.05	0.14	
2011	0.09	0.02	0.02	0.76	0.04	0.08	
2012	0.09	0.03	0.01	0.74	0.02	0.10	
2013	0.04	0.01	0.00	0.28	0.00	0.01	0.66
2014	0.02	0.01	0.00	0.29	0.00	0.00	0.67
2015	0.04	0.01	0.01	0.27	0.00	0.00	0.68

[a]Fuel sulfur regulations begin to affect non-road diesel in 2007. We assume fuel sulfur levels of distillates follow distillate sales trends in the U.S. For marine diesel oil (MDO), we used U.S. commercial sales data for U.S. distillate No. 4. Because MDO is a blend of marine gas oil and residual oil, we weighted this by low, medium, and high sulfur residual oil finished products statistics.
[b]For marine gas oil (MGO) with fuel sulfur level 0.35%, we used U.S. commercial sales data for U.S. fuel oil No. 2.
[c]For marine gas oil (MGO) with fuel sulfur level 0.1%, we used U.S. commercial sales data for U.S. high sulfur diesel.
[d]For marine gas oil (MGO) with fuel sulfur level 0.05%, we used U.S. commercial sales data for low sulfur diesel.
eFor ultra-low sulfur diesel with fuel sulfur level 0.0015%, we used U.S. commercial sales data for ultra-low sulfur diesel.

Table A.45: *Weighting factors used to construct the mean net total fuel-cycle of ocean going marine vessels using low sulfur heavy fuel oil in the U.S. exclusive economic zone over time.*

Year	f^{FQ} 1.5%	f^{FQ} 1%	f^{FQ} 0.1%
2000	1		
2001	1		
2002	1		
2003	1		
2004	1		
2005	1		
2006	1		
2007	1		
2008	1		
2009	1		
2010		1	
2011		1	
2012		1	
2013		1	
2014		1	
2015			1

Table A.46: *Weighting factors used to construct the mean net total fuel-cycle climate forcing calculations of marine vessels using distillates in the U.S. exclusive economic zone over time.*

Year	f^{FQ} 1%	f^{FQ} 0.05%	f^{FQ} 0.0015%
2000	1		
2001	1		
2002	1		
2003	1		
2004	1		
2005	1		
2006	1		
2007		1	
2008		1	
2009		1	
2010		1	
2011		1	
2012		1	
2013			1
2014			1
2015			1

Table A.47: *Mean and 95% confidence interval greenhouse gas (GHG) emissions of selected farmed protein sources (100-y time horizon).*

Protein Source	GHGs[a] (kg CO_2e 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 and 95% confidence intervals constructed using bootstrap analysis methods as described in [Orloff and Bloom, 2014].
[b]Mean values (n=57) from [Clune et al., 2017]. The mean values include a wide variety of legume types and farming practices (organic, conventional, irrigated, non-irrigated, etc.). We normalized to a unit protein using a mean value of 0.25, based on the protein contents of chickpeas (0.24), lentils (0.26), cowpeas (0.25) and green peas (0.25) on a dry basis as given in [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]. The mean values include a variety of farming practices and life cycle boundaries (consequential and attributional). We used the mean protein content of tofu on a dry basis for four different varieties and two different locations, 0.52, as given in [Min et al., 2005].
[d]Mean values (n=20) from: (n=19) [Clune et al., 2017], (n=1) [Ziegler et al., 2013]. The mean values include a variety of different 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 the 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]. The 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) from [Clune et al., 2017]. The mean values include a variety of different 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]. The 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. The mean values include a variety of aquaculture practices and feed compositions. The 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) from [Clune et al., 2017]. The mean values include a wide variety of different animal husbandry methods (culled dairy cattle, rangeland beef, etc.) with different system boundaries (consequential and attributional).
[i]We normalized to a unit protein by dividing the GHG emissions per retail yield by the ratio of protein to retail yield, 0.20, as given in [Nijdam et al., 2012].

Table A.48: *Fractional allocation of greenhouse gas emissions by farm activity for chicken, pork, and beef from [Steinfeld et al., 2006].*

Activity	Chicken	Pork	Beef
Crop agriculture	0.44	0.38	0.04
Crop processing and transport	0.10	0.23	0.01
Enteric fermentation		0.04	0.60
Manure management	0.29	0.24	0.30
On-farm fossil fuel	0.18	0.10	0.06

Table A.49: *Fractional allocation of greenhouse gas emissions by farm activity for farmed salmon and farmed prawns.*

Activity	Salmon[a]	Prawns[b]
Crop agriculture	0.29	0.18
Crop processing and crop transportation	0.16	0.01
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
On-farm fossil fuel	0.04	0.26
"Other"		0.17

[a]Farm activity fractions from [Pelletier and Tyedmers, 2007; Pelletier et al., 2009].
[b]Farm activity fractions from [Cao et al., 2011].

Table A.50: *Fractional allocation of greenhouse gas emissions by farm activity for legumes and tofu from [Blonk et al., 2008].*

Activity	Legumes	Tofu
Crop agriculture	0.60	0.37
Crop processing and crop transportation	0.40	0.63

Table A.51: *Fractional allocation of livestock and crop agriculture farm activities to individual greenhouse gases (CO2, CH4, and N2O) from [Steinfeld et al., 2006].*

Source	CO_2	CH_4	N_2O
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

Table A.52: *Fractional allocation of aquaculture farm activities to individual greenhouse gases (CO_2, CH_4, and N_2O) from [Pelletier and Tyedmers, 2007; Pelletier et al., 2009].*

Source	CO_2	CH_4	N_2O
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

Table A.53: *Vessel characteristics of the Eastern Bering Sea catcher/processor pelagic trawler fleet.*

`Vessel name	Length (m)	Beam length (m)	Gross Tons	Power (kW)	Hull Type	Refrigeration
ALASKA OCEAN	115	18.3	4555	4661	Steel	Y
AMERICAN DYNASTY	83	16.5	5111	4847	Steel	Y
AMERICAN ENTERPRISE	64	14.3	1537	2237	Steel	Y
AMERICAN TRIUMPH	87	16.5	5015	6085	Steel	
ARCTIC FJORD	84	15.1	3326	4519	Steel	Y
ARCTIC STORM	102	14.8	4068	3729	Steel	Y
ENDURANCE	85	18.0	2117	3952	Steel	Y
HIGHLAND LIGHT	82	12.8	2417	4288	Steel	Y
ISLAND ENTERPRISE	93	13.7	2766	3579	Steel	Y
KATIE ANN	90	13.5	1593	3281	Steel	Y
KODIAK ENTERPRISE	80	13.4	1584	4474	Steel	Y
NORTHERN EAGLE	104	15.8	5190	4922	Steel	Y
NORTHERN GLACIER	61	13.4	1109	2237	Steel	Y
NORTHERN HAWK	104	15.8	5190	6562	Steel	Y
NORTHERN JAEGER	102	15.5	3732	5369	Steel	Y
OCEAN PEACE	61	15.2	1557	2051	Steel	Y
OCEAN ROVER	78	16.5	4345	4474	Steel	Y
PACIFIC GLACIER	84	15.2	3308	4922	Steel	Y
SEATTLE ENTERPRISE	82	13.2	1519	2908	Steel	Y
STARBOUND	91	14.6	2266	3729	Steel	Y
U.S. ENTERPRISE	68	12.8	1319	2908	Steel	Y

Table A.54: *Commercial marine compression ignition engine categories taken from [ICF International, 2009].*

Category	Vessel type	Power Rating (kW)	n Vessels
1	Small harbor craft	<1,000	
2	Small ocean going propulsion	1,000 > 3,000	5
3	Ocean going propulsion	> 3,000	16
Unknown			0

Table A.55*: Mean (and 95% confidence interval) of fuel consumption of the Eastern Bering Sea catcher/processor pelagic trawl fleet [Fissel et al., 2016].*

Year	n Vessels	Fuel consumption (liters)
2012	14	6.19 (± 0.26) x 10^7
2013	15	6.65 (± 0.47) x 10^7
2014	16	8.45 (± 0.60) x 10^7
2015	14	8.00 (± 0.50) x 10^7

Table A.56: Mass and materials used in the manufacture of fishing gears obtained from the literature.

Gear type	Gear material	Amount (kg / ton)	Study
Longline	Steel	0.09	*[Fulton, 2010]*
	Nylon	1.87	
Pelagic trawl	Steel	0.006	
	Nylon	0.008	
	Lead	0.052	
	Polyethylene	0.008	
Purse seine	Nylon	5.17	*[Laso et al., 2018]*
	Lead	5.14	
	Ethylene vinyl acetate (EVA)	2.13	
	Poly-steel	0.46	
	Maintenance nylon	2.33	
	Maintenance lead	2.31	
	Maintenance ethylene vinyl acetate (EVA)	0.96	
	Maintenance polysteel	0.21	
Auto-line	Steel	0.97	*[Svanes et al., 2011]*
	Polyester	0.65	
	Poly-steel	0.78	
	Polypropylene	0.52	

Table A.57: *Annual catch of pollock and bycatch at the vessel level for the Eastern Bering Sea catcher/processor pelagic trawl fleet. Annual catch (2012-2015) data obtained from the Pollock Conservation Cooperative and High Sea Catcher's Cooperative Annual Reports (https://alaskafisheries.noaa.gov/sites/default/files/reports/pcchscc15.pdf).*

Vessel Name	Pollock 2012 (mt)	Bycatch 2012 (mt)	Pollock 2013 (mt)	Bycatch 2013 (mt)	Pollock 2014 (mt)	Bycatch 2014 (mt)	Pollock 2015 (mt)	Bycatch 2015 (mt)
Alaska Ocean	35,300	1,748	41,835	1,853	39,112	1,037	41,780	1,076
American Dynasty	35,685	2,588	38,547	2,793	39,029	2,032	41,572	1,487
American Triumph	36,783	3,056	38,275	3,238	38,815	2,958	39,336	905
Arctic Fjord	25,746	870	34,034	753	27,690	655	28,448	449
Arctic Storm	28,903	5,051	11,807	2,880	29,604	3,907	30,196	1,139
Island Enterprise	23,490	941	23,666	795	25,323	465	27,600	328
Katie Ann	573	5,625	1,242	15,898	1,346	9,525	751	3,720
Kodiak Enterprise	20,451	1,568	27,239	740	19,695	1,369	24,626	480
Northern Eagle	37,912	2,673	43,515	4,034	41,940	2,615	39,723	1,625
Northern Glacier	698	10,561	489	6,834	700	8,420	667	6,352
Northern Hawk	20,823	978	22,008	647	22,015	317	22,352	352
Northern Jaeger	37,139	3,537	38,389	3,597	36,852	2,972	38,157	1,065
Ocean Rover	38,148	3,014	34,126	3,276	38,325	2,621	40,667	1,789
Pacific Glacier	30,931	993	29,623	752	29,849	477	32,761	428
Seattle Enterprise	28,946	1,834	30,119	760	30,358	1,453	25,809	377
Starbound	23,896	1,063	25,839	893	25,520	840	25,006	605
TOTALS	425,424	46,101	440,753	49,741	446,173	41,665	459,451	22,177

Table A.58: *Annual production of pollock products produced on-board the catcher/processor pelagic trawler vessels. Annual production (2011-2015) data in 1000 metric tons [Fissel et al., 2016].*

Year	Whole fish	Headed & Gutted	Roe	Deep-skin fillets	Other fillets	Surimi	Minced Fish	Fishmeal	Other products	All products
2011	0.11	38.83	11.66	32.25	58.32	70.8	23.49	39.11	20.18	294.75
2012	0.24	25.54	9.3	36.84	47.55	77.93	25.06	21.08	10.57	254.11
2013	0.16	37.28	8.37	36.83	59.63	80.85	23.47	20.98	12.21	279.78
2014	0.31	34.77	11.71	32.68	63.68	87.81	19.98	23.25	13.57	287.76
2015	1.11	25.38	12.01	34.56	57.44	95.94	19.71	26.45	12.6	285.2

Table A.59: *Annual disposition of frozen Alaskan pollock fillet blocks to top three markets. The annual (2011-2015) disposition is given in kilograms.*

Year	Germany	United States	Netherlands
2011	28,511,682	28,676,160	17,202,871
2012	21,505,865	38,715,772	12,419,555
2013	37,765,189	31,905,158	14,349,376
2014	44,699,342	24,098,998	13,612,406
2015	40,818,165	23,536,170	13,986,859

Table A.60: *Annual disposition of frozen Alaskan pollock surimi blocks to top three markets. The annual (2011-2015) disposition is given in kilograms.*

Year	Japan	South Korea	United States
2011	25,806,775	19,864,183	7,511,293
2012	33,527,091	22,293,154	8,040,964
2013	28,152,864	30,731,582	4,687,660
2014	36,844,575	29,135,274	11,417,914
2015	41,817,290	30,869,382	8,292,269