RESEARCH ARTICLE

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

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Sustainability is a common goal and catchphrase used in conjunction with seafood, but the metrics used to determine the level of sustainability are poorly defined. Although the conservation statuses of target or nontarget fish stocks associated with fisheries have been scrutinized, the relative climate impacts of different fisheries are often overlooked. Although an increasing body of research seeks to understand and mitigate the climate forcing associated with different fisheries, little effort has sought to integrate these disparate disciplines to examine the synergies and trade-offs between conservation efforts and efforts to reduce climate impacts. We quantified the climate forcing per unit of fish protein associated with several different U.S. tuna fishing fleets, among the most important capture fisheries by both volume and value. We found that skipjack tuna caught by purse seine, a gear type that is often associated with relatively high bycatch of nontarget species, results in lower climate forcing than all other sources of proteins examined with the exception of plants. Conversely, skipjack tuna caught by trolling, a gear type that is often associated with relatively low bycatch of nontarget species, generates higher climate forcing than most other protein sources with the exception of beef. Because there is a range of selectivity and climate forcing impacts associated with fishing gears, examining the trade-offs associated with bycatch and climate forcing provides an opportunity for broadening the discourse about the sustainability of seafood. A central goal of more sustainable seafood practices is to minimize environmental impacts, thus mitigation efforts—whether they target conservation, habitat preservation, or climate impacts—should consider the unintended consequences on fisheries conservation.

Keywords: Climate change, Sustainable fisheries, Bycatch, Skipjack

1. Introduction

Explosive growth in sustainable seafood is driven by consumer demand and policy (Del Giudice et al., 2018). This trend is partially reflected in seafood markets, as some major retailers have committed to source seafood from only certified sustainable fisheries (Sampson et al., 2015). Key sustainability issues have typically centered on the status of targeted fish stocks, the impact of a fishery on the ecosystem (including bycatch), and the performance of the fishery management system (Beddington et al., 2007; Smith et al., 2010; Costello et al., 2016). Fisheries have fully utilized 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). Ecosystems are affected not only by the extraction of target species but also by the unintended impacts on nontarget species or bycatch (Gilman, 2011). In particular, there are often concerns related to protected species of marine mammals, sea turtles, sharks, sea birds, and juvenile tuna (Oliver et al., 2015; Werner et al., 2015; Gilman et al., 2016; Bayless et al., 2017; Phillips et al., 2017; Swimmer et al., 2017).

These conservation challenges have led to a fundamental shift toward more sustainable fishing practices. For example, gear modifications (e.g., bycatch excluder devices, streamer lines, circle hooks), time/area closures, quotas, discard bans, and numerous other methods have sought to reduce the ecological impacts of bycatch (O'Keefe et al., 2014; Hamilton and Baker, 2019). Despite extensive efforts by industry to reduce the impacts from bycatch, there will always be some unintended catches. The trade-offs inherent in these catches are illustrated across different gear types. More selective fishing gears such as pole-and-line and trolling gears typically have limited bycatch but lower catch rates (Miller et al., 2017). Meanwhile, less selective gears such as longlines and purse seines are capable of catching more fish at a time, which is often also associated with a greater

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bycatch risk (Watson et al., 2009; Gilman, 2011; Watson and Bigelow, 2014).

Several organizations certify the sustainability of fisheries, including the Marine Stewardship Council (MSC) and Friends of the Sea (Gutiérrez et al., 2012). The number of fisheries certified by the MSC grew by nearly 170% in recent years (from 17 certified fisheries in 2006 to 361 certified fisheries in 2018; MSC, 2017, 2019). The MSC provides fisheries that use sustainable fishing practices with an eco-label certificate while also working to influence actors in the seafood supply chain (e.g., brands, restaurants, and retailers) to supply certified sustainable seafood. The MSC criteria include sustainability of target fish stocks, minimizing environmental impact, and effectiveness of fisheries management. The MSC defines the minimization of environmental impact as the maintenance of the structure, productivity, function, and diversity of the ecosystem on which the fishery depends (MSC, 2020a). Decades of empirical research and management efforts have sought to improve the sustainability of seafood and fisheries globally through conservation efforts that are largely in line with the MSC (or other eco-label) sustainability goals.

Although the conservation benefits of sustainable fishing practices are well studied (Beddington et al., 2007; Smith et al., 2010; Costello et al., 2016), the implications of such practices for climate change are not (Iles, 2007; Madin and Macreadie, 2015; Ziegler et al., 2016; Frazão Santos et al., 2020). This may partially be a reflection of the existing legal framework governing fisheries management. For example, although the U.S. Magnuson-Stevens Fishery Conservation and Management Act addresses the effects of fishing activity on target stock conservation, allocation of fishing rights, costs, benefits, efficiency, bycatch, communities, and safety of life at sea (MSRA, 2006), climate change impacts are not an explicit consideration. Even amid an increasing adoption of ecosystem-based fisheries management, "ecosystems" have scarcely considered or even mentioned the impacts of fishing on the climate, despite analyzing at length the impacts of climate change on fishing (e.g., Holsman et al., 2019).

The disparate treatment of sustainability dimensions (e.g., climate impact and conservation) is also reflected in carbon footprint studies. Although the carbon footprints of different fisheries have been evaluated (Thrane et al., 2009; Guttormsdóttir, 2009; Svanes et al., 2011; Buchspies et al., 2011; Vázquez-Rowe et al., 2013; Ziegler et al., 2013, 2016; McKuin et al., 2019), the climate impact of adopting specific conservation practices (e.g., more selective fishing gears) has not been considered.

The marine fuels used to power fishing vessels over large distances in pursuit of catch also drive the broader sustainability of seafood. Some vessels venture beyond sovereign waters to fish in the high seas where Sala et al. (2018) demonstrated that more than half of fishing may not be profitable without fuel subsidies. Additionally, a number of studies have explored whether closing the high seas could lead to conservation benefits; for instance, White and Costello (2014) concluded that closing the high seas to fishing may reduce ecological impacts while also improving the overall profitability of fishing. By contrast, Sala et al. (2018) found tuna fleets to be profitable in the high seas, suggesting possible lost profitability if the high seas were closed. It is an open question, however, whether closing the high seas to fishing would result in a climate benefit.

The breakdown between traditional metrics of seafood sustainability and the anthropogenic climate impacts of fishing on the planet has recently been recognized, however (Madin and Macreadie, 2015; Ziegler et al., 2016; Frazão Santos et al., 2020), and there has been a call for more integrative, or nexus, approaches that consider synergies and trade-offs within and across sectors when considering sustainable development goals (Ziegler et al., 2016; Liu et al., 2018). Such a nexus approach requires both a recognition of the problem and a body of empirical research that supports analysis of synergies and trade-offs.

U.S. tuna fisheries provide a unique opportunity for exploring synergies and trade-offs among conservation goals and climate impacts. The United States is one of the top tuna fishing nations (approximately 300,000 tonnes y^{-1}), and it is a major supplier of certified sustainable tuna, making up 15% of the tuna fisheries with either a "certified" or "in assessment" status with the MSC (MSC, 2020b). The fleets range in scale from small artisanal to large industrial, with a suite of gear types, fishing locations, jurisdictions, and operating parameters (**Table 1**).

To explore the synergies and trade-offs among conservation goals and climate impacts of seafood, we examined six U.S. tuna fleets (see Text S1 for details) that operate in different regions of the Pacific Ocean (**Figure 1**). Four fleets operate in both the high seas and exclusive economic zones (EEZs) of the United States and, in some cases, other sovereign nations (Figure 1A), and two fleets operate nearshore (Figure 1B and C). First, we sought to test whether a trade-off between climate and conservation goals may exist with fleets that employ more selective fishing gears (e.g., troll gear with relatively low rates of bycatch), but that may consume more fuel per quantity of fish caught than less selective gears (e.g., purse seine and longline gear with relatively high rates of bycatch). Second, we sought to test whether closing the high seas to fishing would result in a climate benefit in the form of reduced carbon emissions, due to reducing the average travel distances by fishing vessels. We combined fuel use consumption and fuel-specific global warming potentials (GWPs) of the selected fleets to provide a first estimate of the climate forcing of tuna protein caught by U.S. fleets using two different time horizons (20 and 100 years). To make comparisons between nearshore and distant water fishing, we separately calculated the climate forcing of tuna protein for fleets that operate both within the U.S. EEZ and on the high seas. We also estimated the bycatch ratio of the tuna catches to evaluate the trade-offs and synergies with the climate impact of these fleets. To provide context of our results for the broader food system, we compared the climate forcing of tuna protein to farmed sources (e.g., plant-based, fish, and livestock).

Table 1. Major gear types, descriptions, and operating parameters of the U.S. tuna fleet. DOI: https://doi.org/10.1525/elementa.2019.081.t1

Gear	Gear Description	Vessel Length	Average Catch Size per Fishing Event	Average Trip Duration	High Seas Activity?
Purse seine[a]	Large nets (>2 km long and 200 m deep)[b]	50–80 m[c]	20 tonnes	Up to several months[c]	Yes[c]
Longline[a]	Passive gear that consists of a mainline gangions, and thousands of baited hooks. The average length of a longline is 45 km[d]	16–30 m[e]	<1 tonne[f]	<1 month[f]	Yes[f]
Temperate troll/hook-and-line[g]	<20 hooked fishing lines of various lengths attached to the outriggers of fishing vessel[h]	6–32 m[i]	<1 tonne[j]	1–3 days[i, k]	Yes[l]
Tropical troll/hook-and-line[g]	<6 hooked fishing lines of various lengths attached to the outriggers of fishing vessel[h]	13–21 m[m]	<200 kg[n]	<1 day[o, k]	No[o]

[a] Less selective.

[b] NOAA Fisheries (2019a).

[c] Havice et al. (2019).

[d] NOAA Fisheries (2019b).

[e] NOAA Fisheries (2020).

[f] WPRFMC (2019).

[g] More selective because gears catch fish one-at-a-time.

[h] NOAA Fisheries (2019e).

[i] Matteson (2020).

[j] Based on average albacore weight: 33 kg.

[k] Larger vessels may take longer trips.

[l] Pacific Fishery Management Council (2019).

[m] WCPFC (2017).

[n] Based on average skipjack weight: 19 kg.

[o] NOAA Fisheries (2019c).

2. Methods

Our analysis of the fuel use intensity (FUI; l fuel tonnes catch^{-1}), climate forcing of tuna protein, and bycatch impacts included the compilation of many parameter values (**Figure 2**). Here, we have summarized the methods we used in our analysis for brevity. However, extended methods including text, tables, and figures are available in the Supplementary Materials.

2.1. Hypothesis testing

We considered several hypotheses related to the selectivity of fishing gears (less selective vs. more selective) and fishing territories (U.S. EEZ vs. high seas). First, we tested the hypothesis that the FUI and climate impact (kg CO_2e kg tuna protein^{-1}) of less selective gears (e.g., purse seine and longlines) are less than or equal to the FUI and climate impact of highly selective gears (e.g., troll and surface methods which include both troll and pole-and-line gears). Second, we tested the hypothesis

that the FUI, climate impact, and bycatch ratio (tonnes or individuals, tonnes tuna^{-1}) for activity within the U.S. EEZ are less than or equal to that on the high seas. We used an independent-sample, single-tailed, unequal varianc Student t-test to test a one-sided hypothesis using Microsoft Excel. As a robustness check on statistical assumptions of normality, Kolmogorov–Smirnov tests were also performed. Significance was based on P values < 0.05.

2.2. FUI of fishing gears

We estimated the FUI of four different fishing gears used by six U.S. tuna fleets (**Figure 1**, **Table 2**). We made separate estimates of the FUI with fishing effort and catch partitioned between the U.S. EEZ and the high seas for two fleets (Hawaii longline and North Pacific surface methods fleets). We used an activity-based approach to estimate the fuel consumption. This approach has been employed in shipping emission inventories (Endresen et al., 2003;
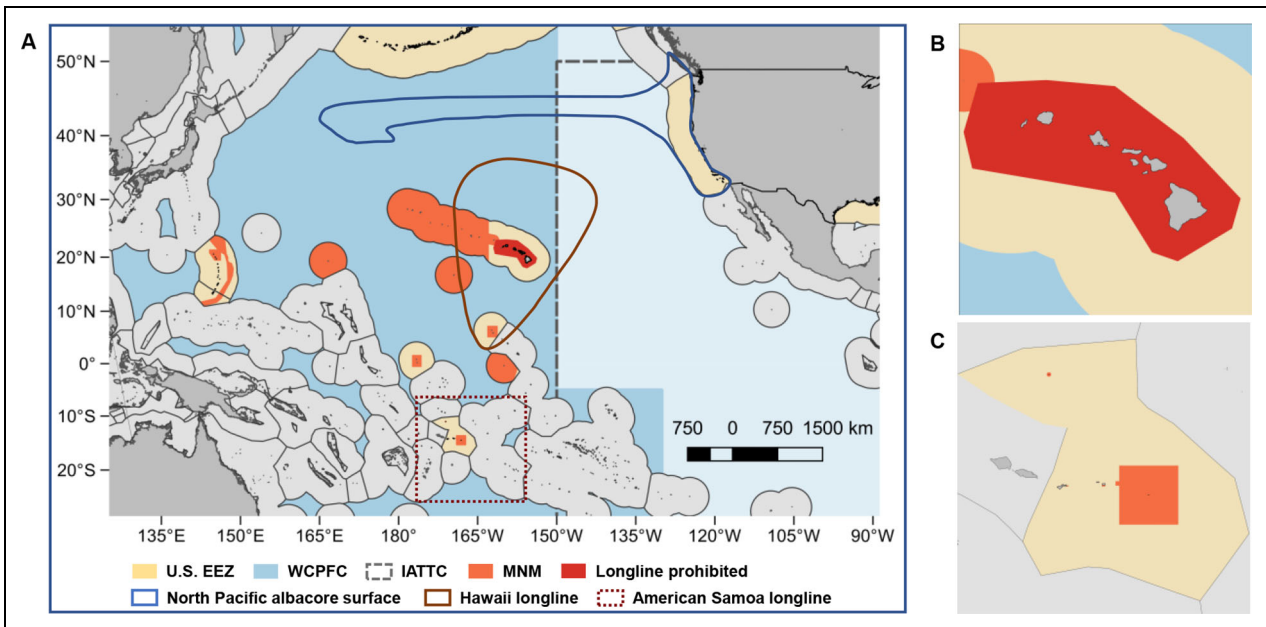
Figure 1. Map showing the spatial extent of the fishing areas that operate within the jurisdictions of regional fisheries management organizations. Regional fisheries management organizations include the Western and Central Pacific Fisheries Commission (WCPFC; blue shaded area) and the Inter-American Tropical Tuna Commission (lighter blue area bounded by gray dashed line). Restricted fishing areas include U.S. marine national monuments (MNMs; orange shaded area) and longline exclusion zone (red shaded area). Left panel (A): the U.S. purse seine fleet operates in the WCPFC convention area with the majority of landings in the exclusive economic zones (EEZs) of Micronesia, Polynesia, Melanesia, U.S. territories, and the high seas (Havice et al., 2019); the U.S. North Pacific albacore surface gear fleet operates in the EEZs of the United States and Canada, and on the high seas (dark blue outline; NOAA Fisheries, 2019e); the Hawaii longline fleet operates within the U.S. EEZ including the Hawaiian Islands (except the longline exclusion zone and the Papahānaumokuākea and Pacific Remote Islands MNMs), Johnson Atoll, and Palmyra Atoll and on the high seas (brown outline; NOAA Fisheries, 2019e); the American Samoa longline fleet operates within the EEZ of the U.S. (except the Rose Atoll MNM) and neighboring claimed maritime jurisdictions of other sovereign nations, and on the high seas (dashed burgundy outline; NOAA Fisheries, 2019e); top right panel (B): the Hawaii troll fleet operates within both state and federal waters of the Hawaiian Islands (NOAA Fisheries, 2017b; within the longline exclusion zone and the U.S. EEZ boundary of the Hawaiian Islands); Bottom right panel (C): the American Samoa troll fleet operates within both state and federal waters of the American Samoa (NOAA Fisheries, 2017a; U.S. EEZ boundary of the American Samoa except the Rose Atoll MNM). DOI: https://doi.org/10.1525/elementa.2019.081.f1

Eyring et al., 2005; Smith et al., 2015; Moreno-Gutiérrez et al., 2015), fishing vessel emission inventories (Coello et al., 2015), and a recent economic analysis of fishing vessels on the high seas (Sala et al., 2018). We used fishing effort (time spent fishing and searching for fish) to estimate the vessel activity time. Fishing effort has been previously used to estimate vessel activity and fishing fuel consumption (Tyedmers, 2001; Bastardie et al., 2010). Our activity-based methodology includes vessel registry data and fleet logbook data for fishing effort. Fishery catches were compiled from published landing reports and stock assessments (see Text S2 for details).

2.3. Total fuel-cycle climate forcing over time
Our climate forcing estimates include crude oil extraction, crude oil refining, and vessel exhaust phases of the fuel cycle over a span of 20 years (1996–2015). Our analysis includes multiple marine fuels (distillates and heavy fuel oil), fishing territories (U.S. EEZ and high seas), engine types (medium-speed diesel and high-speed diesel), and time horizons (20 and 100 years; see Text S3 for details).

2.4. Climate forcing of tuna protein over time
We estimated the protein- and species-specific climate forcing of tuna over time (1996–2015) by combining FUI, total fuel-cycle estimates (20- and 100-year time horizons), fishing vessel engine speeds and fuel types, and protein yields of tuna (see Text S4 for details). Following Tyedmers and Parker (2012), we calculated the protein yields as the product of the edible yield and the protein content. The edible yield of tuna is reported as 60%–62% of the total yield (Herpandi et al., 2011; Tyedmers and Parker, 2012; Garrido Gamarro et al., 2013; Dominy et al., 2014). The mean and standard deviation of the percentage of protein contents are 23.85 ($\pm$1.11, $n = 3$) for skipjack (Liu et al., 2014), 23.6 ($\pm$2.5, $n = 56$) for albacore (Rasmussen and Morrissey, 2007), 23.52 ($\pm$0.61, $n = 3$) for bigeye (Peng et al., 2013), and 23.72 ($\pm$0.16, $n = 3$) for yellowfin (Peng et al., 2013).

2.5. Bycatch impacts of tuna protein
We estimated the bycatch ratios of marine mammals and other species of concern (Table 2). We separately estimated the bycatch ratios of marine mammals by fishing
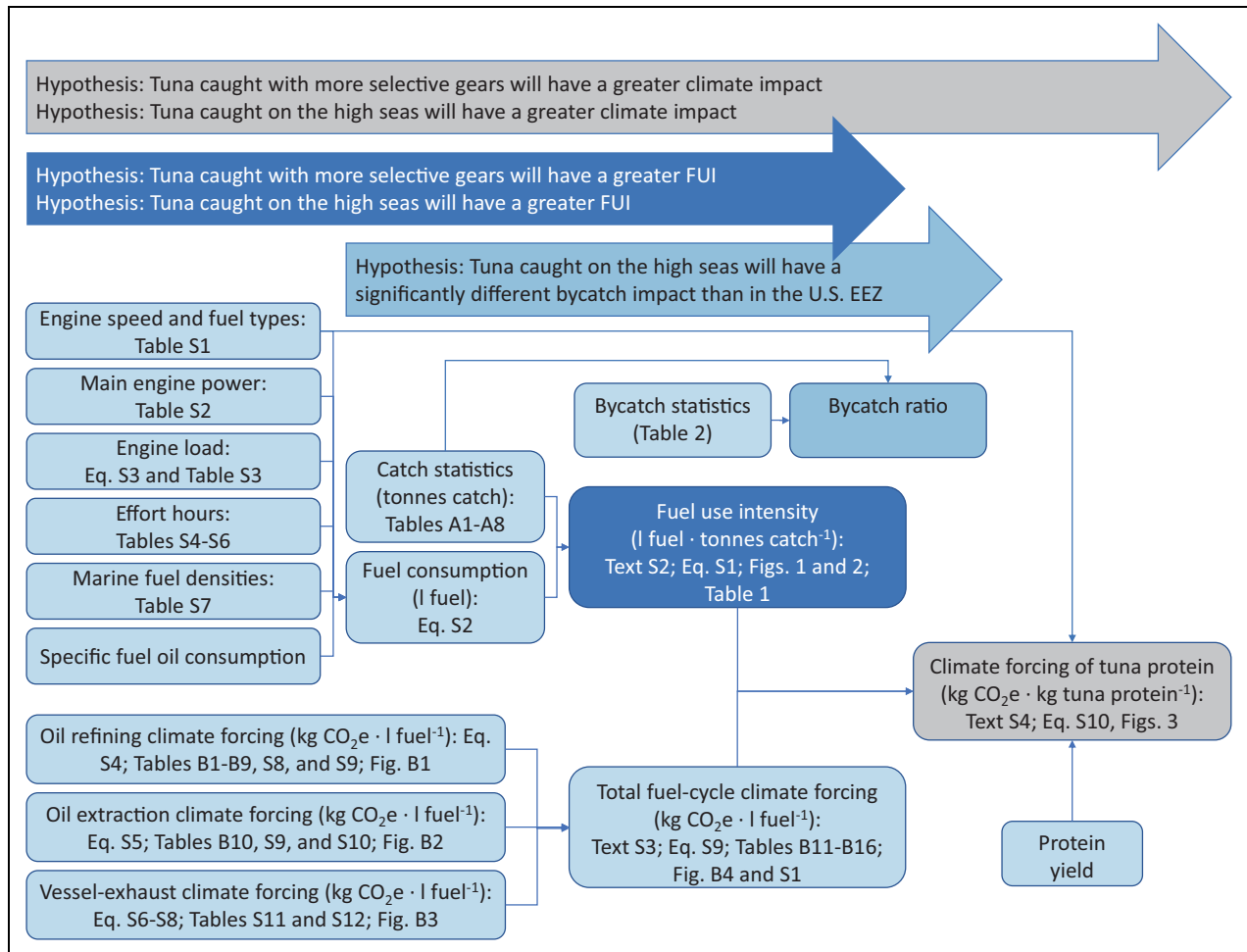
Figure 2. Overview of the study hypotheses and calculations of the fuel use intensity, climate forcing of tuna protein, and bycatch ratio. Study hypotheses related to gear selectivity and fishing territories are shown in arrows. The flowchart shows the inputs to the climate forcing of tuna protein which includes the fuel use intensity (FUI), total fuel-cycle climate forcing, and protein yield (product of edible yields and protein contents). DOI: https://doi.org/10.1525/elementa.2019.081.f2

territory (within and outside the U.S. EEZ) for the Hawaii longline fleet. Our non-mammal bycatch analysis is similar to Hornborg et al. (2013). However, instead of discards only, we also reported retained catches of each of our species of interest.

2.6. Comparison to farmed protein sources

We compared our climate forcing per unit tuna protein to the greenhouse gas emissions of other farmed protein sources including livestock (chicken, pork, and beef), farmed fish (salmon and prawns), and plant-based proteins (legumes and tofu) from a literature review (Blonk et al., 2008; Katajajuuri et al., 2008; Cao et al., 2011; Head et al., 2011; Ziegler et al., 2013; Farmery et al., 2015; McCarthy et al., 2015; Santos et al., 2015; Smetana et al., 2015; Teah et al., 2015; Clune et al., 2017). We normalized the greenhouse gas emissions per unit protein on 20- and 100-year time horizons (see Text S5 for details).

2.7. Construction of confidence intervals

We constructed 95% confidence intervals of the FUI, total fuel-cycle climate forcing, climate forcing of tuna protein, and farm-raised animal protein by calculating the standard error of the mean. We propagated the error for selected variables using the derivative method (Bevington and Robinson, 2003). We applied this method to the fuel consumption, total fuel-cycle climate forcing, and the climate forcing of tuna protein. For fuel consumption, we propagated the error for the main engine power, engine load factor, and fuel density variables. For the total fuel-cycle climate forcing, we propagated error for crude oil extraction emission factors, crude oil refining emission factors, the lower heating values, fuel densities, the emissions of black carbon, and the GWP of short-lived pollutant variables (e.g., sulfur oxides, nitrogen oxides, black carbon, and organic carbon). For the climate forcing of tuna protein, we propagated error for the FUI, the total fuel-cycle climate forcing, the edible yield, and the protein content.

3. Results
3.1. Fuel use intensity

We found wide variation in the FUI with respect to gear types and species (**Table 3**, **Figure 3**). Here, we focus on skipjack

Table 2. Selected bycatch species by gear, fleet, units for bycatch, and data sources. DOI: https://doi.org/10.1525/elementa.2019.081.t2

Fleet/Region	Gear	Bycatch	Units	Source
U.S. WCPFC-CA[a]	Purse seine[b]	Silky shark and striped marlin[c]	Tonnes	(Morison and McLoughlin, 2016[d]; NOAA Fisheries, 2015, 2016[e])
		Marine mammals, sea turtles, whale shark, and oceanic whitetip shark	Individuals	(Morison and McLoughlin, 2016[d]; NOAA Fisheries, 2015, 2016[e])
Hawaii and America Samoa	Longline	Silky shark and striped marlin	Tonnes	(NOAA Fisheries, 2018)
		Marine mammals, sea turtles, sea birds, albatrosses	Individuals	(NOAA Fisheries, 2018)
		Oceanic whitetip shark	Individuals	(NOAA Fisheries, 2019d)
Hawaii and America Samoa[f]	Troll	Striped marlin	Tonnes	(NOAA Fisheries, 2011, 2012, 2013, 2014, 2015, 2016)
North Pacific	Surface	Negligible		(Stern-Pirlot et al., 2018)

[a] Western and Central Pacific Fisheries Commission (WCPFC) conventional area (CA).

[b] Non-fish aggregating device associated sets.

[c] To report 2014–2015 silky shark bycatch in terms of tonnes, we calculated the mean weight per individual (31.2 kg) from and applied the mean weight per individual to the number of individuals reported annually to the WCPFC (Rice and Harley, 2013; NOAA Fisheries, 2015, 2016).

[d] Time period between 2010 and 2013.

[e] Time period between 2014 and 2015.

[f] Negligible bycatch reported.

and albacore because there is more than one fleet targeting these species, which allows a comparison across practices. The FUI of skipjack tuna caught by the American Samoa troll fleet using highly selective gears was significantly greater than the U.S. purse seine fleet (**Table 4**). The FUI of albacore tuna caught by the American Samoa longline fleet was significantly greater than the FUI of albacore tuna caught by the North Pacific surface methods fleet (**Table 4**).

We also compared the FUIs of two fleets (North Pacific surface methods and Hawaii longline) that operate inside versus outside the U.S. EEZ (**Figure 4**). The FUIs of the North Pacific surface methods fleets for activity outside the U.S. EEZ were significantly greater than fleet activity that takes place in the U.S. EEZ (**Table 4**). The FUI of the Hawaii deep-set longline for activity outside the U.S. EEZ, however, was not significantly different than the FUI for activity that takes place in the U.S. EEZ (**Table 4**).

3.2. Climate impact of fishing gears
We combined the FUIs and the total fuel-cycle climate forcing to estimate the climate forcing of tuna protein over time on 20- and 100-year time horizons. Here, we considered fleets targeting the same species and compared the climate forcing of those using highly selective gears to those using less selective gears (**Figure 5**). We found that the climate forcing of skipjack tuna protein caught by the American Samoa troll fleet (highly selective gear) was significantly greater than the U.S. purse seine fleet (less selective gear; **Table 4**). We also found that the climate forcing of albacore protein caught by the North

Pacific surface methods fleet (highly selective gears) was significantly greater than the American Samoa longline fleet (less selective gear; **Table 4**).

3.3. Climate impact of restricted high seas fishing
We compared the climate forcing of tuna protein for activity outside the U.S. EEZ to activity in the U.S. EEZ for two different fleets (Hawaii longline and North Pacific surface methods; **Figure 6**). With the exception of the Hawaii longline fleet, the climate forcing from fleets that operate on the high seas has a significantly greater forcing than the fleets that operate in the U.S. EEZ (**Table 4**).

3.4. Comparisons of climate forcing among protein sources
Here, we compared the mean (and 95% confidence interval) protein-specific climate forcing of tuna among the six different fleets. To better understand the sustainability of tuna in the larger scope of food systems, we also compared and ranked (in order of low to high) the climate forcing of tuna protein along with other sources of protein (**Figure 7**).

The mean climate forcing varies widely between the two fleets targeting skipjack on both time horizons (4.3 [$\pm$ 1.5] and 53 [$\pm$ 13] kg CO_2e kg tuna protein^{-1} on a 20-year time horizon; 5 [$\pm$ 0.7] and 48 [$\pm$ 11] kg CO_2e kg tuna protein^{-1} on a 100-year time horizon for the U.S. purse seine and American Samoa troll fleets, respectively). The climate forcing of skipjack caught with highly selective gears (troll) is as much as 12 times higher than the skipjack caught with the less selective gear (purse seine).

Table 3. Literature values of fuel use intensity of tuna and pelagics and comparisons to this study. DOI: https://doi.org/10.1525/elementa.2019.081.t3

Region/ocean	Primary target	Fuel use intensity (l fuel tonnes tuna^{-1})	Source
Purse seine			
Pacific	Albacore	323	(Parker and Tyedmers, 2015)
Pacific	Bigeye	471	(Parker and Tyedmers, 2015)
Pacific	Skipjack	349	(Parker and Tyedmers, 2015)
Pacific	Yellowfin	362	(Parker and Tyedmers, 2015)
Pacific	Skipjack/yellowfin	527	(Hospido et al., 2006)
Pacific	Tuna	412	(Wilson et al., 2009) [a]
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 ($\pm$ 57) [b]	This study, U.S. fleet
Pacific	Skipjack	266 ($\pm$ 47) [b, c]	This study, U.S. fleet
Troll			
	Large pelagics	1,612	(Parker and Tyedmers, 2015)
Atlantic	Albacore/skipjack	1,107	(Tyedmers and Parker, 2012)
Atlantic	Bluefin/albacore	1,136	(Basurko et al., 2013)
Pacific	Skipjack/yellowfin	3,896 ($\pm$ 590) [b, c]	This study, American Samoa
Pacific	Skipjack	2,354 ($\pm$ 357)	This study, American Samoa
Pacific	Albacore/bigeye/yellowfin/skipjack	2,246 ($\pm$ 888) [b, d]	This study, Hawaii
Pacific	Yellowfin	1,512 ($\pm$ 597)	This study, Hawaii
Pacific	Albacore	573 ($\pm$ 83)	This study, North Pacific
Pole-and-line			
Atlantic	Albacore	1,485	(Tyedmers and Parker, 2012)
Atlantic	Bluefin/albacore	1,080	(Basurko et al., 2013)
North America	Large pelagics	1,495	(Parker et al., 2015)
Longline			
Pacific	Albacore	1,135	(Tyedmers and Parker, 2012)
Pacific	Albacore	1,915	(Krampe, 2006) [a]
Pacific	Bluefin/bigeye	3,660	(Krampe, 2006) [a]
Pacific	Bigeye	2,024	(Gilman et al., 2014)
Pacific	Tuna	1,765	(Wilson and McCoy, 2009) [a]
Pacific	Albacore/bigeye/yellowfin/skipjack	1,124 ($\pm$ 230) [b, e]	This study, American Samoa
Pacific	Albacore	849 ($\pm$ 174)	This study, American Samoa
Pacific	Albacore/bigeye/yellowfin/skipjack	1,256 ($\pm$ 181) [b, f]	This study, Hawaii
Pacific	Bigeye	1,023 ($\pm$ 295)	This study, Hawaii

[a] As reported in Tyedmers and Parker (2012).

[b] Fuel use intensity estimate of tuna by mass allocation of tuna relative to all pelagic species.

[c] 5-year mean and 95% confidence interval of all pelagic species 4,747 ($\pm$ 719) l fuel tonnes tuna^{-1}.

[d] 5-year mean and 95% confidence interval of all pelagic species 4,372 ($\pm$ 1,728) l fuel tonnes tuna^{-1}.

[e] 5-year mean and 95% confidence interval of all pelagic species 1,184 ($\pm$ 242) l fuel tonnes tuna^{-1}.

[f] 5-year mean and 95% confidence interval of all pelagic species 1,726 ($\pm$ 245) l fuel tonnes tuna^{-1}.
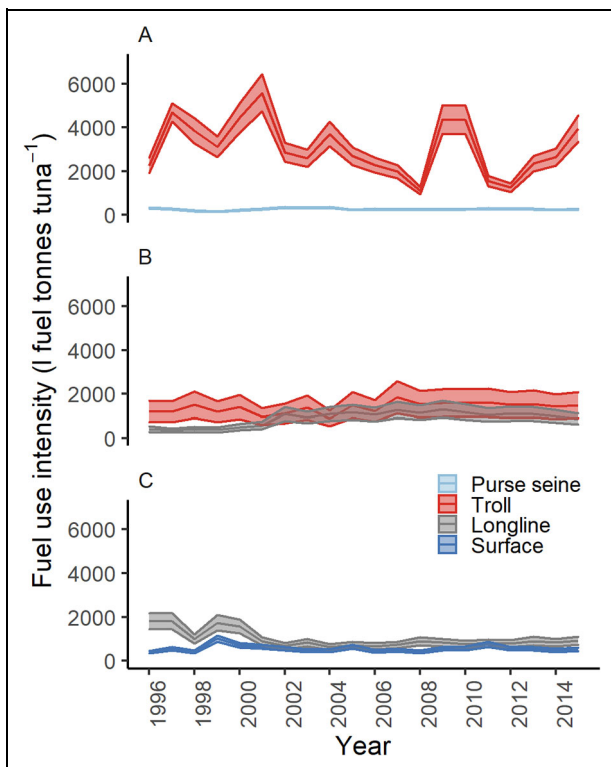
Figure 3. Fuel use intensity of selected U.S. tuna fleets. Top panel (A): Fleets targeting skipjack tuna including the American Samoa troll and the U.S. purse seine fleets. Middle panel (B): Hawaii fleets include troll targeting yellowfin tuna and longline targeting bigeye tuna. Bottom panel (C): Fleets targeting albacore tuna including the American Samoa longline and North Pacific surface methods fleets. Surface methods include troll and pole-and-line gears. Shaded regions represent the 95% confidence interval. DOI: https://doi.org/10.1525/elementa.2019.081.f3

For albacore, however, the mean climate forcing is modestly greater for the American Samoa longline fleet than the North Pacific surface methods fleet on both time horizons (15 [$\pm$ 3] and 18 [$\pm$ 4] kg CO_2e kg tuna protein^{-1} on a 20-year time horizon; 12 [$\pm$ 2] and 17 [$\pm$ 4] kg CO_2e kg tuna protein^{-1} on a 100-year time horizon for the North Pacific surface methods and American Samoa longline fleets, respectively). Meanwhile, the climate forcing is 24 ($\pm$ 8) and 22 ($\pm$ 7) kg CO_2e kg tuna protein^{-1} for bigeye caught by the Hawaii longline fleet and 33 ($\pm$ 14) and 28 ($\pm$ 11) kg CO_2e kg tuna protein^{-1} for yellowfin caught by the Hawaii troll fleet, on 20- and 100-year time horizons, respectively.

Compared to land-based protein sources, skipjack protein caught by the U.S. purse seine fleet has significantly lower climate forcing than most other protein sources with the exception of vegetable protein. Albacore (caught by both the American Samoa longline and North Pacific surface methods fleets) and bigeye tuna (caught by Hawaii longline fleet) protein have climate forcing similar to that of farmed salmon and chicken. In terms of medium–high forcing, yellowfin protein caught with troll gear has

a similar forcing to that of pork. Skipjack caught by the American Samoa troll fleet had a mean climate forcing greater than most other protein sources except beef.

3.5. Bycatch impact of fishing gears
Here, we compared the bycatch ratio of less selective gears (e.g., purse seine and longline) to more selective gears (e.g., troll and surface methods, which include both troll and pole-and-line gears).

With the exception of the Hawaii fleet, the bycatch of troll gears methods is negligible. The bycatch ratio of striped marlin for the Hawaii troll was the highest of the fleets we considered (**Figure 8A**). Although it has been reported that there are concerns related to the bycatch of striped marlin for the American Samoa fleet, the data reflect negligible catch of this species.

For North Pacific surface methods, the catch associated with this fleet is reported to be almost exclusively albacore with minor incidental catches of other tuna (skipjack, yellowfin, and bluefin), eastern Pacific bonito, yellowtail, and mahi mahi (Albacore Working Group, 2017). Thus, like the other highly selective gears considered in this study, the bycatch impact is negligible.

There were relatively high levels of bycatch associated with longlines compared with other fishing gears. We found the bycatch ratio of silky sharks, oceanic whitetip sharks, and sea turtles was highest for the American Samoa longline fleet compared to the other fisheries (Figure 8B, C, and G). In the case of the Hawaii deep-set longline fishery, there are concerns related to protected species interactions (mammals, sea turtles, sharks, and sea birds; Oliver et al., 2015; Werner et al., 2015; Gilman et al., 2016; Bayless et al., 2017; Swimmer et al., 2017). The bycatch ratios of seabirds (shearwaters and boobies), albatrosses, and marine mammals were the highest for the Hawaii deep-set longline fleet compared to the other fisheries (Figure 8E, F, and H).

In the case of the purse seine fleet, there are concerns related to the bycatch of sharks (Oliver et al., 2015) and juvenile tunas (Phillips et al., 2017). In particular, the number of interactions with whale sharks by the U.S. purse seine fleet stands out (Figure 8D) in comparison to the other fleets. From the available data, the fate of whale sharks after these interactions (Morison and McLoughlin, 2016) is unclear, and information on key biological processes is limited (Rice et al., 2015).

3.6. Bycatch impact of restricted high seas fishing
We estimated the bycatch ratio of marine mammals partitioned by fishing territory (within the U.S. EEZ and outside the U.S. EEZ) for the Hawaii longline fleet (Figure S2). We found that the bycatch ratio of marine mammals caught outside the U.S. EEZ was significantly less than the bycatch ratio of marine mammals caught within the U.S. EEZ (**Table 4**).

4. Discussion
This work highlights potential synergies and trade-offs between sustainable seafood practices and climate change. The conversation about sustainable seafood often

Table 4. Statistics for study hypotheses related to fishing gear selectivity and fishing territories. Mean, standard deviations, Kolmogorov–Smirnov statistics and results of student t-tests (independent-sample, single-tailed, and unequal variance) of the fuel use intensity (l fuel tonnes tuna^{-1}), climate forcing of tuna protein (kg CO_2e kg tuna protein^{-1}), and bycatch ratio (individuals per ton of tuna) by hypothesis and by fleet. DOI: https://doi.org/10.1525/elementa.2019.081.t4

Scenario	Fleet	Mean	Standard Deviation	K–S Stat[a]	Fleet	Mean	Standard Deviation	K–S Stat[a]	P Value[b]
Fuel use intensity									
Gear type[c]	U.S. purse seine	269	51	0.106	American Samoa troll	3084	1231	0.098	1.8E-09
Gear type[c]	American Samoa longline	992	395	0.272	North Pacific surface	561	146	0.165	6.0E-05
Fishing territory[d]	North Pacific surface[e]	611	150	0.120	North Pacific surface[f]	934	795	0.195	4.5E-02
Fishing territory[d]	Hawaii longline[e]	1201	180	0.101	Hawaii longline[f]	1085	130	0.170	6.8E-02
Climate impact of 20-year time horizon									
Gear type[c]	U.S. purse seine	3.0	1.1	0.210	American Samoa troll	46	23	0.178	5.7E-08
Gear type[c]	American Samoa longline	13	5	0.233	North Pacific surface	11	4	0.119	3.5E-02
Fishing territory[d]	North Pacific surface[e]	20	22	0.226	North Pacific surface[f]	11	3	0.078	4.9E-02
Fishing territory[d]	Hawaii longline[e]	26	3	0.189	Hawaii longline[f]	29	4	0.120	7.5E-02
Climate impact of 100-year time horizon									
Gear type[c]	U.S. purse seine	4.7	0.9	0.201	American Samoa troll	56	22	0.115	1.2E-09
Gear type[c]	American Samoa longline	18	6	0.203	North Pacific surface	11	3	0.112	4.6E-05
Fishing territory[d]	North Pacific surface[e]	29	28	0.201	North Pacific surface[f]	12	3	0.091	5.4E-03
Fishing territory[d]	Hawaii longline[e]	27	3	0.189	Hawaii longline[f]	26	4	0.133	7.8E-02
Bycatch ratio									
Fishing territory[g]	Hawaii longline[e]	6E-03	2E-03	0.153	Hawaii longline[f]	3E-03	3E-04	0.148	8.9E-03

[a] Kolmogorov–Smirnov (K–S) statistics (stat) used to confirm normal distributions. If critical value ($\alpha = .05$) is less than 0.294, 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 troll and surface methods—which includes both pole-and-line and troll gears) have a higher climate impact than less selective gears (including purse seine and longline).

[d] Fishing territory hypothesis: fleets operating in the U.S. EEZ may have a higher climate impact than fleets operating on the high seas.

[e] Fleet activity on the high seas.

[f] Fleet activity in the U.S. EEZ.

[g] Fishing territory hypothesis: fleets operating on the high seas may have a significantly different bycatch impact than fleets operating in the U.S. EEZ.

emphasizes target stocks and bycatch but rarely does it consider the complexities of climate forcing as well. We provide explicit examples that demonstrate that as gear selectivity increases, bycatch typically decreases but the climate forcing effects increase. This paradox highlights the importance of considering climate forcing when thinking about the intricacies of "sustainability."

4.1. Climate and bycatch impacts of tuna protein and implications for consumers

We hypothesized that more selective gears, with lower bycatch, would have greater climate impacts. This hypothesis was unsupported for the North Pacific surface methods fleet, with negligible bycatch and relatively low estimated climate impacts. However, each of the other
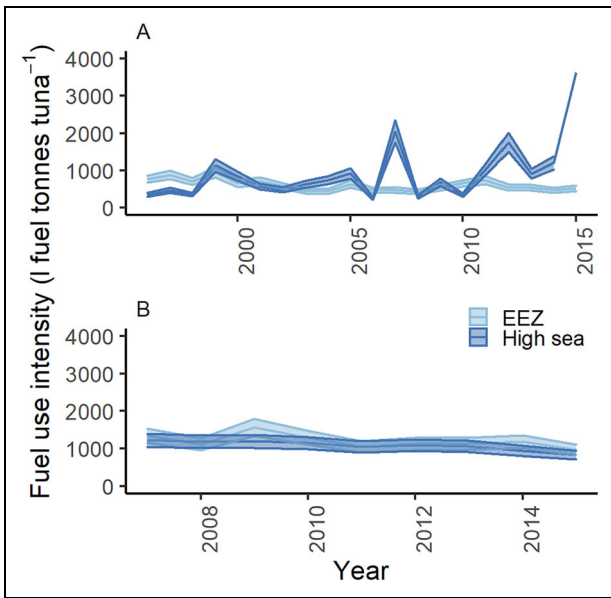
Figure 4. Fuel use intensity of selected tuna fleets between fishing territories. Comparison of fuel use intensity of fleet operations within the U.S. exclusive economic zone to fleet operations on the high seas. Top panel (A): North Pacific surface methods fleets. Surface methods include troll and pole-and-line gears. Bottom panel (B): Hawaii deep-set longline. Shaded regions represent the 95% confidence interval. DOI: https://doi.org/10.1525/elementa.2019.081.f4

fleets supported this hypothesis as expected, with generally lower bycatch for the troll fisheries (although striped marlin was notable exception in the Hawaii troll fleet; Figure 8A) and generally greater climate impacts.

These results can be used to inform consumers, businesses, and programs that provide seafood sustainability assessments (e.g., Monterey Bay Aquarium's Seafood Watch and MSC). For example, Seafood Watch produces guides with three tiered levels that include "best choice," "good alternatives," and "avoid" to help consumers make choices that reduce their impact on the environment. The guiding principles for their recommendations include ecosystem-based fisheries management, healthy fish stocks, avoidance of bycatch, and negligible interactions with threatened, endangered, or protected species (Monterey Bay Aquarium, 2020). Although they have developed a carbon footprint tool, they have yet to incorporate this information into their seafood recommendations. Currently, all of their "best choice" recommendations are sources of tuna caught with trolling lines or handlines and hand-operated pole-and-lines. Thus, these recommendations are encouraging the use of selective fishing gears over other more fuel-efficient gears whose climate forcing may be less, potentially leading to unintended consequences on global climate.

A valuable component of our study compared climate forcing across tuna fisheries and terrestrial protein sources. Our analysis of the climate forcing of tuna protein
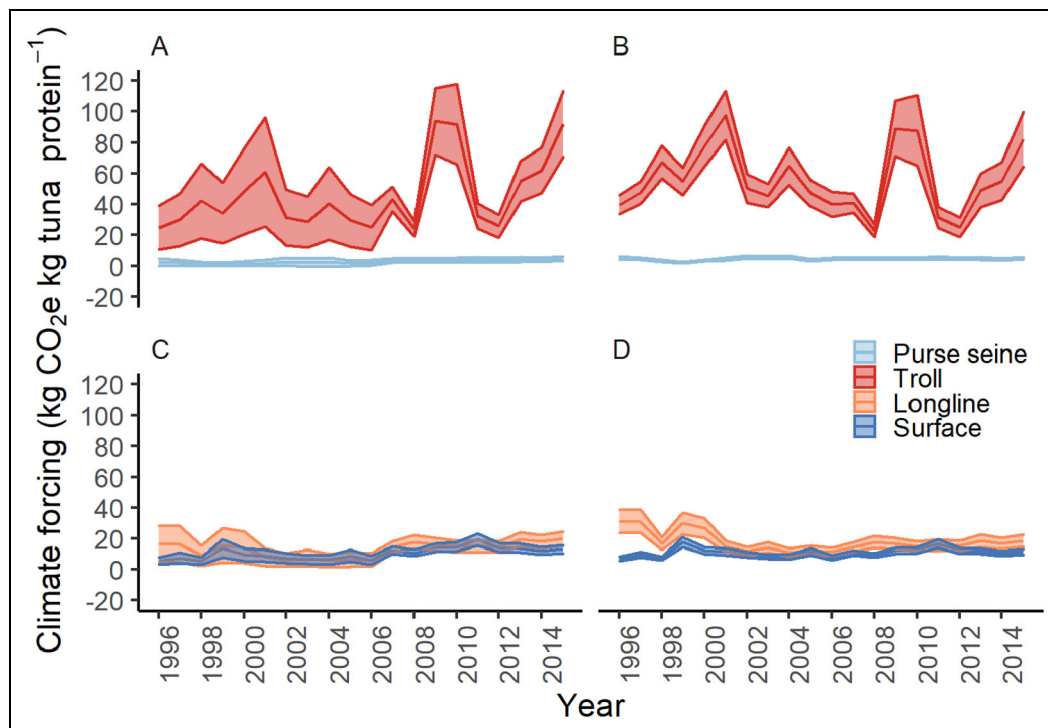

Figure 5. Climate forcing of tuna protein by species and fishing gear types. The fishing gear types include highly selective gears—troll, and surface methods that include both troll and pole-and-line gears—and less selective gears—purse seine and longline. Top panels (A and B): Skipjack caught by the American Samoa troll and the U.S. purse seine fleets. Bottom panels (C and D): Albacore caught by the American Samoa longline and the Northern Pacific surface methods fleets. Left panels (A and C): 20-year time horizon. Right panels (B and D): 100-year time horizon. Shaded regions represent the 95% confidence interval. DOI: https://doi.org/10.1525/elementa.2019.081.f5
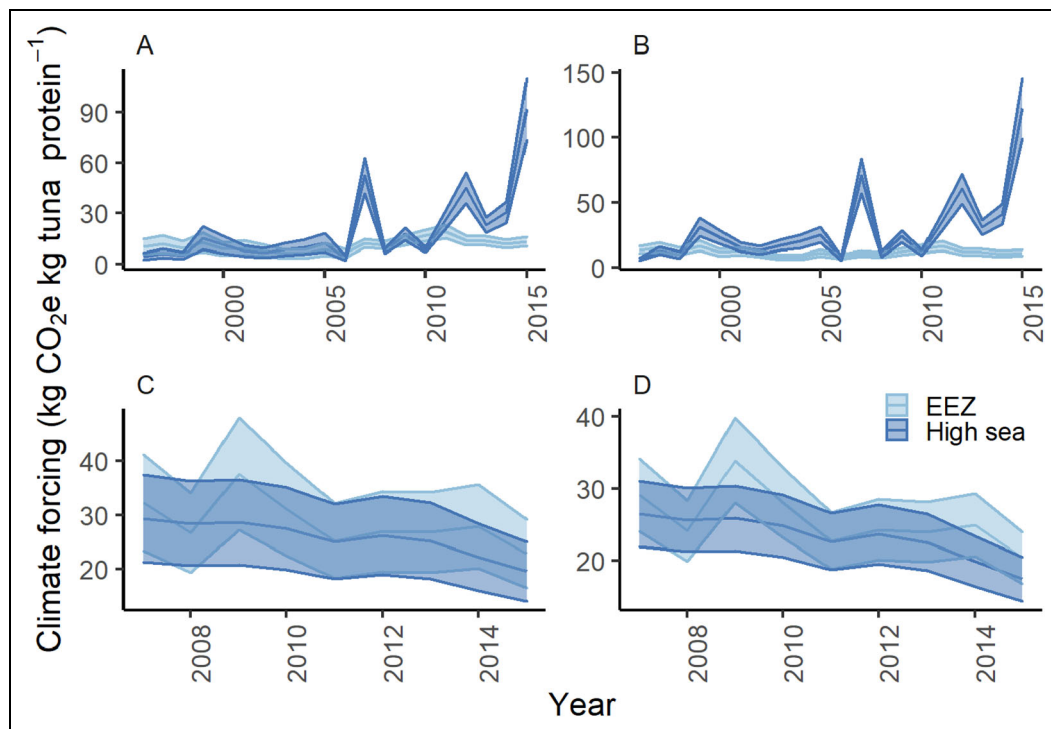
Figure 6. Mean climate forcing of tuna protein comparison between fishing territories on two time horizons. Comparison of climate forcing of tuna protein for fleet operations within the U.S. exclusive economic zone to fleet operations on the high seas. Left panels (A and C): 20-year time horizon. Right panels (B and D): 100-year time horizon. Top panels (A and B): Surface methods include troll and pole-and-line gears. Surface methods include troll and pole-and-line gears Bottom panels (C and D): Hawaii longline fleet. Shaded regions and the error bars represent the 95% confidence interval. DOI: https://doi.org/10.1525/elementa.2019.081.f6

can inform consumers that are concerned about both climate change impacts and bycatch impacts and empower them to make smarter decisions for the planet. For example, consumers might choose to eat seafood with negligible bycatch impacts but a higher climate impact less often, much the way some consumers choose to eat beef less often due to its climate impact. Moreover, they may choose to eat terrestrial protein sources that have no bycatch impacts and a low climate impact more frequently. We note, however, that there is considerable variability in the terrestrial protein sources due to a wide variety of farming practices (e.g., organic, conventional, irrigated, and nonirrigated for crop-based proteins and intensive and free-range animal husbandry methods) and life cycle methods (consequential and attributional). Future studies should consider these methodological differences across studies.

4.2. Climate and bycatch impact of restricted high seas fishing

Marine spatial planning is a tool that is used to make coordinated decisions for using marine resources sustainably. We found mixed results when we evaluated the climate and bycatch impact of closing the high seas to fishing.

On the one hand, we found a potential reduction in climate forcing from a high seas fishing closure in the case of the North Pacific surface methods fleet. Climate forcing of tuna protein caught outside the U.S. EEZ by the North Pacific surface methods fleets is significantly higher than tuna protein caught within the U.S. EEZ—due to a lower catch per unit effort. The 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, a high seas closure could make targeting albacore inside the west coast EEZ unprofitable for the U.S. surface fishery in years when the seasonal migration concentrates offshore.

On the other hand, there was no significant difference in EEZ versus high seas climate forcing for the Hawaii deep-set longline fleet. However, the bycatch of marine mammals in this fleet was significantly greater within the EEZ than beyond it. Thus, these results suggest there can be a conservation benefit to high seas fishing. Adding to this weight of evidence, recent work has suggested that some tuna fleets may be among the minority of high seas fishing operations that are profitable in the absence of subsidies (Sala et al., 2018).

Possible explanations for why fishermen would choose to fish the high seas at a greater fuel cost include effort limits imposed in EEZs (such as the vessel day scheme; Havice, 2013), local depletion of tuna stocks inside EEZs, regional fidelity of tuna stocks situated on the high seas making it difficult or infeasible to target them elsewhere (Sumaila et al., 2010; Squires et al., 2015; Squires et al., 2017), and fuel subsidies (Sumaila et al., 2010; Sumaila et al., 2014). There are also fishery
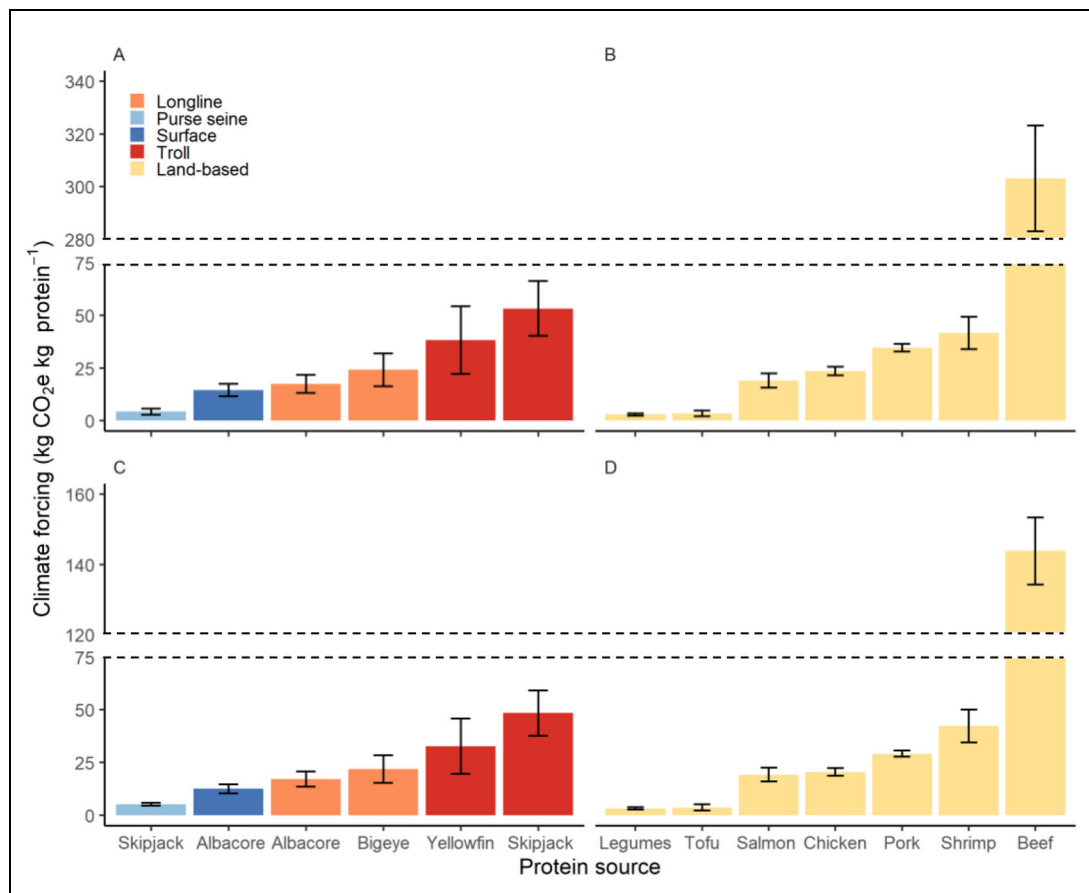
Figure 7. Mean climate forcing comparison of protein sources. Mean climate forcing over a period of 5 years (2011–2015). Protein sources include several species of wild-caught tuna and various land-based sources (farmed) for comparison. Farmed sources include legumes, tofu, salmon, chicken, pork, shrimp, and beef (yellow bars). The wild-caught tuna includes American Samoa longline-caught albacore (orange bars), American Samoa troll-caught skipjack (red bars), Hawaii longline-caught bigeye (orange bars), Hawaii troll-caught yellowfin (red bars), North Pacific surface methods-caught albacore (dark blue bars), and U.S. purse seine-caught skipjack (light blue bars). Surface methods include troll and pole-and-line. Top panels (A and B): 20-year time horizon. Bottom panels (C and D): 100-year time horizon. Error bars represent the 95% confidence interval. DOI: https://doi.org/10.1525/elementa.2019.081.f7

management decisions such as area closures that leave fishermen little choice but to fish the high seas. For example, swordfish longline fishing off California is prohibited inside the west coast U.S. EEZ due to concerns about greater ecological harm if fishing occurred within 200 nautical miles of the coast (Pacific Fishery Management Council, 2018).

4.2.1. Policy recommendations

U.S. leaders plan to reenter the Paris Climate Agreement and have ambitious plans to achieve net-zero carbon emissions by 2050 (Knudsen, 2020). Achieving net-zero carbon emissions will require reductions in all economic sectors, including the fishing industry.

There are a number of different pathways to achieving net-zero emissions in the fishing sector. For instance, compliance offsets are used to meet legally binding caps on carbon in schemes like the European Union's Emissions Trading System (European Commission, 2020). However, compliance offsets require an understanding of sector emissions, and currently, the U.S. lags behind the

European Union in quantifying fishing sector emissions. Thus, quantification of fishing vessel emissions should be prioritized so that we can better understand the targets for mitigation.

Although market-based approaches may lower emission reduction costs and strengthen industry support for climate change mitigation policies (Stavins, 2008), carbon offsets must be complemented by other measures such as energy efficiency. New legislation such as the Ocean-Based Climate Solution Act of 2020 (H.R. 6832 introduced in the 116th Congress) has been introduced in the U.S. that would prohibit federal loan guarantees for fishing vessels unless the construction, reconstruction, or reconditioning of the vessel will increase fuel efficiency or reduce fuel usage.

One emerging approach for reducing fuel usage is replacing main engines with hybrid-electric or battery-electric powered propulsion. A recent study estimated that hybrid-electric or battery-electric powered propulsion could reduce carbon emissions by as much as 20% and 70%, respectively, over conventional engines (Manouchehrinia et al., 2018).

Figure 8. Bycatch ratios of selected fleets. Selected fleets include Hawaii (HI) deep-set longline, American Samoa (AS) longline, United States (US) purse seine, and HI troll. Panels (A and B): bycatch ratios are the catch (tonnes) to the total catch including bycatch (tonnes). Other panels (C–H): bycatch ratios are number (individuals) to total catch including bycatch (tonnes). DOI: https://doi.org/10.1525/elementa.2019.081.f8

Although the electrification of propulsion power is not yet a feasible technology for fleets that make extended trips (e.g., longline and purse seine fleets; Manouchehrinia et al., 2018), this technology is well aligned with coastal fishing vessels (e.g., troll and surface methods fleets). Widespread adoption of battery-electric powered propulsion for fishing vessels may be limited by cost, availability of fast charging stations, and the existing electrical grid infrastructure (Manouchehrinia et al., 2018). However, shifting fuel subsidies to electrification investments for coastal fleets would not only reduce the climate impact of fishing activities, but it would improve air quality in coastal areas and would provide additional jobs (e.g., electrification infrastructure and propulsion retrofits). Furthermore, prioritizing the electrification of fleets that use highly selective gears (e.g., troll and surface methods) would also provide multiple conservation benefits.

4.2.2. Study limitations

Although our FUI estimates are within the range of other studies (**Table 3**) and our catch statistics are robust, there are study limitations that may add to the uncertainty in our estimates. First, our comparisons between fleets targeting the same species but using different gears do not consider spatial and temporal differences, and this may be an oversimplification. Second, we made simplifying assumptions about engine speeds and fuel types due to a lack of data for smaller vessels (e.g., troll and longline fleets) that may introduce a minor amount of error. However, simplifying assumptions about main engine power could be a larger source of error. Because we found only one trolling vessel with an American Samoa port registry, we used the national average of tuna-troller main engine power for this fleet instead of a single value. Third, the relationship between fishing effort and fuel use has been shown to be robust for active fishing gears such as demersal trawls, but the relationship is weaker for purse seines and longlines (Tyedmers et al., 2001). Considerations that could lead to an underestimate include omission of auxiliary engines or support vessels (e.g., support skiffs or search helicopters in the case of the purse seine fleet), and the fact that fishing effort data from logbooks include the

time spent searching for fish and actively fishing, but do not include the time spent steaming to and from the fishing grounds. On the other hand, a consideration that could lead to an overestimate is the assumption that fishing effort (e.g., Hawaii troll, American Samoa troll, and America Samoa longline) and "soak time" (e.g., Hawaii deep-set long line) are equivalent to fishing vessel activity hours, when in fact, there may be periods without main engine propulsion. Another source of uncertainty that may lead to an over-or-under-estimate is that, in some cases (e.g., U.S. purse seine and the North Pacific surface methods fleet), vessel activity time was estimated from foreign fleets targeting the same species and using the same gears. In all cases, however, FUI estimates could be improved if there was increased transparency about fishermen's vessel activity such as making vessel monitoring service data more available.

We acknowledge that calculations across a range of sustainability dimensions (e.g., climate impact and conservation) introduce error in our climate forcing of tuna protein estimates. In particular, there is uncertainty in our edible yield and protein content estimates. Due to the lack of current information, our edible yield estimates did not differentiate between temperate and tropical species, or consider differences in markets and product types (McCluney et al., 2019). Further, we did not consider emerging techniques such as chemical or enzymatic hydrolysis that convert fish waste into value-added products for food processing and other applications (Klomklao and Benjakul, 2017). We also did not consider regional and temporal effects on the nutrient content of tuna (Zudaire et al., 2015) or alternatives to proximate analysis (Vaitla et al., 2018). Future work should consider these sources of uncertainty to improve estimates.

With respect to bycatch impacts, there are some important considerations. First, fleets that employ selective gears (e.g., troll and surface methods) often lack observer coverage, and thus, bycatch impacts are relatively unknown compared to longline and purse seine fleets (Miller et al., 2017). Second, some highly selective fishing methods require a substantial quantity of baitfish whose sustainability and capture emissions were not assessed here (Gillett, 2011). Third, our analyses have focused strictly on U.S. tuna purse seine fleets in the western and central Pacific Ocean, only one of many tuna purse seine regions. The eastern tropical Pacific Ocean (ETP), for example, is home to one of the largest tuna purse seine fleets in the world and largely operates in the high seas. This fishery is particularly notable for prompting one of the first seafood eco-labels as a result of formerly high levels of dolphin bycatch (Hall, 1998). The tuna-dolphin problem led to a U.S. embargo on some tuna catches and was associated with a reduction in the U.S. purse seine fleet in the ETP (O'Connell, 2005). Although the dolphin problem has largely been mitigated, changes in fishing behaviors have led to higher levels of non-dolphin bycatch now as fishers often set gear around fish aggregating devices (FADs) which can support diverse ecosystems of marine species (Hall, 1998; Watson et al., 2009).

4.2.3. Future directions

Although climate forcing is an important consideration for understanding seafood sustainability, there are some important caveats.

First, our analysis did not consider the effects of FADs on the climate impact or on the bycatch ratio estimates. It has been reported that FADs improve the efficiency of tuna purse seine operations but may increase the bycatch associated with these sets (Fonteneau et al., 2013). Future studies should consider the potential climate and bycatch trade-offs of tuna protein caught with fleets employing FADs.

Second, we did not consider the increasingly stringent regulations on the sulfur content in marine fuels (Cullinane and Bergqvist, 2014). Although fuel quality is often overlooked by sustainable seafood advocates, it is an important factor that is shaping the sustainability of seafood production. Reducing the sulfur content in marine fuels may reduce the formation of sulfate aerosols which are known to increase human health risks and contribute to acidification in terrestrial and aquatic environments (Hassellöv et al., 2013; Sofiev et al., 2018). However, reducing the sulfur content of marine fuels will also diminish the cooling effects (Westervelt et al., 2015; Sofiev et al., 2018) which may in turn increase the climate forcing of seafood production. 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 pollutants (e.g., short-lived constituents such as sulfur oxides, nitrogen oxides, black carbon, and organic carbon) than only well-mixed greenhouse gases (McKuin and Campbell, 2016). Future studies should consider the trade-off between climate and air quality goals resulting from fuel sulfur content regulations.

Third, our analysis is narrowly focused on the fuel-related impacts of fishing activities. Although it has been reported that fuel use in the fishing stage is the key driver in the overall GHGs of seafood products—contributing between 75% and 95% of the total GHGs of the product (Ziegler et al., 2016), there are other operational activities (e.g., gear, vessel construction, maintenance, refrigeration systems) and downstream processing activities (e.g., forming raw materials into final products; McKuin et al., 2019). Such downstream activities include transportation of final products which, for tuna, can be substantial (Ziegler et al., 2013). For example, markets for fresh tuna often require products to be shipped by airfreight (e.g., sushi, steaks, and fillets) to consumers instead of more fuel-efficient bulk shipping. Future studies should consider a holistic analysis of the seafood supply chain.

5. Conclusion

The last two decades have seen an explosion of popular sentiment surrounding sustainability and seafood. Consumers often turn to seafood rating systems (e.g., Monterey Bay Aquarium Seafood Watch) and seafood certifications (e.g., MSC) to inform their purchasing decisions. Meanwhile, consumers purchasing airplane tickets or other

transportation options are sometimes given the opportunity to offset the carbon footprint of their travel, while other consumers are purchasing electric cars or other "green" methods to reduce their climate impacts. However, there has been a general lack of connection between these different considerations of sustainability in the modern world. We have sought to explicitly examine the synergies and trade-offs between some conventional metrics for gauging the sustainability of seafood and the metrics for gauging the climate impacts of our choices. Our results suggest that the conversation about sustainable seafood is even more complex than previously assumed. What is good for bycatch species may not necessarily be what is best for the climate, for example. The evidence of climate trade-offs needs to be considered alongside the economic and ecosystem conservation impacts of different fishing methods for a holistic sustainability assessment.

Data accessibility statement

The catch statistics (Appendix A), the total fuel-cycle climate forcing model (Appendix B), and the files used to make the figures are available in the DRYAD repository at the following link: https://doi.org/10.6071/M3768B. The other data sets used in this article have been included in the supplemental material.

Supplemental files

The supplemental files for this article can be found as follows:

Supplemental text (S1–S5), supplemental equations (S1–S11), supplemental tables (S1–S16), and supplemental figures (S1–S2).

Acknowledgments

We gratefully acknowledge helpful feedback on a previous version of this article from D. Lobell, M. Beman, G. Villalba, M. Beutel, P. Tyedmers, D. Merrill, Y. J. Shrader, M. Cronin, and B. Steiner.

Funding

Disclaimer

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of NOAA or the Department of Commerce.

Competing interests

The authors have no competing interests to declare.

Author contributions

Contributed to conception and design: JEC, BLM, SS, JTW.
Contributed to acquisition of data: BLM.
Contributed to analysis and interpretation of data: BLM, JEC, JTW, SS.
Drafted and/or revised the article: BLM, JTW, SS, JEC.
Approved the submitted version for publication: BLM, JTW, SS, JEC.

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