Fuel Use and Greenhouse Gas Emissions from Offshore Fisheries of the Republic of Korea

Jeong-A Park1,2, Caleb Gardner1, Myo-In Chang3, Do-Hoon Kim2, Young-Soo Jang2*

1 Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia, 2 Department of Marine and Fisheries Business and Economics, Pukyong National University, Busan, Republic of Korea, 3 Ministry of Oceans and Fisheries Korea, Sejong, Republic of Korea

* ysjang@pknu.ac.kr

Abstract

Greenhouse Gas (GHG) emissions from the offshore fisheries industry in the Republic of Korea (Korea) were examined in response to growing concerns about global warming and the contribution of emissions from different industrial sectors. Fuel usage and GHG emissions (CO2, CH4, N2O) were analysed using the ‘Tier 1’ method provided by the Intergovernmental Panel on Climate Change (IPCC) from the offshore fishery, which is the primary domestic seafood production sector in Korea. In 2013, fuel usage in the offshore fishery accounted for 59.7% (557,463 KL) of total fuel consumption of fishing vessels in Korea. Fuel consumption and thus GHG emissions were not stable through time in this industry, increasing by 2.4% p.a. for three consecutive years, from 2011 to 2013, despite a decrease in the number of vessels operating. GHG emissions generated in offshore fisheries also changed through time and increased from 1,442,975 tCO2e/year in 2011 to 1,477,279 tCO2e/year in 2013. Changes in both fuel use and GHG emissions per kg offshore fish production appeared to be associated with decreasing catch rates by the fleet, which in turn were a reflection of decrease in fish biomass. Another important feature of GHG emissions in this industry was the high variation in GHG emission per kg fish product among different fishing methods. The long line fishery had approximately three times the emissions of the average production while the jigging fishery was more than two times higher than the average. Lowest emissions were from the trawl sector, which is regarded as having greatest environmental impact using traditional biodiversity metrics although had lowest environmental impact in terms of fuel and GHG emission metrics used in this study. The observed deterioration in fuel efficiency of the offshore fishery each year is of concern but also demonstrates that fuel efficiency can change, which shows there is opportunity to improve efficiency with changes to fishery management and harvesting operations.

Introduction

The Korean government has expressed a desire to reduce Greenhouse Gas (GHG) emissions from industries including fisheries due to rising concern about Global Warming (Korean
Ministry of Environment, 2014). Extensive analysis of GHG emissions from fisheries has been conducted in part as a response to GHG emission targets that are binding under international law by the Kyoto Protocol [1, 2, 3, 4].

The Republic of Korea (Korea) has committed to voluntary restrictions, which has led to strengthening of the country’s GHG governance. This has included annual reduction targets and an allocation plan for GHG enacted in September 2014 [5]. Korea has also established the “Korean Allowance Unit” (KAU) to control GHG from domestic industry with a target from 2015 to 2017 of 1,687 million KAU [5], which is equivalent to 1,687 million tCO₂e (tons of carbon dioxide equivalent).

Although fisheries were not included as a mandated industry in the first three years of the GHG allocation plan, the reduction of GHG emissions remains a significant issue for Korean fisheries because the Korean government has set targets to reduce GHG emissions by 5.2% below business-as-usual (BAU) levels by 2020 [5]. Furthermore, it is possible that the level of GHG emissions from the fisheries industry will impact on seafood exports in response to increased global awareness in protecting the environment [6].

Precise measurement of GHG emissions is an important first step in management and several studies have been conducted to evaluate GHG emissions generated by fisheries in Korea [7, 8, 9, 10]. However, accurate measurement of the GHG is complicated by diversity in some fishing methods [8, 10], and also assessment methods. Examples of method issues with GHG emissions include the use of only carbon dioxide for the total GHG emissions, the application of stationary combustion factor instead of mobile combustion factor in the GHG calculations [7, 9], and using prior version of net calorific values of the fuel type based on the Energy Act standards which were amended in December 2011 in Korea [7, 8, 9].

The quantitative analysis presented here shows fuel usage and GHG emissions from Korea’s largest fishery sector, the offshore fishery, which covers operations with trip lengths of greater than one day [11]. Many fishing method categories are used including larger industrial methods such as purse seine and benthic trawl although more artisanal methods such as dive are also part of the offshore fishery. The aim of this analysis of the offshore fisheries of Korea was to quantify the scale of fuel use and emissions from different components of the fishery and also to determine if there were any processes resulting in change between those recent years where data were available. This was intended to provide insight on whether there were opportunities to address the government’s desire to reduce emissions.

Amongst the diverse range of fisheries in Korea, the offshore fishery is of special interest because it is the largest contributor to Korean domestic seafood production and likely to be most impacted by regulation due to a higher proportion of fuel and energy use [12]. Changes in this Korean industry is also of interest because fisheries have unusually high cultural value in Korea with per capita consumption (60.4 kg) more than three times the global average (18.9 kg) [13] and 1.7% of the global catch taken by this nation with only 0.7% of the global population [14].

We determined GHG emissions from this fishery using the ‘Tier 1’ method and also applied water-borne navigation emission factors which are included in mobile combustion emission factors. Both are provided by the Intergovernmental Panel on Climate Change (IPCC). This study estimated the emissions of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), which typically account for 95 percent of energy system emissions and are largely driven by the combustion of fossil fuels as GHG emissions [15].

Domestic fisheries production in Korea

In 2013 approximately 3 million tons of seafood, valued of KRW 7.2 trillion (US$ 6.6 billion), were produced in Korea from capture fisheries (marine and inland) and aquaculture [16]. The
volume of overall domestic fisheries production has stagnated since 2009 although within this there have been substantial changes with cultured seaweed production increasing significantly while fish production has greatly reduced (Table 1). Most change in volume of fish production has been from a few main species, notably squid, mackerel, and hairtail. This decline in catch appears to have come from several sources including overfishing, indirect ecosystem impacts, and illegal and unregulated catches from other nations within Korean waters [17]. In particular there was an estimated 0.7 million tons of catch from illegal fishing by Chinese registered vessels in the Korean Exclusive Economic Zone (EEZ) in 2012 [17]. This volume accounts for about 21% of total seafood production from the EEZ in the same year.

Fisheries production in Korean offshore
The Korean General Marine Fishery has inshore and offshore components and contributed 51.9% of the total Korean domestic seafood production in 2013 [16]. From 2000, Ministry of Oceans and Fisheries in Korea has reduced the number of fishing vessels which have worked in General Marine Fishery for many reasons including EEZ declarations of adjacent countries, the fisheries agreements with adjacent countries, and responding to the depletion of stocks. As a result, the number of vessels has been reduced by 2.3% during the last three years so that 2,780 vessels operated in the Korean offshore fishery in 2013. Most vessels were in the size range of 20–50 tons (38.9%), followed by 50–100 tons (23.6%) and 10–20 tons (13.8%; Table 2). The main species produced by the offshore fishery were squid, hairtails, mackerel, and anchovies. A wide range of method categories were recorded with Danish trawl, pair trawl and otter trawl accounting for most yield, followed by gillnet, large purse seine, jigging and anchovy dragnet (Table 3).

To investigate whether the offshore fisheries production varied by fishing type during last three years, a paired T-test was used to compare catch data from 2011–2012 and 2012–2013 (PASW Statistics Version 18.0). This did not reject the null hypothesis at the significance level of 0.1 levels, implying that there were no significant changes in production by method category during this three year period.

Methods and Materials
IPCC ‘Tier 1’ method
This study estimated GHG emissions from Korean offshore fisheries using Tier 1 of the three methods provided by the IPCC. Tier 1 is the basic method and it is designed to be used for all categories and is readily available nationally or internationally in combination with the IPCC default emission factors. The Tier 1 method can be applied with either default values or country-specific information. According to the IPCC, ‘Fishery’ is classified as water-borne navigation and mobile combustion, which requires the use of mobile rather than stationary emission factors [15]. The Water-Borne navigation calculation is based on the amount of fuel burned and on emission factors for CO₂, CH₄, and N₂O (Eq 1) [15]:

\[
GHG \, Emissions = \sum (Fuel \, Consumed_{fuel \, type} \times Emission \, Factor_{fuel \, type})
\]

Direct emissions of GHG
Water-borne navigation causes emissions of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), as well as smaller volumes of carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO₂), particulate matter (PM) and oxides of
nitrogen (NOx) [15]. This study estimated the emissions of CO2, CH4 and N2O only as per the standard approach of the IPCC Tier 1 method. Estimating the emissions of these three compounds is considered to be sufficient to represent the full GHG emission because they are responsible for 95% of energy system emissions from the combustion of fossil fuels [15].

Table 1. Recent change in production (1000 t) of the upper 15 seafood taxa harvested from the Korean EEZ. Source: Statistics Korea (Each year).

|          | 2000 | 2007 | 2013 |
|----------|------|------|------|
| Total yield Upper 15 taxa | 2514 | 3275 | 3135 |
| Squid    | 404  | 397  | Red macroalgae 406 |
| Sea mustard | 212  | 321  | Kelp 373 |
| Anchovy | 201  | 309  | Sea mustard 327 |
| Oyster | 177  | 250  | Squid 255 |
| Mackerel | 145  | 221  | Oyster 240 |
| Bonito | 137  | 214  | Anchovies 209 |
| Red macroalgae | 130  | 211  | Bonito 201 |
| Other fish | 107  | 144  | Mackerel 102 |
| Pollock | 86   | 98   | Hairtail 47 |
| Hairtail | 81   | 66   | Herring 45 |
| Yellowfin tuna | 49   | 54   | Yellowfin tuna 44 |
| Croakers | 31   | 42   | Krill 38 |
| Bigeye tuna | 30   | 41   | Snow crab 38 |
| Spanish mackerel | 26   | 37   | Flatfish 37 |
| Pacific saury | 25   | 36   | Small yellow croaker 35 |

Table 2. Vessel sizes in the Korean offshore fishery by method category in 2013. Source: Ministry of Oceans and Fisheries(MOF) Korea (2013).

| Fishing Types                  | Total (Vessels) | 1–5 | 5–10 | 10–20 | 20–50 | 50–100 | 100–200 | More than 200 |
|--------------------------------|-----------------|-----|------|-------|-------|--------|---------|--------------|
| Total (Vessels)                | 2,780           | 196 | 237  | 383   | 1,081 | 657    | 186     | 40           |
| Large Danish Trawl             | 47              | 0   | 0    | 0     | 13    | 33     | 1       | 0            |
| Large Pair Trawl               | 72              | 0   | 0    | 0     | 0     | 20     | 52      | 0            |
| Eastern sea area Danish seine  | 38              | 0   | 0    | 0     | 10    | 28     | 0       | 0            |
| Medium Size Danish Seine       | 39              | 0   | 0    | 0     | 26    | 13     | 0       | 0            |
| Medium Size Pair Trawl         | 18              | 0   | 0    | 0     | 2     | 16     | 0       | 0            |
| Large Trawler                  | 52              | 0   | 0    | 0     | 0     | 52     | 0       | 0            |
| Eastern Sea Area Otter Trawler | 38              | 0   | 0    | 0     | 5     | 33     | 0       | 0            |
| Large Purse Seine              | 143             | 0   | 0    | 0     | 47    | 56     | 40      | 0            |
| Small Purse Seine              | 72              | 2   | 32   | 34    | 2     | 2      | 0       | 0            |
| Jigging                        | 480             | 0   | 21   | 70    | 288   | 94     | 7       | 0            |
| Anchovy Dragnet                | 383             | 1   | 6    | 38    | 208   | 116    | 14      | 0            |
| Gillnet                        | 377             | 0   | 43   | 131   | 172   | 31     | 0       | 0            |
| Stow Net                       | 208             | 0   | 9    | 6     | 87    | 103    | 3       | 0            |
| Lever Lift Net                 | 3               | 0   | 3    | 0     | 0     | 0      | 0       | 0            |
| Diver                          | 235             | 188 | 47   | 0     | 0     | 0      | 0       | 0            |
| Trap                           | 200             | 0   | 10   | 19    | 58    | 112    | 1       | 0            |
| Dredge                         | 74              | 5   | 34   | 34    | 1     | 0      | 0       | 0            |
| Long line                      | 301             | 0   | 32   | 51    | 209   | 9      | 0       | 0            |
The Korean government has offered tax-free oil for all fishing vessels and the oil supply data is managed by National Federation of Fisheries Cooperatives (SUHYUP) [18] in Korea. This tax-free oil data was used to quantify total amount of fuel use in Korean offshore fisheries, as per previous research on fuel usage in this industry [19, 20, 21, 22]. The total number and size of vessels were obtained from the Fisheries Information Service in Korea [23], which is operated by the Ministry of Oceans and Fisheries. Catch data were sourced from Fisheries Production Statistics in Statistics Korea [16]. Emission factors using CO2, CH4 and N2O Emissions calculations were derived from IPCC (2006) [15] water-borne navigation factors as part of mobile combustion as Korea does not regional GHG emission factors for application. The amount of CH4 and N2O emissions were converted to Carbon Dioxide equivalents (CO2e) by multiplying each by their Global Warming Potential (GWP) and then combining with CO2 to derive the overall amount of GHG emission expressed as CO2e. GWP of each emission and Net Calorific Values by fuel type were based on the Greenhouse Gas Emissions Trading Act and the Energy Act standards in Korea [24]. This regional data was considered more accurate than global data supplied by the IPCC (Table 4).

Table 3. Total production and main species in Korean offshore by method category in 2013. Source: Statistics Korea (2013).

| Fishing Types          | Yield (M/T) | Main taxa in catch                                      |
|------------------------|-------------|--------------------------------------------------------|
| Large Danish Trawl     | 11,822      | flatfish, brown croaker, blackthroat sea perch, blackmouth angler |
| Large Pair Trawl       | 55,758      | hairtail, croaker, anchovy, silver pomfret, Spanish mackerel, gizzard shad |
| Eastern Sea Area       | 9,090       | flatfish, saifin sandfish                              |
| Danish Seine           |             |                                                        |
| Medium Size Danish Seine| 16,263     | blackthroat seaperch, brown croaker, flatfish, blackmouth angler |
| Medium Size Pair Trawl | 19,641      | hairtail, anchovy, Spanish mackerel, gizzard shad       |
| Large Trawler          | 64,186      | hairtail, squid                                        |
| Eastern Sea Area       | 37,052      | squid                                                  |
| Otter Trawler          |             |                                                        |
| Large Purse Seine      | 163,856     | hairtail, mackerel, yellowtail, Spanish mackerel, horse mackerel, sardine, herring, squid |
| Small Purse Seine      | 20,142      | horse mackerel, mackerel, herring, anchovy              |
| Jigging                | 42,567      | hairtail, puffer, squid                                |
| Anchovy Dragnet        | 139,965     | anchovy, Spanish mackerel, herring                     |
| Gillnet                | 62,196      | flatfish, pacific saury, cod, small yellow croaker, swimming crab, akami paste shrimp, snow crab |
| Stow Net               | 46,611      | hairtail, anchovy, silver pomfret, blackmouth angler, small yellow croaker, swimming crab, southern rough shrimp |
| Lever Lift Net         | 32          | coral fish                                             |
| Diver                  | 8,678       | Manila clam, Korean common penshell, egg cockle        |
| Eel Fish Trap          | 8,874       | white-spotted congor                                   |
| Trap                   | 39,555      | swimming crab, snow crab, whelk, octopus              |
| Dredge                 | 160         | Korean common penshell                                 |
| Long Line              | 14855       | hairtail, puffer                                       |

doi:10.1371/journal.pone.0133778.t003

Data source for estimate GHG Emissions
The Korean government has offered tax-free oil for all fishing vessels and the oil supply data is managed by National Federation of Fisheries Cooperatives (SUHYUP) [18] in Korea. This tax-free oil data was used to quantify total amount of fuel use in Korean offshore fisheries, as per previous research on fuel usage in this industry [19, 20, 21, 22]. The total number and size of vessels were obtained from the Fisheries Information Service in Korea [23], which is operated by the Ministry of Oceans and Fisheries. Catch data were sourced from Fisheries Production Statistics in Statistics Korea [16]. Emission factors using CO2, CH4 and N2O Emissions calculations were derived from IPCC (2006) [15] water-borne navigation factors as part of mobile combustion as Korea does not regional GHG emission factors for application. The amount of CH4 and N2O emissions were converted to Carbon Dioxide equivalents (CO2e) by multiplying each by their Global Warming Potential (GWP) and then combining with CO2 to derive the overall amount of GHG emission expressed as CO2e. GWP of each emission and Net Calorific Values by fuel type were based on the Greenhouse Gas Emissions Trading Act and the Energy Act standards in Korea [24]. This regional data was considered more accurate than global data supplied by the IPCC (Table 4).
Results and Discussion

Status of fuel consumption by fishing types in offshore Korea

Fuel consumption of the fishery by method category was analysed using the last three years data (2011 to 2013) and tax-free oil sales data (Table 5). In 2013, the total tax-free oil consumption of the Korean fleet was 934,311 KL with 59.7% (557,463 KL) of this used by the offshore fleet. Thus, reduction in fuel use and GHG reductions in the offshore sector has a significant impact on the aggregate GHG emissions by Korean fisheries as it accounts for a significant proportion of the total.

The three-year average of the total oil consumption of the offshore fishing vessels in Korea was 545,006 KL p.a. with greatest usage by the Large Purse Seine Fishery, Jigging Fishery, Large Pair Trawl Fishery and Anchovy Dragnet Fishery. This usage was proportional to the tonnage of harvest and the size of vessels.

Trawl fisheries generally operated with large vessels so that annual fuel consumption per vessel was high (Table 6). Of these, the Large Pair Trawl Fishery had the highest annual fuel consumption per vessel, 827KL, based on 2011–2013 averages. This was followed by Large Trawler (680KL), Large Purse Seine Fishery (605 KL), and Medium Size Pair Trawl (587 KL).

Importantly, aggregate fuel consumption increased despite a decrease in the number of vessels by 2.3% in 2013 compared to 2011 (Table 6). Two factors were identified that contributed to this: first the average annual fishing days increased slightly from 2011 to 2013 (186 to 190 days) [25]; and secondly, the average age of vessels operating in the fleet increased during this period, which is known to result in a decrease in combustion efficiency (Table 7) [26]. The number of older, less efficient vessels (over 16 years) has increased sharply while the number of younger vessels (under 10 years) reduced during this period (Table 7).

Analysis of fuel consumption by oil type over the last three years indicated that the oils used in offshore fisheries were diesel oil, residual fuel oil (B-A and B-B), blended oil (MF-30) and lubricant. Most fishing method categories used diesel oil (over 99%) while the Large Pair Trawl Fishery, Large Trawler, and Anchovy Dragnet Fishery used residual fuel oil at 15%, 41% and 14% respectively of total fuel usage. The consumption of MF-30 and lubricant in the vessels was less than 1% across all of the method categories [18].

---

Table 4. Global Warming Potential (GWP) by GHG and Net Calorific Values by fuel types used for offshore fishing vessels. Net Calorific Values used were revised values first published in December 2011. Source: Ministry of Government Legislation.

| Emissions    | Global Warming Potential (GWP) |
|--------------|-------------------------------|
| CO2          | 1                             |
| CH4          | 21                            |
| N2O          | 310                           |

| Fuel Types               | Unit | Net Caloric Valuesa |
|--------------------------|------|---------------------|
| Gas/Diesel Oil           | L    | 35.3                |
| Residual Fuel Oil (B-A)  | L    | 36.4                |
| Residual Fuel Oil (B-B)  | L    | 38.0                |
| Lubricant                | L    | 37.0                |

a Revised December 2011
Table 5. Annual tax-free oil consumption by method category in Korean offshore fisheries.

| Fishing types                        | 2011 (KL) | 2012  | 2013  | Three-year average | Portion (%) |
|---------------------------------------|-----------|-------|-------|--------------------|-------------|
| Total Domestic                        | 919,349   | 900,380 | 934,311 | 918,013           | 100.0       |
| Total Offshore                        | 544,185   | 533,371 | 557,463 | 545,006           | 100.0       |
| Large Danish Trawl                   | 14,968    | 15,121 | 15,542 | 15,210            | 2.8         |
| Large Pair Trawl                     | 58,994    | 54,283 | 61,223 | 58,167            | 10.7        |
| Eastern Sea Area Danish              | 4,278     | 4,680  | 4,599  | 4,519             | 0.8         |
| Medium size Danish Seine             | 12,445    | 12,072 | 13,079 | 12,532            | 2.3         |
| Medium Size Pair Trawl               | 11,500    | 12,217 | 10,544 | 10,754            | 2.0         |
| Large Trawler                        | 38,427    | 32,008 | 34,922 | 35,119            | 6.4         |
| Eastern Sea Area Otter Trawl         | 10,403    | 10,318 | 8,839  | 9,853             | 1.8         |
| Large Purse Seine                    | 85,685    | 86,119 | 87,553 | 86,452            | 15.9        |
| Small Purse Seine                    | 8,099     | 8,099  | 8,204  | 8,134             | 1.5         |
| Jigging                               | 76,494    | 79,083 | 84,757 | 80,111            | 14.7        |
| Anchovy Dragnet                      | 54,011    | 52,192 | 56,196 | 54,133            | 9.9         |
| Gillnet                               | 32,640    | 33,356 | 32,046 | 32,681            | 6.0         |
| Stow net                             | 40,257    | 40,795 | 41,893 | 40,982            | 7.5         |
| Diver                                | 4,242     | 4,023  | 3,661  | 3,976             | 0.7         |
| Trap                                 | 47,793    | 49,778 | 52,941 | 50,171            | 9.2         |
| Long Line                            | 43,541    | 40,794 | 41,002 | 41,779            | 7.7         |
| Others                               | 406       | 423    | 464    | 431              | 0.1         |

doi:10.1371/journal.pone.0133778.t005

Table 6. Tax-free oil consumption per vessel by method category in the offshore fishery based on 2011–2013 averages.

| Fishing types                        | Oil usage (KL) | Vessels | KL/Vessel | Vessels | KL/Vessel |
|---------------------------------------|----------------|---------|-----------|---------|-----------|
| Total Offshore Fisheries              | 545,006        | 2,822   | 193       | 97.7    | 102.4     |
| Large Danish Trawl                   | 15,210         | 47      | 324       | 100.0   | 103.8     |
| Large Pair Trawl                     | 58,167         | 70      | 827       | 102.9   | 103.8     |
| Eastern Sea Area Danish              | 4,519          | 39      | 117       | 97.4    | 107.5     |
| Medium size Danish Seine)            | 12,532         | 41      | 303       | 92.9    | 105.1     |
| Medium Size Pair Trawl               | 10,754         | 18      | 587       | 94.7    | 91.7      |
| Large Trawler                        | 35,119         | 52      | 680       | 102.0   | 90.9      |
| Eastern Sea Area Otter Trawl         | 9,853          | 39      | 255       | 97.4    | 85.0      |
| Large Purse Seine                    | 86,452         | 143     | 605       | 100.0   | 102.2     |
| Small Purse Seine                    | 8,134          | 73      | 111       | 97.3    | 101.3     |
| Jigging                               | 80,111         | 487     | 165       | 98.0    | 110.8     |
| Anchovy Dragnet                      | 54,133         | 387     | 140       | 97.5    | 104.0     |
| Gillnet                               | 32,681         | 379     | 86        | 99.7    | 98.2      |
| Stow net                             | 40,982         | 215     | 190       | 92.9    | 104.1     |
| Diver                                | 3,976          | 235     | 17        | 100.4   | 86.3      |
| Trap                                 | 50,171         | 201     | 249       | 101.5   | 110.8     |
| Long Line                            | 41,779         | 315     | 132       | 93.2    | 94.2      |
| Others                               | 431            | 81      | 5         | 93.9    | 114.2     |

doi:10.1371/journal.pone.0133778.t006
GHG emissions in offshore fisheries in Korea

Korean offshore fisheries GHG (CO₂, CH₄, N₂O) emissions were calculated by applying IPCC Tier 1 method (Table 8). In the calculation, the net calorific value and the emission factors were applied differently by fuel types and the proportion of fuel used for the vessels of each fishing method category. Blended oil (MF-30) and lubricant were replaced by diesel oil’s emission factor and net calorific value as their proportion was less than 1%.

It was apparent that GHG emissions generated by the aggregate offshore fisheries increased from 1,442,975 tCO₂e/year in 2011 to 1,477,279 tCO₂e/year in 2013. In 2012, the GHG emissions were lower than in 2011 because in 2012 the average annual fishing days in offshore fisheries decreased by approximately 6% compared to 2011. This was due to a temporary spike in international oil prices from a EU ban on oil imports from Iran as a sanction for Iran’s nuclear development in 2012 [27]. The amount of GHG emissions for the last three-year average was identified at 1,444,202 tCO₂e/year.

Comparison of GHG emissions across fishing method categories showed that the Large Purse Seine Fishery generated the highest GHG emissions followed by the Jigging Fishery and the Large Pair Trawl Fishery. At the other extreme, GHG emissions from the Diver Fishery, Eastern Sea Area Danish Seine and Small Purse Seine Fishery were low relative to other fishing methods.

GHG emissions per vessel and per production of 1kg fish varied by fishing type and were highest in in 2013 due to change in the number of fishing days and also change in efficiency of vessels (Table 9). The GHG emissions per kg of fish increased for each of the three consecutive years due to the decrease in catch rate during this period so that by 2013, GHG emissions per kg fish product were 16% higher than in 2011. Over this three-year period, catch rate had an overall decline of 10.6% from 2011 (306.3 t/vessel) to 2013 (273.9 t/vessel) [28, 29]. Although this change in catch rate and resultant increase in GHG emissions was clearly not desirable, it does illustrate that if decline in catch rate was reversed there would be substantial benefits for fuel consumption and reduction of GHG emissions.

Higher catch rates can be achieved through effective management of catch and this produces far greater proportional changes in emissions than modifications to engines or gear [30]. We note that implicit in this observation is the assumption that higher abundance of stock will translate into higher catch rates and thus reduced fuel consumption. Other factors modifying the relationship between stock abundance and fuel consumption are temporal changes in catchability of the stock and changes to gear selectivity. Many of the target species in the Korean offshore fishery are schooling and this behavior tends to mask the effect of changes in abundance on catch rate.

The Large Pair Trawl Fishery generated the highest per vessel GHG emission of all fisheries in 2013 followed by vessels in the Large Trawler and Large Purse Seine Fishery method categories. This was nearly identical to trends in tax-free oil consumption by fishing method category (Table 5), however there was divergence in the trend between tax-free oil consumption and GHG emissions per kg of production for the Long Line Fishery, Jigging Fishery and Large Danish Trawl Fishery with disproportionately higher emissions in each case.

Table 7. Fishing vessels proportion by age in the Korean offshore fishery. Source: Ministry of Oceans and Fisheries(MOF) Korea.

| Year | Total (Vessel) | Less than 5 years | 6 to10 years | 11 to 15 years | 16 to 20 years | Over 21 years |
|------|----------------|------------------|-------------|---------------|---------------|--------------|
| 2011 | 2,845          | 489              | 673         | 541           | 539           | 603          |
| 2012 | 2,842          | 471              | 634         | 545           | 567           | 625          |
| 2013 | 2,780          | 466              | 494         | 539           | 599           | 682          |

doi:10.1371/journal.pone.0133778.t007
Conclusion

This quantitative study assessed the fuel use and the GHG emissions from the offshore fisheries, which dominate domestic seafood production in Korea.

Fuel usage by offshore fisheries in 2013 accounted for 59.7%(557,463 KL) of total fuel consumption of fishing vessels in Korea which shows that changes in these fisheries will have a

Table 8. GHG emissions by fishing method category in the Korean offshore fishery.

| Fishing types                        | In 2011(tCO₂e) | In 2012(tCO₂e) | In 2013(tCO₂e) | Three-year average(tCO₂e) |
|--------------------------------------|----------------|----------------|----------------|---------------------------|
| Total Offshore Fisheries             | 1,442,975      | 1,412,353      | 1,477,279      | 1,444,202                |
| Large Danish Trawl                   | 39,479         | 39,883         | 40,992         | 40,118                   |
| Large Pair Trawl                     | 157,560        | 144,977        | 163,514        | 155,350                  |
| Eastern Sea Area Danish Seine        | 11,284         | 12,343         | 12,130         | 11,919                   |
| Medium size Danish Seine             | 32,826         | 31,841         | 34,496         | 33,055                   |
| Medium Size Pair Trawl               | 30,333         | 26,948         | 27,810         | 28,363                   |
| Large Trawler                        | 104,841        | 87,326         | 95,278         | 95,815                   |
| Eastern Sea Area Otter Trawl         | 27,439         | 27,215         | 23,313         | 25,989                   |
| Large Purse Seine                    | 226,002        | 227,146        | 230,929        | 228,026                  |
| Small Purse Seine                    | 21,361         | 21,362         | 21,638         | 21,454                   |
| Jigging                              | 201,760        | 208,589        | 223,555        | 211,301                  |
| Anchovy Dragnet                      | 144,652        | 138,523        | 149,937        | 144,370                  |
| Gillnet                              | 86,091         | 87,980         | 84,524         | 86,198                   |
| Stow net                             | 106,182        | 107,601        | 110,497        | 108,093                  |
| Diver                                | 11,190         | 10,612         | 9,657          | 10,486                   |
| Trap                                 | 126,059        | 131,294        | 139,637        | 132,330                  |
| Long Line                            | 114,845        | 107,597        | 108,147        | 110,196                  |
| Others                               | 1,072          | 1,116          | 1,225          | 1,138                    |

doi:10.1371/journal.pone.0133778.t008

Table 9. GHG emissions per vessel and by production (per kg fish) by fishing method category in the Korean offshore fishery.

| Fishing types                        | GHG emissions per vessel (tCO₂e/ vessel) | GHG emissions per production (kg CO₂e/ kg fish) |
|--------------------------------------|------------------------------------------|-----------------------------------------------|
|                                      | In 2011 | In 2012 | In 2013 | In 2011 | In 2012 | In 2013 |
| Total Offshore fisheries             | 507     | 497     | 531     | 1.67     | 1.79     | 1.94    |
| Large Danish Trawl                   | 840     | 849     | 872     | 3.20     | 3.38     | 3.47    |
| Large Pair Trawl                     | 2,251   | 2,101   | 2,271   | 2.63     | 2.68     | 2.93    |
| Eastern Sea Area Danish              | 289     | 316     | 319     | 1.84     | 1.82     | 1.33    |
| Medium size Danish Seine             | 782     | 740     | 885     | 2.13     | 2.06     | 2.12    |
| Medium Size Pair Trawl               | 1,596   | 1,497   | 1,545   | 1.27     | 1.03     | 1.42    |
| Large Trawler                        | 2,056   | 1,679   | 1,832   | 1.51     | 1.13     | 1.48    |
| Eastern Sea Area Otter Trawl         | 704     | 698     | 613     | .56      | .66      | .63     |
| Large Purse Seine                    | 1,580   | 1,588   | 1,615   | 1.03     | 1.28     | 1.41    |
| Small Purse Seine                    | 289     | 289     | 301     | 1.06     | 1.05     | 1.07    |
| Jigging                              | 412     | 426     | 466     | 4.48     | 4.22     | 5.25    |
| Anchovy Dragnet                      | 368     | 359     | 391     | .94      | 1.04     | 1.07    |
| Gillnet Fishery                      | 228     | 231     | 224     | 1.18     | 1.45     | 1.36    |
| Stow net                             | 474     | 503     | 531     | 2.12     | 2.43     | 2.37    |
| Diver                                | 48      | 45      | 41      | 1.14     | 1.18     | 1.11    |
| Trap                                 | 640     | 634     | 698     | 3.01     | 2.75     | 2.88    |
| Long Line                            | 356     | 334     | 359     | 6.88     | 7.02     | 7.28    |

doi:10.1371/journal.pone.0133778.t009
significant impact on fuel use and GHG emissions for the entirety of the Korean fisheries. Those fisheries that used larger vessels (Large Pair Trawl Fishery, Large Trawler and Large Purse Seine Fishery) had higher fuel consumption and higher fuel per vessel among all offshore fishing types over the last three-years, from 2011 to 2013 on average. The larger scale of vessels operating with these method categories did not appear to result in substantial gains in efficiency in terms of emissions per kg of catch with many other method categories having lower emissions per kg of catch, including small purse seine and medium sized pair trawl.

Another important result from this study was the 2.4% increase in fuel consumption that has occurred despite a decrease in the number of vessels in each of the consecutive years. Although this is small in scale, we are confident that this increase represents a real change because fuel consumption data is collected at the point of supply and monitored closely by the SUHYUP because it has implications for tax-free status of this fuel.

The increase in fuel consumption showed that the fuel efficiency of vessels in the offshore fleet deteriorated each year, which increases GHG emissions independently of change in catch rate. Decline in efficiency of vessels was most apparent from those fisheries that had larger sized vessels where aging of the vessels appeared to have affected fuel combustion efficiency. In 2013, the highest proportion of older vessels (over 16 years) was in the Large Purse Seine Fishery 98.6%, Large Trawler 92.3%, Eastern Sea Area Danish 89.5% and Large Danish Trawl Fishery 89.4% method categories. These four categories contributed around one third of the offshore fishery production so this decline in fuel consumption efficiency from 2011 to 2013 would significantly impact the GHG emissions of the overall Korean fishery if efficiency continued to deteriorate. Reduced efficiency should create an economic incentive for fishers to renew engines but if this fails there may be a need for policy or additional incentives to promote engine replacement.

Our results also showed that GHG emissions generated by the entire offshore fisheries increased from 1,442,975 tCO₂e/year in 2011 to 1,477,279 tCO₂e/year in 2013. In 2013, the Large Purse Seine Fishery generated the highest GHG emissions of all the offshore fisheries, closely followed by Jigging Fishery. A factor contributing to the increase in emissions across the fleet was that the GHG emissions per kg of production increased every year due to decline in catch rate. This decline in catch rate is consistent with a decrease in fish abundance, with concerns about the status of fish stocks expressed previously by the National Fisheries Research and Development Institute Korea [31] due to deterioration of coastal habitats and excessive catch, resulting in an overall decline of 10.6% [28, 29]. Decrease in fish abundance results in an increase in fishing effort to obtain the same output with associated increase in the fishing vessels’ working time, fuel consumption and GHG emissions [32].

Although decline in fish stocks appear to have contributed to an increase in fuel consumption in the Korean offshore fisheries, there is also a positive aspect to this result because it shows that management of fish harvests and thus fish stocks provides a method for controlling GHG emissions. Rebuilding of stocks through tighter controls on catch also provides benefits to fishing industries of greater economic yield and more stable production across years [33, 34]. This interaction between management decisions directed to fishery catch controls and GHG emissions was explored by Farmery et al. [28] who showed that targeting higher stock abundance and sustainable higher economic yield from fisheries can reduce the GHG emissions substantially. They estimated a reduction in GHG emissions of 80% through shifting the management target from MSY(Maximum Sustainable Yield) to MEY(Maximum Economic Yield).

This analysis also showed that GHG emissions per kg offshore fish production was highly variable between fishing method category and was very high for some. The Long Line Fishery was more than three times the average and Jigging Fishery more than two times higher than...
the average for the total offshore fisheries. This suggests that the Korean government has
opportunity to reduce overall emissions by managing the catch allocation between different
fishing method categories. This is clearly complicated however as management and policy
needs to balance between competing objectives. In these two particular fisheries, jigging sup-
plies catch from squid that are difficult to harvest by other methods, while long lining is often
seen as a more ecologically preferable to dragged gears such as trawl despite the higher emis-
sions shown here for long lining.

This study was restricted to an analysis of the GHG emissions of offshore fishery. Expansion
to the total Korean fisheries including deep-sea and coastal fisheries in the future would allow a
more integrated analysis of GHG emissions for Korean fisheries. Our analysis detected impor-
tant changes over the three-year period where data were available so future analysis with a lon-
ger term dataset would be helpful to determine if changes in efficiency and GHG emissions
were continuing in Korean fisheries.

Author Contributions
Conceived and designed the experiments: JAP CG YSJ. Analyzed the data: JAP. Contributed
reagents/materials/analysis tools: MIC DHK. Wrote the paper: JAP CG MIC DHK YSJ.

References
1. Ellingsen H, Olaussen JO, Utne IB. Environmental analysis of the Norwegian fishery and aquaculture
industry—A preliminary study focusing on farmed salmon. J. Mar. Policy. 2009; 33(3): 479–488.
2. Crilly R, Esteban A. Small versus large-scale, multi-fleet fisheries: The case for economic, social and
environmental access criteria in European fisheries. J. Mar. Policy. 2013; 37: 20–27.
3. Vázquez-Rowe I, Villanueva-Rey P, Mallo J, De la Cerda JJ, Moreira MT, Feijoo G. Carbon footprint of
a multi-ingredient seafood product from a business-to-business perspective. J. Clean. Prod. 2013; 44:
200–210
4. Ziegler F, Winther U, Hognes ES, Emanuelssoa A, Sund V, Ellingsen H. The Carbon Footprint of Nor-
wegian Seafood Products on the Global Seafood Market. J. Ind. Ecol. 2013; 17(1): 103–116.
5. Ministry of Environment Korea. GHG emission allocation plan of Korea: the ETS during the first period
(2015–2017). 2014; 1–59.
6. Lee JH. A quantitative analysis of GHG emissions from the Korean large scale purse seine fishery
using LCA method. J. Kor. Soc. Fish. Tech. 2013; 49(3): 282–290.
7. Jo JH, Kim SJ. A study on the implementation strategy of the Post Kyoto system in offshore fisheries.
R&D report published in Korea Maritime Institute. 2010; 1–193.
8. Lee JH, Lee CW. A Quantitative Analysis of GHG Emissions from the Korean Offshore Large Scale
Fisheries Using an LCA Method. J. Kor. Fish. Aqu. Sci. 2011; 44(4): 383–389.
9. Park SW, Lee KH, Kang MJ, Park SK, Lee CW, Lee JH. Economic analysis on development of low-carbon
gear for anchovy boat seine. J. Kor. Soc. Fish. Tech. 2013; 49(3): 291–300.
10. An YI. Fishing efficiency of high capacity (360W) LED fishing lamp for squid Todarodes pacificus. J.
Kor. Soc. Fish. Tech. 2014; 50(3): 326–333.
11. Encyclopedia of Korea Culture. 2015. Available: http://encykorea.aks.ac.kr/. Accessed 5 March 2015.
12. Park SW, Lee KH, Kang MJ, Park SK. Economic analysis of development of low-carbon trawl gear. J.
Kor. Soc. Fish. Tech. 2012; 48(4): 360–369.
13. FAO (Food and Agriculture Organization). Consumption of Fish and Fishery Products 2011. 2011.
Available: http://www.fao.org/fishery/statistics/global-consumption/en
14. FAO (Food and Agriculture Organization). The State of World Fisheries and Aquaculture 2012. 2012.
Available: http://www.fao.org/fishery/statistics/global-production/en
15. IPCC (Intergovernmental Panel on Climate Change). IPCC Guidelines for National Greenhouse Gas
Inventories. 2006. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
16. Statistics Korea. Fisheries Production Statistics. 2013. Available: http://kosis.kr.
17. Lee KN, Jung JH. Estimating the fisheries losses due to Chinese's illegal fishing in the Korean EEZ. J.
Kor. Fish. Bus. Admin. 2014; 45(2): 73–83.
18. National Federation of Fisheries Cooperatives (SUHYUP) Korea. Tax-free oil sales data. 2011–2013.
19. Kang YS, Lee KN. A study on the Stable Supply of Fishery Oil in Korea. J. Kor. Fish. Bus. Admin. 2000; 31(1): 115–133.
20. Kang YJ, Kim KS. The new approach of the estimation of average annual catch by the coastal vessel fishing. J. Kor. Fish. Res. 2004; 21: 27–35.
21. Kang YS, Kim DH, Jung JG. A Study on an the Effectiveness of the Fishery Buy-Back Program through Analysing Fishery Tax-free Fuel Consumption. J. Kor. Island. 2012; 24(2): 115–127.
22. Lee KN, Jung JH. Analysis of Prediction Supply of Fisheries Fuel in Korea. J. Kor. Fish. Bus. Admin. 2012; 43(1): 49–61.
23. Ministry of Oceans and Fisheries Korea, Fisheries Information Service. 2011–2013. Available: www.fips.go.kr.
24. Ministry of Government Legislation Korea. National Legal Information Center. 2014. Available: http://law.go.kr.
25. Statistics Korea. Fisheries Management Research Statistics. 2011–2013. Available: http://kosis.kr.
26. Lee HD. Improvements to the fuel-overspending fishing vessels. Korea Maritime Institute, J. Kor. Fisheries Trends. 2009; 7: 7–13.
27. The Bank of Korea. Information of International Economy. 2012; 37: 1–7.
28. Mauder MN. A general framework for integrating the standardization of catch per unit of effort into stock assessment models. J. Can. Fish. Aqua. Sci. 2001; 58(4): 795–803.
29. Kwon YJ, An DH, Lee JB, Zhang CI, Moon DY. Standardization of CPUE for bigeye (Thunnus obesus) and yellowfin (Thunnus albacares) tunas by the Korean longline fishery in the Indian Ocean. J. Kor. Soc. Fish. Tech. 2008; 44(3): 194–206.
30. Farmery A, Gardner C, Green BS, Jennings S. Managing fisheries for environmental performance: the effects of marine resource decision-making on the footprint of seafood. J. Clean. Prod. 2014; 64: 368–376.
31. NFRID (National Fisheries Research and Development Institute Korea). Korean Coastal and Offshore Fishery Census. 2010; 1–483.
32. Lee KN. Test of Fishing Activity Levels using Schaefer Model. J. Kor. Ocean and Polar Res. 2009; 31 (2):157–165.
33. Choi JY, Kim DH. An Exploratory Study on Determining Optimal Fishing Effort and Production Levels of Danish Seine Fishery under the Sandfish Stock Rebuilding Plan. J. Kor. Fish. Bus. Admin. 2012; 43(1): 1–9.
34. Gardner C, Hartmann K, Punt A, Jennings S. In pursuit of maximum economic yield in an ITQ managed lobster fishery. Fish. Res. 2015; 161: 285–292.