Assessing greenhouse gas emissions from Scotland's fishing fleet

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1 Executive summary

1.1 Context and objectives

In December 2020, the Scottish Government launched Scotland's Fisheries Management Strategy 2020-2030[1]. This strategy sets out a vision for Scotland to be a world-class fishing nation. It aims to deliver responsible and sustainable fisheries management that provides access to high protein, low carbon food. Specifically, the Strategy commits to taking action to understand and mitigate the impacts of climate change on our seas. One key task is to assess how greenhouse gas (GHG) emissions vary by fishing vessel type.

ClimateXChange, on behalf of the Scottish Government, commissioned Seafish to carry out the assessment of GHGs by vessel type. The emissions of interest are constrained to those associated with energy use on the vessel. Emissions associated with onshore activities, from transport and refrigeration, are considered out of the scope of this study.

Vessel types considered in this report cover a range of characteristics:

- The main gear used by the vessel: e.g. passive or active.
- The length of the vessel and sometimes the power of the engine.
- For demersal trawlers, the main species targeted in value: Nephrops or whitefish.
- For some vessel types, the area where the vessel mainly operates: the North Sea, West of Scotland, Area 7 (Irish and Celtic sea) or the English Channel.

Estimation of fuel use relies on statistical models linking the vessel's physical characteristics (length, engine power, gross tonnage), vessels' activity (days at sea) and information on annual fuel use. Methods developed for this project differ from the approach historically developed at Seafish, by using different groups of vessels when developing the statistical models. This change in method improved the robustness of results.

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[1] https://www.gov.scot/publications/scotlands-future-fisheries-management-strategy-2020-2030/

1.2 Main findings

In general, the longer a vessel is, the more fossil fuel is used to power the vessel and the more it emits per day of activity. The vessel types with highest emissions in the Scottish fishing fleet are composed of the largest trawlers: whitefish trawlers over 24 metres, pelagic trawlers and large Nephrops trawlers (over 300 kW). This is the result of a combination of high fuel intensity at the vessel level and the number of vessels of this type. These vessels are also amongst the most active in the Scottish fleet, with an average[2] number of days at sea significantly higher than vessels using passive gear, especially those under 10 metres.

The vessels emitting lower GHG per kilogramme of fish landed are large vessels using efficient fishing techniques: demersal seine, pair trawl, pair seine, and pelagic trawl. Small hook vessels, but also small pots and traps vessels, also have a low emitter profile when considering this indicator. At the other end of the spectrum, trawlers targeting Nephrops are among the highest emitters per kilogramme of fish, only exceeded by longlines and low activity vessels. Overall, the average GHG emissions per kilogramme of fish landed is 0.85 kg CO_2 equivalent for the entire Scottish fleet because of the high quantity of pelagic fish landed, with most vessel types emitting between 1.5 and 3 kg CO_2 equivalent per kg of fish landed.

The vessels emitting lower GHG per £ pound sterling landed are almost all in passive gear segment under 12 metres long, with the exception of large pelagic trawlers. The vessels with the highest GHG emitted by value landed are Nephrops trawler segments and two segments showing a higher variability in daily fuel use: Longliners and Demersal trawlers over 24 metres. Overall, the average GHG emissions per £ of fish landed is 0.69 kg CO_2 equivalent for the entire Scottish fleet, with vessel types emitting between 0.14 and 1.65 kg CO_2 equivalent per pound of fish landed.

The varying results arising from the different metrics above highlight that there are range of perspectives to take when considering emissions from the fishing fleet. Which metric or metrics are most appropriate will depend on the context of the particular decision or policy being considered.

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[2] In this report, average refers to the mean.

Contents

2 Introduction

The Scottish government has set a net-zero target by 2045 in line with the Climate Change Committee (CCC) recommendations. It also sets a further target to reduce emissions by 75% by 2030.

The Kyoto protocol named seven major greenhouse gases (GHG): carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, Nitrogen trifluoride, and sulphur hexafluoride. Carbon dioxide, produced by burning fossil fuels in, for example, coal power stations or engines, accounts for the majority of emissions. The primary sources of other greenhouse gases, like methane and nitrous oxide, include industrial processes and waste management, such as agriculture and landfill sites.

Sources of GHG emissions in seafood and their relative importance – including vessel fuel use, refrigerants, etc. – are set out in a specific standard by the British Standards Institution (BSI): the PAS2050:2:2012 specification for assessing GHG emissions in seafood and other aquatic food products. Several published studies acknowledge the distinctive and significant contribution that vessel fuel consumption makes to fishery-related emissions. These include studies at a global level (see Parker et al. 2018), locally for the Scottish pelagic fleet (see Sandison et al. 2021), and in Seafish analysis of selected UK seafood product chains (Harman et al., 2008).

In December 2020, the Scottish Government launched Scotland's Fisheries Management Strategy 2020-2030[3]. This strategy sets out a vision for Scotland to be a world class fishing nation delivering responsible and sustainable fisheries management which provides access to a high protein, low carbon food. Specifically, the Strategy commits to taking action to understand and mitigate the impacts of climate change on Scotland's seas, one key aspect being the establishment of a "baseline [emission] per fleet segment". The information available prior to this project does not provide sufficiently up-to-date data to define this baseline.

The research proposed here aims to assess **the baseline Greenhouse Gas (GHG) emissions per fishing fleet segment**. The emissions of interest are constrained to those associated with the vessel itself. Emissions associated with onshore activities, from transport or from onshore refrigeration, are considered out of the scope of this study.

2.1 Scotland's fishing fleet

This section provides a description of the different fishing fleets operating around Scotland. It details the different types of gear used by Scottish vessels then explains how vessels are regrouped into coherent segments.

2.1.1 Typology of fishing vessels

There are two main categories of fishing gears: active gears and passive gears. This distinction is based on the relative behaviour of the fishing gear and the target species. For passive gears, the fish moves toward the gear, while fishers chase fish with their active gears. This distinction is important notably when approaching fuel consumption. A detailed presentation of fishing gears can be found in a Seafish publication detailing a large variety of fishing methods (Montgomerie, 2015).

Trawls

Trawls are active gears. They are netting bags that are towed through the water to catch fish on their path. The trawl opening must be maintained when towed by one fishing

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[3] Future fisheries: management strategy - 2020 to 2030 - gov.scot (www.gov.scot)

vessel. This may be achieved by the insertion of a rigid frame (beam trawl). Another solution lies in the attachment of otter boards (also called trawl doors) in front of the trawl to maintain the horizontal opening of the trawl. Fitting chains on the lower part and floats on the upper part maintains the vertical opening of the trawl.

Demersal trawl

Demersal trawls are towed on the seabed. In Scotland, they are used to target a large variety of species: whitefish, such as cod, haddock, monkfish or Nephrops. The position on the seabed and the trawl opening is controlled by the towing speed.

Pelagic trawl

Pelagic trawling is a method of towing a trawl in mid-water, i.e. at any point in the water column between the surface and seabed. It is generally used to target shoaling species such as mackerel, herring and sprats.

The position of the net between the surface and seabed is controlled by the speed of the vessel, the length of the cable connecting the net to vessel (the trawl warp) and the weights of the gear. The net is opened vertically using a chain clump on each lower wing end and by the pull of the upper bridle.

Demersal seines

Demersal seines are circling nets that are shot around fish concentration. In Scotland, demersal seiners are targeting whitefish (mainly haddock). Demersal seines are similar to trawls in shape, without the need to use doors to keep the gear opened.

Dredges

Dredges are rigid structures towed along the seabed to target various shellfish species. In the UK, the main dredge fishery is for king scallops and, to a lesser extent, queen scallops, mussels, oysters, and razor clams. Each dredge is designed specifically to suit the fishery and target species.

Scallop dredges consist of a triangular frame, about 750mm wide, with a toothed bar at the front to flip the scallops out of the seabed and into a collecting bag behind it. This bag is made of chain links forming a chain mesh on the bottom and chain or netting on the top.

Pots and traps

Modern pots and traps tend to differ in shape, size and construction materials according to the behaviour of the target species and local fishing practices. However, they will all be similar in that they will have at least one tapered entrance that makes it easy for the fish to enter but very difficult for them to find their way out again.

The traps can either be shot individually or more commonly in strings (fleets), where several pots are attached to one long rope and laid on the seabed, with a dhan or buoy to mark the location of each end of the fleet. If the pots are very lightweight, as in Nephrops creels, an anchor or weight may be added at both ends of the fleet.

Hooks

A basic longline consists of a long length of line, light rope or more common now is heavy nylon monofilament, with multiple branch lines with hooks on (snoods) attached at regular intervals. On smaller inshore vessels, where baiting and handling the gear is done by hand, they may use lines that are only a few hundred metres long with a few hundred hooks attached. The larger ocean-going longline vessels with modern automatic baiting and hauling systems will shoot lines that are several miles long with many thousands of hooks on. As in most fishing methods, the amount of gear used is dictated by the size of the vessel.

There are two main types of longline fishing — demersal longline, where the lines are set on the seabed, and pelagic or midwater longlines, where the lines are set at a specific position in the water column to suit the behaviour of target species.

Nets

In basic terms, any gill net is a curtain of fine netting hung in the water, either anchored to the seabed (gill nets or set nets) or allowed to drift with the tide (drift nets) for fish to swim into and become entangled or meshed in the fine netting. Trammel nets are similar to a gill net but are made up of three layers of netting. Two outer layers of large mesh with a sheet of fine small mesh sandwiched between them.

2.1.2 The Seafish segmentation

Throughout this report, we will use the segmentation developed by the Seafish economics team over the last decade. This segmentation was developed as part of the regular Seafish economic data collection. It consists of aggregating vessels in homogenous segments, based on a combination of:

- the main gear used by the vessel,
- the length of the vessel and sometimes the power of the engine,
- for demersal trawlers, the main species targeted in value: Nephrops or whitefish,
- for some segments, the area where the vessel mainly operates: the North Sea, West of Scotland, Area 7 (Irish and Celtic sea) or the English Channel.

In total, 29 segments are defined, with the addition of two segments for less active vessels (grossing less than £10,000 per year), one segment for vessels that do not fit in other segments, and one segment for inactive vessels (vessels registered but without any activity recorded for the year) (see Figure 1).

A detailed version of the segmentation rules is available in the appendix (section 7). The segmentation is evaluated every year. Over the years, Seafish realised that this segmentation was more fluid than expected, as some vessels may move between segments every year for several reasons:

- Change in market conditions: some segments are defined by the top group of species landed by value. A change in quota allocations or different price trends between whitefish and Nephrops may change the allocations of vessels between value whitefish trawl segments or Nephrops trawl segments.
- Change in activity: vessels are allocated to gear groups based on the days at sea spent using each group of fishing gear: some vessels use trawl and dredge in the same year. Depending on sea and market conditions, vessels may spend more days dredging for Scallops or trawling for Nephrops.
- Change in fishing grounds: this is notably the case for Nephrops trawlers for which segments are defined according to three areas: the North Sea, West of Scotland and Area 7. Some vessels may therefore switch segments depending on their activity.

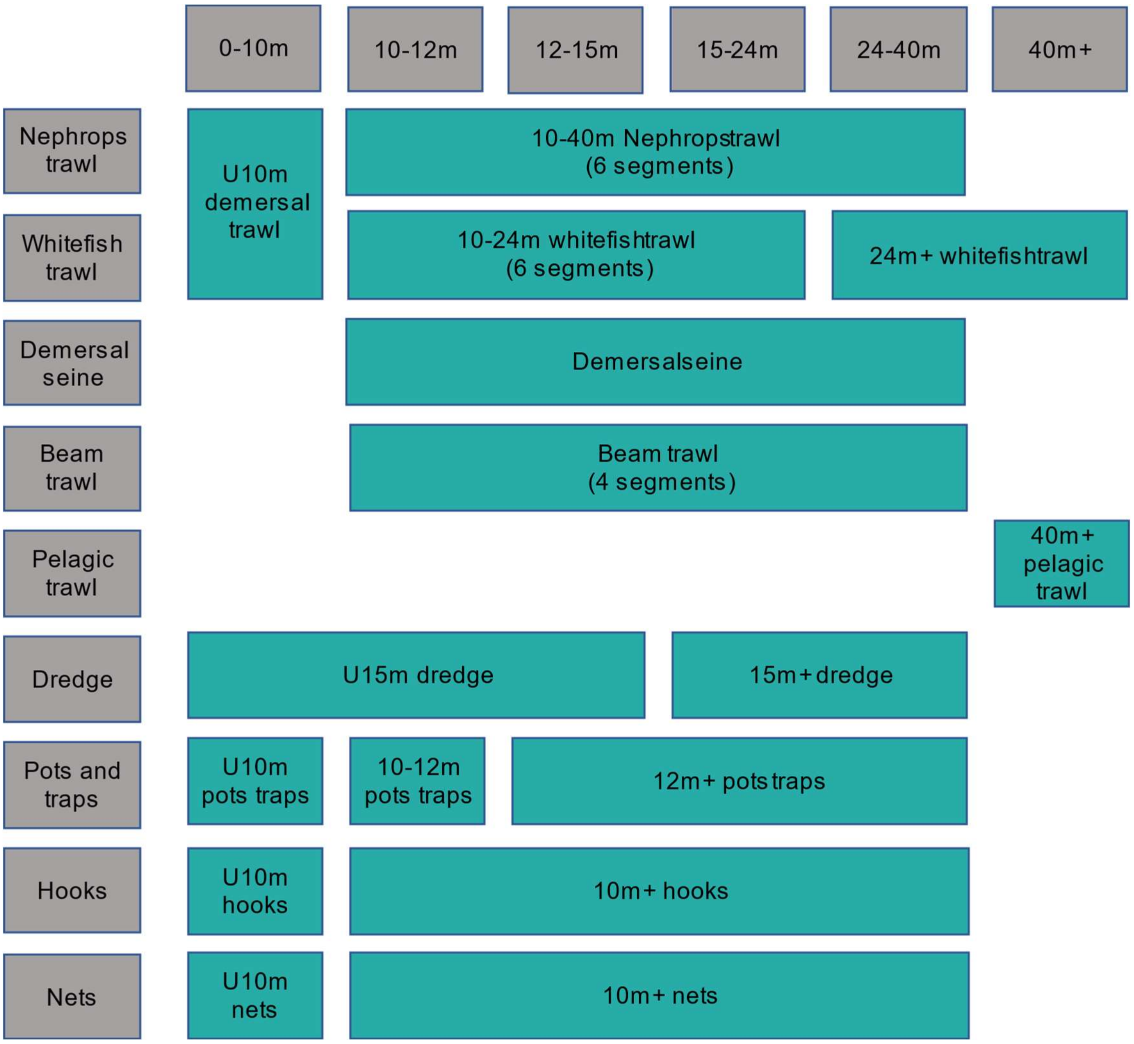

Figure 1: First steps of the Seafish segmentation: grouping vessels by the main gear used and vessel length classes

2.2 Greenhouse gas emissions in fisheries

This section provides a description of the different sources of greenhouse gas emissions in fishing fleets.

2.2.1 Sources of GHG emissions in the fishing industry

All fishing vessels may be modelled following a similar model (Figure 2), which has been described in several publications (see notably Harman et al. 2008, Winther et al. 2009 or Parker 2012). The BSI standard PAS 2050:2011 also has a specific chapter related to seafood and other aquatic food products, describing notably the different GHG sources to be considered when looking at a fishing vessel.

Several sources may be considered:

- Energy consumption is expected to have a significant impact on the fuel emissions of a fishing vessel. Energy is used for propulsion but also for powering all auxiliary systems (onboard electricity, hydraulics). All fishing vessels currently in the fishing fleet are relying on fossil fuels, mainly marine diesel[4]. Alternative fuels such as biofuels or hydrogen are currently at the pilot level, at best.

- Refrigerant losses may potentially have a significant impact, but their use is highly dependent on the existence of an onboard refrigeration system.
- Inputs such as ice or bait result in some GHG emissions which should be accounted within the total emissions of the fishing vessel but are highly variable amongst the fleet and are estimated to have a low impact on the total GHG emissions (see notably Harman et al. 2008). Bait is only used by some gears (pots & traps and hook) and the emissions associated with the ice notably depend on the source of the electricity used to produce it.
- Gears and packaging used onboard fishing vessels are generally considered to have a potential low impact (see notably Parker 2012).
- Some standards, like the Norwegian NS4918 standard, also integrate the impact of the construction of fishing vessels into the overall GHG emissions, using an estimation of the expected lifetime of the vessel and the total landings achieved during it. The PAS2050 standard (used in the UK) does not require it.

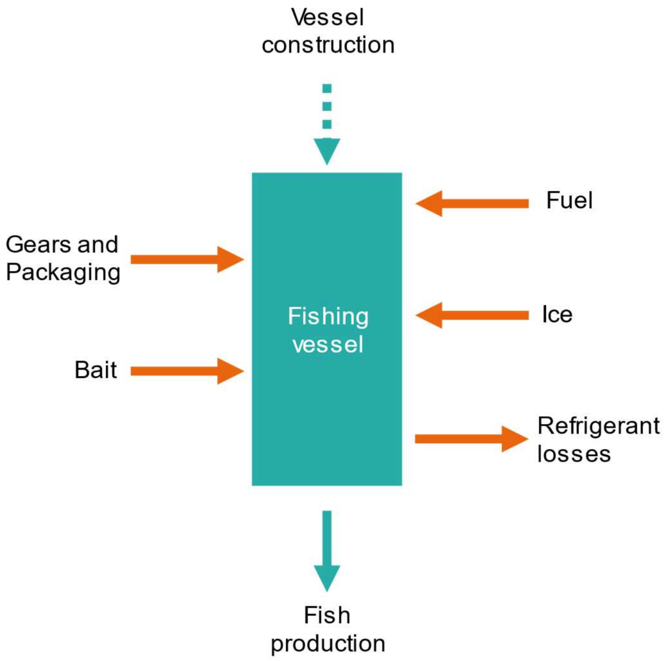

Figure 2: Flow diagram of theoretical vessel inputs and outputs related to emissions

2.2.2 Sources of variability in GHG emissions

<u>Diversity of vessel designs and motorisation</u>

Many fuel-intensive sectors have been evaluating their fuel emissions over the last 20 years. The automotive industry, but also manufacturers of lorries, tractors or construction machinery, can provide typical fuel consumptions for all the vehicles they produce. Legally, manufacturers are mandated to indicate the fuel efficiency of their products before any sale. For each type of car, lorry or tractor, the engine options are limited, well known, and commercialised by hundreds (lorries and tractors) or thousands (cars).

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[4] Although marine diesel and road diesel have very close specifications, they do not follow the same standards: marine diesel specifications are defined by the IMO MARPOL convention, while road diesel specifications follow the EN 590 standard.

The fishing sector is in a different position: almost all fishing vessels are unique, sister ships are the exceptions. Each vessel has its own combination of engine, gearbox and shaft, which makes it more complex to generalise fuel consumption based on a sample of fishing vessels.

How fishing methods may influence fuel consumption

The physical stress supported by the engine is different when vessels are steaming, shooting gear or towing gear. Several research papers have explored the allocation of fuel consumption based on the activities realised by fishing vessels in comparable fleets operating in Europe (Table 1). There is notably a significant difference between vessels using active gears (demersal trawlers, seiners, dredgers) and vessels using passive gears (pots & traps, nets, hooks).

Active gears usually require more fuel to be used when the gear is in action. For these vessels, the fishing time represents more than 75% of the fuel consumption of a fishing trip.

For passive gears, steaming from and to the fishing grounds is the main activity in terms of fuel consumption.

Table 1: Variation of fuel consumption pattern depending on fishing gear for comparable fleets in Europe

Fishing gear	Fuel consumption allocation in a fishing trip		Reference
	% Steaming	% Fishing	
Danish seine (16 m)	20	80	Thomas et al., 2010
Semi-pelagic trawler (28 m)	51-54	46-49	Sala et al., 2011
Coastal trawler (24 m)	24	76	Parente et al., 2008
Trawler (39 m)	25	75	Basurko et al., 2013
Gillnetter (26 m)	76	24	Basurko et al., 2013
Hand liner (26 m)	86	14	Basurko et al., 2013

3 Methodology

This section presents how we have approached the data collection for this project and how we've used existing data and new data to estimate daily fuel consumption for the Scottish fishing fleet.

A key aspect of this method is that data collection has not been limited to Scottish vessels (the focus of this project). Instead, we have used as much information as possible to improve our sample. Over the years, vessels were able to move from one nation to the other and discussions with the industry led us to consider that the difference between vessels is better captured by the Seafish segmentation than by the nation where the vessels are registered. Although we primarily contacted Scottish companies for this project, vessels currently registered in England and Northern Ireland were not ruled out. The data collection and the statistical analysis integrated all vessels in our sample in order to develop the statistical models, but the final emission results are based on the Scottish fishing fleet only (i.e. the statistical models are only applied to the Scottish fleet in order to calculate the data presented here).

3.1 Data sources

The British fishing fleet can be quite complex to model and analyse due to a range of different factors: scale, gear and fishing typology, fishing areas, species targeted, seasonality, vessel length and engine power. The variety and heterogeneity of the British fleet is the main factor considered when fleet survey exercises are designed and implemented. The main objective is to collect data through the whole spectrum of the fleet typology.

3.1.1 Existing Seafish data

Since the early 2000s, Seafish has been involved in the collection of economic data for the UK fishing sector. Every year, Seafish staff contact skippers and vessel owners to get permission to access their balance sheets describing costs and earnings. A short survey is performed when collecting these permissions, notably collecting information on daily fuel use. Skippers and owners usually respond directly during the survey, without consulting any record they would have kept. Seafish has always considered that the impact on the estimation accuracy generated by relying on the skipper/owner memory, and not an actual record, would be minimal.

Seafish retrieves annual fuel costs from the detailed cost structures collected for all vessels in the sample. However, there are no strict accounting rules in the UK forcing the reporting of fuel costs as a standalone item. For most of the accounts collected by Seafish, fuel costs are aggregated with other costs, such as lubricants or sometimes maintenance. Due to these shortcomings, Seafish were not able to relate daily fuel use, days at sea and annual fuel costs from the accounts collected for the Seafish sample. Moreover, the data collected during the initial years did not allow Seafish to estimate linear regressions between the daily fuel use and vessel characteristics for each Seafish segment.

3.1.2 New data collected

The fuel data collection process for this study was designed and implemented using a hybrid approach to test different methods, strategies, and channels. Depending on local arrangements, fuel data holders may be the vessel owner, the agent, rarely the accountant and most of the time the fuel provider. However, all stakeholders consulted consider that the vessel owners are the fuel data owners. As a result, an initial list of stakeholders, with and without vessel ownership was proposed. The main aim was to combine stakeholders that were data owners and/or data holders.

The list was kept open and flexible through the whole data collection stage to maximise results due to different reasons:

- Several companies confirmed that they do not have such data.
- Some companies communicated that they do have the data but are unable to provide it for different reasons (GDPR, time and human resources, infrastructure to separate fishing from other accounts)
- Several vessel owners forwarded researchers to their fuel providers.
- Companies joined the data provision after showing interest in the project.

Information requested and approach

The information requested of the different stakeholders was always the same, volume of fuel supplied per week/month and date, for at least a whole year among the 2016-2021 period. The price or cost of fuel supplied was not requested.

Data delivered	PLN	Vessel Name	Location	Litres Delivered

As well as the fuel consumption, the Personal License Number (PLN) or the Registry of Shipping, and Seamen number (RSSNO), the name of the vessel was also requested so that fuel data could be correlated with vessel characteristics such as vessel length, power of the engine, gross tonnage, type of gear, and most common fishing area. PLN, RSSNO and vessel name are not considered confidential information. The harbour where the fuel was provided was also requested to be able to define and model an origin for the fishing trip or landing of the catch.

The format of the data provided was chosen by the data supplier: excel records, csv dataset, list of refills on pdf, copies of invoices, etc. The main objective was to ease the effort required by the data supplier as it can be a very time-consuming process.

The main constraints encountered during the data collection stage were:

- **Timing and deadlines:** The data was initially requested prior to the end of year festivities when fishers and processors remain busy until after summer. The bulk of the data was agreed to be supplied by most of the stakeholders towards the new year. Tax return and fiscal year also added pressure to the people in charge or able to supply the data from different companies.
- **GDPR and data holder/owner issues:** Conversations were had with different fuel suppliers regarding their ability to supply the data. While some of them provided the information relatively quickly with just a verbal confirmation from the vessel owners, others requested written or signed permission from the owner. Some of these discussions about data sharing agreements were still ongoing at the time of writing this report.

3.2 Generating relationships between vessel characteristics and fuel use

The main assumption behind the method developed for this project is that fuel use can be linearly explained by the fishing vessels' physical characteristics. The three physical characteristics considered here are the length of the vessel, the engine power and the gross tonnage, which is an indication of the vessel volume. These dimensions are known for every fishing vessel registered in the UK. More characteristics are known but were not used for the statistical analysis for the following reasons:

- The previous method to allocate fuel consumption per segment relied on the Vessel Capacity Unit (VCU), but including VCU would cause statistical issues (multicollinearity) as this indicator is a combination of the length and an approximation of the gross tonnage
- The age of the vessel is often a characteristic cited to explain differences in fuel use, with the underlying assumption that recent vessels should be more efficient than the older part of the fleet. However, there is no information regarding potential improvements made to the vessel recorded in databases (modification of the engine, of the shaft, refitting), which significantly reduces the ability for this indicator to inform the level of fuel use statistically.

We used the Seafish sample data from 2014 to 2020, using the latest record for each vessel in the sample, in combination with the new data collected.

To estimate these relationships, we have regrouped the vessels following the Seafish segmentation but based on the main gear they are using. Some segments are close in terms of vessel compositions, with vessels switching between segments depending on external circumstances. Keeping them apart, at least for estimating fuel consumption, lowers the statistical robustness of the results. For this reason, the 29 active Seafish segments were regrouped into less than a dozen gear groups. We then tested if splitting these large groups into subgroups may improve the quality of the regressions (Figure 3).

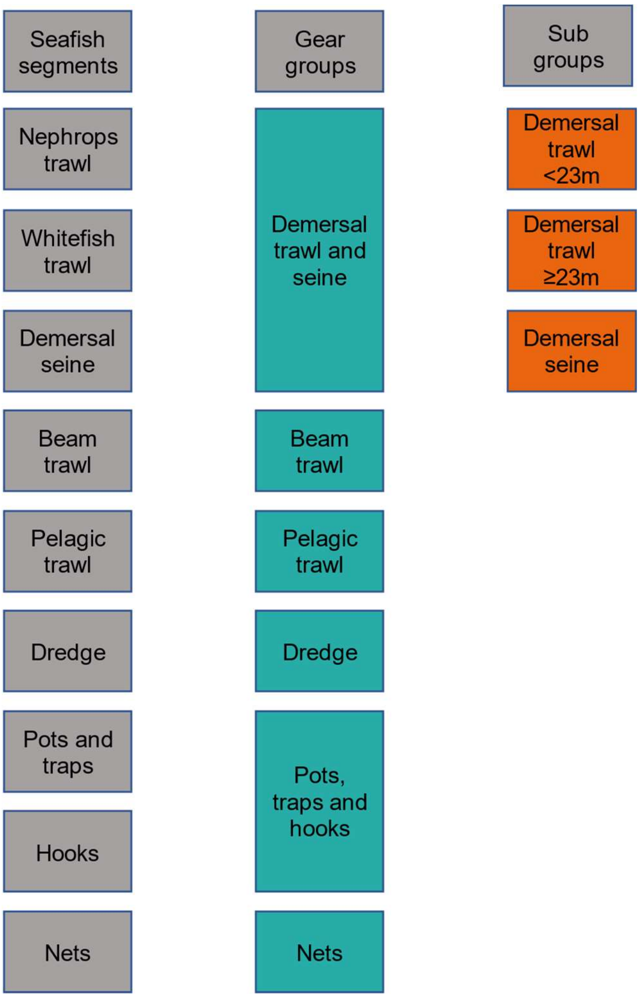

Figure 3: Segment groups, alternative to the Seafish defined segments, implemented to improve the power of the statistical regressions

Statistical regressions were fitted for each gear group, with one group being split into three: demersal trawlers and seiners (DTS) are split into two sub-groups of demersal trawlers (based on the size of the vessels) with an additional group for seiners and vessels working in pairs.

Minority gears were regrouped for the projections, as there's no sample to estimate separate models for them. The minority gears are:

- **Hooks -** The sample used does not contain enough vessels using hooks to be able to create a standalone group. After discussions with some stakeholders, we regrouped these vessels with vessels using pots and traps.

- **Polyvalent passive gears** (PGP) **and mobile and passive gears** (PMP) are grouped with pots and traps, as they mostly fall in the pots and traps segment in the Seafish segmentation (mainly targeting crustaceans).
- **Purse seiners** (PS) **and Trawlers using pelagic gears** (TM) to target whitefish species or equivalent (squid) are grouped with Demersal Trawlers.

All segments have been modelled using the following routine (see Appendix 4 for more details, in particular regarding the R packages used to perform the different tests):

1. Select a first model for the entire gear group based on a recursive search of the best combination.
2. Test if splitting the gear group into two or more sub-groups improves the quality of the regression, using a recursive Chow test.
3. If this is the case, recheck for each subgroup if the general model must be fitted again, or if it is necessary to modify the variables integrated into the linear regression.
4. Recursively eliminate all variables not significantly participating in the linear regression
5. Apply the model to the part of the vessel population using the same gears.

This process allows us to define a specific model for each subgroup (given in Appendix 5). Subgroup models vary in the explanatory variables (e.g. vessel length or power) used to estimate the fuel consumption, as determined by the approach outlined above.

3.3 Estimating emissions from fuel use

The estimation of the daily fuel use for each vessel (Section 3.2), is combined with the number of days at sea recorded by Marine Scotland for each fishing vessel in the Scottish fleet to estimate the annual fuel consumption. The GHG emissions are estimated using a value for each diesel litre burned. The value used in calculations here is 3.05 kg of CO_2 equivalent emitted per litre of fuel burned by a fishing vessel. This value also includes all steps that occur prior to the delivery of fuel (e.g. extraction and transport of fuel) to the fishing vessels and has been estimated by Norwegian researchers (Winther et al., 2009). It has been used in various Seafish projects about carbon emissions in fisheries, notably the two tools available on the Seafish website[5].

4 Key results

4.1 Daily fuel consumption per segment

This section presents the main results of the statistical analysis. More details can be found in appendix 4 (section 10.1).

The first step of our approach consists of estimating daily fuel use for each vessel in the Seafish population, based on models derived from the different linear regressions. For several groups, we were able to perform specific regressions only because we received enough new data during this project to complement the data already collected during the annual survey. Considerations for each segment are outlined below.

Demersal trawlers

We concluded that there are two groups of demersal trawlers, which are differentiated with a threshold on vessel length. The statistically tested best fit was 23 metres. This

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[5] See the page Seafood CO2 Emissions Profiling Tool

means that the fuel consumption for smaller trawlers is calculated differently from larger trawlers.

The first model integrates length, engine power, the ratio between engine power and length and the ratio between gross tonnage and length. For larger vessels, the length of the vessel does not participate in the statistical explanation of the daily fuel use.

Demersal seiners and pair vessels

Thanks to data collected during this project, we were able to estimate a specific model for seiners and pair vessels (pair trawlers and pair seiners). These vessels use active gears but, unlike demersal trawlers, they do not require doors which has a significant impact on their fuel consumption due to lower drag. Nonetheless, they are amongst the vessels with highest daily fuel use per day at sea.

The model integrates length, engine power, the ratio between engine power and length, the ratio between gross tonnage and length and the ratio between gross tonnage and power.

Pelagic trawlers

Seafish have encountered difficulties for several years when collecting data for this specific segment. In this study, a different approach was used when collecting data for this segment. We approached different stakeholders than during the annual data collection run by Seafish, and limited the questions to fuel use. As a result we were able to collect sufficient data for the pelagic trawlers.

The model integrates the ratio between gross tonnage and vessel length.

Dredgers

The data collection for this project significantly improved the information describing fuel use for dredgers. Based on the data available, the fuel consumption is well described as a function of the engine power.

Pots and traps

Pots and traps are generally well represented in the Seafish sample but large vessels (over 10 m) are under-represented in the sample and this project has not improved that.

Based on the data available, the model integrates the ratio between power and gross tonnage.

Hooks

These vessels are not well represented in the Seafish sample, and this project has not improved that. The variability in the sample did not allow a separate model to be generated. After discussion with some industry stakeholders, we have regrouped these vessels with the group of pots and traps to have a reference to use to predict each vessel's daily fuel use.

Nets

Like the pots and traps, these vessels are well represented in the Seafish sample except that large vessels (over 10 m) are underrepresented.

Based on the data available, the model integrates the ratio between power and gross tonnage.

In general, large vessels using passive gears are not well represented in the Seafish segment, and they may benefit from a dedicated pilot during the regular Seafish economic data collection, during which fuel use data is collected.

The range of daily fuel use estimated is represented for each segment using a boxplot (Figure 4): the box limits are defined by the first and the third quartiles for each segment, while the middle line shows the median of the segment. Lines on each side of the box show the range between the minimum and the maximum daily fuel use for each segment. Some segments present a wider variability, which is the result of a high variability in the main vessel characteristics:

- The segment Demersal trawlers over 24m combines vessels from 24 meters long to 45 meters long, with a gross tonnage ranging from 168 GT to 748 GT,
- The segment Dredgers over 15m combines vessels with power ranging from 128 kW and 1095 kW.
- The segment longliners combines vessels from 10 meters long to 38.25 metres long.

Vessels using active gear are on average burning more fuel per day than vessels using passive gear. Within a similar gear group, length is a significant variable to explain daily fuel consumption, the larger a vessel is, the more fuel it burns daily.

Pelagic vessels are the group burning far more fuel than any other segment on a daily basis: their daily fuel use ranges from 10,000 to 35,000 litres, with a median just over 25,000 litres, while almost all other segments have a daily fuel use below 2,000 litres. Pelagic vessels are significantly larger than the rest of the Scottish vessels with an average length of 72 metres and an average engine power of 5800 kW, compared to an average length of fewer than 12 meters and an average engine power of 200 kW for the rest of the Scottish fleet.

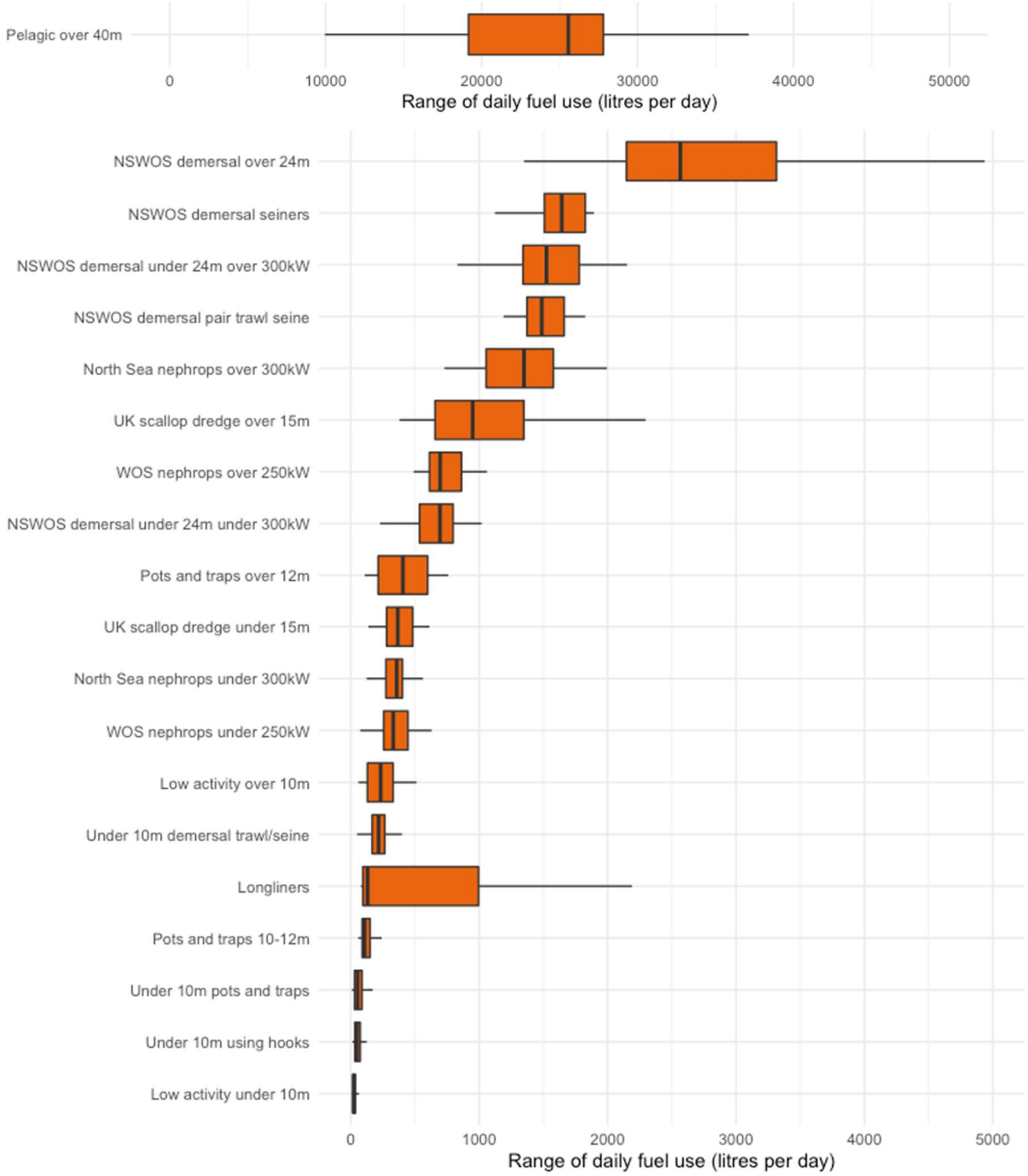

Figure 4: Range of the daily fuel use per Seafish segment (only segments of more than five vessels) – pelagic vessels are represented on a different X axis.

4.2 From fuel consumption to GHG emissions

Annual fuel consumption is estimated for each vessel by multiplying the modelled daily fuel use by the number of days at sea recorded by the Marine Management Organisation (MMO). These fuel consumptions are then translated into greenhouse gas emissions by using an emission ratio of 3.05 kg of CO_2 equivalent per litre burned (see appendix 4 (section 10.1) for the method and Figure 5 for the results).

The key lesson from this indicator is that the segments with the highest average length are the larger emitters in absolute value: large demersal trawlers, large pelagic trawlers, and vessels over 300 kW are the highest GHG emitters. This is the result of a combination of high fuel intensity at the vessel level and the number of vessels in these segments. Vessels in these segments are also amongst the most active in the Scottish fleet, with an average level of days at sea significantly higher than passive gear segments, especially those under 10 metres. The only exceptions are:

- the pelagic trawler segment: a few vessels (20) that are only active 40 days a year on average, but have individually high fuel use.
- the under 10 metres pots and traps segment: there are many vessels (551) that are active 87 days a year on average and have individually small fuel use.

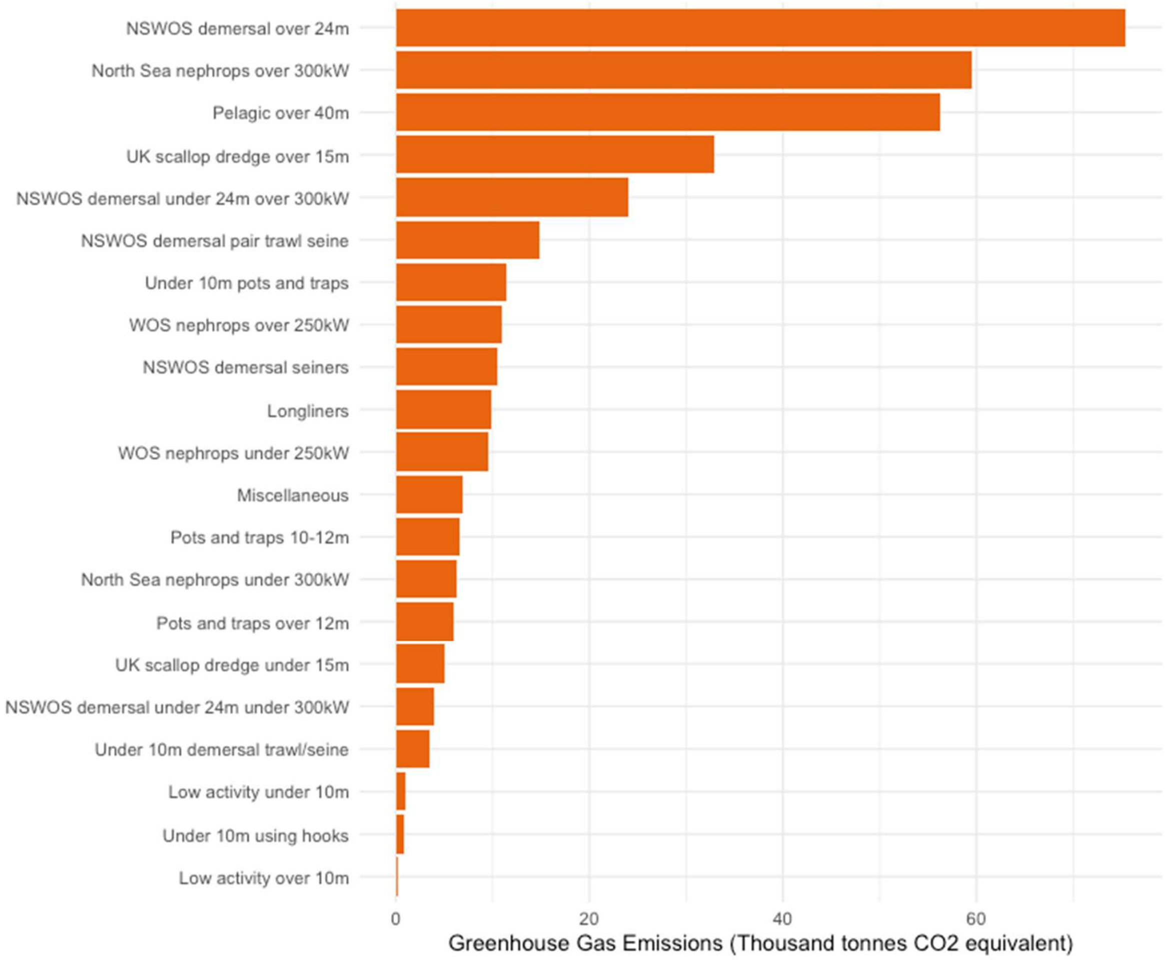

Figure 5: Greenhouse Gas Emissions per Seafish segment (only segments of more than five vessels)

4.3 GHG emissions per kilogramme of fish landed

GHG emissions per kilogramme of fish landed represents another metric for comparing fleet segments. We have used the landing information provided by the MMO for all vessels to determine this indicator. A detailed table can be found in Annex 6 (section 12).

Like several other publications (see notably STECF 21-08, page 46), the results presented in this report tend to show that per kilogramme of fish landed, the segments with the lowest GHG output are composed of large vessels using efficient fishing techniques: seine, pair trawl, and seine and pelagic trawl. Small hook vessels but also small pots and traps vessels also have a low emitter profile when considering this indicator. At the other end of the spectrum, trawlers targeting Nephrops are amongst the highest emitting segments, only exceeded by longlines and low activity vessels. For most Scottish segments, the average GHG emissions associated with one kilogramme of fish landed ranges from 1 to 3 kilogrammes equivalent CO_2, with the exceptions being the under 10 metres vessels using hooks and the pelagic trawlers over 40 metres. The results for the low activity vessels over 10 metres is mainly linked to the low level of activity and not the physical characteristics of the vessels.

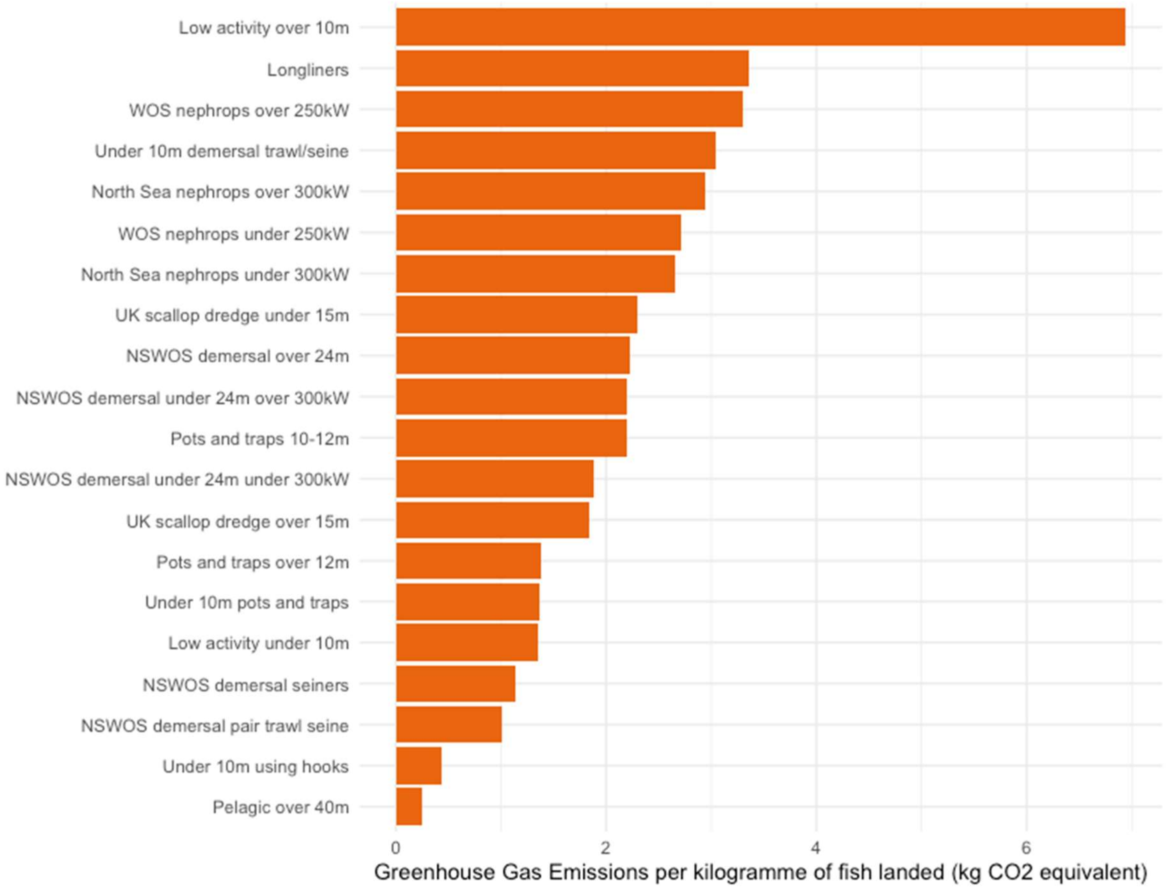

Figure 6: greenhouse gas emissions per kilogramme of fish landed (only segments of more than five vessels).

4.4 GHG emissions per pound sterling of fish landed

These emissions could also be compared with the monetary value of fish landed by each segment, GHG emissions per pounds sterling of fish landed represents another metric for comparing fleet segments. We have used the information on value landed provided by the MMO for all vessels to determine this indicator. A detailed table can be found in Annexe 6 (section 12).

The vessels that result in the least GHG emitted by value landed are almost all in passive gear segment under 12 metres long, with the exception of large pelagic trawlers. The vessels with the highest GHG emitted by value landed are Nephrops trawler segments and the three segments showing a higher variability in daily fuel use: Longliners, Demersal trawlers over 24 metres and Scallop dredgers over 15 metres. The segment regrouping low activity vessel over 10m has the highest ratio of GHG emitted by value landed, but the results are skewed by the low level of activity of this segment.

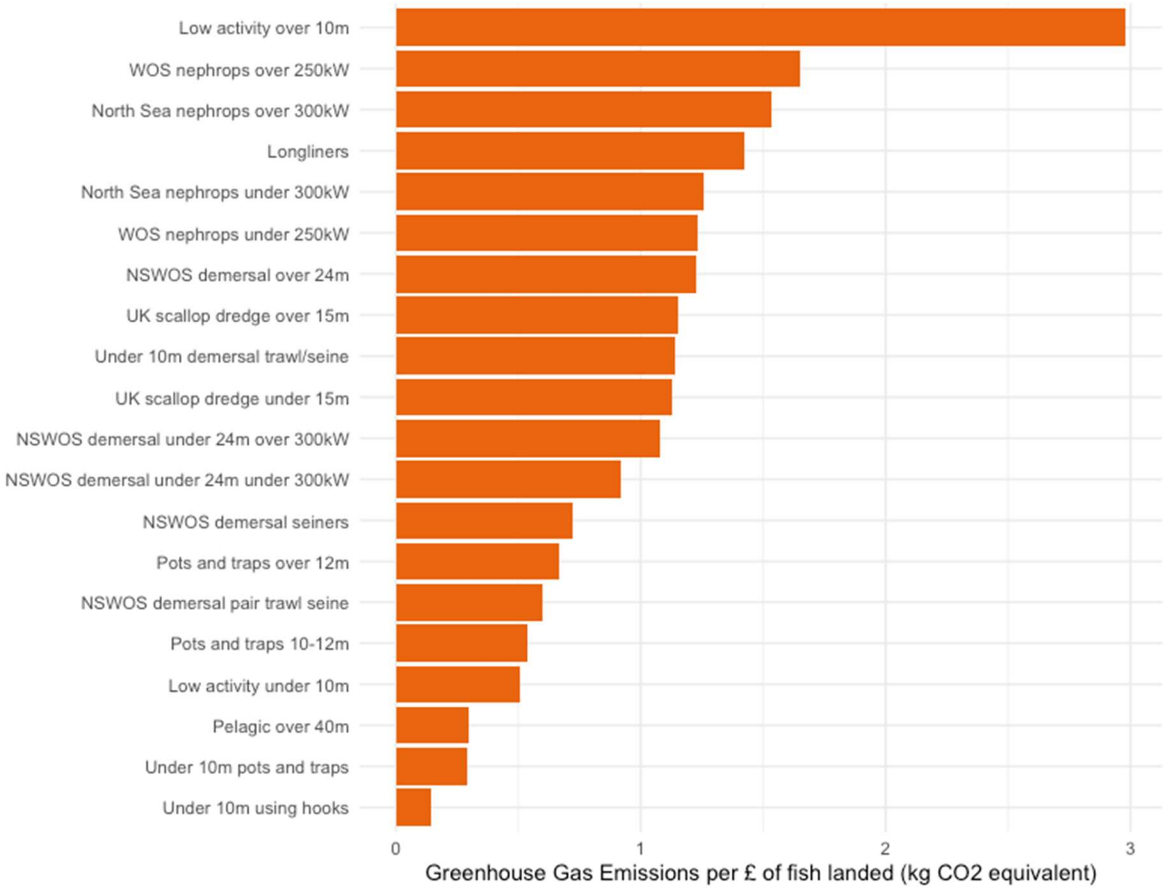

Figure 7: Greenhouse gas emissions per value of fish landed (only segments of more than five vessels).

5 Conclusions

Despite some hurdles, new data collected here has allowed for development of new approaches to estimate daily fuel consumption, and therefore emissions, by vessel characteristics. A particular hurdle to access the data was data ownership. We believe this could be overcome in the long term by agreeing on better protocols to identify data owners and data providers.

A baseline has been established for the greenhouse gas emissions associated with the primary source for fishing vessels: the use of fossil fuel. Other sources such as refrigerant losses were not covered by this data collection. Overall, the baseline is in line with other assessments: the larger a vessel is, the more it emits per day of activity.

The segments emitting most of the greenhouse gas of the Scottish fishing fleet are composed of the largest trawlers: whitefish trawlers over 24 metres, Pelagic trawlers and large Nephrops trawlers (over 300 kW). This is the result of a combination of high fuel intensity at the vessel level and the number of vessels of this type. These vessels are also amongst the most active in the Scottish fleet, with an average number of days at sea significantly higher than vessels using passive gear, especially those under 10 metres. A summary table ranking segments according to key metrics is available in the Appendix (Section 13).

Combining the estimates with landings data, we were also able to estimate two important indicators to provide an additional perspective of emissions of each segment: the greenhouse gas emissions per kilogramme of fish landed and the greenhouse gas emissions per value landed. Using these indicators, additional segments are highlighted as important when developing policy to reduce emissions.

Some segments are indeed high emitters, but they are also very efficient in catching fish for a given level of greenhouse gas emission. The vessels emitting lower GHG per kilogramme of fish landed are large vessels using efficient fishing techniques: seine, pair trawl, pair seine and pelagic trawl. Small hook vessels, but also small pots and traps vessels, also have a low emitter profile when considering this indicator. At the other end of the spectrum, trawlers targeting Nephrops are among the highest emitters per kilogramme of fish, only exceeded by longlines and low activity vessels. Overall, the average GHG emissions per kilogramme of fish landed is 0.85 kg CO_2 equivalent for the entire Scottish fleet, with most vessel types emitting between 1.5 and 3 kg CO_2 equivalent per kg of fish landed.

Some segments are also high emitters, but the value of fish landed is higher than other segments. The vessels emitting lower GHG per pound sterling landed are almost all in passive gear segment under 12 metres long, with the exception of large pelagic trawlers. The vessels with the highest GHG emitted by value landed are Nephrops trawler segments and two segments showing a higher variability in daily fuel use: Longliners and Demersal trawlers over 24 metres. Overall, the average GHG emissions per £ of fish landed is 0.69 kg CO_2 equivalent for the entire Scottish fleet, with vessel types emitting between 0.14 and 1.65 kg CO_2 equivalent per pound sterling of fish landed.

When looking at the three metrics above, the four Nephrops trawl segments are all high emitters. At the other end of the spectrum, the pelagic trawl segment is one of the largest emitters of the Scottish fleet, but it is also very efficient, with the lowest ratio of CO_2 equivalent per kilogramme of fish landed and close to the lowest ratio of CO_2 equivalent per value of fish landed.

A key outcome of this research has been to establish the baseline greenhouse gas emissions of the Scottish fishing fleet. In addition, our results indicate that consideration of other metrics is important to provide context and understanding to inform policy efforts to minimise emissions.

The GHG associated with the fish acquired by the final consumer rely also on the organisation of the post-harvest sector, which generate further greenhouse gas emissions due to transport, cold storage, and product losses. On average, a kilogramme of fillet eaten by the final consumer is equivalent to 2 to 2.5 kg of fish landed by the fishing vessels (see for example FAO 1992). One of the key factors inflating the GHG emissions associated with the fillet is linked to the destination of the other fish fractions (head, bones, skin, etc.). If these fractions are considered as waste, their emissions are accounted with the fillet. If other uses are found, the share of emissions associated with these fractions is associated with these new uses. It is therefore essential for the seafood sector to identify as much as possible the potential use of co-products to avoid the loss of fractions which could be part of a commercial offer: fishmeal used to feed various animals (pigs, poultry, farmed fish), fractions reintegrated in preparations such as soups, or prepared meals, but also other potential co-products. Nonetheless, the evaluation of greenhouse gas emissions associated with seafood value chains tends to indicate that the production step is one of the major emitters in the supply chain, except if the product is transported by air freight (see notably Harman et al. 2008, Winther et al. 2009 or Parker 2012). For all other operational modes in post-harvest, fishing activities remain the value chain step explaining a large share of the greenhouse gas emissions.

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7 Appendix 1 – Qualifying criteria for the Seafish fleet segments

Seafish Segment	Main ICES Area	Main DAS Gear	Main Species by value	Main Gear Type	Power Main Engine	Vessel Length	Value of landings
Area VIIA demersal trawl over 10m	VIIA	Demersal trawls and seines				>= 10m	
Area VIIA nephrops over 250kW	VIIA	Demersal trawls and seines	Nephrops		>= 250 kW	>= 10m	
Area VIIA nephrops under 250kW	VIIA	Demersal trawls and seines	Nephrops		<250 kW	>= 10m	
Area VIIb-k trawlers 10-24m	VIIDE, VIIFG, VII other	Demersal trawls and seines	Not Nephrops			>= 10m & <24m	
Area VIIb-k trawlers 24-40m	VIIDE, VIIFG, VII other	Demersal trawls and seines	Not Nephrops			>= 24m & <40m	
UK Gill netters over 10m		Drift Nets and Fixed Nets	Not Nephrops			>= 10m	
UK Longliners over 10m		Gears using hooks	Not Nephrops			>= 10m	
Low activity vessels over 10m						>= 10m	< £10,000
Low activity vessels under 10m						< 10m	< £10,000
Miscellaneous vessels over 10m						>= 10m	
North Sea beam trawl over 300kW	NS	Beam Trawl	Not Nephrops		>= 300 kW	>= 10m	
North Sea beam trawl under 300kW	NS	Beam Trawl	Not Nephrops		< 300 kW	>= 10m	
North Sea nephrops trawl over 300kW	NS	Demersal trawls and seines	Nephrops		>= 300 kW	>= 10m	
North Sea nephrops trawl under 300kW	NS	Demersal trawls and seines	Nephrops		< 300 kW	>= 10m	
North Sea and West of Scotland demersal trawl over 24m	NS, WoS		Not Nephrops			>= 24m	
North Sea and West of Scotland demersal pair trawls and seines	NS, WoS	Demersal trawls and seines	Not Nephrops	Paired Trawl		>= 10m	
North Sea and West of Scotland demersal seiners	NS, WoS	Demersal trawls and seines	Not Nephrops	Scottish Seiner		>= 10m	
North Sea and West of Scotland demersal trawl under 24m, over 300kW	NS, WoS	Demersal trawls and seines	Not Nephrops		>= 300 kW	>= 10m & <24m	
North Sea and West of Scotland demersal trawl under 24m, under 300kW	NS, WoS	Demersal trawls and seines	Not Nephrops		< 300 kW	>= 10m & <24m	

Seafish Segment	Main ICES Area	Main DAS Gear	Main Species by value	Main Gear Type	Power Main Engine	Vessel Length	Value of landings
UK pelagic trawl over 40m		Pelagic: Trawl, Seiner / Purse Seiner	Mackerel			>= 40m	
UK pots and traps 10m-12m		Pots and Traps				>= 10m & <12m	
UK Pots and traps over 12m		Pots and Traps				>= 12m	
South West beam trawl under 250kW	VIIDE, VIIFG, VII other	Beam Trawl			< 250 kW	>= 10m	
South West beam trawl over 250kW	VIIDE, VIIFG, VII other	Beam Trawl			>= 250 kW	>= 10m	
UK demersal trawls and seines under 10m		Demersal trawls and seines				< 10m	
UK drift and fixed nets under 10m		Drift Nets and Fixed Nets				< 10m	
UK pots and traps under 10m		Pots and Traps				< 10m	
UK hooks under 10m		Gears using hooks				< 10m	
West of Scotland nephrops trawl over 250kW	WoS	Demersal trawls and seines	Nephrops		>= 250 kW	>= 10m	
West of Scotland nephrops trawl under 250kW	WoS	Demersal trawls and seines	Nephrops		< 250 kW	>= 10m	
UK scallop dredge over 15m		Dredges	Scallops, queen scallops, cockles			>= 15m	
UK scallop dredge under 15m		Dredges	Scallops, queen scallops, cockles			<= 15m	

8 Appendix 2 - Main characteristics of the Scottish segments

	Vessels (number)	Length (m) (average)	Power (kW) (average)	Ton GT (average)	Days at sea (average)	Quantities landed (tonnes) (average)	Value landed (£ 000s) (average)	Age of vessel (year) (average)
Under 10m demersal trawl/seine	51	9,7	109	11	68	17	45	31
North Sea Nephrops under 300kW	46	13,8	171	36	101	45	95	42
North Sea Nephrops over 300kW	47	20,1	433	160	167	241	462	23
WOS Nephrops under 250kW	51	15,2	171	41	130	50	111	42
WOS Nephrops over 250kW	23	17,3	307	82	147	101	202	40
NSWOS demersal over 24m	36	27,8	730	334	204	880	1602	18
NSWOS demersal pair trawl seine	18	26,0	530	252	182	840	1418	27
NSWOS demersal seiners	14	26,0	569	264	162	724	1145	13
NSWOS demersal under 24m over 300kW	38	21,1	490	185	174	406	829	19

	Vessels (number)	Length (m) (average)	Power (kW) (average)	Ton GT (average)	Days at sea (average)	Quantities landed (tonnes) (average)	Value landed (£ 000s) (average)	Age of vessel (year) (average)
NSWOS demersal under 24m under 300kW	9	16,9	265	77	154	170	349	35
Pelagic over 40m	20	72,9	5791	2737	41	12553	10323	7
UK scallop dredge under & over 15m	82	18,9	321	102	129	197	325	32
Under 10m pots and traps	551	8,0	80	5	76	12	57	24
Pots and traps 10-12m	87	11,2	144	12	145	27	109	30
Pots and traps over 12m	23	16,2	267	82	189	195	405	24
Under 10m using hooks	90	7,8	70	4	40	16	49	25
Longliners	18	17,6	228	91	139	124	293	39
Other	13	27,7	705	272	174	660	850	38
Low activity	497	6,8	39	3	19	1	4	29
All Scotland	1714	11,4	209	68	79	226	279	27

9 Appendix 3 - Sample Size

Table 2: Existing Seafish Sample size by year and segment – number of vessels identified each year (from 2014 to 2020) and total number of vessels for the period 2014-2020 (without duplicates)

	Total	2014	2015	2016	2017	2018	2019	2020
North Sea Nephrops ≥300kW	54	15	9	8	7	1	7	7
North Sea Nephrops <300kW	75	5	26	9	8	14	4	9
WOS Nephrops ≥250kW	39	8	11	6	3	7	0	4
WOS Nephrops <250kW	84	15	29	11	11	14	1	3
Area VIIA Nephrops ≥250kW	19	1	3	3	3	4	0	5
Area VIIA Nephrops <250kW	28	1	8	2	5	5	2	5
Area VIIA demersal trawl	9	2	2	1	2	0	0	2
Under 10m dem trawl/seine	121	19	34	17	12	21	4	15
NSWOS demersal >24m	64	11	20	8	12	5	2	7
NSWOS demersal seiners	47	10	16	7	4	5	0	5
NSWOS demersal <24m >300kW	49	5	14	6	5	10	3	7
Other trawlers	65	9	14	13	11	13	0	5
North Sea beam trawl < 300kW	6	1	0	0	1	2	0	2
Other beam trawlers	43	0	12	9	7	3	1	11
Pelagic over 40m	8	2	4	1	0	0	0	1
UK scallop dredge over 15m	48	9	9	11	7	7	2	3
UK scallop dredge under 15m	135	19	27	21	22	24	1	22
Under 10m pots and traps	693	121	163	83	73	114	45	94

	Total	2014	2015	2016	2017	2018	2019	2020
Pots and traps 10-12m	143	16	39	19	19	20	8	22
Pots and traps over 12m	68	8	25	15	9	7	1	3
Nets	138	30	39	22	17	20	3	7
Hooks	98	21	9	12	13	12	12	19
Miscellaneous	12	1	0	1	5	2	1	2
Low activity	544	72	127	69	57	81	65	73
All Sample	2590	401	640	354	313	391	162	333

Table 3: New data collected for this project, by year and segment – number of vessels identified each year (from 2014 to 2020) and total number of vessels for the period 2014-2020 (without duplicates)

		Total	2016	2017	2018	2019	2020	2021
North Sea Nephrops ≥300kW	Demersal trawl	1		1				
North Sea Nephrops <300kW		1		1				
WOS Nephrops ≥250kW		3		3				
WOS Nephrops <250kW		4		4				
Area VIIA Nephrops ≥250kW		7		7				
Area VIIA Nephrops <250kW		7		7				
Area VIIA demersal trawl		1		1				
Under 10m dem trawl/seine		6		5				1
NSWOS demersal >24m		2	2	2	2	2	2	2
NSWOS demersal seiners		2	2	2	2	2	2	2
NSWOS demersal <24m >300kW		1	1	1	1	1	1	1
North Sea beam trawl < 300kW		3				1	3	3
Pelagic over 40m		8	6	7	6	7	7	7
UK scallop dredge over 15m	Dredge	10	1	1	1	10	9	7
UK scallop dredge under 15m		1				1	1	1
Under 10m pots and traps	Pots and traps	4		2	1		1	1
Pots and traps 10-12m		1				1		
Miscellaneous	Other	1		1				
Low activity under 10m		1		1				
All Sample		64	12	46	13	25	26	25

10 Appendix 4 – Methodology

10.1 Method for model selection

All statistical tests and estimations have been performed under the open-source statistical package R.

The fuel consumption estimations are based upon three variables that are available for all vessels:

- main engine power;
- length of the vessel;
- gross tonnage.

There is some collinearity between these three variables: vessel length and gross tonnage are positively correlated. Engine power is also correlated with vessel length. Multicollinearity affects essentially the estimation of the regression parameters, not the fuel consumption estimates. The scope of this project focuses upon the projections than the regression itself, multicollinearity is perceived as a minor issue for this project.

There are two variables that we are not using:

- VCU (vessel capacity units) is a combined indicator, using notably engine power and a measure close to gross tonnage. Adding it to the regression would induce more collinearity and will not improve our ability to find convergent regressions.
- Age of the vessel is in theory an indicator that would help explain the fuel consumption, but only if vessels were not altered. Any improvement of the engine, the gearbox, the shaft or even the hull may significantly change the fuel consumption of a vessel.

For each group of vessels, we’re applying the same method. It consists of:

1- identifying the best model,
2- verifying that all parameters are significant,
3- checking that the group can’t be separated into two or more subgroups.

The first step of the routine consists in identifying the best model for a specific vessel group. For this, we use the routine *glmulti*, which select the best combination of variables to be used in regressions. *glmulti* is used with two main options:

- The function tries not only the different permutations of variables but also combinations: products (such as engine power multiplied by gross tonnage) and ratios (engine power divided by gross tonnage).
- The function is selecting the best model using the Akaike information criterion (AIC).

Once the model is identified, we perform an initial regression. We then check the statistical significance for each coefficient. We recursively remove all coefficients that are not significant at 5%.

Once the model is defined, we perform specific checks to test for heteroscedasticity using the function *coeftest* with the option *vcov = vcovHC(regression, type = "HC1")* . Using this option allows us to obtain results coherent with other statistical packages, like Stata.

10.2 Method for estimating group stability

To evaluate each group's stability, we perform a series of Chow tests. The Chow test is a statistical test aimed at identifying if two regressions on two different data sets have the same coefficients (Figure 8). It consists in evaluating three regressions:

- A regression A of *k* variables on the first data set (number of observations N_A);
- A regression B of *k* variables on the second data set (number of observations N_B);
- A regression C of *k* variables on the union of both data sets (number of observations N_A+N_B).

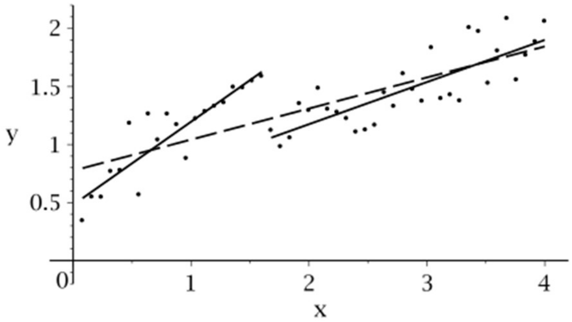

Figure 8: Example of a structural change - two local regressions (plain lines) may provide a better explanation than a global model (dashed line)

The test consists in evaluating if the sum of squared residuals for regression C is significantly different from the sum of squared residuals for regressions A and B. The Chow statistic takes the following form:

$$\mathrm{F} = \frac{\left(S_C - (S_A + S_B)\right)/k}{(S_A + S_B)/(N_A + N_B - 2k)}$$

This ratio is in fact an F-test of equality of variance, which has an F-distribution with *k* and N_A+N_B-2k degrees of freedom.

To perform a recursive test, the sample is first ordered. The Chow statistic is then calculated for different sizes of subsamples: from $k + 2$ elements to N_A+N_B-k-2 elements. This gives us the distribution of the Chow statistic which is compared with the threshold of a F-test with *k* and N_A+N_B-2k degrees of freedom at 5% (Figure 9), to identify possible structural breaks.

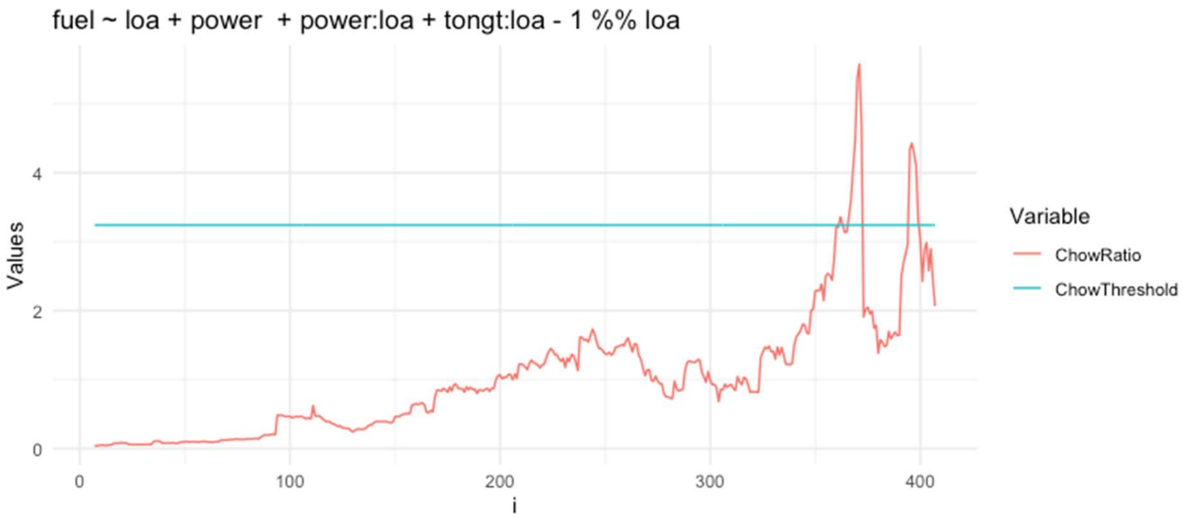

Figure 9: Recursive chow for the statistical regression for all demersal trawlers, the sample is ordered by ascending vessel length

11 Appendix 5 – Model specifications

For each group of vessels, we report here the result of the selected model.

11.1 Demersal trawlers

11.1.1 Below 23 metres

Model:

$$fuel \sim \alpha \cdot length + \beta \cdot power + \gamma \cdot length \cdot power + \delta \cdot ton\ gt \cdot length$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-11.3553	4.2766	-2.655	0.008283	**
β	4.2264	0.7283	5.803	1.45E-08	***
γ	-0.157	0.0465	-3.377	0.000813	***
δ	0.3332	0.0597	5.581	4.76E-08	***

Residual standard error: 331.2 on 354 degrees of freedom

Multiple R-squared: 0.8062, Adjusted R-squared: 0.804

F-statistic: 368.2 on 4 and 354 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-11.3553	4.387965	-2.5878	0.010056	*
β	4.2264	0.809476	5.2211	3.04E-07	***
γ	-0.157	0.054551	-2.879	0.004232	**
δ	0.3332	0.074002	4.5028	9.12E-06	***

11.1.2 Above 23 metres

Model:

$$fuel \sim \alpha \cdot length + \beta \cdot power + \gamma \cdot length \cdot power + \delta \cdot ton\,gt \cdot length$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-33.18499	14.47687	-2.292	0.025968	*
β	5.59489	1.20298	4.651	2.31E-05	***
γ	-0.12902	0.03382	-3.815	0.000363	***
δ	0.27426	0.04073	6.734	1.31E-08	***

Residual standard error: 586.8 on 52 degrees of freedom

Multiple R-squared: 0.9669, Adjusted R-squared: 0.9644

F-statistic: 379.9 on 4 and 52 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-33.18499	13.20889	-2.5123	0.01514	*
β	5.59489	1.106163	5.0579	5.62E-06	***
γ	-0.12902	0.029856	-4.3216	7.01E-05	***
δ	0.27426	0.040604	6.7547	1.22E-08	***

11.2 Demersal seiners

Model:

$$fuel \sim \alpha + \beta \cdot length + \gamma \cdot ton\,gt + \delta \cdot power \cdot length + \zeta \cdot ton\,gt \cdot length + \eta \cdot ton\,gt \cdot power$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-7.73E+03	3.32E+03	-2.33	0.02984	*
β	5.94E+02	2.21E+02	2.685	0.01386	*
γ	2.57E+01	1.15E+01	2.229	0.03687	*
δ	-5.13E-01	1.94E-01	-2.641	0.01528	*
ζ	-2.23E+00	6.66E-01	-3.343	0.00308	**
η	6.72E-02	2.10E-02	3.192	0.00438	**

Residual standard error: 298.2 on 21 degrees of freedom

Multiple R-squared: 0.5678, Adjusted R-squared: 0.4649

F-statistic: 5.517 on 5 and 21 DF, p-value: 0.002136

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	-7.73E+03	3.07E+03	-2.5186	0.01996	*
β	5.94E+02	2.30E+02	2.5796	0.01748	*
γ	2.57E+01	1.19E+01	2.1566	0.04278	*
δ	-5.13E-01	2.17E-01	-2.3698	0.02746	*
ζ	-2.23E+00	6.55E-01	-3.3996	0.0027	**
η	6.72E-02	2.47E-02	2.7234	0.01273	*

11.3 Pelagic trawlers

Model:

$$fuel \sim \alpha \cdot ton\ gt \cdot length$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.1275	0.0144	8.856	3.59E-08	***

Residual standard error: 12000 on 19 degrees of freedom

Multiple R-squared: 0.805, Adjusted R-squared: 0.7947

F-statistic: 78.43 on 1 and 19 DF, p-value: 3.588e-08

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.1275	0.014597	8.734	4.44E-08	***

11.4 Dredgers

Model:

$$fuel \sim \alpha \cdot power$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	2.55655	0.08141	31.4	<2e-16	***

Residual standard error: 256.7 on 139 degrees of freedom

Multiple R-squared: 0.8765, Adjusted R-squared: 0.8756

F-statistic: 986.3 on 1 and 139 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	2.55655	0.089447	28.582	< 2.2e-16	***

11.5 Beam trawlers

Model:

$$fuel \sim \alpha \cdot length + \beta \cdot ton\ gt \cdot length$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	38.91514	8.41231	4.626	4.94E-05	***
β	0.19022	0.04883	3.895	0.000422	***

Residual standard error: 472.7 on 35 degrees of freedom

Multiple R-squared: 0.9329, Adjusted R-squared: 0.9291

F-statistic: 243.4 on 2 and 35 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	38.91514	7.86634	4.947	1.88E-05	***
β	0.19022	0.03656	5.2029	8.68E-06	***

11.6 Pots & Traps and Hooks

Model:

$$fuel \sim \alpha \cdot power + \beta \cdot ton\ gt$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.50595	0.02758	18.35	<2e-16	***
β	4.93283	0.13793	35.76	<2e-16	***

Residual standard error: 78.15 on 912 degrees of freedom

Multiple R-squared: 0.8162, Adjusted R-squared: 0.8158

F-statistic: 2025 on 2 and 912 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.50595	0.059946	8.4401	< 2.2e-16	***
β	4.93283	0.936472	5.2675	1.73E-07	***

11.7 Nets

Model:

$$fuel \sim \alpha \cdot power + \beta \cdot ton\,gt$$

Standard regression:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.58405	0.08882	6.576	7.21E-10	***
β	3.10751	0.27082	11.474	< 2e-16	***

Residual standard error: 94.82 on 153 degrees of freedom

Multiple R-squared: 0.7925, Adjusted R-squared: 0.7898

F-statistic: 292.1 on 2 and 153 DF, p-value: < 2.2e-16

Coefficient after robust tests:

	Estimate	Std. Error	t value	Pr(>|t|)	
α	0.58405	0.10274	5.685	6.44E-08	***
β	3.10751	0.41297	7.5247	4.22E-12	***

12 Appendix 6 – Detailed results

Table summarising the model results

	Median daily fuel use (litres per day at sea)	Annual fuel use per segment (thousand litres)	Tonnes CO_2 equivalent per segment	kg CO_2 equivalent per kg of fish	kg CO_2 equivalent per £ landed
Under 10m demersal trawl/seine	217	855	2,607	3.04	1.14
North Sea Nephrops under 300kW	1,349	10,938	33,359	2.95	1.54
North Sea Nephrops over 300kW	358	1,797	5,481	2.65	1.26
WOS Nephrops under 250kW	696	2,509	7,652	3.30	1.65
WOS Nephrops over 250kW	332	2,282	6,961	2.71	1.23
NSWOS demersal over 24m	2,680	23,141	70,580	2.23	1.22
NSWOS demersal pair trawl seine	1,488	5,027	15,331	1.02	0.60
NSWOS demersal seiners	1,643	3,799	11,587	1.15	0.72
NSWOS demersal under 24m over 300kW	1,524	11,114	33,897	2.20	1.08
NSWOS demersal under 24m under 300kW	695	947	2,888	1.89	0.92
Pelagic over 40m	26,015	20,140	61,427	0.24	0.30
UK scallop dredge under & over 15m	53	3,029	9,240	1.37	0.29
Under 10m pots and traps	108	1,665	5,079	2.20	0.54
Pots and traps 10-12m	406	2,030	6,190	1.38	0.66

	Median daily fuel use (litres per day at sea)	Annual fuel use per segment (thousand litres)	Tonnes CO_2 equivalent per segment	kg CO_2 equivalent per kg of fish	kg CO_2 equivalent per £ landed
Pots and traps over 12m	590	10,022	30,568	1.89	1.15
Under 10m using hooks	47	208	633	0.44	0.14
Longliners	131	2,463	7,513	3.37	1.42
Other	1,972	5,144	15,690	1.83	1.42
Low activity	25	397	1,210	1.66	0.62
All Scotland	70	107,507	327,893	0.85	0.69

13 Appendix 7 – Summary table

Table summarising the model results

	Average **daily fuel use** (litres per day at sea)	Annual fuel use **per segment** (thousand litres)	kg CO_2 equivalent **per kg of fish**	kg CO_2 equivalent **per £ landed**
1	Pelagic over 40m	All	Longliners	WOS nephrops over 250kW
2	NSWOS demersal over 24m	NSWOS demersal over 24m	WOS nephrops over 250kW	North Sea nephrops over 300kW
3	Other	Pelagic over 40m	Under 10m demersal trawl/seine	Longliners
4	NSWOS demersal under 24m over 300kW	NSWOS demersal under 24m over 300kW	North Sea nephrops over 300kW	Other
5	NSWOS demersal seiners	North Sea nephrops over 300kW	WOS nephrops under 250kW	North Sea nephrops under 300kW
6	NSWOS demersal pair trawl seine	UK scallop dredge under & over 15m	North Sea nephrops under 300kW	WOS nephrops under 250kW
7	North Sea nephrops over 300kW	Other	NSWOS demersal over 24m	NSWOS demersal over 24m
8	UK scallop dredge under & over 15m	NSWOS demersal pair trawl seine	NSWOS demersal under 24m over 300kW	UK scallop dredge under & over 15m
9	WOS nephrops over 250kW	NSWOS demersal seiners	Pots and traps 10-12m	Under 10m demersal trawl/seine
10	NSWOS demersal under 24m under 300kW	Under 10m pots and traps	UK scallop dredge under & over 15m	NSWOS demersal under 24m over 300kW
11	All	WOS nephrops over 250kW	NSWOS demersal under 24m under 300kW	NSWOS demersal under 24m under 300kW
12	Longliners	Longliners	Other	NSWOS demersal seiners
13	Pots and traps over 12m	WOS nephrops under 250kW	Low activity	All

	Average **daily fuel use** (litres per day at sea)	Annual fuel use **per segment** (thousand litres)	kg CO_2 equivalent **per kg of fish**	kg CO_2 equivalent **per £ landed**
14	North Sea nephrops under 300kW	Pots and traps over 12m	Pots and traps over 12m	Pots and traps over 12m
15	WOS nephrops under 250kW	North Sea nephrops under 300kW	Under 10m pots and traps	Low activity
16	Under 10m demersal trawl/seine	Pots and traps 10-12m	NSWOS demersal seiners	NSWOS demersal pair trawl seine
17	Pots and traps 10-12m	NSWOS demersal under 24m under 300kW	NSWOS demersal pair trawl seine	Pots and traps 10-12m
18	Under 10m pots and traps	Under 10m demersal trawl/seine	All	Pelagic over 40m
19	Under 10m using hooks	Low activity	Under 10m using hooks	Under 10m pots and traps
20	Low activity	Under 10m using hooks	Pelagic over 40m	Under 10m using hooks

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