NAFC Marine Centre
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Estimation of the Carbon Footprint of Shetland's Atlantic Mackerel (*Scomber scombrus*) Processing and Supply Chain

Frances Sandison

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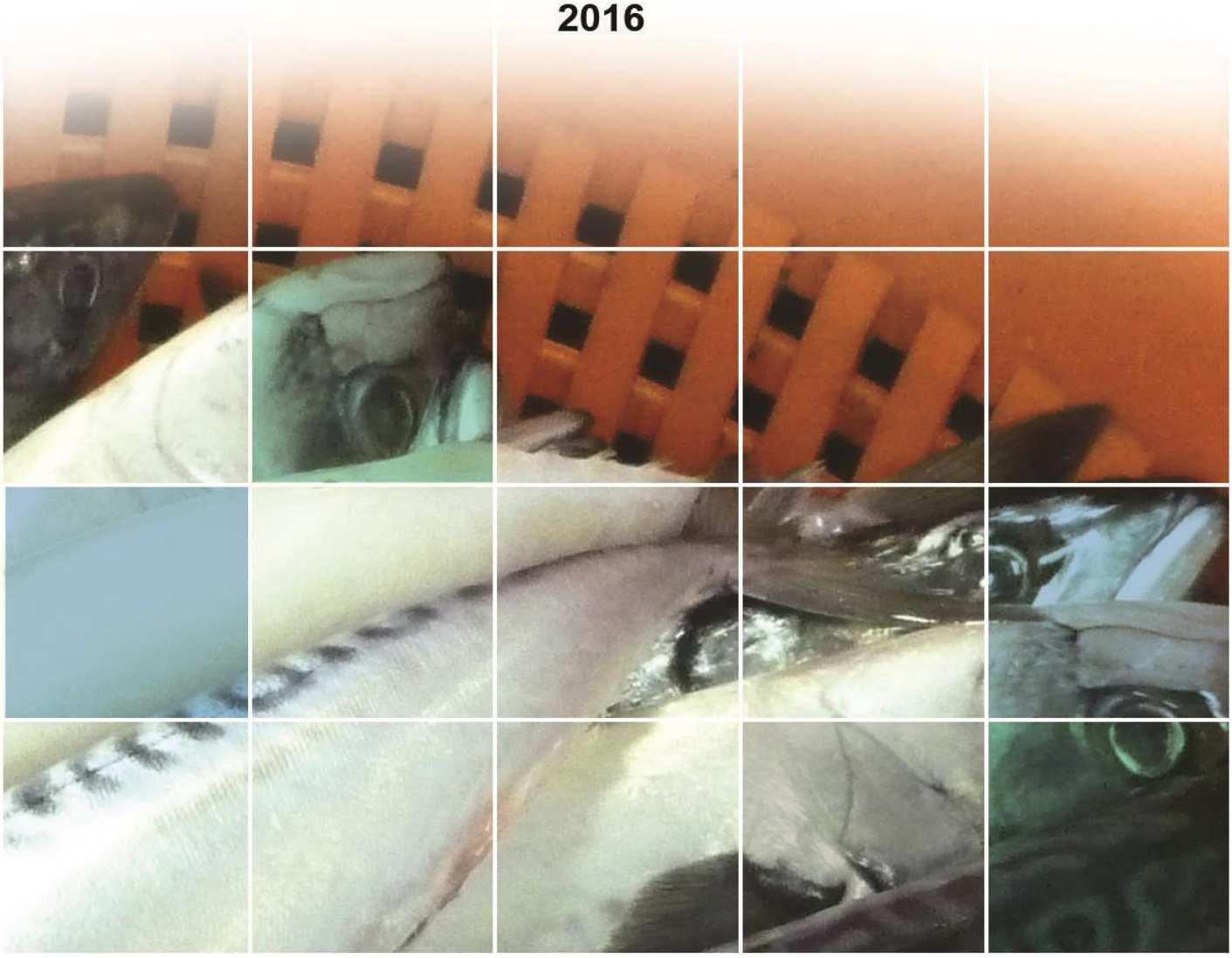

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1 Executive Summary

This study investigates the carbon footprint (CF) of Atlantic mackerel (*Scomber scombrus*) as landed and processed through Shetland. This study builds on previous work by the author (Sandison, 2015) examining the CF of the capture/landing phase, to give an overview of the chain through to arrival at its first post-processing destination.

The carbon footprint chain for Atlantic mackerel as processed through Shetland has been found to be low in comparison to other protein processing chains, and particularly efficient in terms of processing itself. Electricity usage was found to be the biggest contributing factor in the processing phase. The processing of Atlantic mackerel is relatively energy efficient and potential improvements are likely to depend on future improvements in machinery and improvements in electricity emissions. Although it is possible for processing plants to seek out the most efficient energy suppliers, this will likely be largely government led.

Packaging was found to have minimal impact on the chain as a whole, suggesting that the materials and methods used are efficient. Transport was undertaken via small containership to the country of purchase and found to be one of the most efficient options for cargo transport.

The chain up until this end point produced CF values that consolidated the position of Atlantic mackerel as a low carbon foodstuff in comparison with many other seafood and terrestrial meat products.

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2 Introduction

2.1 Background

Seafood has historically been an important foodstuff, with culture and economy often shaped around its significance. Today the fishing industry remains our last wild caught widely exploited food source and is a globally traded commodity (Smith *et al.,* 2010), as well as supporting over 180 million jobs around the globe (FAO Fisheries and Aquaculture Department, 2010). It is thought that 15% or more of the average protein intake for half the human population comes from fisheries and seafood (FAO Fisheries and Aquaculture Department, 2012) while only approximately one fifth of fish landed globally is used for non-direct human consumption.

Management structures and other conservation safeguards are in place to allow for future sustainable harvesting of fish resources, as well as to avoid the biological, environmental and economic damage that can come from prolonged overexploitation. Though it has been considered an important issue with regards to terrestrial food chains for some time now, the issue of climate change in the context of seafood sustainability is something only recently addressed. Global meat systems, in particular beef, are reported as the second largest causal factor of greenhouse gas emissions (Rifkin, 2011), ranked only behind global electricity production and in front of global transport. Like many aspects of food security, the issue of climate change represents a real threat to commercial fisheries, marine ecosystems and food webs. Some projections predict a 30-70% increase in catch potential in high latitudes and potential decrease of around 40% in the tropics (Cheung *et al.,* 2010).

There is increasing consumer interest in ethical food purchase (67% of UK consumers are more likely to purchase a product with a lower carbon footprint (Carbon Trust, 2012)) combined with an increasing scientific and political interest in the sustainable management of resources for future generations and for biological, ecological and economic security. Various food labels are now offered to help consumers make an informed choice about the ethics of their food. One example of this is found in the Carbon Trust's 'footprint' label, which is used to signify products committed to reducing their carbon impact (Carbon Trust, 2016). Another is that of the Marine Stewardship Certification (MSC) of fisheries (MSC, 2011). This label looks at the overall sustainability of fish products, though it is yet to start

factoring in carbon footprint. Labels such as these are often seen as desirable for products as they have the potential to increase their marketable value.

2.2 An Overview of Carbon Footprinting and Life Cycle Analysis in Capture Fisheries.

The term carbon footprint (CF), also known as carbon profile (CP), is used to refer to the emissions of greenhouse gases over a product's lifetime, from its creation (cradle) to its eventual disposal or recycling (grave/cradle). The emissions are made up predominantly of carbon dioxide, although there are several other gasses that also play an important role. Many of these actually have a higher warming value but are not as significant because they are present in much lower quantities. A conversion factor is used to account for the difference in warming potentials between greenhouse gasses and this is expressed as a single figure – carbon dioxide equivalent (CO_2 e). This allows for direct comparison between products regardless of the gaseous mix produced.

A full life cycle analysis is the scientifically preferred method of measuring the impact of any one product over its life. However, carbon footprinting is seen to be a major part of this and, as it is easier to understand and produce, it is often the one desired/preferred by businesses. With both LCA and CF, a chain can be examined from end to end or any subsection within can be considered (cradle to grave or cradle to gate). There are many existing guidelines and specifications available to offer advice on how to perform a CF/LCA, including system boundaries, suggested inputs and outputs to consider and allocation methods. This is the result of an effort to standardise reports to allow for better cross comparison. The guidelines in question offer support at varying levels, with some focused on general LCAs and CFs (ISO 14044 and 14040 - BSI, 2006a; BSI, 2006b), and others with focus given to a specific area, e.g. BSI (2012), which is specific to CFs of seafood products.

Many meta-studies have concluded that the capture phase is one of the most significant contributors to the overall carbon footprint of a fisheries product (e.g. Avadi & Feron, 2013, Parker, 2012). The main exceptions to this are the use of air transport or those that are part of a multi-ingredient product in which the additional ingredients have a high CF value (Parker, 2012). The high contribution of the fishing phase is caused by the production of emissions from diesel fuel used to power the fishing vessels (Hospido & Tyedmers, 2005),

though refrigeration leakage is also seen to have a notable effect in some fisheries (Zeigler *et al.,* 2013; Vazquez-Rowe *et al.,* 2010, Irribarren *et al.,* 2011).

Because of the significance of fuel use to the overall CF, fishing method and gear type have a considerable effect on the end result (e.g. Tharne, 2004a; Tyedmers, 2000; Vázquez-Rowe, *et al.,* 2010, Madin & Macreadie, 2015). Fisheries targeting small pelagics have been found to have one of the lowest CF values (particularly purse seine method, though pelagic trawl method is also seen to be highly efficient). Demersal trawling is thought to be one of the most energy intensive methods (Parker & Tyedmers, 2014).

2.3 Processing Contribution in CF Studies

Processing is generally found to have a minor contribution to meat supply chains (e.g. MacLeod, *et al.,* 2013, Winther *et al.,* 2009). However, the lower the impact of the chain as a whole, the more important the contribution of processing to the end figure. Pelagic fisheries have one of the lowest emission rates for the capture phase. Additionally, given that small pelagic fish typically require minimal processing (often whole and frozen), this limits the amount of energy required to process as well as loss of mass from the fish due to discarded guts/head etc. This in turn limits the CF impact of the processing phase.

Just as gear type and fishery plays an important part in the resulting CF for the capture phase, the location of processing – on board ship, on land, country, etc. – may have a strong effect on the end CF figure. For example, on-board processing facilities are powered by diesel fuel which has a high global warming potential in comparison to most land based electricity run plants. Similarly, the country in which land based processing takes place can have a considerable effect on global warming potential. This is due to the mix of energy production which varies between countries, with some countries having 'greener' electricity (with a larger proportion of the national grid provided by renewable sources rather than fossil fuels) than others. For example the emission rate figures for use of one kilowatt of electricity for Norway is 0.17k emission per kWh in contrast with the European average of 0.531 k/kWh (Seafish, 2016). Additionally, Winther *et al.* (2009) found that products processed in Norway had a lower CF value than those exported and processed elsewhere, partially because of the cleaner energy mix and partially because of the increased use of

additional products gained through otherwise discarded mass (or 'coproducts' such as the use of heads/guts/etc. as fishmeal).

2.4 The Scottish Mackerel Fishery

Atlantic mackerel is the Scottish fishing industry's single most valuable landed species, with 2012 caches totalling over £131 million (SPSG, 2014). Although there have been recent threats to the sustainability of the stock caused by international dispute of quota (SPSG, 2014), it is still considered one of the more healthy and well managed commercial fish stocks. Following international quota agreements, the fishery re-gained its MSC sustainability certification (MSC, 2016).

The Scottish fishery for mackerel is made up of two main components – the large pelagic trawler fleet that dominates landings, and a smaller inshore fishery. The former operates during two annual fishing seasons –from January to February and from October to November, while the later operates a single season over the summer months from June-October.

Inshore boats in the Shetland Isles typically land their catch to the local fish markets (Leiper, pers. comm., 2016), while the pelagic trawler fleet land their catch directly to the large scale processing plants in the UK and Norway. Shetland possesses only a single large pelagic processing factory, Shetland Catch, which processes landings from international vessels as well as the local and national fleet. In this study focus is given only to the chain through Shetland Catch because of its larger scale processing, and to better align with the scope of Sandison (2015). It is however recommended that should future attention be given to the small vessel fishery for Atlantic mackerel, the processing and supply chains should also be addressed.

2.5 The Shetland Processing Chain

Pelagic fish caught by the large refrigerated sea water vessels are landed directly to the local processing plant, with fish being pumped from their vessel holding tanks on the vessel into chilled seawater holding tanks in the factory building. Water is drained off as the fish are

passed over a series of conveyer belts to weigh. Damaged fish or fish of a different species are discarded at this stage along with any future off-cuts from processing. All discards or unwanted bycatch is passed on to a local fishmeal processing plant.

Marketable fish are graded automatically by size and weighed out into 20kg portions. These portions are packaged in cardboard boxes with a thin plastic sheet lining. (Boxes are assembled on site by specialised machinery). Boxed fish are quality checked by operatives before cardboard lids and plastic strapping are mechanically applied to individual boxes.

The finished boxes are stacked on a metal carry frame and moved to crates where they are transported in stacks. Crates are then frozen for approximately 20 hours. Finally, frozen crates are then passed on to container ships to be moved to their destination (either country of purchase or off site storage in country of future sale).

2.6 Aims and Objectives

Previous work has shown the Shetland chain for Atlantic mackerel to be efficient in terms of carbon emissions to the point of landing (Sandison, 2015). This project aims to expand this research by considering the processing and transport phases of the Atlantic Mackerel chain in Shetland and considers the following; processing and landing in Shetland (gate-gate) and onward transport to the first point of landing in its country of purchase (also gate-gate). The specific aims of the project are as follows:

- To investigate the processing, packaging and onward transport CF of Atlantic mackerel in Shetland.
- To interpret this within the wider chain.
- To compare this with the published figures for terrestrial meat systems and other commercial fish supply chains.

3 Methods

3.1 Data Collection

The proposed areas of focus for this study (processing and transport) were divided into two separate phases in the supply chain, with the start gate defined as fish entering processing directly from the capture vessels and the initial end gate defined as packaged product leaving the in-house storage of the processing plant. The next section (transport) then ended at the point that the product arrived at port in its country of purchase/onward sale.

Offsite storage in the country of purchase also features in the supply chain and is under the remit of the fish producers. It was the initial intention of this study to include this section in the analyses. However, on examination it was found that the complexity of this stage of the analysis and the difficulty in getting data made this impractical within the time frame of the project. This stage should be considered as a standalone section and perhaps included with full transport to the initial consumer at a later date. Figure 1 shows the re-set gate boundaries for the project. The two sections considered in this project are described within the large rectangular boxes.

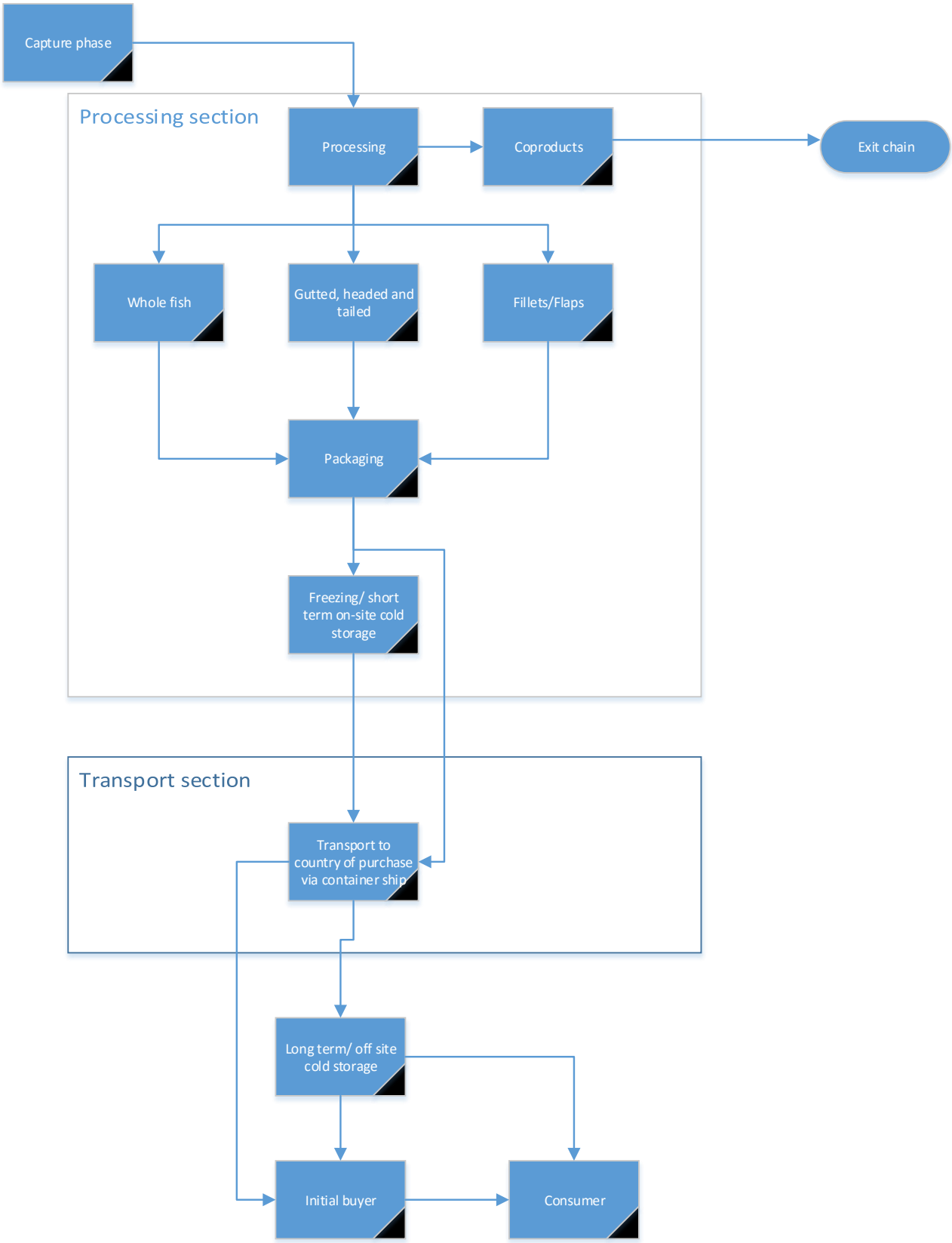


Figure 1: Processing and transport carbon chain for Atlantic mackerel landed in Shetland

3.1.1 Processing Inputs/Outputs

The processing inputs and outputs that were considered for the two assessed phases of the project are shown in Table 1.

Table 1: Processing inputs and outputs for processing and transport phases of supply chain

Processing inputs	Processing outputs	Transport inputs	Transport outputs
• Electricity - in kilowatt hours (kWh)	• Emissions from electricity (in carbon dioxide equivalent - Co_2e)	• Packaged product - plastics (polyethylene and polypropylene) - cardboards	• Fuel emissions - Co_2 e from petrol/diesel consumption
• Landed fish - in metric tonnes (mt)	• Processed fish - Bycatch and discards		
• Consumables - Maintenance oil - Fuel for forklifts (LPG and Diesel) - Cleaning agents - PPE	• Consumables - Emissions from fuel usage (forklifts - Co_2 e) - Emissions from consumable use (Co_2 e)		

The data for the processing stage was obtained from the primary source by means of interview and access to business spreadsheets/invoices. In some cases further detail was obtained from the service providers for the processing plant (e.g. contact with electricity provider). For transport, data was obtained through interview with the transportation company and the processing plant, with further secondary data (e.g. emission rates) provided by the online greenhouse gas assessment tool used in the analysis. Where appropriate these assumptions were validated by independent data/research available on the topic (e.g. greenhouse gas emissions per kWh of electricity used).

3.2 Data Analysis

3.2.1 Processing

In order to calculate the end figure of carbon footprint (CF) for the processing plant, data for all fish landings (mackerel, herring, other) to the processing plant and total electricity usage per month were obtained. Electricity usage was allocated per month by percentage mass to

the different fish species landed in that time frame, in keeping with the methodology used in Sandison (2015), based on guidelines in the PAS (BSI, 2012). For time periods where nothing was processed, the electricity usage was allocated by percentage mass of the yearly landings. Kilowatt hours per tonne of finished product were then calculated. Emission rates for 2014 were obtained from the energy companies involved. As these were found to be in keeping with the suggested European average by the tool, no further calculations were required.

The contribution of landed bycatch and discards (including non-target species, damaged fish and any off-cuts) post landing gate was calculated as a percentage of the annual landings. As all discards and off-cuts are sent on to be processed into fishmeal or sold as bait, this was treated as coproduct. The contribution was particularly low (approximately 1 %) and was not found to have any effect on the end figure. Although the chain detailed three end products- whole, headed and gutted and fillets, the latter two were only introduced in 2015, and at such low quantities as to have little or no estimated impact on the chain. As such only the major supply chain for the whole frozen product was assessed.

Consumables used in the maintenance of the plant were calculated. At this point consumables with long life spans (crates, PPE, etc.) were excluded from the future analysis due to their likely negligible contribution to the end figure (BSI, 2012). The focus for this section was on maintenance oils and fuels used on site. Although cleaning supplies were also intended to be included in the analysis, these figures could not be obtained at the time of the project and so had to be discounted. While this omission should be noted, it is expected that this will have a minimal contribution to the overall figure (BSI, 2012).

Finally, the contribution of packaging was assessed. Here all packaging materials and weights were obtained and categorised as polyethylene, polypropylene, cardboard or polystyrene. Their contribution was calculated as weight in kilograms per kilogram of final product and run through the tool with emission rates and conversion factors provided by the tool.

The analysis was performed on the total average data for the study period (2012-2015) as well as with breakdown of analysis by year. From here further breakdown was undertaken

to examine component contribution for both transport and processing sections. Finally seasonal contributions were also examined.

3.2.2 Transport Section

The next section of the analysis focused on the transport section of the chain. Product is shipped by small container ship travelling at approximately 13.5 knots from the processing plant to a number of locations around the world. Durations and distance from the point of origin (Lerwick) to the destination were obtained for the several major buyer areas. This could then be added into the tool to allow for emission related factors to be calculated. This analysis was repeated to look at other possible transportation methods. These are categorised as follows;

-Small container ship (travelling at approximately 12 knots)

-Large container ship (travelling at approximately 17 knots)

-Short haul airfreight (less than 4 hours)

-Long haul airfreight (more than 4 hours

All end analysis was undertaken using the Seafish online emission profiling tool, though the final figure (given in kg of CO_2 equivalent emitted per tonne of fish landed) was then converted to tonne of CO_2 equivalent (t CO_2e) per tonne of fish landed to allow for easier comparison with other studies.

4 Results

4.1 Overall CF Figures

The extended carbon footprint (CF) estimation for Atlantic mackerel landed in Shetland, inclusive of capture and processing, is shown in Figure 2. The results reported here consist only of Shetland vessels landing to Shetland Catch as additional fleet data from the major contributors of catches to Shetland Catch from outwith Shetland were not available (Sandison, 2015).

The total carbon footprint for this point in the chain is 0.534 tonnes of CO_2 equivalent per tonne of fish (tCO_2e per t fish). Of that, 0.390t CO_2e is caused by the initial capture section of the chain (shown in green in Figure 2 and 0.144t is caused by the processing section of the chain (shown in blue).

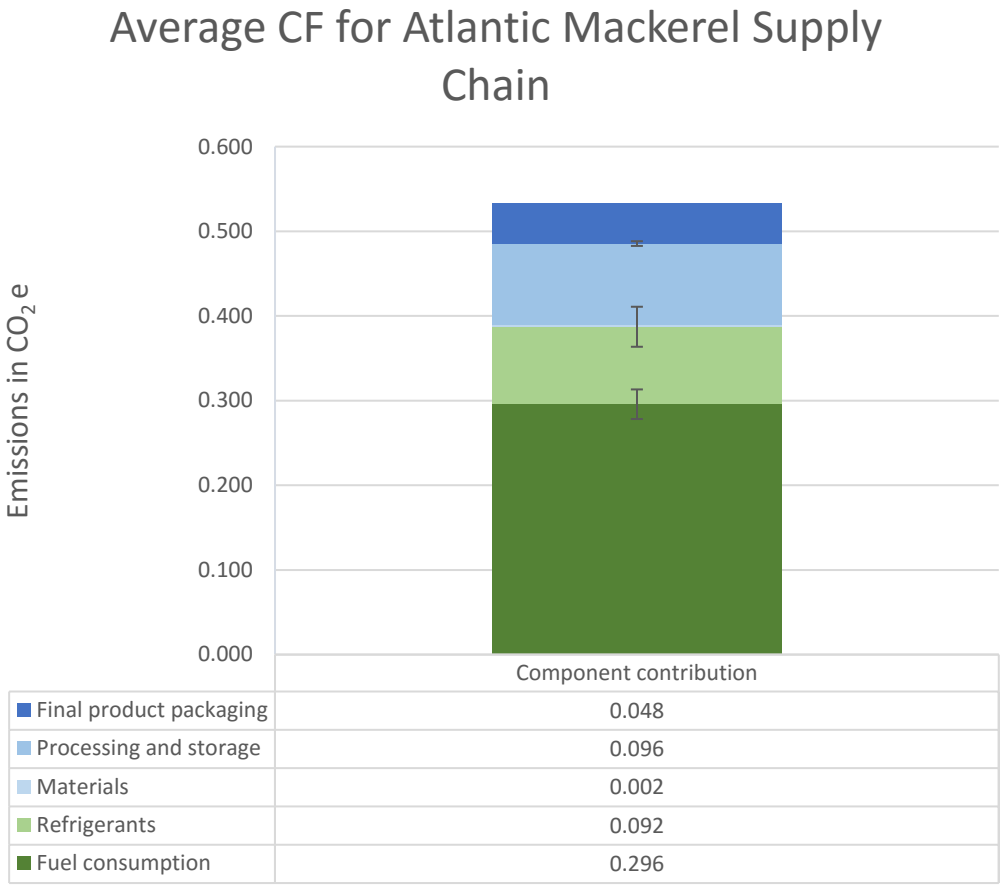
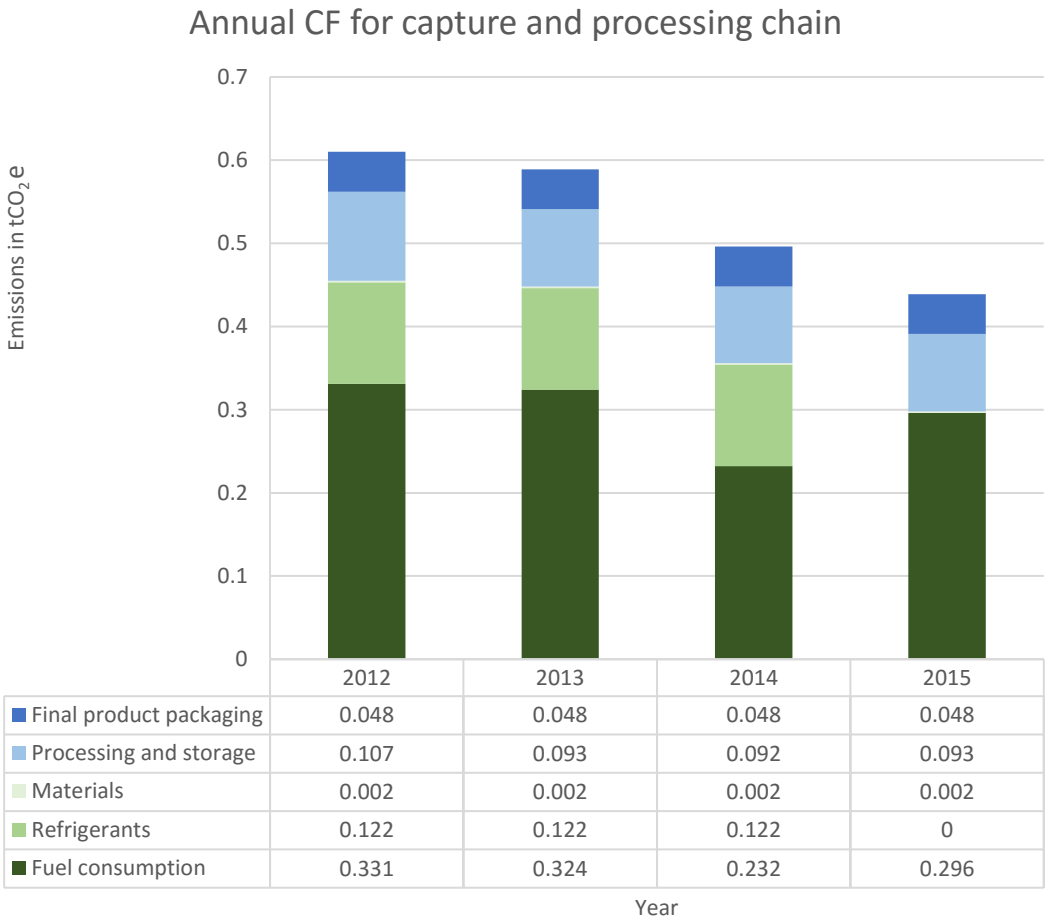


Figure 2: Carbon footprint for the capture and processing of Atlantic mackerel through Shetland Catch, via the Shetland pelagic fleet, with detailed breakdown of contributors (Standard error is also shown).

An annual decline in total CF can be seen in Figure 3. Fluctuations are seen in the annual fuel consumption (as was noted in Sandison 2015), processing and storage CF. Fuel consumption shows a decline between the years of 2012-2014. An average of the fuel consumption of the previous years were used as a proxy for fuel consumption in 2015 due to an absence of data. The reliance on previous years' data is the likely cause of the estimated increase in fuel consumption in 2015. It should be noted that if the trend of lowered fuel expenditure per tonne of final product is consistent with previous years, the 2015 CF figure would be

reduced by at least 0.064t CO_2e. Average refrigeration leakage emissions were not included in the 2015 total, based on the assumption that all the vessels have met the legal requirements to convert from the R22 refrigeration system to Ammonia by January 2015.

Processing emissions exhibit an initial decrease from 2012, though thereafter they remain relatively constant (Figure 3).



	2012	2013	2014	2015
Final product packaging	0.048	0.048	0.048	0.048
Processing and storage	0.107	0.093	0.092	0.093
Materials	0.002	0.002	0.002	0.002
Refrigerants	0.122	0.122	0.122	0
Fuel consumption	0.331	0.324	0.232	0.296

Figure 3: Annual breakdown of component contribution to overall CF figure for capture and processing chain

Following an initial downward trend in the processing phase from 2012-2013 (Figure 3), it remains constant at approximately 0.141t CO_2 e. The capture phase however continues to decrease. It is clear that while 2015 fuel figures show a rise in the capture section because of fuel estimates being based on an average, the removal of refrigeration emissions still result in an overall decrease in CF contribution. If actual fuel emissions in 2015 follow trends in previous years, the decrease between 2014 and 2015 would be more marked still.

4.2 Processing Component Contribution Analysis

Figure 4 shows the breakdown of individual components of the overall processing CF. Packaging and consumables emissions remain constant although the impact of the latter on total emissions is negligible. Electricity usage is the biggest overall contributor and although it shows an initial decrease from 2012-2013, it appears to virtually level out thereafter.

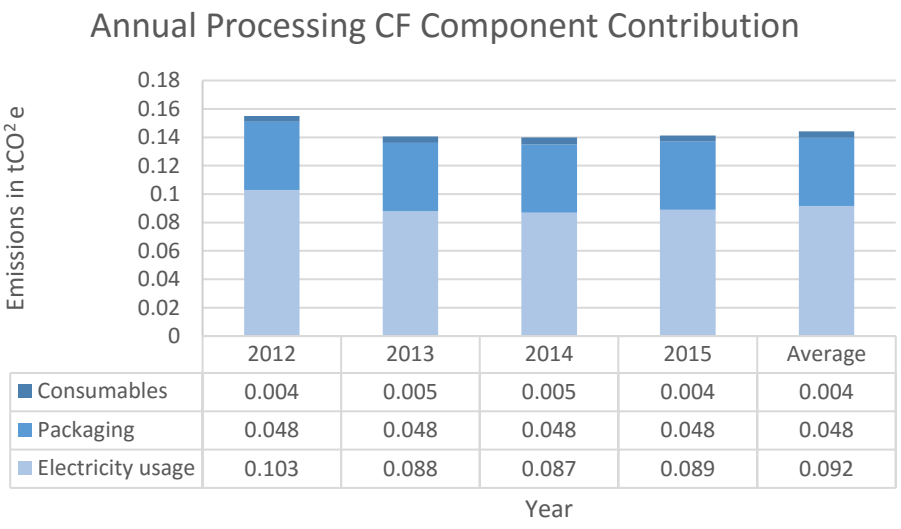


Figure 4: Annual component contribution to processing CF

Figure 5 shows an increasing trend both in the quantity of fish landed, and the quantity of landed mackerel from 2012-2014. Landings of other pelagic species reduced greatly from 2012-2013 and did not feature thereafter. Herring landings also show a decrease from 2012-2014. However, despite an increase in herring landings in 2015, total landed fish weight was lower than both 2013 and 2014, primarily driven by a decrease in mackerel landings.

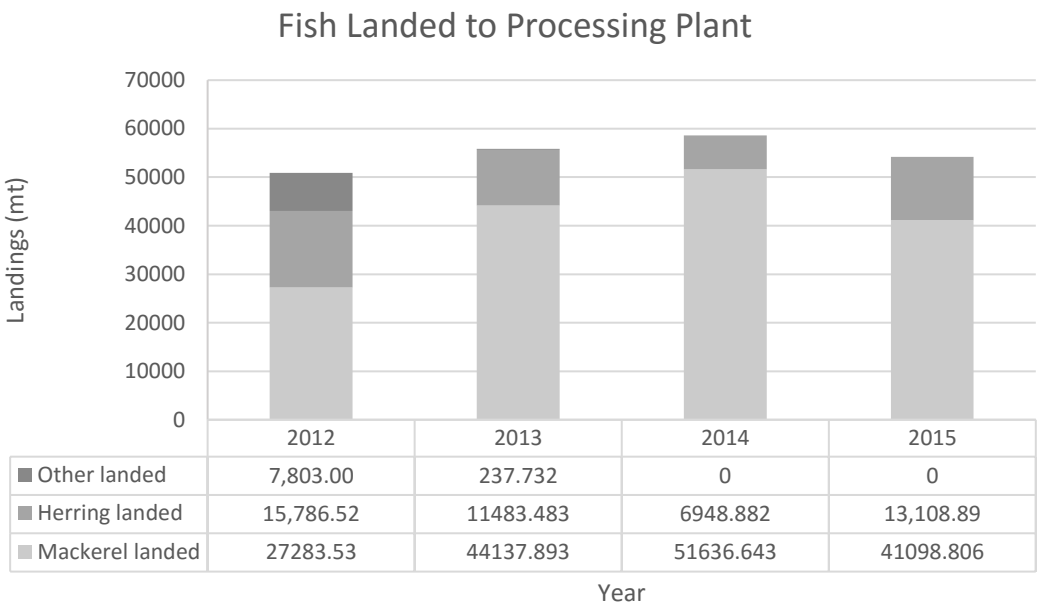


Figure 5: Annual landings of fish to the processing plant in metric tonnes (mt)

Post 2012 there is a considerable drop in the amount of electricity required to process a tonne of mackerel (Figure 6). This continues to fall until 2014 after which there is again a slight rise, in keeping with an inverse trend to that seen in mackerel landings (Figure 5).

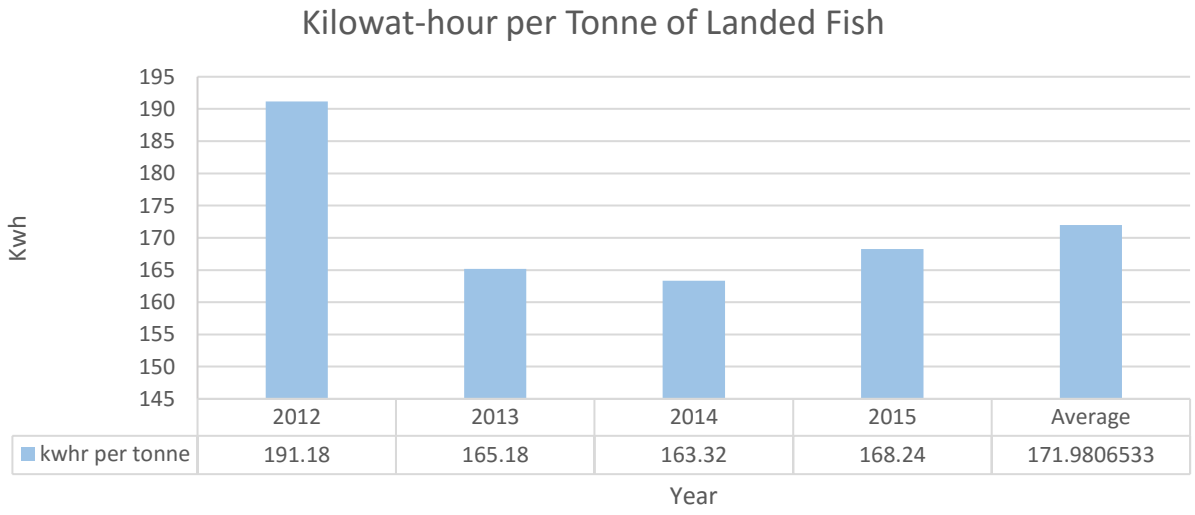


Figure 6: Electricity usage per tonne of fish processed in kilowatt hours (kWh)

Figure 7 highlights that the emissions caused by packaging comes almost entirely from the cardboard component. The polyethylene sheeting used to line the cardboard box packaging has no noticeable effect on the emissions rate. The contribution of polypropylene strapping used to bind the boxes is also minor (0.002t CO_2 e).

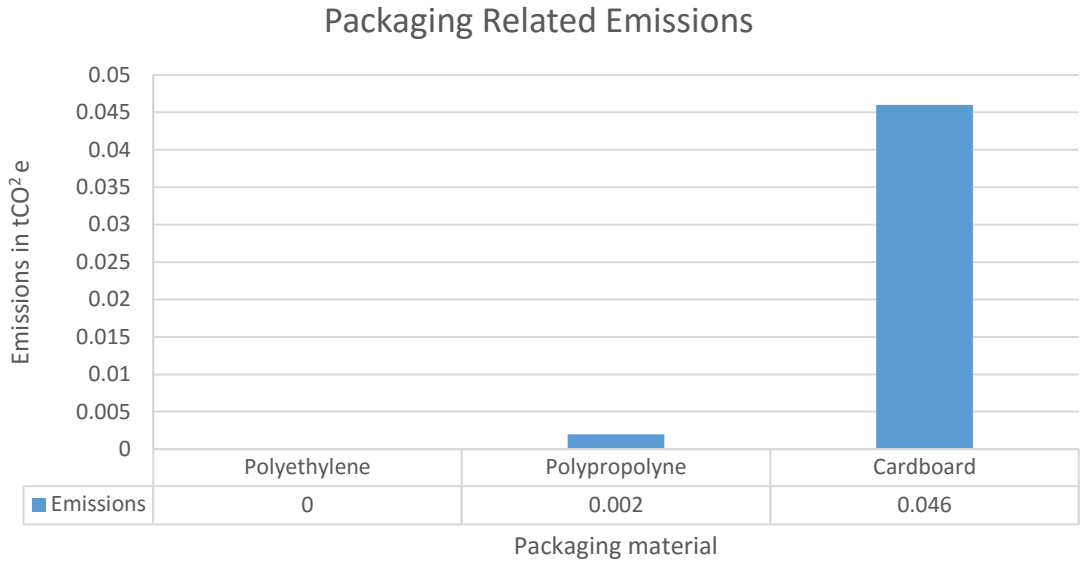
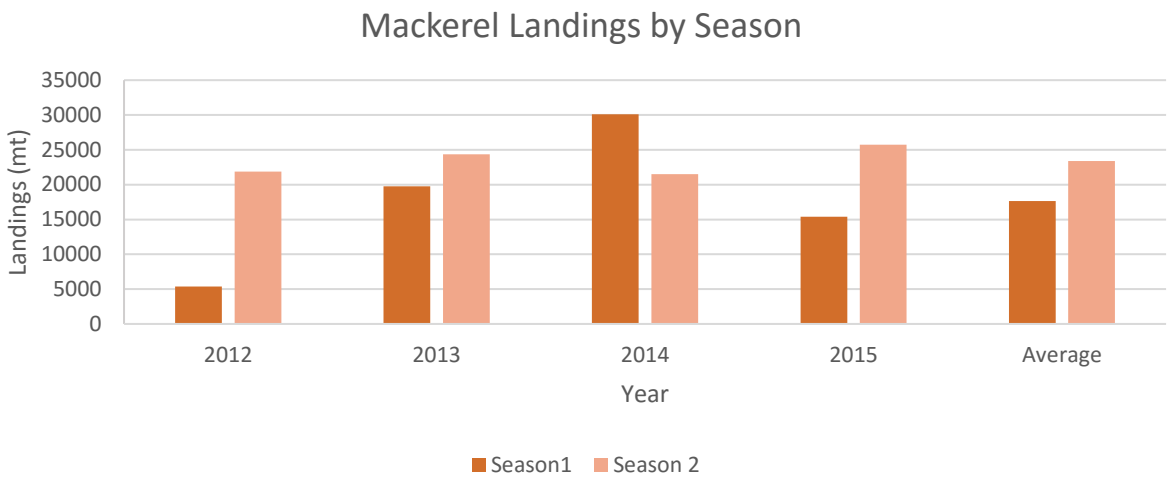
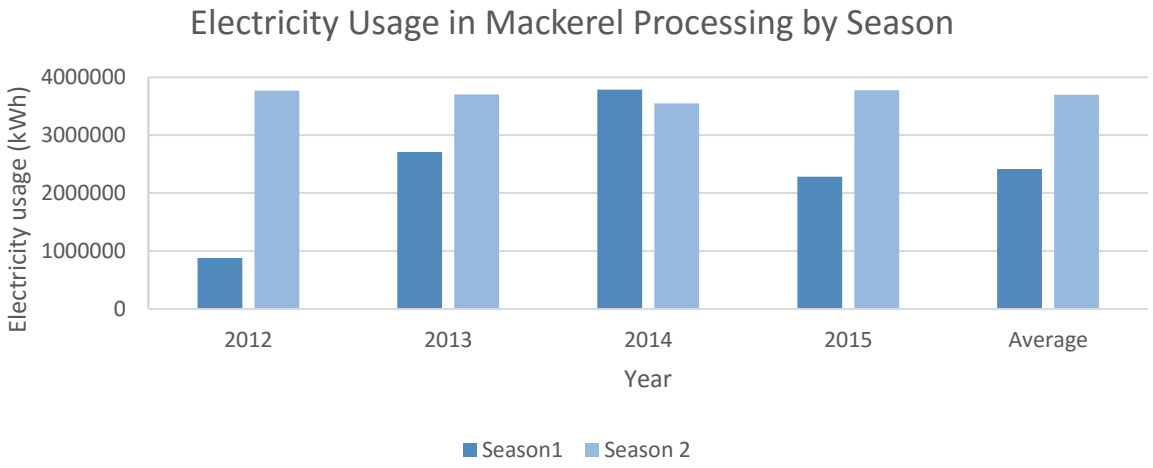


Figure 7: Packaging emissions component analysis.

4.3 Seasonal Analysis

On the whole, landings of mackerel are higher in the late season (Season 2) than in the early season (Season 1), although this was not the case in 2014 (Figure 8). A similar pattern is seen in electricity usage by season (Figure 8). However, the kWh used to process a tonne of mackerel by season does not contrast as much between seasons. There is generally a higher value for the later season, although this is not the case in 2015 which shows similar values for both later and earlier season.





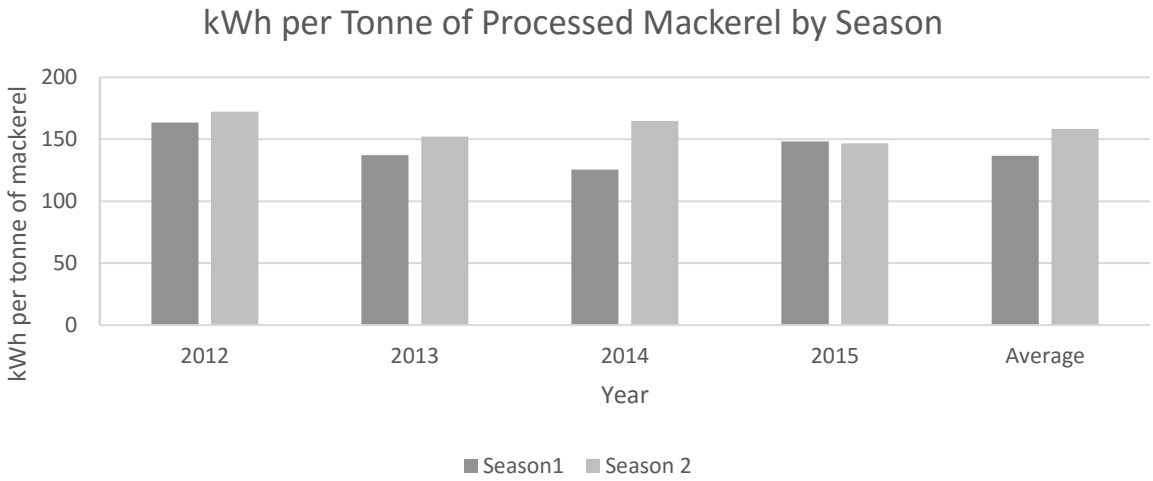


Figure 8: Seasonal analysis of mackerel processing showing annual breakdowns of landings, electricity usage and kWh per tonne of processed fish.

4.4 Transport

Transport is undertaken by a small container ship with an average speed of approx. 13.5 knots. ulting in increased emissions.

Table 2 shows a list of the most frequent destinations for products from the processing plant (data provided by shipping agency). There is a clear relationship between distance travelled and resulting emissions, with greater distances resulting in increased emissions.

Table 2: Transport emissions to major areas of purchase from Lerwick, expressed in nautical miles, hours and tonne of emissions per tonne of product.

Destination	**Distance (nm)**	**Average Travel Time (hr)**	**Emissions (CO_2e)**
St Petersburg, Russia	1257	93.12	0.098
Klaipeda, Lithuania	880	65.28	0.069
Gdansk, Poland	831	61.68	0.065
Szczecin, Poland	715	53.04	0.056
Cuxhaven	498	36.96	0.039
Harlingen, Holland	478	35.52	0.037

Comparison of transport by the current method (a small container ship travelling relatively slowly) and by that of a larger faster ship show that the vessel traveling at approximately 17 knots has some efficiency over the smaller vessel (Figure 9). While long haul air travel results in lower emissions than short haul (+4 hours flight), it is evident that both have much greater emission values than either of the shipping options. This highlights that the mode of transport can have more of an impact on the CF value of a product than distance travelled.

Figure 9: Airfreight versus shipping options for transport of goods, showing short haul air travel (<4 hours), long haul air travel (>4 hours), small container ship (traveling at approximately 12 knots) and large container ship (travelling at approximately 17 knots).

5 Discussion

5.1 Post Capture Carbon Footprint

5.1.1 Overall Figures

The general findings of this study show that the CF for Atlantic mackerel in Shetland is dominated by the capture/landing phase, in keeping with what has been seen in similar studies (Parker, 2012, Avadi & Freon, 2013). Processing and packaging together account for approximately 25% of the overall CF, with processing accounting for approximately 17% of the chain to the processing gate, and product packaging adding a further 8% (refer to Figure 2). However it should be noted that landings into Shetland make up only a minority of the Shetland pelagic fleet's overall landings (Sandison, 2015), and a small fraction of the landings for the processing plant. Attempts were made to address this by gaining additional

data from the small selection of vessels from the Scottish fleet that made up the majority of the processing plant's landings. Despite initial agreement and interest in the project, a lack of robust available records and failure to communicate/provide the agreed information precluded the use of this data. As such the connection of the two chains must be interpreted with caution and are perhaps better considered as two separate chains rather than a single ongoing supply line. Nevertheless, because of the general nature of how data is presented in CF/LCA studies and in the absence of more robust data, the initial figures for the capture/landing phase produced in Sandison (2015) will continue to be used as a proxy. This is considered to be acceptable due to the shared region and similar age/technology of the vessels of the Scottish fleet as a whole.

Refrigeration features in the chain because of the timeframe covered by the data. It should be noted that post 2015 this will not feature in the chain due to new legislation banning the use of R22 as a refrigerant on board fishing vessels. At the time of the 2015 study all vessels utilising the R22 method confirmed their immediate intention to convert to the carbon-neutral ammonia method by 2014/2015, in keeping with legislation requirements. As such any post-2015 data would have fishery refrigerant emissions removed from the analysis, possibly reducing the end figure by up to 0.092 tCO_2 e. Despite freezing being a significant step in the processing section of the chain, emissions from refrigeration do not feature in the processing phase because of the use of carbon neutral ammonia as a refrigerant.

Due to the aforementioned lack of additional data, fuel and emission rate data from the capture phase for 2015 were not available. As such, an average of the three preceding years of fuel data were used to estimate usage for 2015. There was a substantial decrease in fuel emissions seen in 2014 (reducing by about 0.1t CO_2 e). It is possible that 2015 fuel emissions are in reality closer to that seen in 2014, rather than the average figure used as its proxy. In this case it is possible that the 2015 CF value could potentially be decreased further.

Despite the estimated increase in fuel emissions in 2015, removal of the refrigeration emissions still results in a lowered overall CF in 2015. This highlights the significance of the contribution of refrigeration leakage. Again, it should be noted that refrigeration leakage values from the initial study were assumed, as no data was available. In the capture phase study (Sandison, 2015) a worst case scenario was adopted with the higher limit of expected

leakage assumed based on the range offered by the Seafish tool. In Winther *et al.* (2009) a leakage rate of 30% was assumed based on their own literary findings. This gave an estimate of 0.024kg refrigerant loss per tonne of round fish landed. This figure is distinctly lower than the current estimation of 0.064kg per tonne used in Sandison (2015). If Winther et al.'s (2009) estimate were to be used rather than a worst case scenario assumption then this would lower the figure from a refrigerant emission value of 0.122 tCO_2 e (Sandison, 2015) to 0.013 tCO_2 e. As was in keeping with many other studies, Winther *et al.'s* calculation methods are not based on actual direct measurements but rather by using reported fleet leakage figures and their own allocation methods based on mass landings and recommendations made by other studies. The authors justify their reported large difference between vessel types by observing that there is a lack of reported leakage rates. This combined with the modern nature of the RSW pelagic vessels and high catch rates make the assumption that the pelagic fleet refrigerant emission rates are lower than the demersal a fair one. This claim is supported by Tharne (2004b)**.** However as with all assumptions it must be interpreted with some caution. Nonetheless it seems likely that the figures for refrigeration used in the capture phase study (Sandison, 2015) were an over estimation. This is however a moot point for post 2015 data. As such this observation, while being borne in mind for interpretation of the current figures, is of limited use for future work.

5.1.2 Analysis of Components

Analysis of the processing phase of the chain suggests that emissions from electricity make up the majority of the contribution, followed by packaging. As with the capture phase, consumables are negligible. This is in keeping with that suggested by the PAS (BIS, 2012). In total, the contribution for the processing and packaging phase comes to 0.144 tCO_2 e. Sandison (2015) found this supply chain to be most in line with that of the Norwegian figures reported by Winther *et al.* (2009). The capture phase quoted in Winther *et al*. (2009) for Atlantic mackerel was found to be approximately 0.5 tCO_2 e per tonne of fish, contrasting with Sandison's (2015) findings of 0.41 tCO_2 e. Winther *et al.* (2009) is considered to be the best comparison to the current study due to methods used, with their initial end point being post-processing and their functional unit in round frozen fish. In Winther *et al.* (2009) whole frozen Atlantic mackerel was found to have a processing and

packaging emission rate of approximately 0.250 tCO_2e, of which approximately 0.083 tCO_2e can be assigned to processing alone. This is in keeping with the findings of 0.096 tCO_2e in the current study. Winther *et al*. (2009) confirm in their study that, as with this study, the biggest contribution to processing is electricity use.

Though the processing figures are similar between the current study and Winther *et al*. (2009), a few differences stand out when examined more closely. The first is that Norway has a much 'cleaner' energy mix than that of Europe and as such a lowered emission rate per kilowatt hour of electricity used (current figures suggest that the European average is found to be 0.531 kg CO_2e per kwh, compared to the Nordic average of 0.17 CO_2e –Seafish, 2016). Assuming that the energy mix at the time of the study was close to this figure, it would suggest that in order to have a similar end GHG emission figure to this study, the efficiency rate would have to be lowered, resulting in less output per kWh of electricity. Even if the energy mix in Norway in 2009 was not as clean as is currently estimated, this would still hold true as long as it was beneath the current European average. It should also be noted that there is a seven year time difference between the two studies. Improvements have likely been made in Norwegian processing plant energy efficiency between 2009 and the present, although the 2009 study was the only comparable data available at the time of this study.

The concept that the emission rate from processing is strongly influenced by how and where the processing takes place (e.g. onboard vessel/ on land, country) has also been observed in previous studies (Sund, 2009). This would suggest that, while improvements can be made in increasing processing efficiency, the biggest significant factor in lowering processing plant emissions is the 'cleanliness' of the energy mix used to provide the electricity. Due to political, economic and public pressures this is likely to shift more towards 'green' power in the near future.

Packaging figures for Winther *et al.* (2009) show the Norwegian chain to have a value of approximately 0.17 tCO_2e, a noticeable increase in the figures from the current study of 0.048 tCO_2e. It is unclear why this difference is so pronounced as, like this study, the Norwegian product is packaged in cardboard boxes. However, it is unclear the ratio of packaging to product, or whether these are assembled on site or shipped readymade. All of

these might have an effect on the end CF value. While the cardboard component of this study's chain's packaging section is the largest contributor, this comparison highlights that, in contrast with many, it is one of the lower emission causing packaging material. Improvements could potentially still be made, possibly with the use of recycled material offering an option to lower this study's packaging impact further, although packaging emissions are relatively low**.**

Further analysis of fish landings, electricity usage and resulting carbon footprint over the various years covered in this study suggest that for maximum efficiency the quantity of mackerel processed (both in terms of absolute fish landed and proportion of total fish landed) could be increased. However it is noted that there will be a point where an increase is unfeasible due to capacity, quota restrictions, seasonal fisheries and finance. However, due to limited capacity an increase in total mackerel processed is likely to cause a decrease in other fish species, which in turn is likely to cause a decrease in efficiency from their perspective. As such a trade-off exists and this should be considered when trying to interpret any possibility of improving processing efficiency.

5.1.3 Seasonal Analysis

On the whole, season two appears to have the higher results for all three factors considered, though it is unclear if this is something significant or an anomaly due to the relatively small data set. There was no noticeable connection between the seasonal analysis in Sandison (2015) and the current study, with high levels of inter-vessel variation seen between season and landing rate/fuel expenditure.

5.1.4 Transport

Transportation method was found to have a considerable effect on the end CF value, more so than distance travelled. Of the four available transportation options, the current transport emissions by small cargo ship could be lowered by the use of a larger, faster container ship. However it is noted that there could be economic reasons why this is not viable, and indeed if a larger ship was used but not filled to capacity it would significantly reduce the improvements predicted here. The use of a container ship in general is shown

clearly to be the best environmental option in terms of CF when compared to air freight. Despite a much shorter travel time, air freight is shown to be much higher in terms of carbon emissions. Short haul flights appear to have the highest impact, though long haul flights still show a considerably increased footprint compared to surface transport. Transport by container ship is generally accepted to be an efficient method of transportation, with Ledgard *et al.* (2011) reporting approximately eight times more efficiency than by truck and roughly 30 times smaller than transport by car. Food miles are seen to be an inappropriate indication of overall CF and are considered to be of much lesser importance than the transport method. Furthermore, frozen product requires marginally more energy than fresh chilled product. This difference is considered minor and given that it allows for slower but more efficient transportation, the difference is balanced out (Ledgard, *et al* 2011).

5.2 Comparison with Other Aquatic Studies

Unfortunately only a limited number of seafood CFs and LCAs were found that specifically address processing, packaging and transport in detail, and although mass allocation is the most commonly used and suggested allocation method (BSI, 2012), many others are utilised. As this can have a pronounced difference on the end result, comparisons between studies using different allocation methods is not advised (Svanes *et al*, 2011). The lack of seafood studies addressing these issues were highlighted by Parker (2012) as a knowledge deficit.

In keeping with the findings of Sandison (2015), Atlantic mackerel processed in Shetland was found to have a relatively low CF value when compared to various processed fish products to a similar end point (Table 3). This is of particular relevance when compared to the Winther *et al*. (2009) value for whole frozen mackerel which is approximately 0.22 tCO_2e higher than this study's findings. Analysis of the contributing factors show this to be in part because of a slightly higher value for the capture phase and for the packaging materials, though their actual processing related emissions were fractionally lower. As was seen in Sandison (2015), there is quite a noticeable difference between the values found in this

study for whole frozen Atlantic mackerel and for the other fish listed. The higher values for the demersal fish typically caught by deep water trawl and for farmed salmon are to be expected given the general conclusions of the literature regarding the importance of the fishing phase on the end result and the differences in emission intensity between gear types. Demersal fish typically have a higher catch related emission cost (Schau *et al.* 2009). Similarly fishmeal is also typically seen to have a high CF value and contribute strongly to the end figure in farmed salmon CF chains (Ziegler, 2013). The value given for herring – another small pelagic fish, is approximately three times higher than the value presented in this study for Atlantic mackerel. Some of this may be fishery related and due to the modern nature of the fishing fleet examined in this study. A similar observation was made in the capture phase study (Sandison, 2015) when comparing figures with Irribarren (2011). However, another explanation could be related to the different processing methods, with this study looking at whole frozen mackerel, and Carlsson-Kanyama & Gonzlaes (2009) looking at a chain for cooked herring. Freezing is known to be an energy efficient method of processing, (Ziegler, 2013) though this is often because it allows slower more efficient transport. It is unclear at this stage whether the action of cooking the fish rather than raw freezing has a significantly higher energy demand. It should also be noted that it is unclear in Carlsson-Kanyama & Gonzlaes (2009) whether or not packaging is included in their assessment, which may cause a further increase in the final figures.

Table 3: Carbon footprint values for fish products from cradle to processing plant gate.

Species	Functional Unit	Location	Year	Authors	Processing	CF
Cod	Fillet, Frozen	Norway	2009	Winther *et al*	Land	~2.2
Cod	Fillet, Frozen	Sweden	2009	Sund	Land	1.8
Cod	Cooked	Sweden	2009	Carlsson-Kanyama & Gonzlaes	Unknown	8.5
Haddock	Gutted, Frozen	Norway	2009	Winther *et al*	Land	~3.6
Herring	Round, Frozen	Norway	2009	Winther *et al*	Land	~0.75
Herring	Cooked, Whole	Sweden	2009	Carlsson-Kanyama & Gonzlaes	Unknown	1.5
Atlantic mackerel	Round, Frozen	Shetland	2015	This study	Land	0.54
Mackerel	Round, Frozen	Norway	2009	Winther *et al*	Land	~0.75
Pollock, Alaskan	Fillet, Frozen	Sweden	2009	Sund	On Board	0.47
Salmon, Farmed	Fillet, Frozen	Norway	2009	Winther *et al*	Land	~2.25

It is also noted that the CF value for mackerel, as reported in this study, is not the lowest presented in Table 3. The CF value reported by Sund (2009) for Alaskan Pollock fillets was marginally lower. Sund (2009) observe that processing has a larger contribution to the Alaskan pollock CF chain than the Norwegian cod chain and attribute it to the fact that pollock processing takes place on the ship and is fuelled by diesel rather than the low emission electricity used in Norway for land based processing of their cod fillets. They attribute the lower emissions to the fishing method, with the pollock caught by pelagic trawl – a known energy efficient fishing method (Schau *et al.,* 2009). Despite cod being caught using a passive method they observe that the catching of pollock is more energy efficient than the fishing method for cod, in part because of the shoaling nature of pollock and also because of the depleted state of the cod stocks. They further hypothesise that fishing method and stock status play a more important role in CF than the proximity of the fishing grounds. This suggests that efficiencies in the capture phase of the pollock fishery is the likely cause of the relatively low CF value, particularly given the functional unit is frozen fillet rather than whole fish, resulting in a much higher level of discard. This would suggest both a higher processing emission rate, and an efficient initial capture phase**.** The higher CF cost for the Shetland processed fish might be due to the fleet tendency to land in Norway rather than to the nearest port. Another possible reason for the higher CF level in this study might be related to quota and landing figures as evidence suggests optimum CF levels are linked to increased landings and increased processing levels (Sandison, 2015). It is therefore possible that having a higher rate of catch and fish into processing has a strong effect on the CF outcome for pollock. Finally, refrigeration emissions may also pay a key role in increasing this study's CF findings.

5.3 In Relation to Other Terrestrial Meat Studies

Carbon footprint values of terrestrial meat products at the processing plant gate are shown in Table 4. The observed values for terrestrial meat systems are shown to be distinctly larger than the majority of those seen for the fish chains in Table 3. Chicken is the lowest in terms of emissions, in keeping with what was seen in the Sandison (2015) where the end of the chain was to farm gate. Though there are some overlaps, with the cod figure by Carlsson-Kanyama and Gonzlaes (2009) being particularly high, fish CFs are on the whole distinctly

lower, with mackerel from this study and other pelagic fish standing out at the very bottom of the collective range. This would suggest that fish in general to this end point are a more efficient protein source in terms of greenhouse gas emissions, although there is a large range of variation within fish products as there is within terrestrial meat products. However, comparisons should be made with caution because, while attempts have been made to ensure the data provided here are as comparable as possible, those quoted for terrestrial animals are given in the functional unit of 'carcass' or 'meat' whereas those presented for fish are generally given simply as they are sold which varies from cooked, frozen, fillet, headed and gutted and whole. Conversion of all products to a single functional unit may alter CF values, potentially increasing the CF of some and lowering others. Similarly because of the functional unit of the meats it is unclear if packaging is included in the different assessments. This again will have some effect on the CF – possibly increasing it to some degree. That said, it is unlikely that these differences would be significant enough to totally skew the basic trend seen here.

White non-ruminant meat has the lowest values in the terrestrial meat systems with poultry exhibiting the lowest in the range. Red ruminant meat is seen to be higher, with beef yielding the highest emission rate. The enteric methane emissions in ruminants as well as differences in feed, farming methods and meat yield are probably the major reasons behind the vastly different values reported.

Table 4: Examples of carbon footprint values of terrestrial meat products from cradle to processing plant gate

Species	Functional Unit	Place of study	Year	Authors	CF
Beef	Carcass	Norway	2008	Weidema *et al*	28.7
Poultry	Carcass	Norway	2008	Weidema *et al*	3.6
Lamb	Lamb meat	New Zealand	2011	Ledgartd *et al*	15.2
Pork	Carcass	Norway	2008	Weidema *et al*	11.6

These results are in keeping with the current literature, suggesting that the most climate friendly diets are that of vegans, vegetarians and pescatarians respectively, with other meat eaters coming thereafter (Carlsson-Kanyama & Gonzlaes, 2009).

6 Conclusion

The carbon footprint chain for Atlantic mackerel as processed through Shetland has been found to be low in comparison to other protein processing chains, and particularly efficient in terms of processing itself. This is likely due to the nature of the product (packaged whole, minimal discards/off cuts) and bycatch/discards being used for co-products (sale to fishmeal plant). However, processing is also efficient in terms of electricity usage. Potential improvements in processing are likely to depend on future improvements in machinery and improvements in electricity emissions. Although it is possible for processing plants to seek out the most efficient energy suppliers, this will likely be largely government led.

Packaging was found to have minimal impact, suggesting that the materials and methods used are efficient, as was the transportation methods used. Both could possibly be improved on although it is likely that any improvement would be minimal and efforts would be more effectively concentrated on the initial energy usage in the processing phase. Offsite storage may contribute significantly to this chain however and this should be considered when interpreting results. It is suggested that this aspect of the processing and transport chain should be later addressed to give a more robust view of the whole impact of the product in terms of carbon emissions.

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