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Greenhouse gas emissions from a Western Australian finfish supply chain

Felicity Denham[a1], Wahidul Biswas[b], Vicky A. Solah[c] and Janet Howieson[a]

[a] *Centre of Excellence Science Seafood and Health, Faculty of Health Sciences, Curtin University, GPO Box U1987, Perth, Western Australia 6845*

[b] *Sustainable Engineering Group, Curtin University, GPO Box U1987, Perth 6845, Western Australia, Australia*

[c] *School of Public Health, Faculty of Health Sciences, Curtin University, GPO Box U1987, Perth 6845, Western Australia, Australia.*

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Abstract

Greenhouse gas (GHG) emissions in the form of carbon dioxide equivalent (CO_2 –eq) from two Western Australian finfish supply chains, from harvest to retail outlet, were measured using streamlined life cycle assessment methodology. The identification of interventions to potentially reduce the GHG emissions was determined from the results obtained. Electricity consumption contributes to the highest GHG emissions within the supply chains measured, followed by refrigeration gas leakage and disposal of unused fish portions. Potential cleaner production strategies (CPS) to reduce these impacts include installing solar panels, recycling the waste, good housekeeping in refrigeration equipment maintenance, and input substitution of refrigeration gas. The results show a combination of these strategies have the potential to reduce up to 39% of the total GHG emissions from fillet harvest, processing and retail.

1. Introduction

The atmospheric concentration of greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), is increasing (Forster et al., 2007). Airborne particles in the gases then absorb more heat, thus resulting in global warming which causes climate change (Forster et al., 2007). To minimise potential increases in temperature, primary industries that release GHG (such as the seafood industry) should apply cleaner production strategies (CPS) to combat climate change (UNEP, 2002). This paper focusses on the global

[1] Corresponding author email address: f.denham@curtin.edu.au

warming impact of the resources utilised in two Western Australian seafood supply chains by calculating the GHG per tonne (t) of fish fillets.

Streamlined life cycle assessment (SLCA), following the steps of International Organisation for Standardization (2006) is the most widely used method for measuring the upstream GHG emissions only, not taking into account the complete product life cycle (Biswas et al., 2010; Engelbrecht et al., 2013; Gunady et al., 2012). Its application models the GHG emissions for the current study.

Numerous studies have concentrated on modelling GHG emissions and other environmental impacts from harvesting fish (Table 1). However, none of these studies includes data from Western Australia where water temperature, fish species, vessel types and logistics, particularly the long distances from port to fishing ground, differ from other countries.

Several SLCA studies have also investigated the environmental impacts of different transport methods of fish once landed to determine the most environmentally friendly and economic system. Studies included the impact of transporting methods for fresh (never been frozen) and frozen fish (Andersen, 2002; Vázquez-Rowe et al., 2012) and comparing truck (Andersen, 2002; Kissinger, 2012; Tlusty and Lagueux, 2009; Vázquez-Rowe et al., 2012), air (Andersen, 2002; Tlusty and Lagueux, 2009; Vázquez-Rowe et al., 2012), boat (Andersen, 2002; Kissinger, 2012; Vázquez-Rowe et al., 2012), and rail (Kissinger, 2012) transportation methods. However, Western Australia’s case differs from these studies as in some cases fish is transported over 2,000 km from the port to the nearest capital city (Department of Fisheries, 2012).

This study is also unique in combining the three supply chain stages in finfish production: harvesting, processing and retailing. The process in environmental supply chain management requires all stakeholders in a supply chain to work together to measure the impact and identify strategies to attain economically viable outcomes with low GHG emissions (Gupta and Palsule-Desai, 2011). Sustainable seafood supply chain management is working as a whole supply chain with the intention of reducing life cycle environmental impact, enhancing social equity and reducing operational costs therefore increasing profit. In seafood supply chains, previous environmental research studies have only focussed on the harvest (Iribarren et al., 2011; Svanes et al., 2011b; Vázquez-Rowe et al., 2011b; Ziegler et al., 2011), processing (Bezama et al., 2012; Hospido et al., 2006; Williams and Wikström, 2011) and transport stages (Coley et al., 2011; Tlusty and Lagueux, 2009) in the supply chain; only Winther et al. (2009) and Ellingsen et al. (2009) followed harvest through to value adding, but ignored the retail stage. Thus a combination of the whole Western Australian seafood supply chain GHG emissions provides a more effective picture of environmental supply chain management.

Food LCA studies specific to Australia follow a similar trend with only 6% covering the retail stage within the supply chain (Renouf and Fujita-Dimas, 2013). Only Hobday et al. (2014) covered the whole seafood supply chain in Australia, but did not cover the species and transport distances associated with Western Australian finfish.

To fill these gaps of the Western Australian finfish industry knowledge and add to the whole supply chain research, this study has aimed to analyse the Western Australian finfish supply chain's GHG from harvest to retailer. The specific objectives were to:

a) assess the global warming impact of the harvest, processing and retail stages of two Western Australian finfish supply chains using a SLCA method;
b) identify the 'hotspots' or the inputs and outputs emitting the highest amount of GHG during the life cycle of the finfish product; and
c) recommend opportunities for possible GHG CPS.

1.1. Description of finfish supply chains examined

The fish was trawl harvested in the North Coast Bioregion as described by The Department of Fisheries (2012). The boat travelled approximately 200km from port before trawling started. The post-trawl fish process included emptying the catch into a hopper, sorting by size into baskets (or polypropylene bags for large fish), cooling in seawater brine for four hours and packing into tubs for cool room storage once the fish reached 0°C. Once the boat arrived at port after ten days at sea, the fish were packed onto pallets by species and unloaded off the boat, onto a truck. The boat underwent cleaning and maintenance before it returned to sea.

City retailers handle a larger quantity than the regional retailers so, from the landing of the harvested fish, two supply chains were chosen for this SLCA analysis, one to a city retailer and one to a regional retailer. The city retailer was located more than 1,000km away from the landing port whereas the regional retailer was within 20km.

- The city retailer processed the fish into fillets on site as required, instead of using a dedicated filleting processing facility.
- The regional processor filleted, packaged and transported fillets to local and surrounding restaurants and the regional retail outlet.

Hence, in summary there were two separate supply chains from landing: chain one with three firms – harvesting, regional processing and regional retailing; and chain two with two firms – harvesting and city retailing. The system boundaries of this research (Figure 1) included transportation of all consumable items to their respective stages and fish waste disposal to landfill. The system boundaries of the proposed SLCA excluded all downstream activities, including food service and restaurant sectors and handling after the product left the retail facility.

As seafood handled in the processing and retail facilities includes other seafood products (e.g. crustaceans), an allocation procedure separated inputs for the finfish products by weight. The inputs allocated included power, water and refrigeration gases as data provided was per facility.

The selected trawl firm provides 20.5% of the finfish from the North Coast Bioregion (Department of Fisheries, 2012) where 73% of the finfish in this region was trawl caught. The species in this region differ from other regions in Western Australia, as the large coastline results in various water temperatures throughout Western Australia. Therefore, this study is representative of firms dealing with species such as Crimson snapper (*Lutjanus erythropterus*), Bluespotted emperor (*Lethrinus punctulatus*) and Rosy threadfin bream (*Nemipterus furcosus*).

From this capture, 8.7% of the fish caught are utilised in the regional processor and 5.9% in the city retailer. The remaining fish is sold to a private processor. Although these supply chains are only a sample of Western Australia's seafood industry, the framework can still be applied in other companies. The study covers the supply chain from capturing the fish, to leaving the retail store, including typical trawling, processing and retailing processes with similar inputs and outputs. The only items that may differ from other Western Australian fresh finfish supply chains are the transport distances of both consumable items to site and fish to processor or retailer, and the method of packaging (whether fillets are packed loosely in carton liners as per the regional processor or if they are vacuum packed). These variations are beyond the scope of this research.

2. Standard methods for streamlined life cycle assessment

The GHG emissions from the Western Australian test seafood supply chain was benchmarked using a streamlined approach, as it did not take into account downstream activities such as fish consumption. This SLCA approach undertaken followed the four steps of International Organisation for Standardization (2006): goal, life cycle inventory, impact assessment and interpretation. The goal was to ascertain the GHG emissions from the Western Australian finfish supply chain. The functional unit was one tonne of processed fish sold at retail. This unit was used to determine the number of stages of fish life cycle for developing an inventory. The inputs (i.e. chemicals, energy) and outputs (i.e. emissions from processes) were quantified for each life cycle stage for developing inventories of one tonne of processed fish sold at retail for city and retailer supply chains. Some of the data for developing inventories came from field survey, while the rest of the data was obtained from literature.

Collaborating firm interviews occurred between August 2012 and September 2013 and were compiled in a life cycle inventory (LCI) spreadsheet. The LCI considers all the relevant inputs and outputs for processes that occur during the life cycle of a product. Inventory data was categorised into consumable items, energy, transport, storage and waste (Table 2).

Preliminary data for LCI: Representatives from each of the supply chain stages, including a trawler off the coast of regional Western Australia, a regional processor, a regional retailer and a city retailer were interviewed face to face to obtain primary information using a structured questionnaire.

The harvest data includes the quantity of fish harvested, diesel and boat maintenance required per year.

The processing and retail data included the quantity of fish purchased, fish waste and its final destination to landfill, electricity and water consumption, consumable materials and the distances all travelled to the site.

Secondary data for LCI: Secondary data included different data sources:

- international literature provided data estimation from elements that were not possible to collect from the field (i.e. refrigeration gas leakage);
- medical safety data sheets for chemical quantities;
- national reports for waste emission recovery and bioelectricity production; and
- international databases to calculate the eco-inventories of raw materials and energy sources (i.e. packaging materials, gloves, chemicals, boat maintenance and paper).

Once the inventory has been developed using both primary and secondary data sources, emission factors for all inputs and outputs were developed for assessing the life cycle GHG emissions of one tonne of fish fillets sold at retail.

Each CO_2, CH_4 and N_2O gas emission from the LCI was developed. The inputs and outputs of the LCI were multiplied by the respective emission factors (Table 3). Energy emission factors were applied to consumable materials when only an energy breakdown analysis was available. Once the inputs were estimated for the production of one tonne of fish fillets sold at retail, then these inputs were multiplied by their respective emission factors. These emission factors were mainly sources from the local databases. In the absence of the local database, new emission data base were created for the inputs (e.g. battery emissions (Lankey and McMichael, 2000; Life Cycle Strategies Pty Ltd, 2012)).

Energy emission factors: Energy included electricity, diesel, steam, LPG, natural gas, crude oil, coal and petroleum and was calculated from Life Cycle Strategies Pty Ltd (2012). These emission factors were also used for consumable materials when only an energy breakdown analysis was available. The energy breakdown for batteries was taken from Lankey and McMichael (2000).

Storage emission factors: Storage included ice production and refrigeration. All refrigeration gas emission factors were calculated using the leakage rates from The Australian Institute of Refrigeration (2012) (30% for boats, 12.5% for walk in cool rooms and 12.5% for display cabinets) and the emission factor from The Department of Sustainability, Environment, Water, Population and Communities (2012) (Table 3). The ice machine energy breakdown and the water and refrigerant quantities contributed to the ice emission factor.

Transportation emission factors: Transportation included of transportation of consumables and fish each facility and was calculated from Life Cycle Strategies Pty Ltd (2012) for ship, international airfreight, articulated truck, car, light commercial vehicles and rail transportation. The refrigerated truck had 20% more energy (Tassou and Ge, 2008).

Waste emission factor: The waste emissions from unused fish portions in this research including heads, viscera, scales, bones, tails etc. were calculated to be 1.39 kg of CO_2 –eq per kg of fish using the Buswell equation (Symons and Buswell, 1933), composition of the waste (Esteban et al., 2007; Khoddami, 2012; Ng, 2010) and anaerobic digestion yields (Curry and Pillay, 2012; Davidsson et al., 2007) to calculate the methane emitted to the atmosphere, instead of harvested for energy. Although some landfill sites in Western Australia are harvested for methane, the average of 38.9% of CH_4 recovered from landfill (Department of the Environment) and the resulting 502 kWh of energy per functional unit (Clean Energy Council, 2013) was included in the waste emission factor.

Finally, following IPCC's fourth assessment report (Forster et al., 2007), all GHGs associated with the production of one tonne of fish fillets sold at retail were converted to 100 year impacts in kg of CO_2 –eq.

After the SLCA, CPS were assessed to mitigate supply chain GHG emissions. These five categories of strategies are described further in UNEP (2002) and van Berkel (2007):

1. Good housekeeping
2. Input substitution: replacing resources with environmentally preferred substances
3. Technological modification: modifying existing structures to increase efficiency
4. Product modification: modifying a product to reduce material consumption and to enhance recyclability
5. Recycling waste.

3. Results and Discussion

3.1. Comparison of the city and regional supply chains

Although both supply chains include transporting the fish from the port, filleting and storage, the supply chain's inventories differed (Table 4). The regional supply chain had an extra stage and the city supply chain consumed more electricity due to a larger and potentially more inefficient refrigeration system (The city supply chain consumed more than six times the electricity consumed in the regional supply chain). The city supply chain also had more tkm (tonnes x km travelled) of refrigerated transport to get the fillets to the retailer due to the large distance from port.

Producing one tonne of fish fillets released a total of 18,870 kg CO_2 –eq from the regional supply chain and 92,560 kg CO_2 –eq from the city supply chain (Figure 2). The Monte Carlo Simulation was run to determine the mean, standard deviation and standard error of the mean from each supply chain (Table 5). The standard deviations were only 2.8% and 3.9% of the mean values of the carbon footprint of the regional and city supply chains, respectively, confirming the validity of this LCA.

3.2. Identification of hotspots

Relative impacts from the various supply chain components are shown in Figure 3. The greatest GHG emissions within the two supply chains measured were from energy (mainly electricity consumption (78% in the regional supply chain and 93% in the city supply chain) followed by refrigeration gases (11% in the regional supply chain and 4% in the city supply chain) and filleting waste (6% in the regional supply chain and 1% in the city supply chain).

Energy consumption was also the hotspot in other seafood LCA studies, however, in this study, the energy use was from electricity used in processing and retail, rather than diesel consumption in the harvest stage as found by Winther et al. (2009), Thrane (2004), and Vázquez-Rowe et al. (2010b, 2011b).

Whilst the supply chains measured required long distant transport (>1,000km), the transportation had a minimal impact in the regional (1.1%) and city (0.05%) supply chains. This is because each consumable purchased had a relatively low weight, resulting in a low tkm. Transport of fish to the city retail outlet had a larger impact than transporting the consumable items to the boat, regional processor and regional retailer.

When comparing these results to previously published work, few studies had the same areas of greatest impact perhaps because they did not include the whole supply chain (Ellingsen et al., 2009; Svanes et al., 2011b; Vázquez-Rowe et al., 2013; Winther et al., 2009; Ziegler et al., 2013), excluded refrigeration gases (Iribarren et al., 2010; Thrane, 2006; Vázquez-Rowe et al., 2011b) or the supply chains did not use refrigerants with a high GHG emission factor (Winther et al., 2009). Previous seafood LCA studies either focussed on the harvest supply chain stage, where energy use was diesel (Ellingsen and Aanondsen, 2006; Svanes et al., 2011a; Winther et al., 2009) or focussed on the processing and retail stages that require electricity used in processing (Vázquez-Rowe et al., 2013; Winther et al., 2009).

If this study excluded the refrigerant leakage, the emissions would be underestimated by 11% and 4% from the regional and city supply chains respectively. Vázquez-Rowe et al. (2013), Ziegler (2013) and Svanes (2011b) found refrigerant leakage to be a hotspot during harvest but did not measure beyond harvest into processing and further handling. Although Iribarren (2010) originally did not include refrigerants in his research, in a later study he found refrigerant leakage to have the greatest carbon emissions from fish capture (Iribarren et al., 2011). Other studies including Thrane (2006) and Vázquez-Rowe (2011b) ignored refrigeration completely in their research. Winther (2009) did include refrigerants, but the study comprised of carbon neutral alternatives. As a result, the energy used in the harvest was the hotspot (Thrane, 2006; Vázquez-Rowe et al., 2011b; Winther et al., 2009; Ziegler et al., 2013) with minimal GHG from processing and retail. None of these aforementioned studies included fish waste.

3.3. Potential cleaner production strategies

As the three greatest GHG hotspots within both supply chains were energy from electricity, refrigeration gas leakage from the cool rooms, ice machines, and display cabinets, and the breakdown of fish waste in landfill, potential CPS are discussed. These include installing solar panels (an input substitution CPS as it is associated with the replacement of conventional electricity solar electricity), the conversion of fish waste to bio-electricity (input substitution, technological modification or recycling CPS) and reducing the GHG emissions from refrigerant leakage equipment (a good housekeeping CPS).

3.3.1. Solar electricity

Electricity as a hot spot is related to refrigeration and low temperatures are required to keep fish food-safe. Other LCA studies in the food industry have found a similar energy hotspot including Sanjuan et al. (2014), Vázquez-Rowe et al. (2013) and Winther et al. (2009). As most of the energy consumption from the supply chains measured in this study is electricity, there is the opportunity of harvesting solar energy as a potential CPS.

Solar energy (an input substitution CPS) is useful for supplementing the bulk of the power used during the day. As the energy consumption from the partnering firms was from refrigeration and freezing non-fish products, it is assumed energy consumption is consistent over a 24 hour period. Therefore, solar panels can be used to supplement grid electricity during the peak sun hours of the day. Peak sun hours are the time per day the sun provides the maximum solar energy, differing in various locations around Australia and in different seasons of the year. The average peak sun hours were calculated from BOM (2013) for both the regional processer and city retailer regions. The solar emission factor was taken from Lund and Biswas (2008) (multicrystalline solar system at 0.075 kg of CO_2 –eq per kWh). Due to the total energy consumption, a 20 kW and a 100 kW system is recommended for the regional processor and the city retailer respectively, resulting in a potential GHG emission reduction of 17.1% and 21.3% respectively. Although a 20 kW and a 100 kW system will cost $ 2,919 and $ 13,365 per tonne of fillets, it will potentially reduce the electricity bill by $1,071 and $7,377 per tonne of fillets per year in the regional processor and the city retailer respectively (Shetty, Personal Communication), resulting in a payback period of less than three years for the regional supply chain and two years for the city supply chain.

3.3.2. Biogas electricity

The filleting waste may also be utilised for biogas (a technological modification and recycling waste CPS), providing a second alternative to grid electricity consumption. Using the Buswell Equation (Symons and Buswell, 1933) and the amino and fatty acid breakdown of the fish species from Western Australia (Esteban et al., 2007; Khoddami, 2012; Ng, 2010), the CO_2, CH_4, ammonia (NH_3) and hydrogen sulphide (H_2S) from the anaerobic digestion process can be predicted.

Although the Buswell Equation assumes complete digestion, it can be used to predict the quantity of potential CH_4 production. Both Davidsson et al. (2007) and Curry and Pillay (2012) calculated the actual methane yield compared to the predicted yield of municipal waste and found 76.7% and 74.9% respectively. If the average (75.8%) is applied to this study, processing all the filleting waste would produce 85.57 kg of CH_4 (Table 6), resulting in 4,757 MJ of energy per functional unit in both supply chains. However, if converted to electricity using a generator, only 46% of the energy is converted (Reedman, Personal Communication), leaving 607.9 kWh per functional unit, theoretically preventing a potential 15.2% and 3.1% of total emissions from the city and regional supply chains respectively.

As the firms in this study produce other products, the energy production from fish waste production would only supply 0.62% and 3.75% of the total energy consumed by the city retailer and regional processor respectively, saving $1 598 and $2 071 per year. As the system would require both a digester such as a stainless steel IBC ($2 850) and a generator to convert the gas to electricity ($11 500), the potential electricity savings would take nine years and seven years to recover costs from the city retailer and regional processor respectively, making biogas a less efficient investment for the potential GHG and electricity cost reductions compared to the solar electricity option.

3.3.3. Refrigeration Modification

The refrigeration emissions as a hotspot in this research, was a hotspot in other food industries including fresh pineapple (Ingwersen, 2012), fish on the boat (Svanes et al., 2011b; Vázquez-Rowe et al., 2013; Ziegler et al., 2013), ice cream (Australian Industry Group, 2011) and butter (Büsser and Jungbluth, 2009). Thus, GHG from refrigeration is not just a seafood issue. However, none of these studies offered potential CPS other than increasing maintenance to reduce the impact.

Equipment maintenance, a 'good housekeeping' CPS, is one method to reduce the GHG emissions from refrigeration. Although the equipment in the current study is regularly serviced, any lapse can increase the current leakage by 2.5% from the display cabinets and walk-in cool-rooms used by the regional processor, regional retailer and city retailer (The Australian Institute of Refrigeration, 2012). Therefore, applying this potential 2.5% savings to the supply chains measured by simple good housekeeping CPS potentially prevents an estimated 0.28% and 0.10% of GHG emissions from the regional and city supply chains respectively.

Another method of reducing the impact of the refrigeration gas GHG in the studied supply chains is to change the refrigerant used (both a 'technological modification' and 'input substitution' CPS). The supply chain partners have recently converted their systems from R22 to the more 'environmentally friendly' R404a refrigerant. Although there are refrigeration gases with little or no GHG available such as ammonia, which would eliminate GHG emissions from refrigeration (ICF Consulting, 2003), refrigerant changes are expensive, particularly when the current R404a systems in the supply chains measured are new. For example, a quote for Sydney Fish Markets to change their refrigerants from R22 to HFC-134a would potentially cost $255.22 per tonne of seafood (Northern Prawn Fisheries, 2014; Sydney Fish Market, 2013). This cost included updating the plant, evaporators, pipework and warm glycol defrost, warm glycol circulation to replace door heater, labour, electrical and controls, refrigerant, contractors costs, contingency and warranty (Northern Prawn Fisheries, 2014). As changing the refrigerant requires complete equipment replacement, it is an expensive project that is unlikely to occur until the current refrigeration units require replacing.

Although changing the refrigerant would improve each supply chain's GHG emissions by up to 11.3% and 4.0% in the regional and city supply chains respectively, the capital cost of updating the equipment without any resultant change in profit is a barrier to change.

In summary, the GHG emissions from refrigerants can potentially be reduced using good housekeeping, technological modification and input substitution. Such changes can potentially reduce the total GHG emissions by up to 11.3% (Figure 4).

3.3.4. Utilising waste

In the supply chains measured, there was 62.5% (by weight) wastage from filleting fish. By isolating this waste during processing and developing by-products from the specific waste streams, resources efficiency may increase by ‘recycling’ the waste, which is one of the CPS. Biogas production has already been discussed, but further possibilities for waste usage include fertiliser and hydrolysate.

Fish waste can be composted into fertiliser for a possibly inexpensive solution. López-Mosquera et al. (2011) composted the fish waste with seaweed and sawdust, applying their composting method to the waste from Western Australia could potentially reduce the GHG by 6.0% and 1.2% from the regional and city supply chains respectively.

Fish waste is also a good source of hydrolysate (fish ground into liquid) that can be used for protein powders, fertiliser, and animal feeds. Aspmo et al. (2005) and Bhaskar and Mahendrakar (2008) only used the viscera and thus, only used 10.3% of the waste product. However, when all the fish waste is used as in Nges et al. (2012), the GHGs would potentially reduce by 6.0% and 1.2% from the regional and city supply chains respectively.

There are barriers to recycling waste that affect both supply chains. Firstly, the cost to transport the waste over 1000 km to the nearest capital city for processing is a major barrier. Secondly, many of the suggestions above require the purchase of capital equipment to convert waste to biogas, fertiliser or hydrolysate. Thirdly, due to the current size of both the regional processor and city retailer, a new premise will also be required for each supply chain to manufacture these recycled products, or potentially outsource them. Thus, further research is required into the feasibility, cost and exact GHG reduction in each supply chain in Western Australia.

Another consideration is that whilst reusing the all the fish waste to create another product can potentially reduce the current GHG emissions by up to 6.0% (Figure 4), these calculations do not account for the GHG in producing the waste products (e.g. electricity consumption). Thus, further research is required into the GHG potential in recycling fish waste.

3.4. Overall improvement opportunities

Overall, if all CPS discussed were applied – installing solar power, maintaining equipment, changing the refrigerant and recycling the fish waste,– the current GHG emissions would reduce potentially by 38.6% and 25.7% from the regional and city supply chains respectively (Figure 4). If extrapolated to the total fish quantity from the North Coast Bioregion, this would be equivalent to a potential savings of 4.9 million tonnes of CO_2 –eq from the regional supply chain or 16 billion tonnes of CO_2 –eq from the city supply chain’s processes.

The two supply chains measured differed mainly in their electricity consumption per functional unit. Although the city supply chain has more significant improvement opportunities through the CPS discussed, the regional supply chain has significantly lower GHG emissions. The regional supply chain has greater opportunity for reducing its current GHG emissions, particularly harvesting solar energy. Although recycling filleting waste into biogas does reduce grid electricity consumption, it is expensive for the quantity of electricity generated. Therefore, installation of solar energy is recommended. The city supply chain had more GHG emissions, particularly as the retailer had a large electricity consumption.

Both supply chains have the same barriers to solar energy installation. Although harvesting solar energy in both supply chains will reduce both GHG emissions and ongoing costs, neither the regional processor nor the city retailer own their own premises. Thus, negotiations with the building owners are required to set up a "green lease" where the lease agreement is set up to recover costs of the solar panels (Council of Australian Governments (COAG) National Strategy on Energy Efficiency, 2012). Despite these barriers, installation of solar panels will result in long term lower energy costs and reduced GHG in both the regional processor and city retailer.

Although replacing refrigeration equipment will also reduce current GHG emissions, the cost of replacing equipment so soon after installing R404a equipment is a large barrier. Therefore, it is recommended both supply chains continue (or increase) their refrigeration maintenance to reduce refrigerant leakage and prevent further GHG emissions.

Despite the quantity of waste disposed in landfill, it had a minimal GHG impact in both supply chains compared to electricity consumption. Although a potential profit can be made from recycling this waste, it will only reduce GHG emissions up to 5.0%. Thus, further research into the profit potential of recycling is recommended only for solid waste reduction purposes as opposed to potential GHG savings.

4. Conclusions and Recommendations

This research was unique as it measured the GHG emissions in finfish production from a whole of chain perspective in Western Australia and included both refrigerants and fish waste emissions.

Electricity had the greatest GHG emissions in both supply chains (78% in the regional supply chain and 93% in the city supply chain). These emissions may be reduced by installing solar panels at the regional processor and the city retailer, resulting in a potential 17.1% and 21.3% respectively.

Other potential CPS discussed in this study (biogas production, refrigeration gas modification and recycling filleting waste) had minimal reduction in GHG emissions, but when combined with solar, a potential 38.6% and 25.7% from the regional and city supply chains respectively could be prevented.

The possible uses from recycling waste have been modelled include using all the waste to create fertiliser or hydrolysate. Using all the waste (including heads, skin, viscera and frames) instead of portions only, provides the best potential of reducing the GHG emissions by 6.0% and 1.2% from the regional and city supply chains respectively. Further research is required to model the effects of these recommendations in Western Australia.

Finally, the outcomes of this research will assist in the enhancement of the framework of the seafood supply chain by enabling stakeholders, including similar Western Australian finfish companies to restructure the supply chain with reduced GHG emissions by implementing CPS.

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6. Tables

Table 1 Studies of various harvest methods

Harvest method	Country	Reference
Trawl harvested fish	Spain	(Iribarren et al., 2010; Iribarren et al., 2011; Ramos et al., 2011; Vázquez-Rowe et al., 2010a)
	Denmark	(Ellingsen and Aanondsen, 2006; Schau et al., 2009)
	Norway	(Ellingsen and Aanondsen, 2006; Schau et al., 2009)
	Antarctic	(Parker and Tyedmers, 2012)
Purse seine	Spain	(Hospido and Tyedmers, 2005)
	Denmark	(Thrane, 2004)
	Norway	(Schau et al., 2009; Svanes et al., 2011a, b)
	Spain	(Iribarren et al., 2010)
Multiple methods within a fleet	Norway	(Schau et al., 2009)
	Denmark	(Thrane, 2006)
	Spain	(Vázquez-Rowe et al., 2011a; Vázquez-Rowe et al., 2010b, 2011b)
	Senegal	(Ziegler et al., 2011)
	Sweden	(Ziegler and Hansson, 2003; Ziegler et al., 2003)

Table 2 Categories of inputs and outputs in the supply chains measured

	Unit per tonne of fish fillet	Regional Supply Chain	City Supply Chain
Consumable Items			
Carton liners	kg	14.400	0.003
Checkout paper bags	kg	53.156	
Checkout plastic bags	kg		14.988
Detergent	kg	17.026	10.479
Esky	kg	81.304	
Fillet covers	kg	13.893	8.960
Grease	kg	0.310	0.310
Hand sanitiser	kg	6.219	0.833
Hand soap	kg	3.110	0.957
Hydraulic oil	kg	1.267	1.267
Lanolin grease	kg	0.001	0.001
Lug buckets/tubs	kg	7.724	7.724
Pallet wrap	kg	0.114	0.114
Paper to wrap purchase	kg	47.841	177.778
Paper towels	kg	14.222	20.741
Plastic bag for fillet	kg	13.821	14.815
Polypropylene bags	kg	2.038	2.038
Rope	kg	1.097	1.097
Rust rinse	kg	4.026	4.026
Thick gloves	kg	0.301	0.301
Water	kg	45208.487	2849.003
Energy			
Electricity	kWh	13918.228	91509.972
Diesel	kg	2851.156	2851.156
Transport			
Ship	tkm	153.493	153.493
Articulated truck	tkm	741.508	101.148
Refrigerated articulated truck	tkm		3384.800
Rail	tkm	60.505	5.934
Light commercial vehicle	km	470.838	396.533
Storage			
R404a refrigeration gas	kg	4.483	8.325
Waste			
Fish waste	kg	1666.667	1666.667
Waste recovered from landfill	kg	663.333	663.333
Energy recovered from waste	kWh	502.264	502.264

Table 3 Emission factors used

	Unit	kg CO_2 –eq	Reference
Energy			
Electricity	Per kWh	0.916	(Life Cycle Strategies Pty Ltd, 2012)
Diesel	Per kg	0.675	(Life Cycle Strategies Pty Ltd, 2012)
Batteries	Per kg	22.98	(Lankey and McMichael, 2000; Life Cycle Strategies Pty Ltd, 2012)
Transport			
Ship	Per tkm	0.02076	(Life Cycle Strategies Pty Ltd, 2012)
Articulated truck	Per tkm	0.1002	(Life Cycle Strategies Pty Ltd, 2012)
Refrigerated articulated truck	Per tkm		(Life Cycle Strategies Pty Ltd, 2012; Tassou and Ge, 2008)
Rail	Per tkm	0.0008760	(Life Cycle Strategies Pty Ltd, 2012)
Light commercial vehicle	Per km	0.4402	(Life Cycle Strategies Pty Ltd, 2012)
Storage			
R404a refrigeration gas	Per kg	3260	(Department of Sustainability Environment Water Population and Communities, 2012)
Waste			
Fish Waste	Per kg	1.39	(Curry and Pillay, 2012; Davidsson et al., 2007; Esteban et al., 2007; Khoddami, 2012; Ng, 2010; Symons and Buswell, 1933)
Consumable Items			
Carton liners	Per kg	1.949	(Nolan-Itu Pty Ltd, 2002)
Checkout paper bags	Per kg	0.5327	(Nolan-Itu Pty Ltd, 2002)
Checkout plastic bags	Per kg	1.949	(Nolan-Itu Pty Ltd, 2002)
Disposable gloves	Per kg	0.5572	
Detergent regional	Per kg	0.5193	(Life Cycle Strategies Pty Ltd, 2012)
Detergent city	Per kg	0.1342	(Life Cycle Strategies Pty Ltd, 2012)
Esky	Per kg	6.4136	(Life Cycle Strategies Pty Ltd, 2012)
Fillet covers	Per kg	0.5572	(Life Cycle Strategies Pty Ltd, 2012; Saeki and Emura, 2002)
Grease	Per kg	0.3890	(Life Cycle Strategies Pty Ltd, 2012)
Hand sanitiser	Per kg	0.3819	(Kim and Dale, 2003; Life Cycle Strategies Pty Ltd, 2012; Renouf et al., 2010)
Hand soap	Per kg	1.0170	(Bishai et al., 2013; Greene, 1996; Life Cycle Strategies Pty Ltd, 2012; Renouf et al., 2010; Vink et al., 2010; Vink et al., 2003)
Hydraulic oil	Per kg	0.4094	(Life Cycle Strategies Pty Ltd, 2012)
Lanolin grease	Per kg	0.3885	(Barber and Pellow, 2006; Hoare, 1974; Life Cycle Strategies Pty Ltd, 2012)
Lug buckets/tubs	Per kg	0.5572	(Life Cycle Strategies Pty Ltd, 2012; Saeki and Emura, 2002)
Pallet wrap	Per kg	2.532	(Nolan-Itu Pty Ltd, 2002)
Paper to wrap purchase	Per kg	0.5327	(Nolan-Itu Pty Ltd, 2002)
Paper towels	Per kg	0.4118	(Hapsari Budisulistiorini, 2007)
Plastic bag for fillet	Per kg	2.532	(Nolan-Itu Pty Ltd, 2002)
Polypropylene bags	Per kg	4.083	(Nolan-Itu Pty Ltd, 2002)
Rope	Per kg	4.083	(Nolan-Itu Pty Ltd, 2002)
Rust rinse	Per kg	1.084	(Berenbold and Kosswig, 1995; Life Cycle Strategies Pty Ltd, 2012)
Thick gloves	Per kg	0.0002427	(Saeki and Emura, 2002)
Water	Per kg	0.000317	(Life Cycle Strategies Pty Ltd, 2012)

Table 4 Inventory differences between supply chains

Regional Supply Chain	**City Supply Chain**
Consumable items	
Water bill included the neighbouring firm's consumption	Water bill was just for the retail stage
Packaged fillets in polystyrene eskies for transporting to the store	Filleted on site and had no reason to transport fillets
Provided paper bags for customer's convenience	Provided plastic bags for customer's convenience
Used less paper to wrap the fillets	Used more paper to wrap the fillets
Energy	
Used electricity to support storage in both processing and retail stages	Only one supply chain stage consumed electricity, but consumed 6 times the consumption of the regional supply chain
Transport	
Fish travelled 20 km in refrigerated van	Refrigerated truck travelled over 2000 km
Consumable items travelled over 2000 km to site	Consumable items purchased in city
Storage	
Displays fillets bunched up in display cabinet using less refrigeration gases per functional unit	Spread fillets out in display cabinet using more refrigeration gases per functional unit
Waste	
No difference	

Table 5 Monte Carlo Simulation uncertainty analysis (1,000 runs)

	Mean	Standard Deviation	Standard Error of Mean
Regional supply chain	18,500	516	0.000884
City supply chain	92,600	3580	0.00122

Table 6 Potential biogas yield in kg per functional unit

	Carbon dioxide	Methane	Ammonia	Hydrogen sulphide
Amino acids	166.00	64.89	36.00	3.08
Fatty acids	56.36	46.93		
Carbohydrates	2.84	1.03		
Total	225.20	112.86	36.00	3.08
Assuming 75.8% digestion	**170.74**	**85.57**	**27.29**	**2.33**

7. Figures

Figure 1 System boundaries of each seafood supply chain

Figure 2 GHG comparision between the harvest to regional retailer supply chain and the harvest to city retailer supply chain

Figure 3 Distribution of GHG in the regional supply chain (left) and city supply chain (right)

Figure 4 Percentage reduction of GHG from installing solar panels, utilising biogas, changing the refrigerant, recycling waste and a combination of the four CPS listed

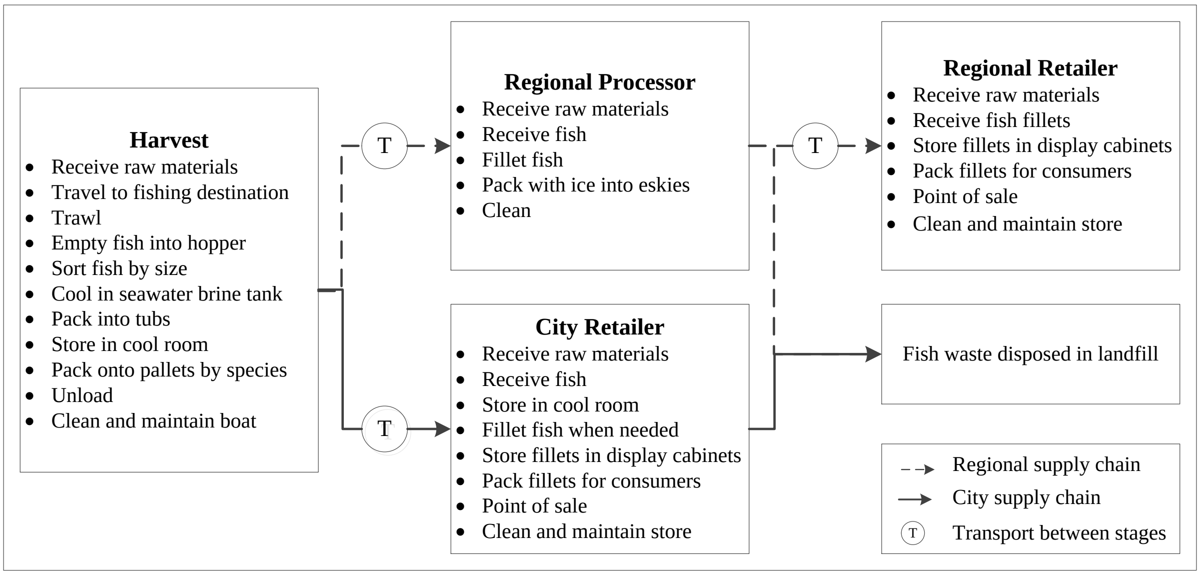

Figure 1 System boundaries of each seafood supply chain

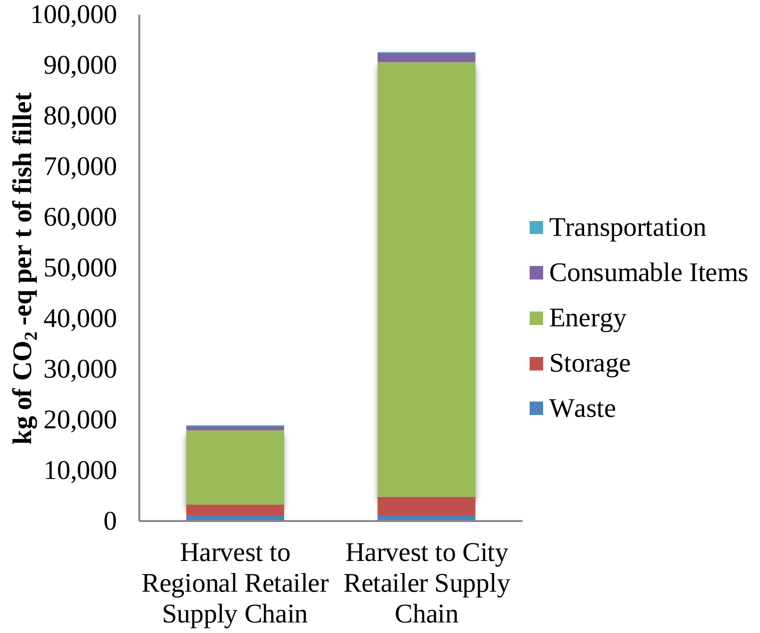

Figure 2 GHG comparision between the harvest to regional retailer supply chain and the harvest to city retailer supply chain

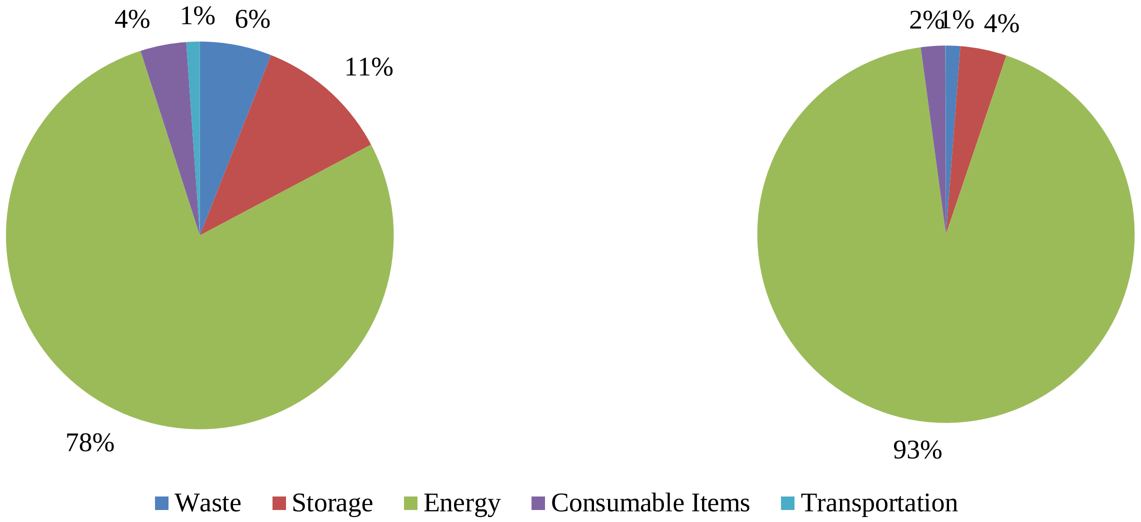

Figure 3 Distribution of GHG in the regional supply chain (left) and city supply chain (right)

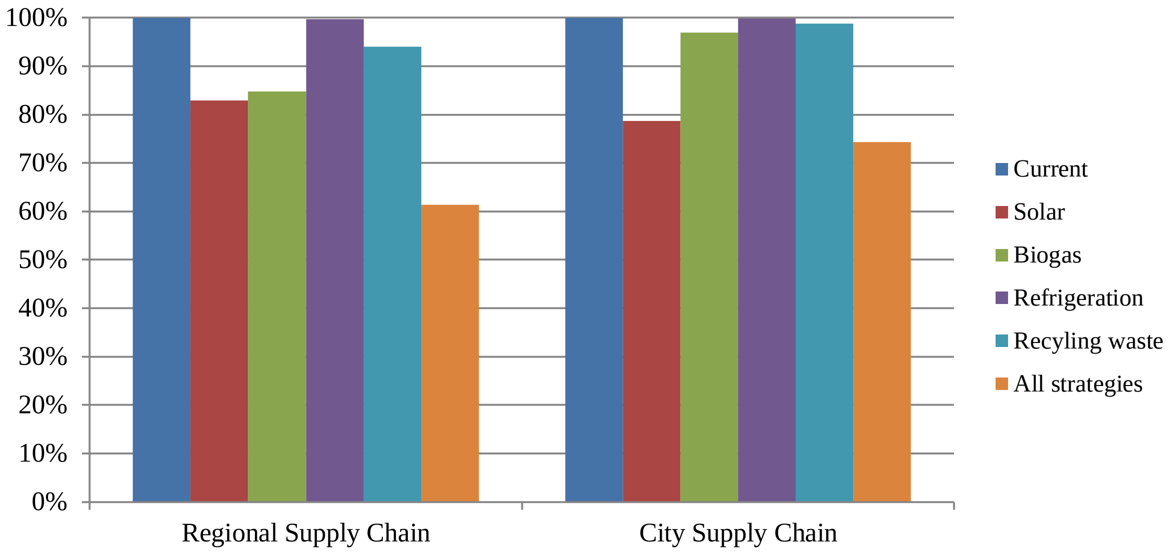

Figure 4 Percentage reduction of GHG from installing solar panels, utilising biogas, changing the refrigerant, recycling waste and a combination of the four CPS listed

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