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Environmental and economic dimensions of fuel use in Australian fisheries

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ABSTRACT

Fisheries globally are facing multiple sustainability challenges, including low fish stocks, overcapacity, unintended bycatch and habitat alteration. Recently, fuel consumption has joined this list of challenges, with increasing consumer demand for low-carbon food production and the implementation of carbon pricing mechanisms. The environmental impetus for improving fishery fuel performance is coupled with economic benefits of decreasing fuel expenditures as oil prices rise. Management options to improve the fuel performance of fisheries could satisfy multiple objectives by providing low-carbon fish products, improving economic viability of the industry, and alleviating pressure on overfished stocks. We explored the association of fuel consumption and fuel costs in a wide range of Australian fisheries, tracking trends in consumption and expenditure over two decades, to determine if there is an economic impetus for improving the fuel efficiency – and therefore carbon footprint – of the industry. In the years studied, Australian fisheries, particularly energy-intensive crustacean fisheries, consumed large quantities of fuel per kilogram of seafood product relative to global fisheries. Many fisheries improved their fuel consumption, particularly in response to increases in biomass and decreases in overcapacity. Those fisheries that improved their fuel consumption also saw a decrease in their relative fuel expenditure, partially counteracted by rising oil prices. Reduction in fuel use in some Australian fisheries has been substantial and this has resulted not from technological or operational changes but indirectly through fisheries management. These changes have mainly resulted from management decisions targeting ecological and economic objectives, so more explicit consideration of fuel use may help in extending these improvements.

1. Introduction

1.1. Fuel use and carbon emissions in fisheries

Fossil fuel consumption is the primary source of energy for modern marine fishing fleets and plays a central role in both the environmental and economic performance of fisheries. Interest in measuring, comparing and improving the energy performance of food production systems, including fisheries, first arose after the oil price shocks of the 1970s (Rawitscher, 1978; Tyedmers, 2004). The issue is of increasing pertinence in recent years as a result of rapidly increasing oil prices, concern over greenhouse gas (GHG) emissions and climate change, and implications for fishing communities and food security (Abernethy et al., 2010; Pelletier et al., 2014).

In the decade from 2002 to 2011, the price of Brent crude oil rose more than 300%, increasing by an average of US$0.70 per month (EIA, 2012). After peaking in 2008, global oil prices dropped during the Global Financial Crisis, but have since increased to be consistently above US$100 per barrel. This increase in oil prices and the resulting burden placed upon diesel-consuming fisheries has easily outpaced any increase in seafood prices, resulting in an overall decrease in profitability (Tveteras et al., 2012). The different trajectories of fuel and seafood prices have sparked concerns over the impact of such energy costs on seafood consumers and fishing communities (Abernethy et al., 2010).

Tracking and improving energy performance is critical in ensuring the long-term sustainability of food production, both economically and environmentally. Changes to fishery-sourced food supply and seafood prices can have drastic socio-economic impacts, particularly in poorer countries that rely heavily on fisheries as a source of food and income (Pelletier et al., 2014). These

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potential impacts will likely become more apparent as oil prices rise and as emissions-based regulations are put in place.

Wild harvest fisheries are unique in that the industrial energy inputs and GHG emissions of their operations, ranging from propulsion and fishing to powering cooling systems and other ancillary activities, are typically from direct fossil fuel consumption (Tyedmers, 2004). In contrast, the energy inputs and GHG emissions of land-based food production systems are largely via inputs to production of fertilizers and pesticides, soil nutrient loss and methane emissions from ruminant livestock. Likewise, energy inputs and emissions in carnivorous aquaculture systems are often dominated by upstream production of fish feeds (Pelletier et al., 2011; Pimentel and Pimentel, 2003; Troell et al., 2004). Tyedmers et al. (2005) estimated that, in the year 2000, the global fishing fleet consumed 42.4 million tonnes of fuel and released over 130 million tonnes of carbon dioxide (CO_2). Emissions from the burning of fuel by fishing vessels typically outweigh the combined emissions associated with processing, packaging and transporting seafood products (Parker, 2012; Sonesson et al., 2010). Exceptions to this include instances where fishery products are transported via airfreight, for example, with live lobster exports (Boyd, 2008; Farmery et al., 2014). In addition to carbon emissions, contributions of fisheries to a wide range of airborne emissions can, in large part, be directly attributed to fuel, including sulphur dioxide (SO_2), photochemical smog particulates, and ozone-depleting substances (CFCs) (Pelletier et al., 2007; Avadí and Fréon, 2013; Parker and Tyedmers, 2013).

In many fishing operations throughout the world, fuel is the second highest cost after wages to crew (Lam et al., 2011). Fuel accounts for a rising portion of fisheries operating costs (Parker and Tyedmers, in press), and is a leading source of concern for the economic viability of fishing operations and fishery-dependent communities (Abernethy et al., 2010). This varies by region, with the role of fuel generally greater in developing countries (FAO, 2007). Abernethy et al. (2010) surveyed UK fishermen on their observations and opinions related to the cost of fuel, and found 100% of respondents expected a “significant reduction in fishing fleet as a result of increasing fuel prices”, while 94% expressed uncertainty about the future of the industry as a result. Many of the world's fisheries are already facing economic pressure from fleet overcapacity, declining fish stocks and highly variable ex-vessel prices; rising fuel prices will serve to exacerbate these challenges.

Analyses over the past decade have measured the fuel use intensity (FUI) of fishing fleets, expressed in litres of fuel burned per tonne of round weight landings (L/t). The FUI of many commercial fishing fleets increased throughout the 1980s and 1990s (Tyedmers, 2001). Fuel prices during those years were low enough to allow for production to occur that would not have been viable with higher prices (*e.g.* use of intensive gear types), and modest increases in costs could more easily be compensated for by technological and operational changes. This trend may have reversed since the beginning of the 21st century; European fleets, for example, have decreased their FUI since 2002 (Cheilari et al., 2013). In addition to fishery-specific assessments, broad analyses of fisheries fuel consumption exist for North Atlantic fisheries (Tyedmers, 2001), Norway (Schau et al., 2009), Denmark (Thrane, 2004), the European Union (Cheilari et al., 2013), Japan (Watanabe and Okubo, 1989), Taiwan (Hua and Wu, 2011) and global fisheries targeting tunas (Parker et al., in press). These analyses identified a number of consistent patterns in fuel consumption. On a macro level, FUI varied by species (related to biological measures such as biomass levels and schooling behaviour), fishing gear and location (Parker and Tyedmers, in press). This variation is on a scale of several orders of magnitude, with some fisheries for small pelagic species requiring less than 50 L/t, while those for crustaceans such as lobsters may require several thousand L/t (Schau et al., 2009; Tyedmers, 2001; Ziegler and Valentinsson, 2008). Similarly, fisheries targeting related species but using different gears also varied markedly in their fuel consumption; tuna fisheries fishing with purse seine required far less fuel than those fishing with longline and pole-and-line gears (Parker et al., in press). On a micro level, FUI was influenced by size of vessel, skipper behaviour, management rules and fishing technique, such as the use of fish aggregating devices or the choice of how far to travel to fishing grounds and whether to fish on days of poor weather (Farmery et al., 2014; Parker et al., in press; Thrane, 2004; Vázquez-Rowe and Tyedmers, 2013).

1.2. *Australian fisheries*

Australia has the third largest fishing zone in the world, owing to its geographic size, island status and territorial claims over Antarctic waters. Despite this, the relatively low productivity of its surrounding waters results in a contribution of only 0.2% to global fisheries landings. The high value of some of the main species targeted makes Australian fisheries some of the most valuable, accounting for a disproportionately high 2% of global landing value (Ridge Partners, 2010). The low-volume, high-price fisheries that drive the value of Australia's fishing industry include those targeting rock lobsters (*e.g.*, *Jasus edwardsii*, *Panulirus cygnus*), prawns (*e.g.*, *Penaeus esculentus*, *Melicertus plebejus*), tunas (*e.g.*, *Thunnus maccoyii*, *Thunnus albacares*), crabs (*e.g.*, *Portunus pelagicus*) and abalone (*e.g.*, *Haliotis laevigata*, *Haliotis rubra*) (Fig. 1).

Total volume of Australian wild fisheries production in 2010–11 was 163,000 tonnes, while the gross value of production (GVP) was AUD$1.3 billion (Skirtun et al., 2012). Value of production has decreased steadily since 2001 as the result of declining ex-vessel prices in many of the most valuable fisheries. Federally managed fisheries, generally located beyond the three nautical mile coastal zone, make up 29% of landings and 24% of fisheries value, while the majority of catch is taken by state-managed fisheries (Fig. 2). Within three nautical miles of the coast, each state manages the fisheries within its jurisdiction, including those where a stock is shared with other states (*e.g.* rock lobster fisheries in South Australia and Tasmania). Western Australia (22%) and South Australia (15%) contribute most to national fisheries GVP (Skirtun et al., 2012). Australian fisheries are heavily export-oriented: 20% of production volume and 50% of production value is typically exported, primarily to East Asian markets of Japan and China; increased demand for live exports to Asia has shifted production and marketing effort to these high-value fisheries since the 1990s. Fisheries export value, however, has also declined steadily over the past decade as prices have dropped (Ridge Partners, 2010).

The effect of fuel costs on fishing is of special interest for Australian fisheries and Oceania more widely because this region of the world has the highest overall costs of fishing, with fuel representing an estimated 20% of total costs on average (Lam et al., 2011). In addition, the operating environment for fisheries is changing with concerns regarding the potential effects of carbon pricing policies, if they are enacted by the federal government. Fisheries and transport were exempt from the recent Australian carbon tax. The fishing industry remains concerned over the increased role fuel plays in the economic performance of fisheries, the effect of potential carbon management options, and the limited capacity of fisheries to respond to fuel costs through efficiency measures and technological improvements (Madon, 2011; NSW Fishing Fleet., 2009).

Understanding the fuel consumption and carbon footprint of fisheries is necessary for assessing the current and future environmental and economic performance of the industry. Energy analyses contribute to economic assessments of fishing sectors, help

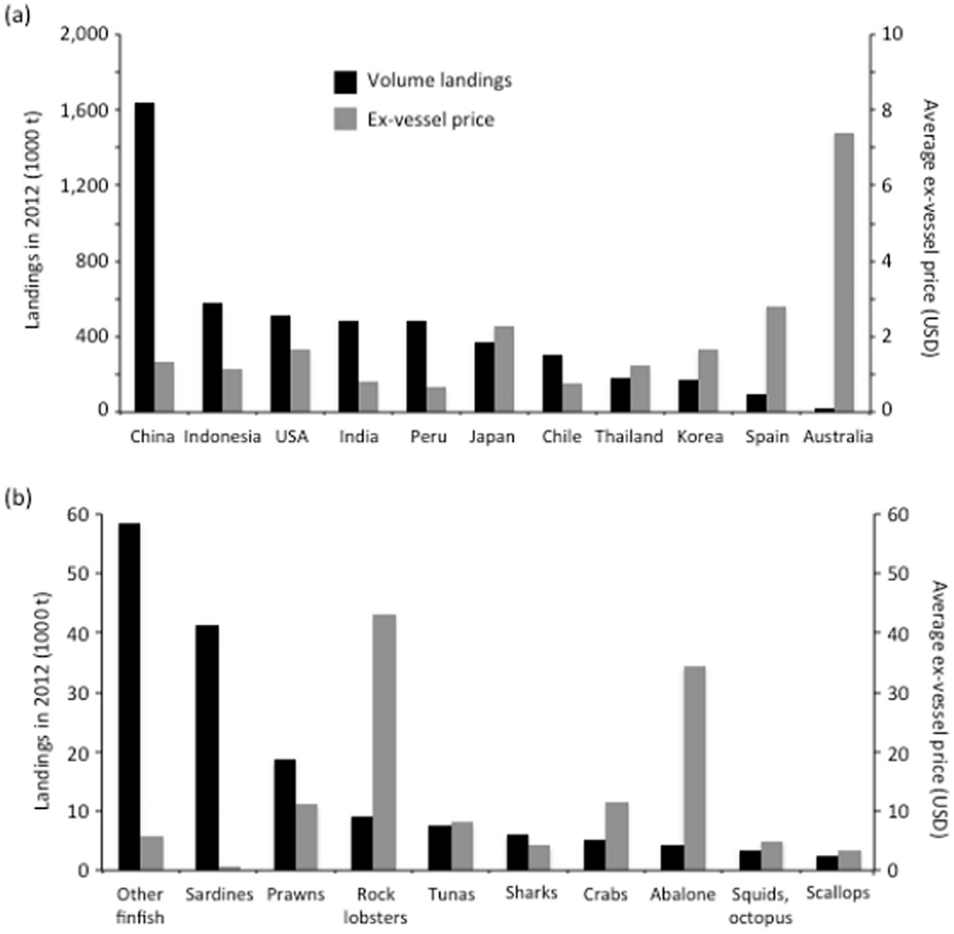

Fig. 1. (a) Landings in 2012 and average ex-vessel price in 2005, for Australia and the top ten fishery production countries by gross value; landings data from FAO's FishStatJ, ex-vessel price for all countries except Australia from Swartz et al., 2013. (b) Landings and ex-vessel prices for different species groups in Australia in 2012; data from ABARES Australian Fisheries Statistics.

in understanding the relative role fisheries play in food production sustainability, and can indicate potential vulnerabilities to fuel price changes and related management options. Here we report the relative FUI and fuel costs of a range of Australian fisheries, examine how fuel consumption by Australian fishing fleets has changed over time, and discuss the energy demands and carbon footprint of Australian fisheries relative to other fisheries around the world and other forms of protein production.

2. Materials and methods

Cost and revenue data for a range of Australian fisheries were sourced from survey-based economic assessments by (a) the Australian Bureau of Agriculture and Resource Economics and Science (ABARES) for Commonwealth managed fisheries; (b) EconSearch Pty Ltd. for South Australian and Tasmanian fisheries, and (c) Dominion Consulting Pty Ltd. for New South Wales fisheries. Data were gathered for a total of 20 fisheries (Table 1). Assessed fisheries accounted for 53% of Australian fisheries landings by volume in 2010/11 and 46% of gross landed value.

The structure of the Northern Prawn Fishery (NPF) on Australia's northern coast allowed for further disaggregation to fishing seasons targeting primarily banana prawns (primarily *Fenneropenaeus merguiensis*) and seasons targeting primarily tiger prawns (primarily *P. esculentus* and *Penaeus semisulcatus*). This disaggregation was based on season-specific effort and catch rates (Barwick, 2013).

While data for the Tasmanian rock lobster fishery were only available for 2010/11, a multiple regression of fuel consumption relative to vessel horsepower and effort allowed for an estimation of the previous years' fuel use based on annual vessel and effort data collected through compulsory logbooks of the fleet.

Fuel consumption was assessed by translating fuel costs and fishing revenue to volume of fuel and round weight of landings. Average vessel landings for each fishery were estimated by dividing vessel revenue from economic assessments by average ex-vessel price per kg of landed product as reported by EconSearch and ABARES (Skirtun et al., 2012). Volume of fuel was estimated by dividing vessel fuel expenditures from economic assessments by average annual offroad (excluding subsidies) diesel prices (ABARES, 2012). FUI estimates used to compare fisheries included only the three most recent years for which data were available (see Table 1 for fishery-specific years). Fuel-related GHG emissions were calculated using 3.1 kg CO_2 per litre (Parker et al., in press), including direct emissions from burning fuel as well as emissions from upstream mining, processing and transport of fuel.

The economic role of fuel use in Australian fisheries was estimated by comparing fuel costs to fishing revenue, assuming that fuel is more economically significant to fisheries which devote a larger portion of their revenues to purchasing fuel. Further, fuel costs were also compared to a subset of other fishing expenditures, including labour, vessel repairs and maintenance, and bait.

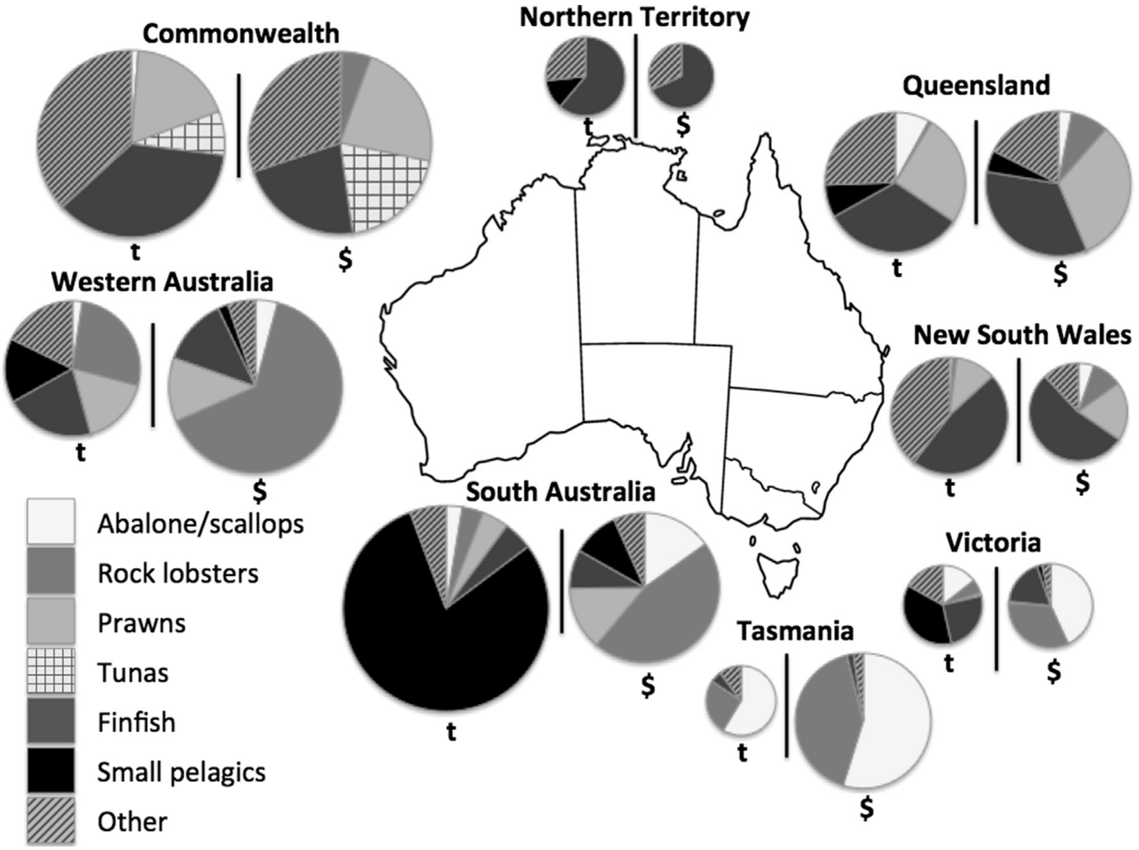

Fig. 2. Relative landings (t) and value ($) of Australian fisheries, showing breakdown by area for each state, as well as Commonwealth (federally managed) sectors. Note that Commonwealth fisheries are located around the country, including tropical rock lobster fisheries in the northeast, prawn fisheries on the northern coast, tuna fisheries primarily in the southeast and east, and finfish fisheries in the southeast.

A subset of 14 fisheries had sufficient annual data to allow for more detailed comparison of FUI. For these fisheries, FUIs throughout the entire period were compared using a one-way analysis of variance (ANOVA) test. A posthoc Tukey test was used to assess whether there were significant differences in FUI between fisheries. Multiple regression analysis was used to assess the relative influence of FUI and diesel prices on the economic role of fuel use (as % of revenue).

Trends were assessed for the same subset of fisheries. Because of varying trends in fuel prices, the study period was divided into three equal periods, and trends were assessed within each period: 1993–1999, 1999–2005, and 2005–2011. These periods generally line up with trends of increasing fuel prices: low and stable during the first period, rising steadily during the second period, and rising more rapidly during the third period (ABARES, 2012). For each fishery, the average annual change in FUI and fuel costs relative to revenue were calculated, and regression analyses were used to determine if trends were statistically significant.

3. Results

Rates of fuel consumption in Australian fisheries ranged from below 100 L/t to over 10,000 L/t (Table 2). The most fuel-efficient fisheries included those targeting small pelagic species with seines and trawls in South Australia and Tasmania, respectively. The most fuel-intensive fisheries were those targeting Tiger prawns in the NPF and the Torres Strait, and those targeting Southern rock lobster in South Australia. The Tiger prawn season of the NPF in particular had average consumption of over 10,000 L/t in three separate years: 2004/05, 2005/06 and 2007/08.

There was a clear pattern of fisheries targeting crustaceans consuming more fuel per tonne than those targeting other species (Fig. 3). The eight most fuel intensive fisheries assessed here all targeted lobster and prawn species. Related to this, the pattern of FUI between fisheries reflected, in part, the relative value of fishery products. Hence, fisheries for tuna and crustaceans were more fuel intensive than those for finfish, which in turn were more fuel intensive than those for small pelagics. The molluscan dive fishery for abalone was an exception to this, as abalone has a much higher price per kg than prawn and tuna fisheries but a relatively lower FUI.

Fisheries also varied in their FUI depending on gear used. The small pelagic trawl fishery in Tasmania, for example, was more fuel intensive than the seine fishery for sardines in South Australia. Similarly, seining vessels in the Southeast finfish fishery consumed, on average, a third the fuel per tonne as their trawling counterparts. Very little difference in FUI was found between finfish trawlers operating in the inshore and offshore fisheries (Table 2).

The proportion of revenue directed to the purchase of fuel in Australian fisheries also varied widely, with less than 3% of revenue in abalone fisheries used to purchase fuel, while over 40% of revenue in fisheries for Tiger prawns was spent on fuel (Table 2). Similarly, fuel accounted for between 3% and 51% of the subset of variable fishing expenditures assessed.

The profitability of Australian fisheries was tied to price of fuel based on percentage of revenue devoted to purchasing fuel. The relationship between the price of diesel and fuel costs was

Table 1
Summary of Australian fisheries included in the analysis and range of years for which data were available. Years refer to the financial year-end.

Fishery	Primary species	Gears	Years
Australian sardine (SA)[a]	Australian sardine (*Sardinops sagax*)	Purse seine	2002–2011
Southeast finfish (CW)[a]	Blue grenadier (*Macruronus novazelandiae*), Tiger flathead (*Platycephalus richardsoni*)	Midwater trawl, seine	1993–2011
Northern prawn fishery (CW)[a]	Banana prawn (*Fenneropenaeus* spp.), Tiger prawn (*Penaeus esculentus*, *Penaeus monodon*)	Bottom trawl	1993–2010
Eastern tuna (CW)[a]	Yellowfin (*Thunnus albacares*), swordfish (*Xiphias gladius*)	Hooks and lines	1993–2011
Southern Shark (CW)	Gummy shark (*Mustelus antarcticus*)	Hooks and lines	1993–2001
Estuary General (NSW)	Mullet (*Mugil cephalus*), bream (*Acanthopagrus australis*)	Mixed	2002
Ocean Trawl (NSW)	Mixed prawns and finfish	Trawl	2002
Abalone (TAS)	Blacklip abalone (*Haliotis rubra*), greenlip abalone (*Haliotis laevigata*)	Dive	2012
Spencer Gulf West Coast Prawn (SA)[a]	King prawn (*Melicertus* spp.)	Bottom trawl	1998–2009
Ocean Trap and Line (NSW)	Snapper (*Pagrus auratus*), leatherjacket (*Oligoplites saurus*)	Mixed	2002
Southern rock lobster (TAS)[a]	Southern rock lobster (*Jasus edwardsii*)	Pots	2003–2011
Southern rock lobster, southern zone (SA)[a]	Southern rock lobster (*Jasus edwardsii*)	Pots	1998–2011
Abalone (SA)[a]	Greenlip abalone (*Haliotis laevigata*), blacklip abalone (*Haliotis rubra*)	Dive	1998–2011
Blue Crab (SA)[a]	Blue swimmer crab (*Portunus pelagicus*)	Pots	1998–2011
Torres Strait Prawn (CW)[a]	Tiger prawn (*Penaeus monodon*), endeavour prawn (*Metapenaeus endeavouri*)	Bottom trawl	1993–2008
Southern/western Tuna (CW)	Mixed tunas and billfishes	Hooks and lines	2002
Southern rock lobster, northern zone (SA)[a]	Southern rock lobster (*Jasus edwardsii*)	Pots	1998–2011
Gulf of St Vincent Prawn (SA)[a]	King prawn (*Melicertus* spp.)	Bottom trawl	1998–2009
Abalone (NSW)	Blacklip abalone (*Haliotis rubra*)	Dive	2002
Small Pelagic (TAS)	Jack mackerel (*Trachurus declivis*), redbait (*Emmelichthys nitidus*)	Midwater trawl	2004–2006

CW = Commonwealth, SA = South Australia, TAS = Tasmania, NSW = New South Wales.

[a] Denotes fisheries for which long-term data were available allowing for more detailed analyses.

significant in all 14 fisheries, while the relationship between FUI and fuel costs was significant in 13 of 14 fisheries. For most fisheries (12 of 14), the price of diesel had more influence on the economic role of fuel costs than fuel consumption rates, although both were highly significant.

Rates of fuel consumption and fuel costs as a percentage of revenue were relatively consistent during the 1990s, but increased in many fisheries in the early years of the 21st century (Fig. 4). Between 1999 and 2005, 9 of 14 fisheries showed increasing rates of fuel consumption while 12 of 14 fisheries showed increasing rates of fuel costs. Since 2005, the trend of increasing fuel use and costs had reversed somewhat, with 9 of 12 fisheries demonstrating a decreasing trend in FUI and 7 of 14 fisheries decreasing their fuel costs. There was a relatively consistent coupling of FUI and fuel costs relative to revenue, in that fisheries with increasing FUI tended to have increasing fuel costs, and vice versa. The economic role of fuel costs, however, tended to increase and decrease more quickly than did actual consumption (Fig. 4).

While both FUI and fuel costs improved in recent years in many fisheries, most Australian fisheries still currently spend more on fuel relative to their revenue than they did in the 1990s and early 2000s. This was despite the trend of many Australian fisheries generally consuming similar amounts of fuel or decreasing their fuel consumption over the same period. This lower consumption of fuel in response to increasing fuel costs was most evident in fuel intensive prawn fisheries. Falling ex-vessel prices in certain fisheries further exacerbated the rising cost of fuel relative to fishing revenue.

4. Discussion

4.1. Rates of fuel use in Australian fisheries

The role played by fuel consumption in Australian fisheries varied significantly between fisheries, in terms of absolute consumption, related carbon footprint, and operational costs. Furthermore, fuel consumption and the impact of fuel costs have changed markedly since the 1990s, during a period when the price of diesel to fishers increased fourfold. This economic impact of fuel costs was greatest across all fisheries in the early years of the 21st century. Interestingly, that impact has lessened somewhat in recent years.

Fisheries examined here were substantially more fuel intensive than most fisheries around the world. The globally averaged FUI of fisheries in 2000 was estimated at 620 L/t (Tyedmers et al., 2005), while the median value of documented FUIs since 1990 is a similar 625 L/t (Parker and Tyedmers, in press). All but four of the assessed fisheries here have a higher FUI than global averages. This is due to the large proportion of fisheries in Australia targeting fuel-intensive crustaceans. Even when compared on the basis of similar species and gears, however, Australian fisheries tend to demand more energy inputs. Trap fisheries for American lobster (*Homarus americanus*), and Norway lobster (*Nephrops norvegicus*), consume around 1000 L/t (Boyd, 2008; Driscoll, 2008) and 2200 L/t (Ziegler and Valentinsson, 2008), respectively, compared to the Australian lobster FUI averages of 3600–6650 L/t found here. Similarly, European trawl fisheries for Atlantic cod (*Gadus morhua*) and other whitefish species generally consume 300–600 L/t, lower than Australia's finfish fisheries (Tyedmers, 2001; Ziegler et al., 2003). Some of these differences are likely explained by differences in local productivity and biomass: Australian lobster fisheries, for example, target species with relatively lower biomass density than those in North America.

The relationships found in Australian fisheries between FUI, target species and gear type reflect those found previously in other regions. Fuel use intensity values documented in the North Atlantic and Europe show a clear pattern of crustacean and demersal fisheries consuming greater amounts of fuel than fisheries targeting pelagic finfish and small pelagic species (Schau et al., 2009; Tyedmers, 2001). These studies also found that trawl fisheries were more intensive than seine fisheries targeting the same species, as was found for Australian whitefish and small pelagic fisheries.

An important relationship between fuel costs and ex-vessel prices was apparent across the industry. Fisheries with higher value products, such as lobster, were found to have higher rates of fuel consumption. High prices allow for much higher rates of fuel

Table 2
Fuel use intensity, fuel-related GHG emissions, and fuel costs relative to revenue and fishing costs in Australian fisheries. Values calculated as the mean of the three most recent years for which data were available.

Fishery	FUI (L/t)	CO_2 emissions (kg CO_2/kg)	Fuel costs (% revenue)	Fuel costs (% costs[d])
Tiger prawn, NPF (CW)[a]	9685	30.0	45.1	
Rock lobster, southern zone (SA)	6650	20.6	9.3	19.7
Rock lobster, northern zone (SA)	5742	17.8	9.7	18.7
Torres Strait prawn (CW)	5300	16.4	46.0	51.1
Ocean prawn fishery (NSW)	4147	12.9	15.8	29.3
Tasmanian rock lobster (TAS)	3608	11.2	5.8	18.7
All prawns, NPF (CW)	3465	10.7	26.1	39.7
Spencer Gulf West Coast prawn (SA)	2092	6.5	11.1	20.8
Southern/western tuna (CW)	1986	6.2	11.9	18.7
Banana prawn, NPF (CW)[a]	1610	5.0	14.7	
Gulf St. Vincent prawn (SA)	1503	4.7	9.8	19.8
Ocean trap and line fishery (NSW)	1319	4.1	11.1	16.6
Abalone (NSW)	1203	3.7	1.4	3.4
SE finfish, offshore trawl (CW)[b]	1091	3.4	21.5	31.1
SE finfish, inshore trawl (CW)[b]	1088	3.4	21.5	29.2
Eastern tuna (CW)	1023	3.2	14.2	23.0
Blue crab (SA)	1000	3.1	10.1	21.7
SE finfish, all trawl (CW)[b]	907	2.8	20.0	33.0
Abalone (TAS)	878	2.7	2.3	14.6
Southern shark (CW)	873	2.7	8.2	12.7
Abalone (SA)	809	2.5	1.8	5.6
SE finfish, all gears (CW)[b]	788	2.4	17.4	29.5
Estuary general fishery (NSW)	549	1.7	6.2	6.3
SE finfish, Danish seine (CW)	316	1.0	6.9	13.1
Small pelagics (TAS)[c]	164	0.5		
Sardines (SA)	92	0.3	12.0	22.3

CW = Commonwealth, SA = South Australia, TAS = Tasmania, NSW = New South Wales.

[a] Expenditure data could not be divided between fishing seasons.

[b] ABARES survey results differentiated between inshore and offshore trawl until 2002. Total trawl and total SE whitefish values here are for 2008–09 to 2010–11, while inshore and offshore values are for 1999–00 to 2001–02.

[c] Revenue calculated based on beach price of Australian sardine fishery, assuming similar value.

[d] Fuel costs as a percentage of a subset of variable fishing costs, including labour, repairs and maintenance, and bait.

use than would otherwise be viable. Furthermore, if ex-vessel prices increase faster than the price of fuel, then some Australian fisheries that are currently limited by fuel costs will become viable and could increase production.

4.2. Decreased FUI in response to biomass and capacity changes

Observed improvements in fishery fuel use could be related to changes in management, stock levels, fishing behaviour, or technology. The relative impact of each of these factors varies. While much work has been done regarding the potential fuel benefits of new technologies and vessel designs, these changes often improve rates of fuel use by only a small fraction. Options such as optimizing propeller diameter, installing fuel meters, and implementing minor gear improvements, while often suggested as ways to decrease fuel consumption, typically only result in less than a 10% improvement (OECD, 2012). Operational changes, notably decreasing vessel speed, have been shown to be more effective, and can be a relatively quick adaptation to higher prices (Abernethy et al., 2010). However, the largest changes in fuel performance have often been attributed to management decisions, particularly those that affect levels of biomass or fishing capacity (OECD, 2012; Parker and Tyedmers, in press). Decreases in the FUI of the Banana prawn fishery in Australia, for example, coincided with a government buyout of vessels to rapidly reduce overcapacity since 2005 (Pascoe et al., 2012). Fuel use in the South Australian southern zone fishery for Southern rock lobster, meanwhile, closely correlate with noticeable changes in catch per unit effort: both fell prior to 2005, increased from 2006 to 2010, and fell again in 2011 (Linnane et al., 2012).

Observed changes in energy performance in accordance with changes in biomass and fishing capacity have been reflected in other fisheries around the world. Swedish fisheries for lobster (*N. norvegicus*) and cod (*G. morhua*) underwent noticeable improvements in FUI as a result of reductions in capacity and increased biomass, respectively (Ziegler and Hornborg, 2014). Poor management and stock decline, meanwhile, may explain increased FUI in Indian Ocean tuna fisheries in recent years (Parker et al., in press). Fisheries elsewhere are also experiencing similar economic impacts from rising fuel prices: European fisheries are dedicating consistently larger portions of their revenue to purchasing fuel while their FUI remains steady or improves (Anderson and Guillen, 2011; Parker and Tyedmers, in press). Findings here complement evidence from Europe and North America suggesting that changes in biomass and capacity have a greater impact on fuel use than technological or operational changes (Mitchell and Cleveland, 1993; Parker and Tyedmers, in press; Ziegler and Hornborg, 2014).

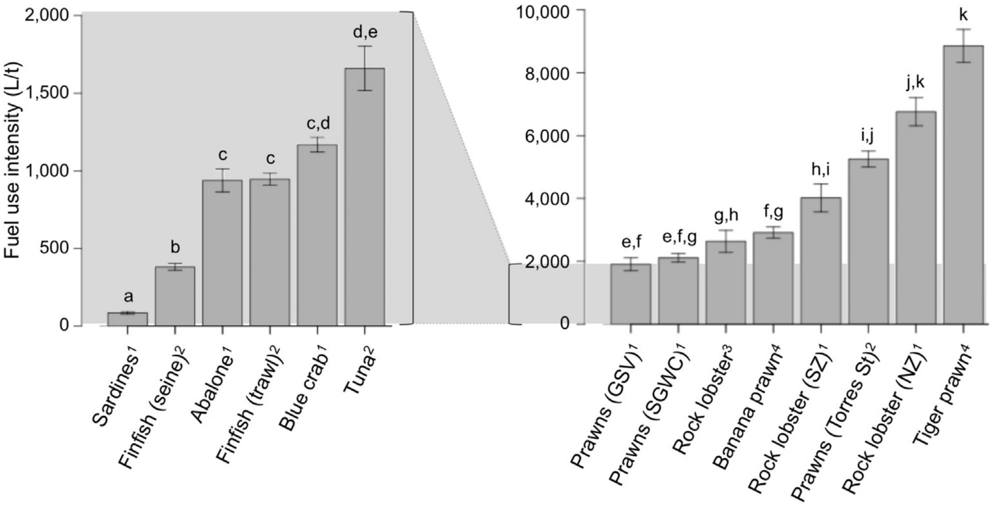

Fig. 3. Fuel use intensities of selected Australian fisheries, showing mean and standard error. Common letters indicate fisheries with FUIs which are not significantly different. Note the difference in *y*-axis values between less and more energy intensive fisheries. 1 South Australia; 2 Commonwealth-managed; 3 Tasmania; 4 Different seasons of the Northern Prawn Fishery (Federal).

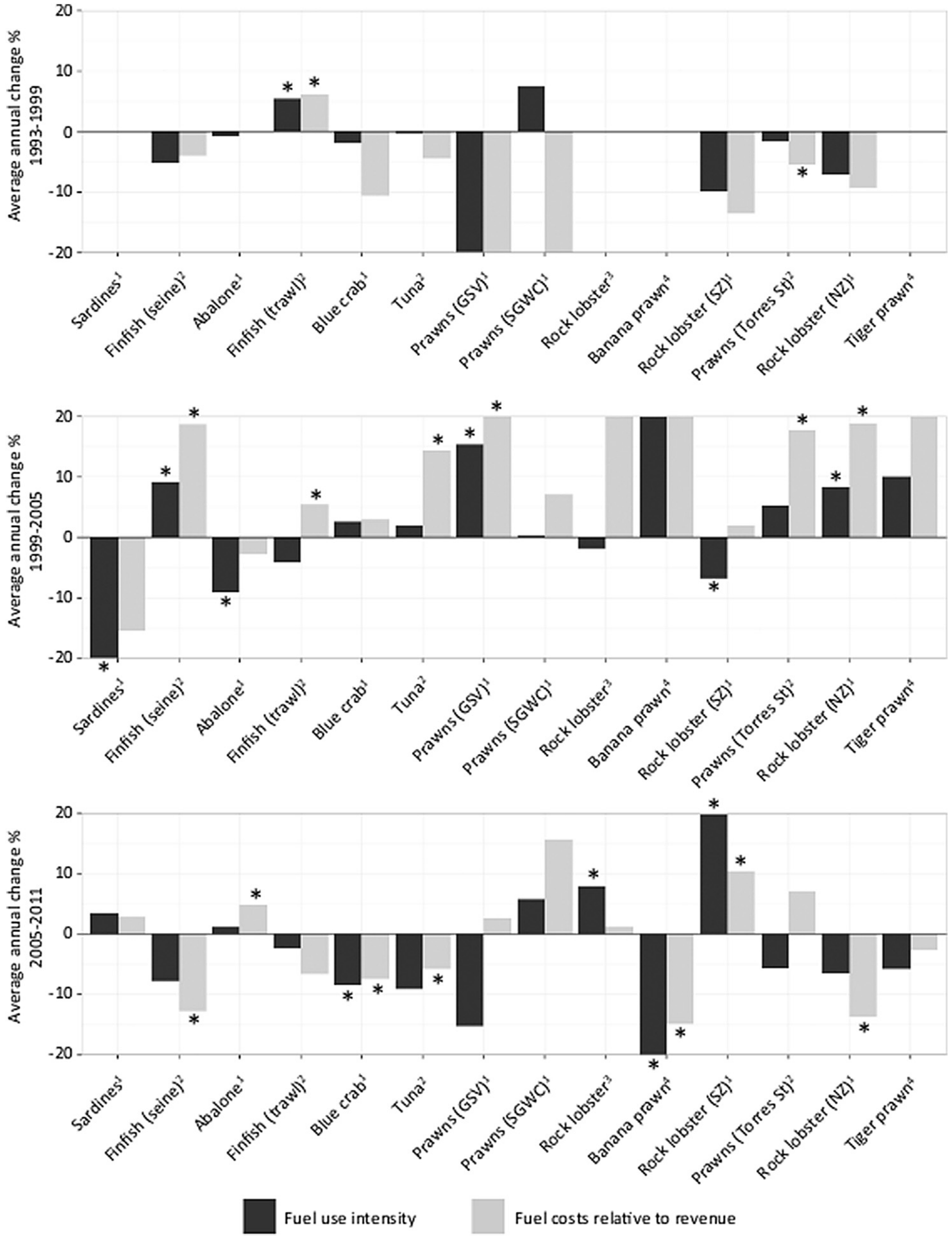

Fig. 4. Average annual change in FUI and fuel costs relative to revenue in Australian fisheries over three time periods: 1993–1999, 1999–2005, and 2005–2011. Asterisks represent significant trends based on regression slope of fuel use and costs against year. Fishery jurisdictions are indicated by superscript: 1 South Australia, 2 Federal, 3 Tasmania, 4 Northern Prawn Fishery (Federal).

4.3. Carbon footprints and carbon taxes

Measurements of the carbon footprint of fisheries and other production systems increasingly call for a life cycle assessment (LCA), where energy and material flows are measured from “from cradle to grave” including upstream and downstream activities (*e.g.* processing, transport) (BSI, 2012; Pelletier and Tyedmers, 2008). A range of LCA studies have been conducted on seafood products, although applications in Australia have taken place only very recently, while most work has been undertaken in Europe (Parker, 2012; Vázquez-Rowe et al., 2012; Avadí and Fréon, 2013). While the characteristics of these fisheries vary substantially, from high-volume, low-value fisheries for small pelagic species (*e.g.* Almeida et al., 2014; Avadí et al., 2013), to low-volume, high-value fisheries for crustaceans (*e.g.* Ziegler and Valentinsson, 2008; Farmery et al., 2014), fuel is consistently found to account for a large portion, and often the vast majority, of life cycle GHG emissions. Fuel consumption can generally be used as a proxy for fishery carbon footprints, allowing for reasonable estimates without the time and effort required for a full LCA study (Parker and Tyedmers, in press).

For many fisheries assessed in this study, fuel is likely the primary driver of life cycle emissions, however, there are upstream and downstream sources of emissions likely to significantly affect the carbon footprint in some cases. Fisheries for rock lobster require bait and their products are often transported by air, which accounts for a significant portion of the life cycle emissions of crustacean products (Boyd, 2008; Driscoll, 2008; Parker, 2012). Air transport is especially significant, and approximately doubles the carbon footprint, of exported Australian lobster (Farmery et al., 2014). Other potential sources of GHG emissions in fisheries-derived products include energy-intensive processing (Parker and Tyedmers, 2013), addition of energy-intensive ingredients such as oil in canned fish (Buchspies et al., 2011), and product loss and waste along the supply chain (Thrane et al., 2009).

The Australian government enacted a carbon tax in 2012, which was subsequently repealed in 2014. Transport and agriculture sectors, including fisheries, were exempted from the tax. In fact, Australian fisheries, like those in many countries, benefit from rebate of a fuel excise, which is otherwise used to fund the national highway system. This reduces the cost of fuel relative to many other industries. Very few countries have an effective carbon control mechanism that includes fisheries. Most policies, such as those in the European Union, Japan, and Australia, exempt fisheries from carbon taxes. New Zealand put a carbon trading scheme in place in 2008 and amended it in 2010 to include fisheries, while Norway has a relatively modest carbon tax on fishers of 50 kr (US$8.40) per tonne of GHG.

The potential effects of a carbon tax or other carbon control mechanism on fisheries could have both desirable and undesirable consequences. In one respect, the increased fuel cost associated with such a policy could spur efficiency improvements, force removal of inefficient vessels from fishing fleets, and provide a competitive advantage to those fisheries with better energy performance. This potential improvement is similar to that modelled in European fisheries over the long term in response to increased oil prices (Arnason, 2007), and the results here suggest that at least some Australian fisheries do have the capability to respond to increased costs by decreasing fuel consumption.

There is, however, a possible negative side effect of the use of a carbon price to reduce fuel consumption in fisheries. Most fishery products globally, particularly non-crustacean products, are less carbon-intensive than land-based protein products (Pelletier et al., 2011; Pimentel and Pimentel, 2003; Tyedmers et al., 2005). Ruminant-based agriculture in particular tends to have comparatively higher GHG emissions from feed production and methane emissions (Sonesson et al., 2010). Production of fisheries in many countries is sensitive to costs of fuel, such as where they are managed for maximum economic yield or where they are marginally profitable because of low prices. If carbon pricing resulted in higher fuel costs, and therefore decreased fisheries production, a shift towards more carbon intensive land-based sources would raise overall GHG emissions. Further, while many more intensive fisheries have some room for improvement as demonstrated here, the less fuel-intensive fisheries – particularly some lower value finfish and small pelagic fisheries that have very low GHG emissions – may actually be more impacted by the increased cost. Hence, carbon pricing could have the inverse effect of that intended.

4.4. Applications to other regions

It is important to consider the extent to which findings here can be applied to diverse fisheries around the world, particularly in regions where fisheries contribute substantially to food security or economic activity. Compared to many regions, Australian fisheries are unique in their relatively high average beach price, high rates of investment to technology, research and management, and strict quota-based management systems. High prices and management funding place Australia in a position of flexibility to, for example, develop and adopt new technologies or transition to more effective regulatory measures, compared to poorer countries or countries fishing less valuable species.

High seafood prices also place Australian fisheries in an interesting situation where the price is often high enough to compensate for rising costs. This translates to a weaker incentive to improve fuel performance at times when prices are high. Conversely, in regions where beach prices are generally much lower, and particularly in developing countries where fuel accounts for a large percentage of variable fishing costs, the economic benefits of improving performance are likely to be greater and more necessary as oil prices rise.

The economic incentive for management decisions that contribute to fuel use reductions is likely to be greatest in areas where catch per unit effort is low due to depressed stocks or overcapacity. Arnason (2007) modelled how economic performance of fisheries in these regions would benefit in the long term from high oil prices driving down capacity and fishing activity in the short term, allowing for stocks to rebound and removing the least efficient vessels from the fleet. Regulatory controls such as those undertaken in some Australian fisheries can be expected to have the same long-term impact, building industry resilience to oil price increases rather than responding to them.

5. Conclusions

Fisheries are facing a wide range of sustainability challenges, and diverse management efforts are developing globally to address them. Fuel consumption and the associated carbon footprint of fisheries is a relatively new addition to this suite of challenges, and is yet to be formally incorporated into fishery policies and regulations. There is, however, interest on the part of industry groups, NGOs, and other stakeholders to address the challenge by measuring, characterizing and improving fuel use (Parker and Tyedmers, in press).

Globally, fisheries perform favourably to many other forms of protein production. Crustacean fisheries are the least efficient, and have similar carbon emissions during production to beef. Finfish fisheries, and especially small pelagics, on the other hand, are often associated with lower emissions during production than chicken, pork or farmed salmon (Parker and Tyedmers, in press). Measuring and improving the carbon footprint of fisheries, then, could be a market advantage for fisheries products, provided that those fisheries also meet other sustainability standards.

Demonstrating the economic benefits of management decisions via improved variable fishing costs and resilience to oil prices can be a valuable tool for encouraging implementation of fisheries management decisions. Australian examples provided here illustrate the extent to which management-driven changes in biomass and capacity can effectively improve fuel consumption, carbon footprint, and fishing costs. It is important that the issue of fuel performance be considered by fishing industries now, as improving performance before further increases in prices is likely to increase resilience. In these efforts, it does more to focus on management efforts to decrease overcapacity and rebuild stocks, than to rely on technology improvements.

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References

ABARES, 2012. Agricultural Commodity Statistics 2012. Canberra, Australia. Australian Bureau of Agricultural and Resource Economics and Sciences.

Abernethy, K.E., Trebilcock, P., Kebede, B., Allison, E.H., Dulvy, N.K., 2010. Fuelling the decline in UK fishing communities? ICES J. Mar. Sci. 67 (5), 1076–1085.

Almeida, C., Vaz, S., Cabral, H., Ziegler, F., 2014. Environmental assessment of sardine (*Sardina pilchardus*) purse seine fishery in Portugal with LCA methodology including biological impact categories. Int. J. Life Cycle Assess. 19 (2), 297–306.

Anderson, J., Guillen, J., 2011. 2010 Annual Economic Report on the European Fishing Fleet JRC Scientific and Technical Reports – Scientific, Technical and Economic Committee for Fisheries (STECF). JRC, Luxembourg.

Arnason, R., 2007. The economics of rising fuel costs and European fisheries. EuroChoices 6 (1), 22–29.

Avadí, Á., Fréon, P., 2013. Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish. Res. 143, 21–38.

Avadí, Á., Vázquez-Rowe, I., Fréon, P., 2014. Eco-efficiency assessment of the Peruvian anchoveta steel and wooden fleets using the LCA+DEA framework. J. Clean. Prod. 70, 118–131.

Barwick, M., 2013. Northern Prawn Fishery Data Summary 2013. NPF Industry Ptd Ltd, Australia.

Boyd, C., 2008. From Ocean to Market : the Life Cycle Biophysical Impacts of the Southwest Nova Scotia Live Lobster Industry. Masters thesis. Dalhousie University, Halifax, N.S. Retrieved from. http://ezproxy.library.dal.ca/login?url=http://wwwlib.umi.com/cr/dalh/fullcit?pmr39181.

BSI, 2012. PAS 2050-2: Assessment of Life Cycle Greenhouse Gas Emissions – Supplementary Requirements for the Application of PAS 2050:2011 to Seafood and Other Aquatic Food Products. British Standards Institution.

Buchspies, B., Tolle, S., Jungbluth, N., 2011. Life Cycle Assessment of High-sea Fish and Salmon Aquaculture. ESU-Services Ltd.

Cheilari, A., Guillen, J., Damalas, D., Barbas, T., 2013. Effects of the fuel price crisis on the energy efficiency and the economic performance of the European Union fishing fleets. Mar. Policy 40, 18–24.

Driscoll, J.D., 2008. Life Cycle Environmental Impacts of Gulf of Maine Lobster and Herring Fisheries Management Decisions. Masters thesis. Dalhousie University, Halifax, N.S. Retrieved from. http://wwwlib.umi.com/cr/dalh/fullcit?pmr44079.

EIA, 2012. Europe Brent Spot Price. Retrieved 1 November, 2013, from. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.

FAO, 2007. State of World Fisheries and Aquaculture 2006. Food and Agriculture Organization of the United Nations, Rome, Italy.

Farmery, A., Gardner, C., Green, B., Jennings, S., 2014. Managing fisheries for environmental performance: the effects of marine resource decision-making on the footprint of seafood. J. Clean. Prod. 64, 368–376.

Hua, J., Wu, Y.H., 2011. Implications of energy use for fishing fleet-Taiwan example. Energy Policy 39 (5), 2656–2668.

Lam, V.W.Y., Sumaila, U.R., Dyck, A., Pauly, D., Watson, R., 2011. Construction and first applications of a global cost of fishing database. ICES J. Mar. Sci. 68 (9), 1996–2004.

Linnane, A., McGarvey, R., Feenstra, J., Hawthorne, P., 2012. Southern Zone Rock Lobster (Jasus edwardsii) Fishery 2010/11. In: Fishery Assessment Report to PIRSA Fisheries and Aquaculture. SARDI Aquatic Sciences, South Australia.

Madon, T., 2011. Inquiry into Carbon Tax Pricing Mechanisms. Commonwealth Fisheries Association, Canberra, Australia.

Mitchell, C., Cleveland, C.J., 1993. Resource scarcity, energy use and environmental-impact – a case-study of the New Bedford, Massachusetts, USA. Fish. Environ. Manag. 17 (3), 305–317.

NSW Fishing Fleet, 2009. The High Cost of Diesel Fuel. NSW Fishing Fleet, Pyrmont, Australia.

OECD, 2012. Green growth and Energy Use in Fisheries and Aquaculture. Trade and Agriculture Directorate, Fisheries Committee, Organization for Economic Cooperation and Development.

Parker, R.W.R., 2012. Review of Life Cycle Assessment Research on Products Derived from Fisheries and Aquaculture. Sea Fish Industry Authority, Edinburgh, U.K.

Parker, R.W.R., Tyedmers, P.H., 2014. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish Fish. (in press).

Parker, R.W.R., Vázquez-Rowe, I., Tyedmers, P.H., 2014. Fuel performance and carbon footprint of the global purse seine tuna fleet. J. Clean. Prod. (in press).

Parker, R.W.R., Tyedmers, P.H., 2013. Life cycle environmental impacts of three products derived from Wild-Caught Antarctic Krill (Euphausia superba). Environ. Sci. Technol. 46 (9), 4958–4965.

Pascoe, S., Coglan, L., Punt, A.E., Dichmont, C.M., 2012. Impacts of vessel capacity reduction programmes on efficiency in fisheries: the case of Australia's multispecies northern prawn fishery. J. Agric. Econ. 63 (2), 425–443.

Pelletier, N., Andre, J., Charef, A., Damalas, D., Green, B., Parker, R., Watson, R., 2014. Energy prices and (sea)food security. Glob. Environ. Change 24, 30–41.

Pelletier, N., Ayer, N., Tyedmers, P., Kruse, S., Flysjo, A., Robillard, G., Ziegler, F., Scholz, A., Sonesson, U., 2007. Impact categories for life cycle assessment research of seafood production systems: Review and prospectus. Int. J. Life Cycle Assess. 12 (6), 414–421.

Pelletier, N., Audsley, E., Brodt, S., Garnett, T., Henriksson, P., Kendall, A., Troell, M., 2011. Energy intensity of agriculture and food systems. Annu. Rev. Environ. Resour. 36, 223–246.

Pelletier, N., Tyedmers, P., 2008. Life cycle considerations for improving sustainability assessments in seafood awareness campaigns. Environ. Manag. 42 (5), 918–931.

Pimentel, D., Pimentel, M., 2003. Sustainability of meat-based and plant-based diets and the environment. Am. J. Clin. Nutr. 78 (3), 660S–663S.

Rawitscher, M., 1978. Energy Cost of Nutrients in the American Diet. PhD. University of Connecticut.

Ridge Partners, 2010. Overview of the Australian Fishing and Aquaculture Industry: Present and Future. Australian Fisheries Research and Development Corporation, Canberra, Australia.

Schau, E.M., Ellingsen, H., Endal, A., Aanondsen, S.A., 2009. Energy consumption in the Norwegian fisheries. J. Clean. Prod. 17 (3), 325–334.

Skirtun, M., Sahlqvist, P., Curtotti, R., Hobsbawn, P., 2012. Australian Fisheries Statistics 2011. Canberra, Australia. Australian Bureau for Agricultural and Resource Economics and Sciences.

Sonesson, U., Davis, J., Ziegler, F., 2010. Food production and emissions of greenhouse gases: an overview of the climate impact of different product groups. Swedish Institute for Food and Biotechnology (SIK), Gothernburg, Sweden.

Swartz, W., Sumaila, R., Watson, R., 2013. Global ex-vessel fish price database revisited: A new approach for estimating 'missing' prices. Environ. Resource Econ. 56, 467–480.

Thrane, M., 2004. Energy consumption in the Danish fishery: identification of ket factors. J. Ind. Ecol. 8, 223–239.

Thrane, M., Ziegler, F., Sonesson, U., 2009. Eco-labelling of wild-caught seafood products. J. Clean. Prod. 17 (3), 416–423.

Troell, M., Tyedmers, P., Kautsky, N., Ronnback, P., 2004. Aquaculture and energy use. In: Cleveland, C. (Ed.), Encyclopedia of Energy, vol. 1. Elsevier, New York, pp. 97–108.

Tveteras, S., Asche, F., Bellemare, M.F., Smith, M.D., Guttormsen, A.G., Lem, A., Vannuccini, S., 2012. Fish is food – the FAO's Fish Price Index. Plos One 7 (5).

Tyedmers, P., 2001. Energy consumed by North Atlantic fisheries. In: Zeller, D., Watson, R., Pauly, D. (Eds.), Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort, and National/regional Datasets, Fisheries Centre Research Reports 9, pp. 12–34.

Tyedmers, P., 2004. Fisheries and energy use. In: Cleveland, C. (Ed.), Encyclopedia of Energy, vol. 1. Elsevier, New York, pp. 683–693.

Tyedmers, P.H., Watson, R., Pauly, D., 2005. Fueling global fishing fleets. Ambio 34 (8), 635–638.

Vázquez-Rowe, I., Hospido, A., Moreira, M.T., Feijoo, G., 2012. Best practices in life cycle assessment implementation in fisheries: Improving and broadening environmental assessment for seafood production systems. Trends Food Sci. Tech. 28 (2), 116–131.

Vázquez-Rowe, I., Tyedmers, P., 2013. Identifying the importance of the "skipper effect" within sources of measured inefficiency in fisheries through data envelopment analysis (DEA). Mar. Policy 38, 387–396.

Watanabe, H., Okubo, M., 1989. Energy input in marine fisheries of Japan. Nippon Suisan Gakkaishi 55 (1), 25–33.

Ziegler, F., Hornborg, S., 2014. Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002–2010. Mar. Policy 44, 72–81.

Ziegler, F., Nilsson, P., Mattsson, B., Walther, Y., 2003. Life cycle assessment of frozen cod fillets including fishery-specific environmental impacts. Int. J. Life Cycle Assess. 8 (1), 39–47.

Ziegler, F., Valentinsson, D., 2008. Environmental life cycle assessment of Norway lobster (Nephrops norvegicus) caught along the Swedish west coast by creels and conventional trawls – LCA methodology with case study. Int. J. Life Cycle Assess. 13 (6), 487–497.