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Drivers of fuel use in rock lobster fisheries

Robert W. R. Parker,[1,2]* Caleb Gardner,[1] Bridget S. Green,[1] Klaas Hartmann,[1] and Reg A. Watson[1,3]

[1]*Institute for Marine and Antarctic Studies, University of Tasmania, 15-21 Nubeena Crescent, Taroona, Tasmania 7053, Australia*
[2]*Institute for the Oceans and Fisheries, University of British Columbia, AERL, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada*
[3]*Centre for Marine Socioecology, University of Tasmania, GPO Box 252-49, Hobart, Tasmania 7001, Australia*

**Corresponding author: tel: +1 604 822 2731; e-mail: r.parker@oceans.ubc.ca*

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Fuel consumption is a leading cost to fishers and the primary source of greenhouse gas emissions from the global fishing industry. Fuel performance varies substantially between and within fisheries, but the drivers behind this variation are unclear and inconsistent across studies. We surveyed rock lobster fishers in Australia and New Zealand to measure rates of fuel use and assess the influence of technological (e.g. vessel size, engine power), behavioural (e.g. distance travelled, speed), and managerial (e.g. catch per unit effort, fishery capacity) factors. Weighted fuel use intensity across the region was 1,890 l/t. Managerial factors were the most influential drivers of fuel use in single day trips while technological factors heavily influenced multi-day trips. Catch per unit effort was the only significant driver present across both types of fishing trips. The vast majority of surveyed fishers identified fuel use as an important aspect of fishing operations, and nearly half had already implemented changes to try to reduce consumption. Our results suggest that efforts to reduce fuel consumption, costs, and emissions in fisheries need to be tailored to the nature of individual fisheries, as the relative roles of technology, behaviour, and management vary.

Keywords: energy, fisheries, fuel, greenhouse gas emissions, lobster.

Introduction

Consumption of fuel by fishing vessels has substantial environmental, economic, and social implications with regards to fishing operations, products and supply chains, and the viability and resilience of fishing communities. Tyedmers *et al.* (2005) estimated that globally in 2000, the world's wild-capture marine fisheries consumed 50 billion litres of diesel fuel. Inputs of diesel fuel are required to propel the vessel, operate gear, run refrigeration and other systems, power onboard processing, and generate electricity for lights, sonar, and other services.

As such, fisheries contribute to the depletion of energy resources and, more pertinently, climate change via emissions of greenhouse gases (GHGs). Fuel-related emissions, including upstream mining, refining, and transport of oil, typically account for between 60% and 90% of the total life cycle emissions of fisheries-derived products (Parker, 2012). Fuel is also the largest operating cost to fisheries after labour, accounting for 20–40% of operating expenses (FAO, 2007; Lam *et al.*, 2011). Globally, fuel inputs to fisheries—in terms of litres burned per tonne of fish landed at the dock—vary between sectors by as much as three orders of magnitude, depending on the species being targeted and the fishing gear being used (Parker and Tyedmers, 2015).

While species and gear differences can explain variation in fuel use across diverse fisheries, both globally and regionally (Tyedmers, 2004; Parker *et al.*, 2015a; Parker and Tyedmers, 2015), it is less clear what drives variation between vessels within a fishery, or between fisheries targeting similar species with the same gear but in different locations. Numerous studies have identified a range of variables which may influence fuel use, and have suggested that changing these variables could have dramatic effects on the fuel performance of individual vessels and fleets. However, results vary between studies and correlations are not consistent between fisheries.

Rock lobster fisheries make up the most valuable sector of Australia's wild-caught fishing industry. In 2012–2013, the Australian and New Zealand industries landed approximately 10 500 and 2800 tonnes of rock lobsters, respectively. While comprising a relatively small percentage of overall fishery landings by volume, rock lobsters account for 30% of the gross value of Australian fisheries production and 40% of fisheries export value (Skirtun *et al*., 2012). The vast majority of landed rock lobsters from Australia and New Zealand are destined for live export, primarily to the Chinese market. Average ex-vessel prices in recent years have ranged from US$50-100 per kg.

Rock lobsters can be found on most coasts of Australia and New Zealand (Figure 1), with the most commercially significant species including Western rock lobster (*Panulirus cygnus*), Southern rock lobster (*Jasus edwardsii*), Eastern rock lobster (*Sagmariasus verreauxi*) and Tropical rock lobster (*Panulirus ornatus*). With the exception of dive fisheries for Tropical rock lobster, commercial fisheries for rock lobsters employ pots or traps, and vessels typically operate between 50 and 150 pots depending on jurisdiction. Fisheries for all rock lobster species, with the exception of the Torres Strait Tropical rock lobster fishery, are managed using individual transferable quotas. All are currently considered by the Australian Government to be sustainably fished (Flood *et al*., 2014), and the fishery for Western rock lobster has been certified by the Marine Stewardship Council as sustainably managed. In 2012–2013, there were a total of 1051 rock lobster fishery license holders or shareholders in Australia and 437 in New Zealand. Of those, 826 and 255 were actively fishing in Australia and New Zealand, respectively (Table 1).

Fuel consumption in Australian rock lobster fisheries has previously been estimated based on expenditure and revenue surveys for South Australia and Tasmania (Parker *et al*., 2015a), which identified rock lobster fisheries as amongst the most fuel-intensive fisheries in Australia, along with other crustacean fisheries. The cost of fuel as a percentage of revenue and total costs, however, was found to be relatively lower in rock lobster fisheries, suggesting that the high value of rock lobster products compensated for the high energy inputs. Farmery *et al.* (2014) assessed the energy use and emissions associated with Tasmanian rock lobster products, and modelled the potential effect of management changes. They suggested that transitioning from maximum sustainable yield to maximum economic yield and removing limits on the number of pots per vessel could drastically improve the fuel performance of the fishery.

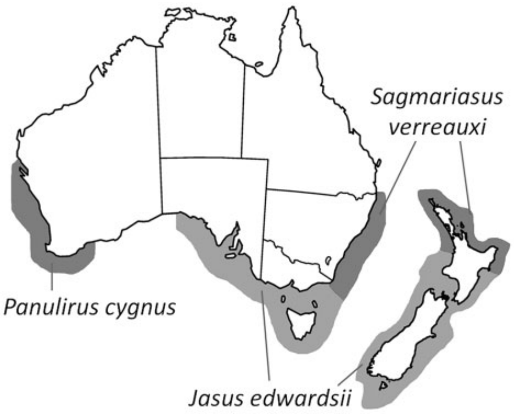

Figure 1. Distribution of commercial trap fisheries for rock lobsters in Australia and New Zealand.

The objectives of this paper are threefold. First, to calculate and compare fuel use intensity (FUI), measured as litres of fuel per tonne of landings (l/t), of a diverse set of rock lobster trap fisheries in Australia and New Zealand. Second, to assess the FUI of fishing vessels and the average fuel performance of each region in relation to a suite of technological, behavioural, and managerial variables. Third, to test the influence of those variables and the predictability of fishery FUI based on a subset of fishery characteristics, thereby determining if control over those variables could potentially be used as a strategy to decrease fuel consumption, operating costs, and GHG emissions in the industry.

Material and Methods

Surveys were distributed to fishers in five Australian rock lobster fisheries (Western Australia, southern and northern zones of South Australia, Tasmania, and New South Wales) as well as New Zealand, all operating with traps and targeting three distinct species of rock lobster (Table 1). Mail and email lists were obtained from government and industry organizations in each region, and surveys were distributed in collaboration with industry partners.

Surveys included questions on the vessel (length, engine power, engine fuel use rates), operations (number of days fished, number of pots, inputs of bait and fuel), trip characteristics (days per trip, distance to fishing grounds), and production (landings of lobster and non-lobster species) in the 2012–2013 fishing year. Respondents were also asked how important fuel use was to their operations, if they had made any operational or behavioural changes in response to the cost of fuel, and how they expected fuel use and costs to affect their operations over the next 5 years (see Supplementary Material).

Returned surveys that did not provide enough information for analysis, and those that reported more than 25% of their catch from non-lobster species, were excluded from analysis.

Table 1. Characteristics of commercial Australian and New Zealand rock lobster fisheries included in analysis by location.

Region	Tasmania	Western Australia	South Australia NZ[a]	South Australia SZ[a]	New South Wales	New Zealand
Primary species	*Jasus edwardsii*	*Panulirus cygnus*	*Jasus edwardsii*	*Jasus edwardsii*	*Sagmariasus verreauxi*	*Jasus edwardsii*
TACC (t)[b]	1103	5500	345	1250	140	2797
Licenses[c]	311	274	68	181	101	437
Active vessels[b]	212	273	48	164	82	255
Primary trip type (days)	Single/multi	Single	Multi	Single	Single	Single/multi

[a] South Australia includes two lobster fishing areas: the northern zone (NZ) fished primarily on multi-day trips, and the southern zone (SZ) including primarily single day trips.

[b] Total allowable commercial catch and number of actively fishing vessels for 2012/2013 fishing year, sourced from regional fishery assessment reports. Tasmanian TACC for 2014/2015 year has been reduced to 1051 t.

[c] Total fishery licenses or number of shareholders sourced from regional assessments (New Zealand Rock Lobster Industry Council, 2014; Stephan and Hobsbawn, 2014).

FUI of each vessel was calculated from total fuel consumption and total round weight landings in the 2012–2013 fishing year. Where direct fuel consumption was not reported, consumption was estimated based on yearly fuel expenditures and average off-road diesel price over the study period (ABARES, 2014), and/or per-trip fuel consumption and number of trips.

Variables of interest were selected based on a review of fuel use literature (including regional and fishery-specific fuel consumption studies, fishery life cycle assessments, government and intergovernmental reports, and energy audits), accessibility of relevant data, and subsequently sufficient return of data from respondents to allow analysis. These included technological factors (length, engine power, engine fuel use rates during steaming, and specific fuel consumption), behavioural factors (trip length, trip distance, estimated average trip speed, reported level of fuel importance, and reported changes to operations), and managerial factors (number of pots, catch per unit effort, and fishery capacity) (Table 2). Regional estimates of total stock biomass were not available; in lieu of biomass estimates, catch per unit effort (CPUE) and total allowable commercial catch (TACC) were used as management-based proxies. Number of pots per vessel and fishery capacity (number of vessels and pots in the fleet relative to TACC) were considered management variables because they were directly controllable through regulations in each fishery. Likewise, CPUE and TACC were considered management variables because they were indirect results of historical management decisions and are the primary management tools in response to observed catchability.

Multiple regression analysis was used to investigate factors that influence FUI. The analysis was conducted for all fishing trips combined, all trips undertaken in a single day, and all trips lasting multiple days. Multiple regression allowed for the examination of individual variables while accounting for observed variation in other variables; however, it did not allow for differentiation between variables which may be related either directly or indirectly in fishing operations, such as the ability of larger vessels to hold more fuel and travel farther from port. In each case a Box-Cox analysis indicated that a log transform was appropriate and examination of residual plots further supported the suitability of this model. Insignificant variables ($p > 0.05$) were removed sequentially in order of least significance from the fully saturated model (without interaction terms) until only significantly related variables remained in each model.

Results

Of 1040 surveys distributed, a total of 81 completed surveys were returned (8%). Regionally, 27 surveys were returned from South Australia, 20 from Tasmania, 16 from Western Australia, 11 from New Zealand, and six from New South Wales. Five surveys were removed from analysis due to incomplete data, and six were removed because rock lobster made up <75% of their catch, leaving a total sample size of 70 vessels.

Vessels varied between and within regions with regard to vessel size, operations, and production (see Supplementary Material). Technologically, fisheries ranged from smaller vessels with smaller, less fuel-intensive engines in Tasmania, New South Wales and New Zealand, to larger vessels with more fuel-intensive engines in Western Australia. Vessel length ranged from 5 to 25 m, with a total average length across all regions of 14 m, and engine power ranged from 50 to 1600 HP with an overall average of 552 HP. Operations in Tasmania and the northern zone of South Australia were characterized by multi-day trips and greater distances to fishing grounds, while trips were shorter and conducted in a single day in Western Australia, New South Wales, and the southern zone of South Australia. CPUE ranged from 0.3 to 5.5 kg/potlift, with an average across all regions of 1.4 kg/potlift.

Fuel costs were identified as "important" or "very important" by 82% of respondents and 41% stated that they had already changed operations in response to fuel costs. Reported changes included reducing distance to fishing grounds (19%), being more selective of fishing days (14%), reducing speed (14%), and installing smaller or more efficient engines (7%). Generally, fishers reporting higher fuel costs were more likely to consider fuel to be an important or very important factor in their operations (Figure 2). There was no relationship observed between perceived importance of fuel and type of fishing trip (single or multi-day) or vessel characteristics.

Average FUI of all vessels was 2355 l/t with a standard deviation of 1289 l/t. The total range of reported FUI was 498 to 7462 l/t. Multiplying average regional values by each region's contribution to overall production, the average FUI of landed rock lobsters in Australia and New Zealand was 1890 l/t. Rates of fuel use were lowest in New Zealand and Western Australia; seven of the ten vessels with the lowest FUI were from those regions. Variation in FUI between regions was found to be statistically

Table 2. Variables included in analysis of fuel use intensity relationships, separated by technology, behaviour, and management categories.

Category	Variable	Unit	Source
Technology	Vessel length	m	Survey
	Engine power	HP	Survey
	Engine fuel rate during steaming	l/h	Survey
	Specific fuel consumption	g/kWh	Calculated from survey
Behaviour	Trip length	Days	Survey
	Distance to fishing grounds	nautical miles (NM)	Survey
	Average trip speed	knots	Calculated from survey[a]
	Stated level of importance of fuel	1–5	Survey
	Stated operational and behavioural changes	Yes/No	Survey
Management	CPUE	kg/potlift	Calculated from survey
	Number of pots	pots	Survey
	Fishery capacity	vessels/1000 t TACC	Management and assessment reports
	Fishery capacity	pots/t TACC	Management and assessment reports; survey

[a] Average trip speed for single day trips was calculated based on the total distance to and from fishing grounds as well as the total distance within fishing grounds while fishing, and the number of hours per trip. Average trip speed was not calculated for multi-day trips.

significant using a two-way ANOVA test (64 and 5 DF, $p = 0.002$) (Figure 3). FUI varied more between vessels operating single day trips than between those operating multi-day trips, reflecting the higher variation in other variables as well: multi-day trips were primarily undertaken in Tasmania and New Zealand and targeted the same species, while single day trips took place across most regions and targeted different species with different CPUEs.

Multiple regression models of rock lobster vessels operating single day and multi-day trips identified different predicting variables, with a combination of managerial and technological factors significantly contributing to both (Figure 4). Across all fishing trips combined, FUI was significantly related to CPUE, engine power, number of fishing vessels per unit TACC, and vessel length (Table 3). FUI of vessels undertaking single day trips was most influenced by managerial factors, with significant relationships to CPUE, engine fuel rate, and number of pots per vessel. FUI of vessels operating multi-day trips was more heavily influenced by technological variables, with significant relationships to engine power, vessel length, and CPUE. The magnitude and direction of predictive relationships between independent variables and FUI for each sector are displayed in Figure 4 and Table S2 (see Supplementary Material). The only factor identified as a significant driver of FUI in both single day and multi-day trips was CPUE, with a modelled decrease in FUI of approximately 20% per kg increase in CPUE. A stronger predictive power of the model was found for multi-day trips ($r^2 = 0.78$) than for single day trips ($r^2 = 0.55$; Figure 5).

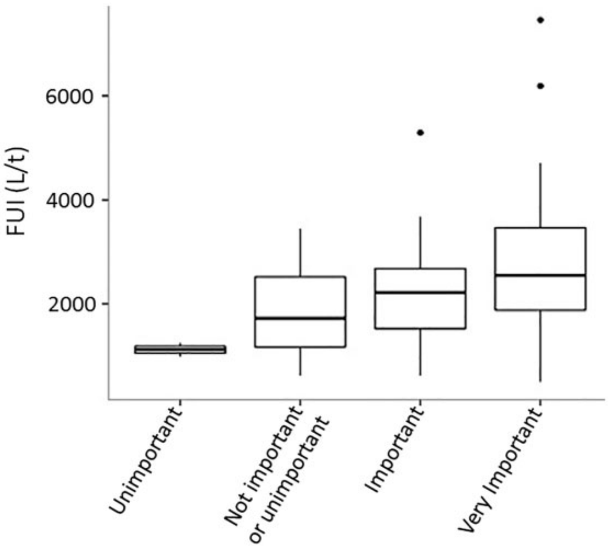

Figure 2. Importance of fuel use and fuel costs to fishing operations, as reported by rock lobster fishers, with distribution of FUI corresponding to each response. No fishers considered fuel use to be "very unimportant."

Discussion

Comparison to other fisheries

The average FUI of landed rock lobster, caught using traps in Australia and New Zealand and weighted by regional production, was 1890 l/t, placing the industry amongst the most fuel-intensive fisheries both regionally and globally (Figure 6). Other lobster fisheries around the world have also reported high levels of fuel consumption, owing primarily to their low catch rates when compared to fisheries targeting schooling fish. Fisheries for American lobster (*Homarus americanus*) caught with traps consume approximately 1000 l/t in the United States and Canada (Driscoll *et al.*, 2015), with the marked difference between American lobster and those fisheries assessed here likely influenced by the much higher CPUE observed in American lobster fisheries. Estimates of FUI for Norway lobster (*Nephrops norvegicus*) include 2160 l/t using traps and 4120 l/t using trawls (Ziegler and

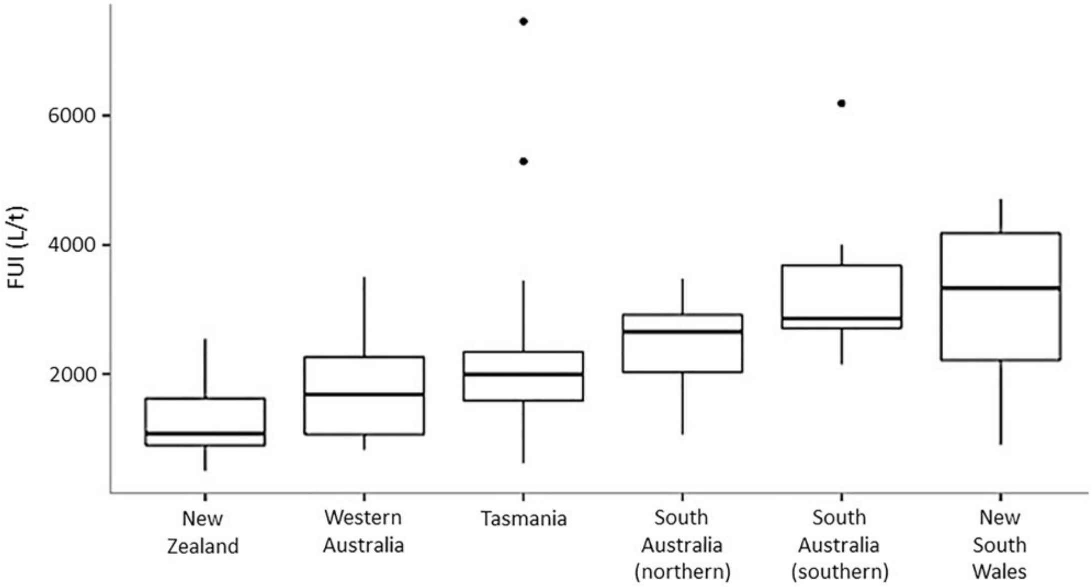

Figure 3. Tukey boxplot distribution of rock lobster vessel fuel use intensity (l/t) by location. Centre line shows median value, box encompasses 50% of values, extending lines encompass all remaining values except outliers (points).

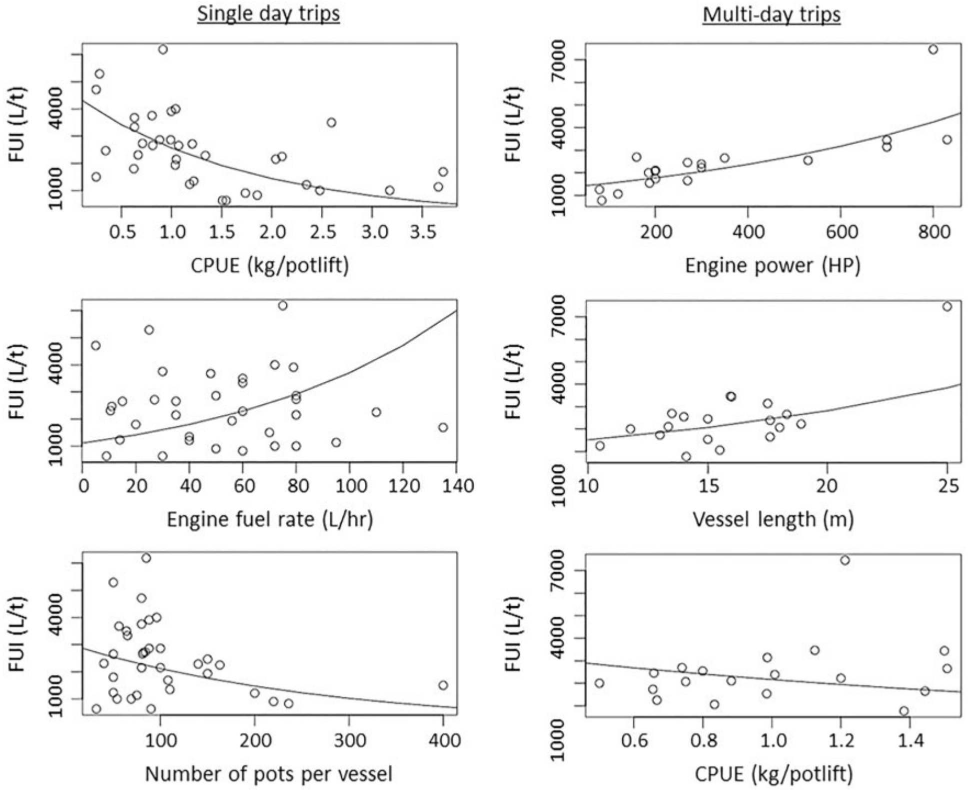

Figure 4. Relationship between fuel use intensity and significant variables for both single day and multi-day rock lobster fishing trips. Regression lines display relationship for each independent variable from multiple regression analysis, holding other significant variables constant at their mean values. See Supplementary Material for scatterplots of all variables.

Valentinsson, 2008, re-calculated to allocate fuel use to landings on a mass basis to maintain consistency). Tropical rock lobster caught by divers in the Torres Strait, Australia, has a FUI between 1000 and 2900 l/t (van Putten *et al.*, 2016).

Technological drivers of fuel use

Technological characteristics of rock lobster fisheries varied markedly between regions. Average engine power and engine fuel use rates in Western Australia, for example, were 2.6 and 4.3 times that of Tasmanian vessels, respectively. Technological factors were found to influence the energy performance of rock lobster vessels here, but to varying degrees in different sectors. Smaller vessels with lower power engines were significantly less fuel-intensive in multi-day trips while these factors were less influential in single day trips. This may reflect the longer distance and time spent travelling in multi-day trips, providing a longer window for technological efficiency measures to have an effect independent of other conditions.

Innovations in engine fuel rates (l/h) and vessel design have received a lot of attention in the literature and are often suggested as ideal options for reducing long-term energy costs in fisheries (Wilson, 1999; Sterling and Goldsworthy, 2007; Basurko *et al.*, 2013). However, evidence of relationships between fuel use and vessel size, engine power, and other technological factors varies considerably between studies. Vessel size in European fisheries, for example, is positively correlated with fuel efficiency in demersal and pelagic trawlers, but negatively correlated with efficiency in beam trawlers and dredgers (Guillen *et al.*, 2016). Ziegler and Hornborg (2014) found little difference in fuel consumption by different size classes in Swedish trawl fisheries with the exception of vessels employing selective trawls, in which case smaller vessels were more efficient. The variable influence of vessel size in fisheries also extends to comparisons between fleets: differences in target species and gear type influence fuel use much more than technological characteristics of individual vessels. Very large tuna purse seiners, for example, are relatively energy-efficient when compared to other fisheries with smaller vessels, and display no significant correlation between size and FUI within the industry (Parker *et al.*, 2015b). Large factory processing trawlers have also been measured amongst the more efficient fishing vessels in cases where they target a species with a highly-localized biomass and schooling behaviour (Fulton, 2010; Parker and Tyedmers, 2012). Generally, larger vessels can be more efficient if their size allows them to take advantage of higher catch rates by traveling to better fishing locations or fishing for longer periods (Ziegler *et al.*, 2016).

Vessels whose energy consumption is linked more closely with gear operation, such as trawlers or dredgers, may benefit more from technological design improvements than vessels operating passive gears like traps. Optimizations in the size and design of otter boards, cables, and net mesh, for example, have been found to significantly reduce fuel consumption rates in some trawling fisheries by up to 40% (Sterling and Goldsworthy, 2007; Parente *et al.*, 2008; Priour, 2009; Khaled *et al.*, 2013). The influence of trip type in the relative role of technological factors in rock lobster fuel performance suggests that vessels travelling great

Table 3. Relationship between independent variables and fuel use intensity in rock lobster fishing trips, in decreasing order of significance.

All trips		Single day trips		Multi-day trips	
Variable	**p^a**	**Variable**	**p^a**	**Variable**	**p^a**
CPUE	<0.01*	CPUE	<0.01*	Engine power	<0.01*
Engine power	<0.01*	Engine fuel rate	<0.01*	Vessel length	0.02*
Fishing capacity	<0.01*	Pots per vessel	<0.01*	CPUE	0.03*
Vessel length	<0.01*	Distance to grounds	0.07	Distance to grounds	0.06
Distance to grounds	0.14	Average speed	0.27	SFC	0.12
Pots per vessel	0.26	Fishing capacity	0.62	Fishing capacity	0.28
SFC	0.35	SFC	0.65	Pots per vessel	0.32
Importance of fuel	0.45	Importance of fuel	0.69	Engine fuel rate	0.66
Days per trip	0.70	Vessel length	0.82	Days per trip	0.67
Engine fuel rate	0.95	Engine power	0.95	Importance of fuel	0.87

Statistically significant relationships, as found in multiple regression analysis, are marked with an asterisk.

[a] *p* values for significant variables are displayed from the final multiple regression model. Insignificant variables were removed sequentially until all remaining values were significant ($p < 0.05$), and *p* values for insignificant variables are displayed from the latest model before the variable was removed.

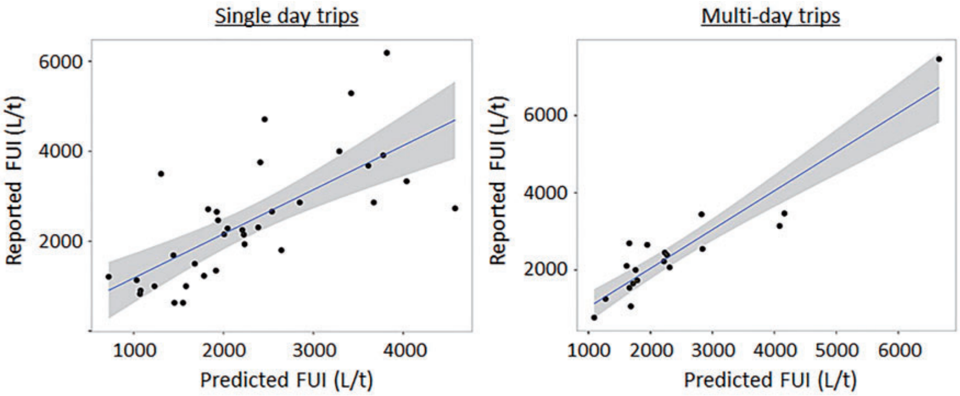

Figure 5. Model fit for single day and multi-day lobster fishing trips, using factors with significant relationships to FUI identified in multiple regression models. Shaded area shows 95% confidence intervals. Single day trip model is based on relationships of FUI with CPUE (kg/potlift), engine fuel rate (l/h), and number of pots per vessel. Multi-day trip model is based on relationships of FUI with engine power, vessel length, and CPUE (kg/potlift).

distances or fishing for long periods of time may also benefit more from design improvement, even if they are operating passive gears.

Behavioural drivers of fuel use

Behavioural adaptations are regularly suggested as cost-effective means to directly improve efficiency and manage rising fuel prices. However, our findings do not suggest that individual fishing behaviour has a substantial effect on the efficiency of rock lobster fisheries. In fact, those fishers that reported changes to their operations—either technological or behavioural—in response to high fuel costs actually performed worse than fishers that did not report any changes. There was a pattern of more fuel-intensive vessels reporting a higher importance of fuel costs. However, reported importance of fuel was not a significant predictor of FUI; rather, the greater importance attributed to fuel was likely in response to high fuel costs, rather than an indication of adaptive behavioural changes.

Numerous behavioural factors have been investigated in the literature, including vessel speed and decisions regarding when and where to fish. Because of the ease with which these behavioural changes can be made, many fishers are likely to rely on them for short-term adaptations (Abernethy *et al.*, 2010; Beare and Machiels, 2012). Reducing vessel speed, for example, has been shown to decrease trip fuel consumption in trawlers by between 10 and 50% (Latorre, 2001; Popp, 2010; Basurko *et al.*, 2013). Speed may have a particularly strong impact on fisheries which travel greater distances, with relatively small reductions in speed associated with dramatic improvement in fuel use during the steaming phase of fishing trips (Parente *et al.*, 2008; Thomas *et al.*, 2010). However, our results did not find any significant relationship between average trip speed and FUI. Importantly, this study assessed average speed across the entire trip, and therefore may have missed potential fuel benefits of controlling speed during certain portions of a trip, particularly during steaming to fishing grounds. Future studies could be improved by differentiating between speed during steaming and speed during fishing, either by soliciting data from fishers or by use of fuel loggers and speed recorders—the latter method being employed by previous studies focusing on the influence of speed in more detail (e.g. Basurko *et al.*, 2013).

A less measurable behavioural factor referred to as the "skipper effect" reflects the overall experience of fishers, and includes decisions such as where to locate stocks or how to respond to

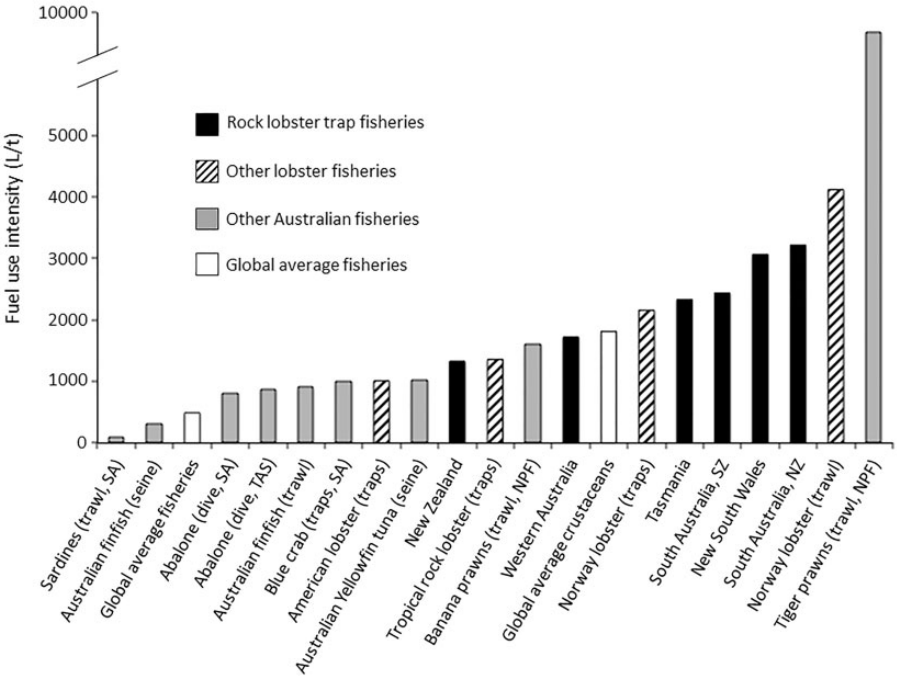

Figure 6. Fuel use intensity of Australian and New Zealand rock lobster trap fisheries compared to other lobster fisheries around the world, non-lobster fisheries in Australia, and the global average fishery FUI. SA = South Australia, TAS = Tasmania, NPF = Northern Prawn Fishery. Data relating to rock lobster fisheries are from the current study. Data relating to other Australian fisheries are from Parker *et al.* (2015a). Data relating to other lobster fisheries are from Driscoll *et al.* (2015); van Putten *et al.* (2016); and Ziegler and Valentinsson (2008). Data relating to global fisheries are from Tyedmers *et al.* (2005) and Parker (2016). Note the break in y-axis.

environmental conditions (Ruttan and Tyedmers, 2007; Vázquez-Rowe and Tyedmers, 2013). Abernethy *et al.* (2010), for example, reported that the most common responses of skippers to rising fuel costs included closer examination of catch by the skipper, more careful use of the tide for travel, and the choice not to fish during poor weather days. Fishers' choices, such as which days to fish and whether to travel farther for additional catch, are based on a combination of economic and environmental factors as well as a balance between total catch rate and catch efficiency, and skipper experience has, as a result, been demonstrated to influence fuel performance through increases in catch rate (Bastardie *et al.*, 2010; Ziegler *et al.*, in press). Skipper effect may explain some differences in FUI between similar vessels operating in the same region in this study, and data relating to skipper experience, such as number of years fishing, may be useful in future studies to try to incorporate this factor.

Managerial drivers of fuel use

CPUE was found here to be the only factor consistently influencing the FUI of rock lobster fishing vessels. Not only was it found to relate significantly to FUI of both single day and multi-day fishing trips, but was also highest in the two regions that demonstrated the most energy-efficient operations: New Zealand and Western Australia. Similar to the single day results presented here, Ziegler and Hornborg (2014) identified increases in biomass as a result of management as more influential to fuel consumption in Swedish fisheries than technological factors such as vessel size. Ziegler *et al.* (2016) also found CPUE to be the main determinant of fuel use in Scandinavian shrimp trawl fisheries.

Management regulations of fisheries can also influence energy performance directly. Driscoll and Tyedmers (2010) demonstrated the dramatic reduction on fuel use resulting from gear restriction in the New England Atlantic herring (*Clupea harengus*) fishery by replacing trawls with less fuel-intensive purse seine gear. Farmery *et al.* (2014) modeled reduction in potential fuel consumption in rock lobster fisheries by changing fishing limits from maximum sustainable yield to maximum economic yield, and increasing or removing the limit on pot numbers. In the southern zone rock lobster fishery of South Australia, a boat buyback scheme was introduced in 1987, which resulted in the removal of 45 fishing licenses and over 2400 pots, and led to a dramatic increase in CPUE between 1987 and 2002 (Sloan and Crosthwaite, 2007). While fuel use data are not available for most of that period, the relationship between FUI and CPUE would suggest that the buyback would have resulted in improved fuel use rates. A similar improvement in CPUE and fuel use—up to 50% reduction—has been documented in the Northern Prawn Fishery of Australia after the implementation of a boat buyback in that fishery (Pascoe *et al.*, 2012; Parker *et al.*, 2015a).

Because rock lobster fisheries target a non-schooling species with a relatively low biomass compared to finfish, it is unlikely that the FUI of rock lobster fisheries could, at a sector-wide scale, reach the levels of efficiency achieved by other fisheries. North American lobster fisheries, for example, experience much higher catch rates per trip than rock lobster fisheries, and still burn much more fuel than most finfish fisheries (Driscoll *et al.*, 2015). However, the range in FUI between fisheries with varying rates of CPUE found here, coupled with evidence of fuel use responding to management changes both theoretically and in practice, suggests that there is substantial room for rock lobster fisheries to improve their performance via management.

Conclusions

We assessed the FUI of rock lobster fishing vessels throughout Australia and New Zealand and explored the relative influence of technological, behavioural, and managerial variables. FUI varied significantly across regions assessed with the most efficient fisheries being those that achieved the highest CPUE. Managerial variables, including CPUE and number of pots per vessel, were more significant drivers of FUI in single day trips. Technological factors, including engine power and vessel length, were more significant in multi-day trips. CPUE was a consistent driver of FUI across both fishing trip types.

If the future of fisheries includes higher energy costs, potential pricing of carbon emissions, and increased demand to provide low-carbon products to consumers, it would be prudent for the industry to seek options to improve fuel performance now. Results here suggest that a combination of technological and managerial factors influence the fuel performance of rock lobster vessels. Management efforts targeted at rebuilding stocks and identifying optimal levels of effort—sector-wide and by individual vessels—are likely to achieve the most effective results across the industry, with the added benefit of improving ecological sustainability of fishing stocks.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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