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# Life cycle assessment of wild capture prawns: expanding sustainability considerations in the Australian Northern Prawn Fishery

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ABSTRACT

Prawns and shrimp are among the most popular seafood consumed globally and their production is responsible for a range of environmental impacts in wild capture fisheries and associated supply chains. Management of the Australian Northern Prawn Fishery has been promoted as a sustainable model for other countries to emulate, although broader environmental impacts, such as those relating to energy and water use or greenhouse gas emissions are not currently monitored under sustainability assessments. We use life cycle assessment (LCA) to assess the environmental impacts of the white banana prawn (*Fenneropenaeus merguiensis*). Fishing operations were the main source of impacts for the supply chain examined, contributing 4.3 kg $CO_2e$ $kg^{-1}$ prawn or 63% of the overall global warming potential. This result was lower than emissions reported for other prawn species, including tiger prawns from the same fishery. Processing and storage were key contributors to ecotoxicity while transport made a negligible contribution to any impact category. We discuss how LCA can complement existing fisheries management, and broaden current seafood sustainability assessments including the potential for emerging fishery-specific indicators to improve the efficacy of seafood LCAs.

## 1. Introduction

Prawns[5] are among the most popular seafood consumed globally and are one of the most important traded fishery products, accounting for 15% of the total value of internationally traded fish products (FAO, 2010). Globally, approximately 6.5 million tonnes are produced annually with around half of this production from wild capture fisheries and the rest from prawn farms (FAO, 2012). Despite the recent growth of aquaculture production, wild capture prawns remain an important source of food and fisher livelihoods (Bondad-Reantaso et al., 2012). Prawn fishing and the use of trawls has been linked to a range of environmental impacts, the extent and reversibility of which vary with trawl type and location (Brewer et al., 2006; de Groot, 1984; Eayrs, 2007; Pitcher et al., 2009), but it is the management of bycatch and discards that has dominated sustainability discussions around prawn fisheries for decades (Gillett, 2008). Tropical prawn trawl fisheries accounted for over 27% of total estimated discards in global marine fisheries, or over 1.8 million tonnes per year (Kelleher, 2005).

Negative consequences of trawling, such as the incidental mortality of non-target species, have notably improved over the last decade (He and Balzano, 2011) with the emergence of ecosystem-based fisheries management (EBFM). However, the ability of EBFM to sustain healthy marine ecosystems and the fisheries they support (Zhou et al., 2010) will be continuously challenged by outside pressures, including climate change, which will have potentially detrimental consequences for some fisheries (IPCC, 2014). Crustacean fisheries directly contribute to climate change through greenhouse gas (GHG) emissions from the burning of fuel, and are characterised by the highest fuel use intensities in fisheries (Parker et al., 2014; Parker and Tyedmers, 2014). Prawn fisheries can also have very high energy use for the amount of food produced (Gillett, 2008). Energy use, and the resulting emissions,

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*Abbreviations:* CED, cumulative energy demand; EBFM, ecosystem-based fisheries management; EP, eutrophication potential; GDI, global discard index; GHG, greenhouse gas; GWP, global warming potential; LCA, life cycle assessment; NPF, Northern Prawn Fishery; PPR, Primary productivity required; SIP, seafloor impact potential.

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[5] ‘Prawn’ refers to both shrimp and prawn within Caridea and Dendrobranchiata.

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are not typically included in sustainability assessments of prawn fisheries and their products, or in seafood more generally. Methods such as emergy accounting (Wilfart et al., 2013; Zhang et al., 2012) and Life Cyclce Assessment (LCA) have emerged to evaluate energy efficiency and carbon emissions along product supply chains, however the use of fossil fuel in fishing vessels has largely been excluded from the ecosystem approach (Pelletier et al., 2007).

GHG emissions and use of resources such as water are increasingly of interest in regard to food sustainability and security, as climate change alters food systems; and good quality water becomes scarcer in arid countries like Australia. The regulation of GHG is expanding with 16 emissions trading schemes, covering 70% of global emissions, expected to be in place by 2015 (ICAP, 2014). The absence of these indicators from sustainability assessments undertaken by government, industry or certification groups such as the Marine Stewardship Council (MSC) means that current levels of impacts are not well understood. As a result, improvements through time have not been monitored as has occurred with other areas of improving fisheries practice such as bycatch reduction.

LCA has emerged as a standardised environmental management tool capable of analysing environmental burdens along the supply chain of products and processes (ISO, 2006a, b). There has been a recent surge of LCAs in seafood systems, however, further development of the methodology is required in order to effectively cover the wide range of environmental impacts linked to fishing (Vázquez-Rowe et al., 2012a).

Australia's largest prawn fishery, the Northern Prawn Fishery (NPF), is considered sustainable under third party assessments, including those conducted by the Marine Stewardship Council (MSC, 2012) and under the *Environment Protection and Biodiversity Conservation Act 1999* (FRDC, 2012) of the Australian Commonwealth Government. These assessments cover a specific range of environmental criteria, however, they do not consider impacts relating to resource use, GHG emissions, or emissions of nutrients and toxins during fishing or along the supply chain. Neither do they address differences in these impacts between target species. In this study we used LCA to examine the impacts of the supply of 1 kg of banana prawn from the NPF. We discuss how LCA can complement existing fisheries management and the potential for emerging fishery-specific indicators to improve the efficacy of seafood LCAs. We selected this fishery as a case study based on its importance to the Australian economy and because it was one of the first Australian fisheries demonstrating the ecological sustainability of its supporting ecosystem (Zhou and Griffiths, 2008). This research adds an Australasian example to the growing body of seafood LCA literature and provides an example of how LCA can augment current concepts of seafood sustainability by broadening the scope of environmental considerations.

## 2. Methods

### 2.1. Northern prawn fishery case study

The NPF is the most valuable fishery managed by the Commonwealth Government of Australia with gross value of production of $94.8 million in 2010–11, accounting for over 4% of the total for Australian fisheries and aquaculture (Woodhams et al., 2012). The NPF is a multispecies fishery comprising 52 boats using otter trawl gear in 2010/11. A total of 9673 tonnes were landed in the same period, with white banana (*Fenneropenaeus merguiensis*) and tiger prawns (*Penaeus esculentus*; *P. semisulcatus*) accounting for 80% of the total annual catch (Woodhams et al., 2011). A number of byproduct species are also landed, including endeavour prawns (*Metapenaeus endeavouri; M. ensis*), scampi (*Metanephrops* spp.), Moreton Bay bugs (*Thenus* spp.) and commercial scallops (*Amusium* spp.) (AFMA, 2013). The fishery is located off Australia's northern coast, between Cape York in Queensland and Cape Londonderry in Western Australia (Fig. 1).

The white banana prawn fishery is effectively a single-species subfishery within the larger NPF, temporally and spatially separated from the other species (Zhou et al., 2014). Catch rates of white banana prawns are volatile and heavily affected by environmental conditions, with higher catches generally occurring after wetter than average summers (Vance et al., 2003). The variability of white banana prawn biomass makes it difficult to set appropriate catch or effort limits (Buckworth et al., 2013) and the NPF is managed using input controls implemented under the Northern Prawn Fishery Management Plan 1995 (Barwick, 2011). The banana prawn fishery commences when the NPF season opens and usually operates for a few weeks in April/May. Banana prawns are generally caught during daylight hours on the eastern side of the Arnhem Land coast and in Joseph Bonaparte Gulf where the industry use spotter aircraft to identify aggregations to target. More than half of a vessel's daily prawn catch is banana prawns in the banana prawn subfishery. All NPF vessels have catch handling, packing and freezing capabilities and all prawns are frozen at sea. Catch is landed in Karumba or Darwin, or delivered to a mothership which lands the combined catches from different vessels in Townsville. Prawns are stored frozen before transport to processing.

The other main subfishery, the tiger prawn fishery, operates from August to November. Tiger prawns are taken at night and the majority of catch comes from the southern and western Gulf of Carpentaria and along the Arnhem Land coast (Woodhams et al., 2012). More than half of a vessel's daily prawn catch in the tiger prawn subfishery is tiger prawns (Barwick, 2011).

The supply chain of the banana prawn is depicted in Fig. 2 and the following systems were modelled: fishing - including spotter plane, cold-storage, transport to processing, and processing. Under current sustainability assessments, the NPF is assessed as one fishery although distinctions between the two subfisheries are important for our purposes as they have very different fuel use, bycatch rates and final markets. The majority of the catch from the tiger prawn fishery is exported to Japan via sea freight, while approximately 80–90% of white banana prawns are sold on the Australian domestic market (AFMA, 2013). An LCA for tiger prawns was not carried out, however the global warming potential (GWP) of the fishing stage and transport to international market stage of the tiger prawn supply chain were modelled for comparison.

### 2.2. Data collection

Data on catch volume, days fished and fuel cost for all vessels operating in the NPF was sourced from the Department of Agriculture, Fisheries and Forestry (ABARES, 2011; Woodhams et al., 2011). Fuel cost for each subfishery was not available, therefore the total fuel cost available for the fishery for 2009–11 was allocated across the banana and tiger subfisheries based on the proportion of total days fished in each, consistent with other trawl fishery LCAs (Parker et al., 2014). Fishers recorded a total of 5031 boat days in the banana subfishery over the two year period, and 11 228 boat days for the tiger subfishery. Specific catch and financial performance information for the NPF fleet were only available for 2009–11 at the time of our study. As annual catch volume varies in the fishery, sensitivity of results to catch variation was assessed by comparing the life cycle impact results for 1 kg of banana prawn using three different scenarios: (a) base case scenario, using catch data and boat days from 2009 to 2011; (b) 10% increase in catch with the same number of boat days; and (c) 10% decrease in catch with the same number of boat days.

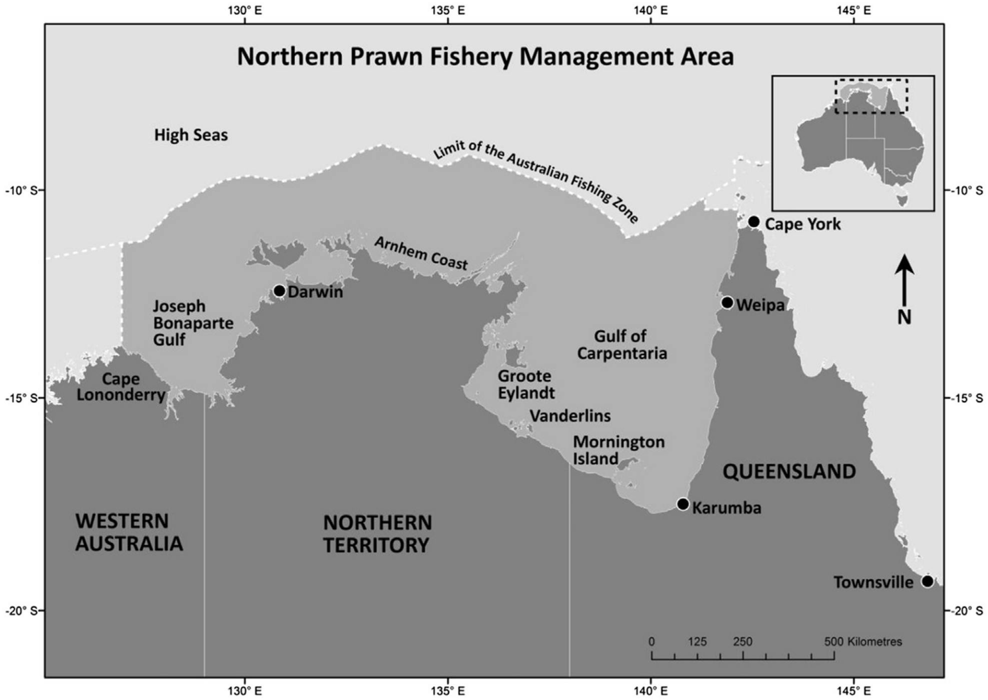

**Fig. 1.** The northern prawn fishery, Australia.

*2.2.1. Banana prawn life cycle inventory*

The average fuel use per kilogram of banana prawn caught was calculated using data from three sources: (i) for 2011–12 from independent fishers who predominantly use a mothership to land catch, (ii) for 2012 from a company that did not use a mothership, and (iii) for 2009–2010 and 2010–11 from ABARES reports (George et al., 2012; Woodhams et al., 2011) which included a mix of mothership users and non-users. Data from (i) and (ii) were provided in total annual litres and converted to l/kg. Fuel use in litres was calculated for the ABARES data by dividing the total fuel cost for 2009–2010 and 2010–11 by the average price of diesel (Motormouth, 2012), minus the rebate of AUD $0.38 per litre. Fuel use for freezing has not been separated from fuel use for fishing in this study, as freezing occurs on-board the fishing vessels. Fuel use for the spotter plane was provided by a private company and converted to KJ. The abiotic effects of antifoul use, fishing gear and cardboard packaging of frozen prawns were also included for the capture stage as these goods need to be regularly replaced, unlike other capital goods such as the fish boats themselves. The life span of the fishing gear was determined through discussions with fishers and retailers. Refrigerant use on boats and at processing was not included in the LCA due to data availability and the current phase out of the main refrigeration gas, R22, in Australia. The impacts of fuel used for freezing on the boats are captured under the GWP and CED indicators. Truck operation was increased by 22% to account for energy used in freezing equipment (Berlin and Sand, 2010).

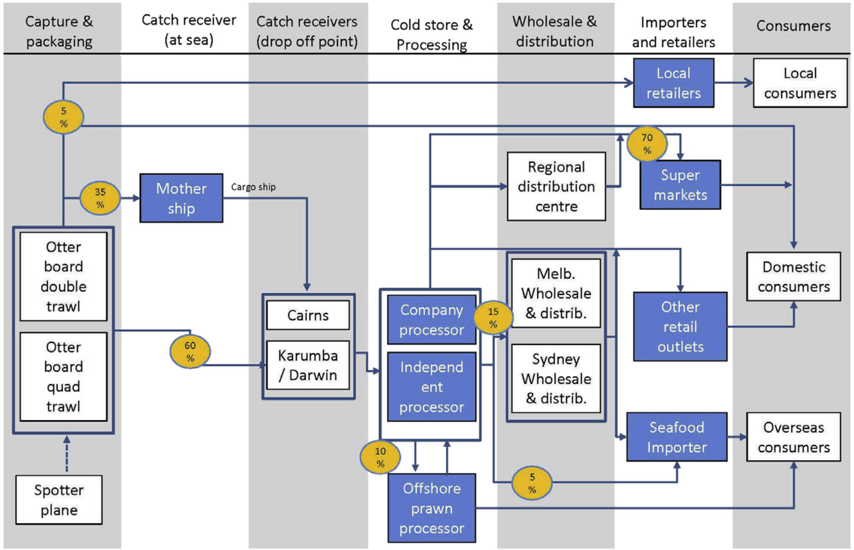

**Fig. 2.** Supply chain of banana prawns from the Northern Prawn Fishery.

Refrigerant use was captured for cold storage as the data was adapted from Ziegler et al. (2011). Refrigerant use in the NPF is presented in the discussion section.

Processing refers to the activities that occurred within a land-based processing facility. Figures on total water and electricity at processing were sourced from a facility belonging to one of the largest vertically integrated companies operating in the NPF. Processing was minimal and involved thawing in fresh water, grading and repacking. Some of the catch packed at sea is not reprocessed ashore and would therefore require fewer inputs than the prawns examined here. Banana prawns accounted for 30% of the total products processed at the facility and input use was allocated based on mass. Data on cold-storage was calculated based on data reported by Ziegler et al. (2011) for pink shrimp, and relate to land-based cold-storage only. Transport distance from landing to processor via truck, or truck and mothership, was calculated through Google Maps. Capital goods such as fishing boats, vehicles and buildings, were excluded as they are generally of minor importance for LCA (Ellingsen and Aanondsen, 2006; Ellingsen and Pedersen, 2004; Hospido and Tyedmers, 2005; Thrane, 2004). The retail and consumption stages of the supply chain were not included.

### 2.2.2. *Tiger prawns*

Fuel use in litres for tiger prawns was calculated by dividing the total fuel cost for 2009–2010 and 2010–11 by the average price of diesel (Motormouth, 2012), minus the rebate of AUD $0.38 per litre. Transport distance from Australia to Japan was calculated using Google maps and time taken for refrigerated sea freight calculated using Ports.com.

## 2.3. *Life cycle impact assessment*

Environmental impacts associated with the capture, storage, processing and transport of banana prawns were evaluated using Life Cycle Assessment (LCA), a holistic method for the standardised assessment of products and production methods along the supply chain (ISO, 2006a, b). The functional unit of comparison used was 1 kg of frozen prawn at the processor gate, represented in the results section as $kg^{-1}$ prawn, which is approximately 550 g of prawn meat. Impact categories, or indicators, were selected from the Australian Indicator Set (v2) (Life Cycle Strategies, 2012). Life cycle inventory libraries that originate from Europe or the United States are not always relevant for Australia, therefore locally adapted libraries have been developed to help standardise the interpretation of ISO 14040 in Australia (alcas.asn.au/AusLCI). These Australasian libraries were used where possible, and Ecoinvent libraries used where local data was not available. Impact assessment methods were selected from the Australian impact method available in Simapro 7.

Of the indicators available through the Australian indicator set, global warming potential (GWP), eutrophication potential (EP), water use, cumulative energy demand (CED) and marine aquatic ecotoxicity were deemed the most relevant to the systems examined. They also complimented indicators selected for inclusion in the National Life Cycle Inventory (LCI) for agricultural products (Eady et al., 2014). For the GWP indicator, 100-year impacts were based on the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006). We used sensitivity analysis to test variation in our GWP and EP results from the locally adapted methods with the methods commonly used in other LCAs: CML 2 baseline 2000 and ReCiPe. The indicator for embodied energy, CED, is included in the Australian indicator set but not in CML or ReCiPe. It was included in this study given that crustacean fisheries are one of the most energy intensive. Total energy flows for CED were based on lower heating values. Marine aquatic ecotoxicity values were taken from Lundie et al. (2007) and updated in 2010 based on the consumer price index 2005/6. The measurement unit for this indicator was different to those used in other LCA methods and the results were therefore not comparable.

Australia is an arid continent so the water use indicator was included, noting it is less well developed than other indicators (Grant and Peters, 2008) and is simply an inventory of the total amount of water used. The normalisation factors for this indicator were taken from the Australian Bureau of Statistics (Australian Bureau of Statistics (2006)) and no distinction was made between types of water used (see for example Mekonnen and Hoekstra, 2012; Owens, 2001). All water use in this assessment refers to unspecified water of natural origin. Ozone layer depletion and photochemical oxidation (smog) indicators were not included, despite their common use in seafood LCAs conducted in the Northern Hemisphere. The use of ozone-depleting substances (ODS) is not significant in Australia, where most ODS emissions are from pre-existing sources such as old equipment or leaking landfills (Fraser et al., 2013), and smog incidents are rare (Grant and Peters, 2008). Prawns from the NPF are treated with a 1% sodium metabisulphite solution for the cosmetic discolouration 'black spot', however, the contribution of this preservative to ozone layer depletion in CML, per kilogram of prawn, is negligible. While ocean acidification is of relevance to seafood systems, it is caused by increased atmospheric $CO_2$ (Lough and Hobday, 2011) and is captured by the global warming indicator.

A number of LCA studies have presented fishery-specific impact categories, such as the global discard index (GDI) (Vázquez-Rowe et al., 2012b), the seafloor impact potential (SIP) (Nilsson and Ziegler, 2007), and primary productivity required (PPR), alongside conventional impact categories. Seafloor damage, bycatch and discards were excluded from the life cycle impact assessment but are discussed throughout this study. Primary production can limit global fisheries yield (Chassot et al., 2010) and PPR is an expression of the primary productivity consumed by an organism given its trophic level (TL). This indicator is not currently formalised into LCIA methods and is calculated by the equation (Pauly and Christensen, 1995).

$$\mathrm{PPR} = (\mathrm{catch}/9) \times 10^{(\mathrm{TL}-1)}$$

The PPR estimate is based on a ratio of 9:1 for the conversion of wet weight to carbon and 10% transfer efficiency per trophic level (TL). TL for prawns was taken from the Seas around us project (www.seasaroundus.org).

# 3. Results

## 3.1. *Banana prawns*

The global warming potential (GWP) of one kilogram of frozen whole white banana prawns for the supply chain examined was 7.2 kg $CO_2e$ (Table 1, Fig. 3). The fishing stage was the source of 63%, or 4.3 kg $CO_2e$ $kg^{-1}$ prawn of this GWP. About 60% of the emissions at capture were due to the operation of the trawl vessel engine which uses fuel for fishing and freezing. The use of a spotter plane made a negligible contribution to the GWP, as did on-board packaging and the antifoul used on the boats. Despite weighing in excess of 1000 kg per boat, the trawl gear of steel otter boards contributed only 0.03 kg $CO_2e$ $kg^{-1}$ prawn, due to their repeated use over time. The transport stage made little contribution to any indicator measured. GWP of transport was less than 4% or 0.3 kg $CO_2e$ $kg^{-1}$ prawn (Fig. 3), for either a journey of 2800 km by refrigerated truck from Far North Queensland to the south of the State, or a 1700 km journey on a mothership, followed by 1500 km from Cairns to Brisbane by refrigerated truck.

**Table 1**
Life cycle impact assessment results for 1 kg of frozen banana prawn (2009–2011).

| LCA stage | Process | Global warming potential (kg $CO_2e$) | Eutrophication potential (kg $PO_4e$) | Cumulative energy demand (MJ) | Water (L) | Marine aquatic ecotoxicity (day) |
|---|---|---|---|---|---|---|
| a. Capture | Fishing boat engine | 4.20 | 9.93E-03 | 61.42 | 0.47 | 1.84E-11 |
| | Aircraft engine | 2.61E-05 | 1.42E-08 | 3.93E-04 | 2.98E-06 | 1.19E-16 |
| | Packaging (cardboard) | 0.05 | 5.03E-05 | 0.92 | 1.61 | 3.18E-12 |
| | Antifoul | 1.49E-03 | 2.16E-05 | 0.03 | 0.08 | 4.51E-11 |
| | Gear | 0.03 | 1.74E-05 | 0.65 | 0.05 | 9.31E-13 |
| Sub total | | 4.29 | 0.01 | 63.03 | 2.20 | 6.76E-11 |
| b. Storage | Freezer | 1.43 | 8.00E-04 | 20.30 | 3.60 | 2.49E-10 |
| c. Processing | Water | 0.01 | 4.33E-06 | 0.14 | 15.91 | 9.68E-13 |
| | Electricity | 1.19 | 6.71E-04 | 16.98 | 2.97 | 2.08E-10 |
| Sub total | | 2.64 | 1.48E-03 | 37.41 | 22.47 | 4.58E-10 |
| d. Transport | truck/mothership | 0.27 | 1.27E-04 | 3.96 | 0.03 | 1.20E-12 |
| Total | | 7.20 | 0.01 | 104.40 | 24.71 | 5.27E-10 |

Fuel use by fishing vessels was the main source of cumulative energy use, and was closely aligned to the GWP, accounting for 60% of the CED indicator or 63 MJ $kg^{-1}$ prawn. Storage and processing together accounted for 37.41 MJ $kg^{-1}$ prawn. Fuel use was also the main contributor to the eutrophication potential indicator, accounting for 86% of EP or 0.01 kg $PO_4e$ $kg^{-1}$ prawn (Table 1, Fig. 3). Diesel fuel used on the fishing vessels contributed to eutrophication through the production of nitrogen oxides.

The processing stage accounted for the largest share of total water use, 76% or 16 L $kg^{-1}$ prawn. The fishing stage contributed less than 10% to water use, although the main source of water consumption for this stage was cardboard packaging. Processing and cold-storage together accounted for 87% of marine aquatic ecotoxicity, due to emissions from the use of coal-fired electricity in Queensland. Antifoul accounted for less than 10% of total ecotoxicity, however, at capture it was the source of 67% of the ecotoxicity.

The banana prawn has a trophic level (TL) of 3 and following the equation developed by Pauly and Christensen (1995) the PPR was calculated at 11.1 t C $kg^{-1}$ for landed banana prawns.

### 3.2. Tiger prawns

Tiger prawns required comparatively more fuel than banana prawns and therefore had much higher fuel use intensity (FUI) per kilogram. The GWP of the fuel used to catch tiger prawns was 7.6 times greater than banana prawns per kilogram, equating to almost 28 kg $CO_2e$ $kg^{-1}$ prawn (Table 2). The majority of tiger prawns are exported to Japan and the GWP for this transport stage was 13.6 kg $CO_2e$ $kg^{-1}$ prawn by airfreight or 0.33 kg $CO_2e$ $kg^{-1}$ prawn by sea freight, noting that most are shipped by sea. In contrast, the footprint of 1 kg of banana prawn sold in Australia was 0.019 kg $CO_2e$ $kg^{-1}$ prawn for transport of 100 km or 0.77 kg $CO_2e$ $kg^{-1}$ prawn for transport of 4000 km by refrigerated truck to retail.

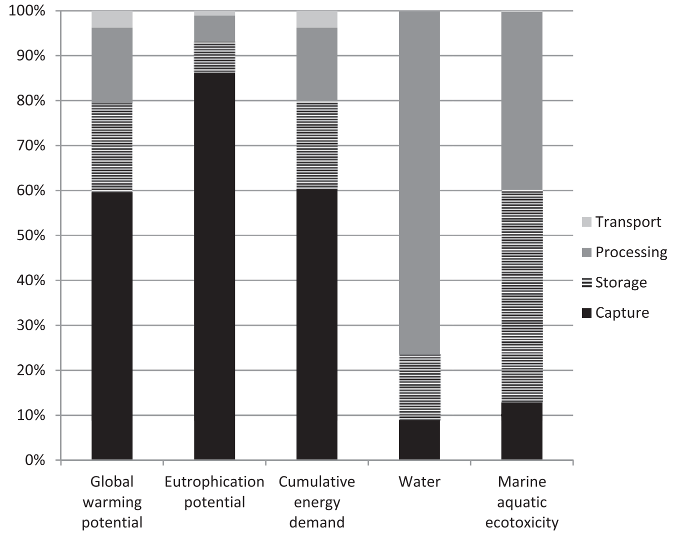

**Fig. 3.** Life cycle impact assessment of 1 kg banana prawn (2009–2011).

### 3.3. Sensitivity and scenario analyses

Sensitivity of results to choice of impact assessment method was small. For climate impacts under the GWP indicator, results differed by less than 0.1 kg $CO_2e$ $kg^{-1}$ prawn between different methods. Results for EP were identical using the Australian indicator set or CML, as EP was quantified according to the Centre for Environmental Studies (CML) 2 Baseline 2000 method (CML, 2001). The ReCiPe method used a different unit of measurement (kg N equivalent) and was therefore not comparable.

Increasing catch through scenario analysis resulted in potential improvements across most indicators, including EP, GWP and CED, as a result of improved FUI. Decreased catch, in contrast, resulted in potentially higher emissions and energy use (Table 3) per kilogram of prawn. Under these scenarios the capture stage remained the main source of impacts for the supply chain modelled. Ecotoxicity and water use were not sensitive to changes in catch rates as they were predominantly influenced by processing.

## 4. Discussion

The supply of prawns to domestic and international markets is responsible for a range of impacts, including GHG emissions, resource use, eutrophication and ecotoxicity that are not currently considered at a fisheries or supply chain level, yet have the potential to impact the fishery and the environment more broadly.

### 4.1. Broadening the scope of seafood sustainability assessments

In terms of resource use, trawl fishing gear is routinely more energy intensive than other gear types (Tyedmers, 2004) and fuel use in prawn trawling in particular is typically greater than in other fisheries (Smith, 2007; Tyedmers et al., 2005). The cumulative energy demand of banana prawns and associated carbon footprint,

**Table 2**
Fuel use intensity and carbon emissions for 1 kg banana and tiger prawn (2009–2011).

|  | Fuel use intensity (l/kg) | Carbon footprint (kg $CO_2e$) from fuel use at fishing | Main retail destination | Distance from processor to retail (km) | Carbon footprint (kg $CO_2e$) from fuel use in transport |
|---|---|---|---|---|---|
| Banana prawn | 1.3 ± 0.3 | 4.2 | Australia | a. 100<br>b. 4000 | a. 0.02<br>b. 0.77 |
| Tiger prawn | 9.9 ± 0.5 | 32 | Japan | 8200 (sea freight)<br>7800 (air freight) | 0.33<br>13.6 |

based on kilograms of $CO_2$ equivalent emissions, is lower than that of tiger prawns from the same fishery, in part due to the aggregations that banana prawns form, which make them easier and more efficient to target. Fishing for tiger prawns is more fuel intensive as they are more dispersed and do not congregate in boils, requiring boats to trawl longer hours for lower catch. The GWP of tiger prawns in the NPF is similar to that of trawl caught pink shrimp, 29 kg $CO_2e$ $kg^{-1}$ shrimp (Ziegler et al., 2011). Aggregating behaviour is rare in penaeids but, in species in which it does occur, is strongest at high stock levels (Die and Ellis, 1999). The GWP of the banana prawn fishery is therefore strongly linked to fishery management and allowing stock abundance to fall may reduce catchability and increase GHG emissions through reduced fuel efficiency.

Fishery management, in the form of capacity reduction programmes over the past decade, has led to decreased fuel use by boats in the NPF (Pascoe et al., 2012), and presumably reduced GHG emissions although these have not been monitored over time. Fuel use intensity (FUI) has fallen from 3 L $kg^{-1}$ for banana prawns in 2006 to 1.5 L $kg^{-1}$ in 2010 and from almost 11 L $kg^{-1}$ for tiger prawns in 2006 to around 7 L $kg^{-1}$ in 2010 (ABARES, 2011). This reduction is attributable to changes in fishery management as well as technological and behavioural changes in fishing businesses, which were driven by external forces such as the increasing cost of fuel. Monitoring GWP relative to catch into the future may be valuable. For example, recent attempts to adjust exploitation levels in this fishery to maximum economic yield, in response to negative changes in economic conditions and the expected trajectory for the fishery (Pascoe et al., 2013), has the potential to further improve FUI and reduce GWP (Farmery et al., 2014).

Seafood LCA studies that include the processing stage of the life cycle are limited (Vázquez-Rowe et al., 2012a). Processing can constitute a key contributor to the potential environmental impacts for seafood products, particularly for more complex processing including canning (Iribarren et al., 2010; Thrane et al., 2009) and packaging in stand-up pouches (Mungkung et al., 2006). Our results were consistent with a Danish study where processing of frozen prawns represented a relatively small overall impact, yet consumed large amounts of water in comparison to other stages (Thrane, 2004). Water use for banana prawn at the processor gate was 25 L $kg^{-1}$ whole prawn, equating to 45 L $kg^{-1}$ prawn meat (assuming a 55% recovery rate). This figure is comparable with other Australian seafood, 71 L $kg^{-1}$ of lobster meat (Farmery et al., 2014) and 61 L $kg^{-1}$ of mixed fish meat (Farmery, in prep). Water use indicators are rarely included in LCAs of food products (Koehler, 2008) despite the high water-intensity of animal products (Pimentel et al., 2004). Water use for seafood production is low in the context of food production, for example in comparison to global average beef production at 15 415 L $kg^{-1}$ (Mekonnen and Hoekstra, 2012), which may be an important consideration given that water availability is likely to limit future food production (Hanjra and Qureshi, 2010), particularly in arid countries like Australia.

**Table 3**
Modelled changes in emissions and energy use per kilogram frozen prawn as a result of potential changes in annual catch in the NPF.

| Scenario | Resulting change in impacts (%) | | | | |
|---|---|---|---|---|---|
| | GWP | EP | CED | Water | Ecotox |
| 10% catch increase | −5 | −7 | −5 | 0 | 0 |
| 10% catch decrease | 7 | 9 | 7 | 0 | 0 |

Processing of banana prawns was also the source of GHG emissions and ecotoxicity impacts. In this study, the provision of coal powered electricity for cold-storage and processing was a greater source of aquatic toxicity than fishing. Previously, ecotoxicity in seafood LCAs has been associated with the use of antifoul (Ziegler et al., 2011) and burning of diesel fuel on fishing boats (Vázquez-Rowe et al., 2010). Most processing involving product transformation of prawns from the NPF occurs outside Australia and the environmental footprint of banana prawns consumed in Australia is therefore dependent on the type of processing undertaken and the mode of transport used if processed off-shore. Airfreight was shown in this study to dramatically increase the GWP of tiger prawns exported to Japan, which is consistent with other LCA studies (Andersen, 2002; Farmery et al., 2014; Winther et al., 2009).

Primary Productivity Required (PPR) is increasingly used in assessments of seafood sustainability, where it serves as a measure of biological resource use from aquaculture or fisheries (Hornborg et al., 2013). This is of importance for some specific fisheries where the rate of biomass removal, in terms of PPR, exceeds the limits required for long-term sustainable marine ecosystem production (Coll et al., 2008). Banana prawns have a relatively low trophic level and therefore appropriate less primary productivity per kilogram than other commercially caught seafood eaten in Australia, including Gould's squid (*Nototodarus gouldi*) TL = 3.5 PPR = 35.1 t C $kg^{-1}$, yellowfin tuna (*Thunnus albacares*) TL = 4.34 PPR = 243.1 t C $kg^{-1}$, and tiger flathead (*Neoplatycephalus richardsoni*) TL = 3.9 PPR = 88.3 t C $kg^{-1}$. Lower PPR values are associated with lower ecosystem costs, however, further research is needed to progress this indicator and standardise its use for quantifying ecosystem effects of fishing (Avadí and Fréon, 2013).

Refrigerant leakage increases the GWP of seafood between 13 and 20% (Iribarren et al., 2011; Vázquez-Rowe et al., 2010, 2012c) and reducing such leakage therefore presents the potential to reduce GWP in many fisheries. Data on refrigerant leakage across the NPF supply chain was not available, however, prawns are rapidly frozen at sea on fishing vessels and stored at −35 °C, sometimes for weeks before unloading. R22 is the most commonly used refrigerant in the NPF, on fishing trawlers, in processing factories and in cold-storage facilities (NPF Industry, 2014). This refrigerant has a climate impact indicator of 1810 kg $CO_2e$ $kg^{-1}$ (IPCC, 2007) and is currently being phased out in Australia. Fishers are therefore looking to new concepts in refrigeration in existing boats and new trawler designs. A recent report on refrigeration technology options for the Northern Prawn Fishery fleet reported that HFC 507A was the only gas suitable to replace R22 (Expert Group, 2013). While this replacement gas does not deplete ozone, it has a much higher GWP of 3985 kg $CO_2e$ $kg^{-1}$ (The Climate Registry, 2014). The GWP of prawns from the NPF will likely increase following the transition of the NPF trawlers and associated cold-chain from R22 to HFC 507A, assuming all other factors remain the same. The contribution of HFC to climate change has been recognised as an unintended negative side effect of actions to limit ozone depletion (Velders et al., 2012).

### *4.2. Integrating new LCA indicators with current sustainability assessments*

The NPF was one of the first Australian fisheries to assess the ecological sustainability of its supporting ecosystem through ecological risk assessment (Zhou and Griffiths, 2008), the same framework that underpins MSC certification (Hobday et al., 2011). The fishery is managed to meet the goal of Ecologically Sustainable Development (ESD) and has been accredited under the EPBC Act 1999 as environmentally sustainable (FRDC, 2012). It has also been recognized by the United Nations FAO as a global model for fisheries management (Gillett, 2008) and has recently received independent third-party accreditation under the Marine Stewardship Council's Certification program for banana and tiger prawns (Pascoe et al., 2013). The fishery was assessed against the MSC standard which is based on three over-arching principles; viability of the target stock, impact on the ecosystem and management of the fishery. The NPF is one of only eight prawn fisheries worldwide that have attained the MSC global standard by meeting the internationally-recognised environmental standards (MSC, 2012).

Prawn trawling, particularly in tropical regions, is responsible for some of the highest rates of bycatch and discards recorded in wild capture fisheries (Dumont and D'Incao, 2011; Eayrs, 2007; Stobutzki et al., 2001). Several LCA studies have included biological indicators to quantify these impacts (for details of published fisheries LCAs using these indicators see Avadí and Fréon, 2013; Vázquez-Rowe et al., 2012a), however, the indicators are yet to be standardised. Results are typically presented as kg per FU (Vázquez-Rowe et al., 2010; Ziegler et al., 2011) and efforts continue to progress this type of indicator in order to better understand the specific environmental impacts (Vázquez-Rowe et al., 2012b). Bycatch in Australia has been estimated at 25% of total catch of trawl fisheries (Davies et al., 2009). Bycatch varies greatly between banana and tiger prawns in the NPF, as banana prawns have a higher mean bycatch catch rate but lower total bycatch than the longer duration trawls of the tiger prawn fishery (Dell et al., 2009; Zhou and Griffiths, 2008). Bycatch in the NPF comprises between 87.5% and 95.2% of the total catch of the fishery (Brewer et al., 2006; Pender et al., 1992), most of which is returned to the sea either dead or dying (Brewer et al., 2007; Pender et al., 1992). Spatial variation in the fishery has been recorded with a bycatch-to-prawn ratio of 0.8:1 in the Joseph Bonaparte Gulf region of the NPF (Dell et al., 2009) and 5:1 in the Gulf of Carpentaria region (Tonks et al., 2008). Bycatch in the Southern Pink Shrimp fishery in Senegal was similarly high, with fish representing 88% of landings by mass and 77% of bycatch discarded (Ziegler et al., 2011). In contrast, discards represented only 3.9% in the Peruvian anchoveta small- and medium-scale fishery (Avadí et al., 2014).

Management actions in the NPF, including compulsory use of a specific suite of Turtle Excluder Devices (TEDs) and Bycatch Reduction Devices (BRDs), have reduced the fishery's impact on bycatch (Brewer et al., 2006; Burke et al., 2012; Heales et al., 2008). An Ecological Risk Assessment with management arrangements for bycatch species and a bycatch and discard action plan has also been implemented in the fishery (Barwick, 2011). The inclusion of a bycatch or discard indicator, such as the GDI proposed by Vázquez-Rowe et al. (2012b), in future fishery LCAs could help evaluate the effectiveness of such plans and management changes. Possibly the most significant management change in the fishery that has affected bycatch has been the reduction in effort and fleet size, from over 300 vessels to the current fleet of 52 (Barwick, 2011).

The use of bottom-trawl gear in fisheries disturbs seabeds, potentially leading to substantial changes in benthic community structure and habitat (Althaus et al., 2009; Collie et al., 2000; Gislason et al., 2000; Kaiser et al., 2006; Williams et al., 2010). Much of the research in this field has taken place in the northern hemisphere where the impacts have often been substantial (Heath and Speirs, 2012; Thrush and Dayton, 2002). The results of such studies have strongly influenced the perceptions of trawl fishery impacts (Dichmont et al., 2013) and resulted in actions such as the proposed phase-out of deep-sea bottom trawling and bottom gillnet fishing by the European Commission (PEW, 2013). Trawling in tropical and subtropical regions of Australia has local and specific impacts, particularly where fishing grounds overlap with vulnerable biota (Pitcher et al., 2009; Svane et al., 2009; Williams et al., 2010). Substantial variation exists in seafloor impacts by trawling, however, and Burridge et al. (2006) found that trawling in Northern Australia did not have a major impact on the demersal fauna. Other authors have shown that trawling is benign on habitats where the benthos is resistant to trawling (van Denderen et al., 2013), or even beneficial to the fishery, where it may increase production of some fish species (Rijnsdorp and van Leeuwen, 1996; van Denderen et al., 2013).

An indicator of seafloor impact potential (SIP) proposed by Nilsson and Ziegler (2007) has been trialled in LCA to measure the amount of seafloor dragged by trawlers and other gear, noting that the SIP for other fishing methods typically amounts to zero (Vázquez-Rowe et al., 2012b; Ziegler et al., 2003). The swept seabed area is calculated by multiplying trawl effort by area swept per hour and results are typically presented as $km^2$ per FU (Vázquez-Rowe et al., 2012b, 2012c; Ziegler et al., 2011). Results are more meaningful however when overlayed with habitat maps to determine fishing pressure in sensitive habitats and recoverability potential, and when concentration of fishing effort is calculated to determine actual area affected by trawling, as described by Nilsson and Ziegler (2007). In the NPF, fishing takes place in depths shallower than 40 m and it is estimated that less than 10% of the total area is trawled (Zhou and Griffiths, 2008). 2.1% of the total area is never trawled due to permanent area closures, including all shallow water seagrass. Areas that are unsuitable for trawling, such as large reef outcrops and areas with low density of the target prawn species, are also not trawled (AFMA, 2013). Of the area that is trawled, some is reportedly unconsolidated sediments that are resilient to perturbation by trawl gear. While the impacts of sparse and infrequent trawl effort are not currently considered a threat to biodiversity in the NPF (Pitcher et al., 2009), the correlation between fishing effort and potential effect on seafloor (Vázquez-Rowe et al., 2012b) suggest that alteration of current gear configurations and fishing intensity could result in greater impacts. The SIP indicator could therefore be used in future LCAs of the NPF to track these types of changes.

## 5. Conclusions

Expanding the scope of environmental considerations in the NPF, by incorporating standardised and emerging life cycle indicators, could enhance current assessments of seafood sustainability and allow improvements in the fishery and other supply chain stages to be monitored though time. Reductions in impacts assessed through LCA may complement the achievement of other management targets, as illustrated by the indirect reduction in GHG emissions that have been occurring as a result of improved efficiency in the fishery. In cases where management actions and GHG emissions do not move together, where there are fuel subsidies for example, life cycle indicators are needed to capture the tradeoffs. NPF stakeholders across the supply chain stand to benefit from the demonstration of targeting broader sustainability goals, through an advantage in a market where consumers are increasingly aware of, and willing to pay for sustainability (Macfadyen and Huntington, 2007). Furthermore, the inclusion of important LCA indicators, such as GWP, as an integral part of existing fishery assessments, is a strategic move in adapting to an increasingly carbon-regulated world.

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