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Life cycle environmental impacts of Spanish tuna fisheries

Almudena Hospido[a,*], Peter Tyedmers[b,1]

[a] Chemical Engineering Department, Institute of Technology, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain

[b] School for Resource and Environmental Studies (SRES), Faculty of Management, Dalhousie University, Halifax, NS, Canada

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Abstract

The environmental impacts of fishing go well beyond their direct effect on targeted stocks and associated ecosystem components and functions. Here we employ life cycle assessment (LCA) to quantify the scale and importance of emissions that result from the range of industrial activities associated with contemporary Spanish purse seine fisheries for Skipjack (*Katsuwonus pelamis*) and Yellowfin (*Thunnus albacares*) tunas. Our analysis encompassed operational inputs to fishing activities along with major inputs to vessel construction and maintenance and post-harvest transport of carcasses to ports in Galicia, Spain. Data were acquired from fishing operations based in each of the Atlantic, Indian and Pacific Oceans, permitting the characterization of both average and basin of origin-specific environmental impacts. Our results indicate that the production and use of diesel fuel while fishing accounts for more than half of the total impacts in six of the seven impact categories analyzed. After fuel inputs, post-harvest transport of carcasses made substantial contributions to each of the environmental dimensions evaluated. In contrast, the use of anti-fouling paint only made a substantial contribution to marine eco-toxicity potential. Comparing the performance of fisheries in the three oceans, Pacific-based operations resulted in the highest emissions across all impact categories modelled. This was largely the result of markedly higher fuel consumption rates together with relatively long post-harvest transport distances. Finally, we modelled two scenarios to quantify the environmental benefits associated with improving tuna abundance and availability. In doing so, we found that efforts to rebuild stocks, particularly in the Atlantic Ocean would not only help reverse the decline of aquatic ecosystems but could result in improvements in the environmental performance of the Spanish tuna fishery.

Keywords: Environment impacts; Life cycle assessment; LCA; Purse seine; Tuna fishery

1. Introduction

1.1. The environmental impacts of fishing

Fishing is the last major food producing activity that relies almost entirely on the extraction of organisms from essentially wild ecosystems. Consequently,

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[*] Corresponding author. Tel.: +34 981563100x16020; fax: 34 981547168.

E-mail addresses: ahospido@usc.es (A. Hospido), peter.tyedmers@dal.ca (P. Tyedmers).

[1] Tel.: +1 902 494 6517; fax: +1 902 494 3728.

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most concern regarding the environmental impacts of fishing has traditionally focused on its direct impacts on targeted stocks (Pauly et al., 2002; Christensen et al., 2003; Myers and Worm, 2003), incidentally caught and often discarded organisms (Alverson et al., 1994; Glass, 2000), physical damage to benthic communities and substrates (Johnson, 2002; Chuenpagdee et al., 2003) and the general alteration of ecosystem structure and function (Jackson et al., 2001). While this focus on largely proximate biological concerns is understandable given the degraded state of many fish populations and aquatic ecosystems, it is essentially myopic as it effectively overlooks the diverse range of environmental impacts that flow from the interlinked series of industrial activities that characterize most modern fishing systems. These include, but are not limited to the impacts associated with the material and energy dissipated in the construction and maintenance of fishing vessels (Watanabe and Okubo, 1989; Hayman et al., 2000), the provision of fishing gear (Ziegler et al., 2003), the combustion of fuel while fishing (Ziegler and Hansson, 2003; Thrane, 2004a; Tyedmers, 2004) and transporting catch to markets or for further processing (Karlsen and Angelfoos, 2000; Andersen, 2002), and the discharge of wastes and loss of fishing gear at sea (Derraik, 2002).

One way to systematically describe and quantify the range of environmental impacts associated with the industrial aspects of fishing is through the use of life cycle assessment (LCA). LCA is a standardized, structured method for calculating a product's, process' or activity's environmental load throughout all its phases, from the extraction of raw materials through production, distribution, use and, where appropriate, recycling and treatment of waste (Consoli, 1993). While originally designed to evaluate the life cycle impacts associated with manufactured products, LCA is increasingly being applied to food production systems (Mattsson and Sonesson, 2003). Within the food sector, it has been used to both compare the environmental performance of competing products, processes, or scales of activities (Andersson and Ohlsson, 1999; Haas et al., 2001), and to identify specific activities or subsystems that contribute most to the total environmental impact of a foodstuff (Andersson et al., 1998; Hospido et al., 2003). To date, LCA has been used to evaluate relatively few fisheries or seafood products (Ziegler et al., 2003; Thrane, 2004b). While the number of fisheries evaluated has been small, a finding common to all is that the fish harvesting stage of the production cycle typically accounts for between 70 and 95% total impacts regardless of the impact category considered.

Here we evaluate the life cycle environmental impacts that result from the industrial processes associated with contemporary Spanish purse seine fisheries for Skipjack (*Katsuwonus pelamis*) and Yellowfin tuna (*Thunnus albacares*) undertaken in each of the Atlantic, Pacific and Indian Oceans. As these highly valuable species are processed into a variety of forms and consumed in countless markets, in order to provide a standard basis of comparison, we characterize impacts up to the point at which frozen carcasses are delivered to ports in Galicia, NW Spain. While the primary purpose of this work is to illustrate the scale of impacts associated with contemporary Spanish tuna fishing operations and contrast potential differences arising from operations undertaken in different oceans, we have a second equally important rationale; identifying opportunities to improve the environmental performance of these fisheries. To this end, we pinpoint those subactivities that contribute most to the overall impacts to focus attention on where future efforts to improve performance could have greatest effect. As an illustration, we explore the potential emission reduction benefits to be gained from efforts to rebuild tuna stocks through the use of two modelled scenarios. Taken together, this research should be of particular value to fisheries managers, LCA practitioners, those organizations and individuals with an interest in the environmental costs associated with providing this important food and, of course, fishing company owners who are not only in the best position to effect change but are likely to face increased costs in the future as a result of the environmental impacts of their activities.

1.2. The Spanish fishery for Skipjack and Yellowfin tuna

Skipjack and Yellowfin tuna are, respectively, mid- and large-sized members of the Scombridae family. Both are relatively abundant and widely distributed in tropical and subtropical marine waters where they often form large mono-specific and multi-species schools, frequently in association with floating debris (Scott et al., 1999; Girard et al., 2004). In the eastern tropical Pacific, schools of large Yellowfin tuna are often associated with dolphin, giving rise to one of the more infamous examples of by-catch and incidental mortality of marine mammals as a result of fishing activities (Lo and Smith, 1986). Driven by consumer pressure and trade sanctions, dolphin by-catch and mortality rates have been greatly reduced but not entirely eliminated within this fishery (Archer et al., 2004). While this issue remains a fisheries management concern in the eastern tropical Pacific, it is explicitly excluded from this analysis reflecting both the certified "dolphin-friendly" nature of the fishing operations analyzed here and the more general difficulty incorporating biodiversity impacts within the LCA methodology (Haas et al., 2001).

Globally, catches of Skipjack and Yellowfin tuna together represent over 70% of total tuna landings. Of the nearly 100 countries that regularly report catches of these two species, Spain consistently ranks among the top five, accounting for approximately 7% of the total aggregate catch, based on annual landings that routinely exceed 200,000 tonnes (FAO, 2004). Not surprisingly, Spanish catches of Skipjack and Yellowfin traditionally came from Atlantic waters with smaller quantities taken in the Pacific (Fig. 1). Beginning in the mid-1980s, however, Spanish vessels began pursuing Skipjack and Yellowfin in the Indian Ocean. Landings from these operations increased rapidly to the point that they now represent approximately two thirds of Spain's total catch of these species (Fig. 1). Spanish, along with other European tuna fishing efforts are likely to continue to expand in the Indian Ocean as it is believed that almost 70% of the world's remaining tuna biomass is located here (DGF, 2004).

Regardless of where they are taken, virtually all Spanish tuna catches are shipped home, mostly to ports in Galicia, for processing and distribution. Within its borders, Galician-based tuna fishing and processing activities are some of the largest and most valuable fisheries industries in Spain (Department of Maritime Affairs and Fisheries, 2001).

From a technological perspective, while a diverse range of fishing gears is used to capture tunas, purse seining accounts for the majority of landings globally. In 2003, fully 60% of all tunas, and 70% of all Skipjack and Yellowfin landed globally were caught by purse seiners (FAO, 2005).

2. Materials and methods

2.1. LCA: definition and stages

Through the efforts of the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO), formal life cycle assessments have been methodologically standardized into a four step process (ISO, 2000):

- *Step 1. Goal and scope definition*. In which the functional unit of the analysis, essentially the basis upon

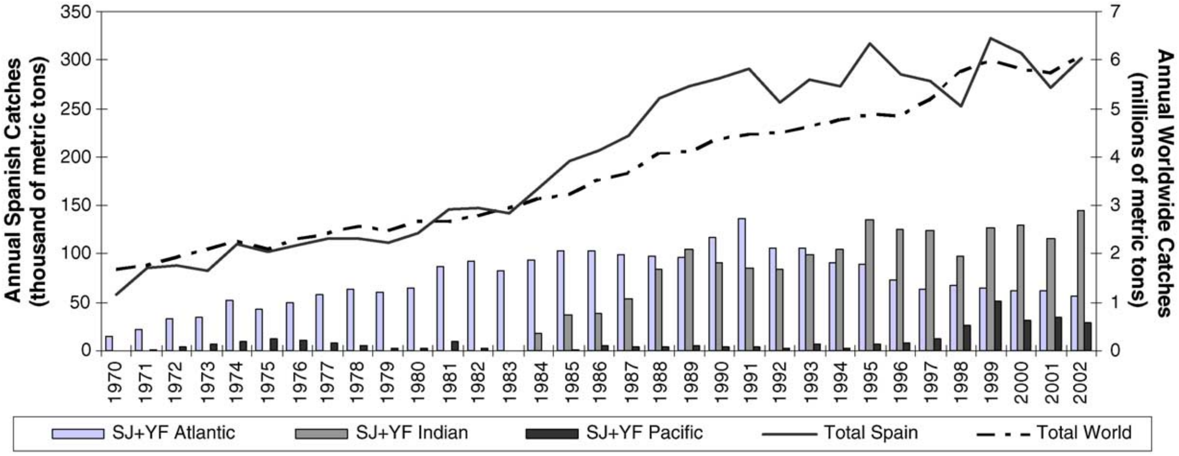

Fig. 1. History of annual Spanish and Worldwide tuna catches, 1970–2002. *Source*: FAO (2004).

which impacts are quantified and compared, is first defined, and then the boundaries of the system to be analyzed and the environmental impact categories of concern are determined.

In our analysis, the functional unit selected is 1 tonne of frozen unprocessed tuna, while its boundaries encompass all major industrial activities required to catch and deliver frozen tuna carcasses to the dockside in Galician ports (Fig. 2). More specifically, we analyzed major operational inputs and outputs associated with both fishing activities undertaken by Spanish purse seiners in each of the Atlantic, Pacific and Indian Oceans and post-harvest transportation activities. In addition, our analysis encompassed three pre-harvest activities namely vessel construction, diesel fuel production, and the manufacture of anti-fouling paint used on fishing vessels to reduce drag.

Methodologically, a problem-oriented (midpoint) approach was adopted and following the recommendations of Guinèe et al. (2001), seven environmental impact categories, namely global warming potential (GWP), stratospheric ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photo-oxidant formation potential (POFP), and finally human toxicity and marine aquatic eco-toxicity potentials (HTP and MTP, respectively), were chosen to quantify the environmental impacts associated with the activities under consideration.

- *Step 2. Inventory analysis*. This time-consuming step involves the compilation and quantification, to the extent that is practicable, of relevant inputs and outputs associated with the activities within the system boundaries, including the use of resources and emissions to air, water and soil. Details of the inventory analysis data collection steps undertaken appear in Section 2.2.
- *Step 3. Impact assessment*. To understand and evaluate the magnitude and significance of the resulting environmental impacts, raw resource inputs and emissions associated with the provision of the functional unit are classified and converted into standardized indicators based on standardized characterization factors; e.g. all greenhouse gases are expressed in terms of CO_2 equivalents (Goedkoop and Oele, 2003b). A further optional step, but one undertaken here, entails the re-expression of the scale of impacts based on their proportional contribution to a given region's or global resource consumption or emission rates (ISO, 2000). This step, typically referred to as the normalization of impacts stage, is particularly useful in highlighting the most serious environmental dimensions of the activity under study. Here, normalization scores were based on global resource consumption and emission rates for 1995 as this was the most recent complete list of global data available (Huijbregts et al., 2003). While all impact assessment computations, including the normalization of results,

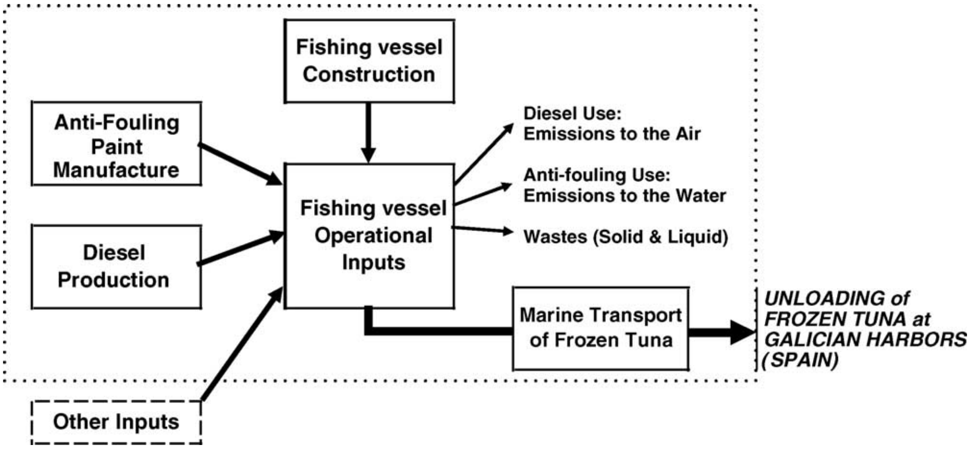

Fig. 2. Block diagram of the system studied. Dotted line represents the system boundaries.

can be undertaken manually, the process is greatly facilitated with the use of dedicated LCA software. In this analysis, we used PRé Consultants' SimaPro 5.1, LCA software (Goedkoop and Oele, 2002).

- *Step 4. Interpretation*. This phase entails the analysis and reporting of results, limitations and implications of the research. In order to more fully explore the latter, we modelled two hypothetical scenarios derived from the base case analysis to assess the potential environmental impacts that could result from changes in how easily and where tuna are caught by Spanish vessels. Specific details regarding the scenarios modelled appear in Section 2.3. As LCAs typically draw upon diverse data sources of variable quality, we undertook sensitivity analyses to explore the impact of changes in input parameters. Results of two of these sensitivity analyses are included.

2.2. Data acquisition

2.2.1. Operational inputs to fishing

Prior LCA and similar analyses of fishing systems have found that direct operational inputs, and in particular fuel consumption, generally dominate the energetic and environmental performance of seafood production (Edwardson, 1976; Watanabe and Okubo, 1989; Ziegler et al., 2003; Thrane, 2004a; Tyedmers, 2004). Consequently, care was taken to acquire detailed, broadly representative data regarding the inputs and outputs associated with contemporary Spanish purse seine operations in each of the Atlantic, Pacific and Indian Oceans. To this end, three Galician tuna fishing companies were surveyed. Vessel-specific data requested included the number and identity of purse seine vessels engaged in tuna fishing, together with their overall length, gross registered tonnage, propulsive engine power and base of operations in 2003. For each vessel, operational data requested included the type, quality and amount of diesel fuel burned, days at sea, crew size, and the quantity, type and application frequency of anti-fouling paint used. Finally, resulting species-specific annual catch data were requested for each vessel.

2.2.2. Vessel construction

As material and energy inputs to vessel construction and maintenance have previously been found to make relatively small contributions to the environmental impacts of seafood products (Hayman et al., 2000; Huse et al., 2002), we restricted our analysis to quantifying only those impacts associated with providing the steel used in vessel hulls, superstructures and engines. In this regard, data were solicited from the technical manager of a Spanish shipyard (Mr. Pedro Lopez, Shipyard Barreras, September 2004, pers. commun.) and two manufacturers of marine diesel engines (Caterpillar, 2004; Wärtsilä, 2003). Following Tyedmers (2000), the amount of steel required to build each vessel was increased by 25% for the hull and 50% for the engines to account for additional inputs required for repairs and maintenance over the life of the vessel. Total mass of steel inputs per vessel were re-expressed on the basis of an average tonne of tuna caught by assuming a functional working life for the hull and engine of 30 and 10 years, respectively (Tyedmers, 2000), and an average annual catch equivalent to 2003 landings. As prior analyses have found that the provision of fishing gear typically makes a smaller contribution to the overall material and energy profile of a fishery when compared with inputs to vessel construction (Rawitscher and Mayer, 1977; Tyedmers, 2000; Ziegler et al., 2003; Tyedmers, 2004), particularly within the context of purse seine fisheries (Tyedmers, 2000), we have excluded it from this analysis.

2.2.3. Quantifying un-monitored emissions

While actual fuel consumption data were solicited from fishing companies, resulting emissions of exhaust gases had to be calculated. This was done using emission factors derived from a study of 40 vessels of various sizes, operating under real-world conditions (Engineering Services Group, 1995). Although none of the vessels monitored in this prior study were fishing boats (vessels monitored included container ships, tugs, Ro-Ro ferries, dredges, bulk carriers and tankers), given the diverse range of operations represented and the current lack of published emission data derived from the monitoring of fishing vessels of any kind operating under real-world conditions, we believe that these values provide a reasonable first approximation of reality.

Life cycle inputs and outputs associated with the extraction, production and distribution of diesel fuel were taken from SimaPro (Table 1). In order to quan-

Table 1
Sources, period and geographical origin of data for the LCA

Element	Database[a]	Period	Geographic area
Fuels			
Diesel oil B	BUWAL 300	1990–1994	Europe, Western
Heavy oil	BUWAL 300	1990–1994	Europe, Western
Raw materials for vessel building			
Steel	IDEMAT 2001	1995–1999	Europe, Western
Iron	IDEMAT 2001	1995–1999	Europe, Western
Anti-fouling ingredients			
Dicopper oxide	Not available	–	–
Zinc oxide	Not available	–	–
Xylene	PRe 4 database	1990–1994	Europe, Western
Ethyl benzene	PRe 4 database	1985–1999	Europe, Western
Sea nine 211	Not available	–	–
Energy			
Electricity	BUWAL 250	1990–1994	Europe, Western
Thermal	BUWAL 250	1990–1994	Europe, Western

[a] Consult literature references at SimaPro 5.1.

tify the amount of anti-fouling paint lost to the marine environment, a typical loss rate of two-thirds of that applied was employed (Mr. Martin Porsbjerg, Hempel, August 2004, pers. commun.). Data regarding the material and energy consumption and resulting emissions associated with the production of anti-fouling paints were obtained from a leading manufacturer, Hempel A/S (Hempel, 2004).

In the normal course of life on board ship, crew members generate solid and liquid wastes. Quantities of solid wastes generated and later delivered to land for disposal were estimated at 2.5 kg per crewmember per day (Mr. Aage Heie, Interconsult Norsas, July 2004, pers. commun.). Discharges of organic matter to the sea were calculated based on the typical amount of wastewater generated per inhabitant-equivalent (Ronzano and Dapena, 2002) and the standard removal rate for biological filters (García, 2000).

In all other situations in which no direct data were available, the databases available with SimaPro 5.1 (Goedkoop and Oele, 2003a) were used to complete the inventory (Table 1).

2.2.4. *Operational inputs to marine transport*

As the fishing activities analyzed span the globe, and the basis of comparison is a tonne of frozen tuna delivered to the dockside in Galicia, it was necessary to account for major operational inputs and emissions associated with the trans-shipment of frozen carcasses.

To this end, the shortest maritime route between each fishing vessel's base of operations and the final destination harbours in Galicia (A. Coruña, La Puebla, among others) was quantified using Dataloy's online shipping mileage calculator (Dataloy, 2000). Associated fuel consumption and resulting emissions were estimated from a real-world analysis of Norwegian frozen fish transport systems (Karlsen and Angelfoos, 2000).

2.3. *Scenario modelling*

In addition to characterizing the environmental performance of contemporary Spanish tuna fishing activities (Scenario 0), we modelled two scenarios to quantify the secondary environmental benefits that could result from improvements in tuna abundance and availability. The first scenario modelled (Sc 1) reflects a situation in which the fuel use intensity of fishing operations, essentially the amount of fuel burned per tonne of fish landed, in two of the three oceans is decreased to the level of the most productive fishery in 2003 (i.e. in the third ocean) while keeping all other aspects of Spanish tuna fishing activities in 2003, including the distribution of harvests, constant. The second scenario modelled (Sc 2) builds on the first in which all tuna are caught using relatively low fuel inputs but reflects a situation, similar to that of the early 1980s, in which all Spanish catches of Skipjack and Yellowfin are caught exclusively from the Atlantic Ocean (Fig. 1).

3. Results

3.1. Inputs to fishing

Of the three companies contacted, two provided the complete range of data requested. In 2003, these two companies operated a total of nine purse seiners that targeted Skipjack and Yellowfin tuna, three in each of the Atlantic, Pacific and Indian Oceans. Together, these vessels landed a total of 78,000 tonnes of these two species, representing fully 25% of total Spanish, and nearly 2% of global tuna landings in 2003 (FAO, 2005). In the process of doing so, the nine boats burned just over 34 million litres of low sulphur (maximum 0.2% S) diesel fuel for an average fuel use intensity of 436 l/tonne (Table 2). Interestingly, average fuel use inputs ranged widely between fishing operations. Vessels based in the Indian Ocean burned an average of 373 l/tonne (S.D. 31) of tuna landed while vessels operating in the Atlantic and Pacific Oceans averaged 442 l/tonne (S.D. 80) and 527 l/tonne (S.D. 43), respectively (Table 2). Both companies painted their vessels every second year with tin-free anti-fouling paint containing two active ingredients, dicopper oxide (Cu_2O) and sea-nine 211 (4,5-dichloro-2-*n*-octyl-4-isothiazolin-3-one). Across all vessels, an average of just under 0.1 l of paint was applied per tonne of tuna landed resulting in emissions of 0.06 l of paint to the marine environment per tonne of tuna (Table 2). This rate of paint loss to the environment is generally consistent with that reported by Thrane (2004b) for Danish fisheries.

Steel inputs vary with vessel size. As a result, the three boats operating in the Pacific Ocean, with an average length of just over 80 m, not only embodied the greatest mass of steel in their hulls, superstructure and engines but because of their proportionally smaller catches in 2003, also had the highest estimated inputs of steel per tonne of tuna landed at 8.7 kg (Table 2). Minimum post-harvest transport distances ranged from 4538 km in the case of tuna caught in the Atlantic Ocean to 9165 and 10,140 km in the case of fish caught in the Pacific and Indian Oceans, respectively.

3.2. Life cycle impact assessment

Fig. 3 presents the relative contribution that various fishing-related activities make to the seven impact categories of interest. In the case of all but one of the impact categories analyzed (marine toxicity potential), the production and/or use of diesel fuel accounts for more than half of the total impact (ranging between 54 and 74%).

Table 2
Summary of inventory data

	Ocean of capture			Total/average
	Atlantic	Indian	Pacific	
Vessel characteristics				
Number of vessels	3	3	3	9
Average length (m)	63.3	65.7	80.5	69.9
Average main engine power (kW)	3182	3305	4386	3625
Average number of crew	28	30	29	29
Annual operating inputs and outputs in 2003—all vessels				
Low sulphur diesel B (m^3)	10131	10946	13061	34138
Tin-free anti-fouling paint (l)	2100	2460	2480	7040
Catch of Skipjack and Yellowfin tuna (tonne)	23452	29554	24994	78000
Inputs of steel for vessels and engines—average per vessel and tonne landed				
Steel in hull/vessel (tonne)	897	921	1280	1033
Steel in hull/tonne of tuna (kg)	4.83	3.97	6.40	4.48
Steel for main engines/vessel (tonne)	125	125	125	125
Steel for main engines/tonne of tuna (kg)	2.44	1.95	2.28	2.12
Transport of frozen carcasses to harbours in Galicia (Spain)				
Distance (km)	4538	10140	9165	8623

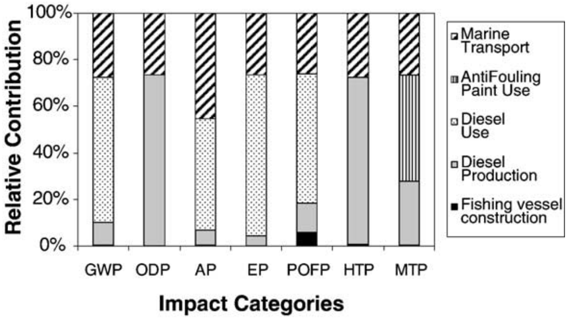

Fig. 3. Relative contribution to environmental impacts associated with the catching and delivery of frozen tuna to Galician harbours. *Note*: Impacts associated with the production of anti-fouling paint and emissions of both solid waste and wastewater are not presented as they each contributed less than 1% of the total impact in all the categories.

More specifically, in the case of most emissions, it is the direct combustion of fuel while fishing that accounts for the majority of fuel use related impacts. Reflecting the great distances that a large proportion of Spanish-caught tuna are transported post-harvest, this activity makes a substantial contribution, of between 26 and 45%, to each of the environmental dimensions characterized (Fig. 3). In contrast, the use of anti-fouling paint only makes a considerable impact, accounting for 46% of the total contribution, to a single impact category, marine toxicity potential. Of dramatically less importance were the impacts that flowed from vessel construction, anti-fouling paint production, and the discharge of crew-generated solid and liquid wastes. Indeed, all of these activities combined contributed less than 7%, and typically well under 2% to all of the emission categories quantified.

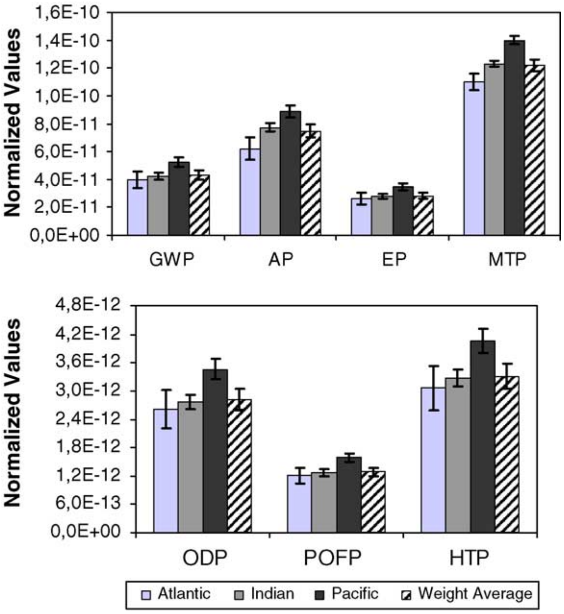

Fig. 4. Weighted average, and ocean of origin specific absolute contributions of Spanish tuna fisheries for Skipjack and Yellowfin tuna in 2003. All values per tonne of tuna delivered to Galician ports normalized relative to total global emissions in 1995. Error bars reflect the range of outcomes that result from increasing or decreasing average fuel inputs by 1 S.D.

By combining the highest average fuel consumption rates with relatively long post-harvest transport distances (Table 2), vessels operating in the eastern tropical Pacific gave rise to consistently higher life cycle emissions in comparison with operations in either the Atlantic or Indian Oceans (Table 3, Fig. 4).

On average, for every tonne of frozen tuna delivered to the dockside, Spanish fisheries released the equivalent of 62 tonnes of 1,4-dichlorobenzene of

Table 3
Characterization values associated with the capture and delivery of 1 tonne of tuna to Galician ports

Impact category (reference substance)	Ocean of capture			Weighted average
	Atlantic	Indian	Pacific	
Global warming potential (kg CO_2)	1600	1700	2200	1800
Ozone depletion potential (g CFC11)	1.4	1.4	1.8	1.5
Acidification potential (kg SO_2)	20	25	29	24
Eutrophication potential (kg $PO_4{}^{3-}$)	3.4	3.6	4.5	3.7
Photo-oxidant formation potential (kg C_2H_4)	0.12	0.12	0.15	0.12
Human toxicity potential (kg 1,4DCB)	180	190	230	190
Marine toxicity potential (kg 1,4DCB)	56000	63000	72000	62000

Table 4
Potential environmental impact reductions (%) associated with hypothetical scenarios

Impact category	Sc 1	Sc 2
Global warming potential (GWP)	6.3	19.3
Acidification potential (AP)	4.7	26.1
Eutrophication potential (EP)	6.4	18.7
Marine toxicity potential (MTP)	2.5	13.9

toxic substances to the marine environment, along with the equivalent of 1.8 tonne CO_2, 190 kg 1,4-dichlorobenzene, 24 kg SO_4, 3.7 kg PO_4^{3-}, 120 g C_2H_4 and 1.5 g CFC11 to the atmosphere (Table 3).

The relative importance of these emissions is easily seen when compared to global emissions in 1995 (Fig. 4). Regardless of where they were conducted, the fisheries analyzed had the greatest relative impact on, in descending order of importance, marine eco-toxicity, acid precipitation, global warming and eutrophication. Markedly less important still were contributions made to human toxicity, ozone depletion and photo-chemical smog generation (Fig. 4).

3.3. Modelled scenarios

The first scenario modelled (Sc 1) in which direct fuel inputs to fishing operations in both the Atlantic and Pacific are reduced to the level at which vessels operating in the Indian Ocean currently burn fuel, while keeping all other aspects of Spanish tuna fisheries constant, would only result in reductions of between 2 and 6% across the four most important impact categories (Sc 1 in Table 4). However, a larger environmental performance improvement could be achieved if all Spanish fishing activities for Yellowfin and Skipjack were undertaken exclusively in the Atlantic Ocean, thereby reducing the sizable emissions that result from the post-harvest transport of carcasses. Combining these two possible changes, i.e. all tuna are taken in the Atlantic at an average fuel combustion rate of 373 l/tonne (Sc 2), would result in improvements of between 14 and 26% over the current situation (Table 4).

3.4. Sensitivity analysis

The environmental impacts described above in the base case analysis result from data derived from a wide range of sources. Consequently, we undertook sensitivity analyses to explore the effect of changing key input parameters associated with the most important hot spots and report here on the effect of changes to two parameters that directly affect emissions from fuel use. Not surprisingly, increasing and decreasing average fuel inputs by one standard deviation directly translated into larger and smaller emissions across all impact categories (Fig. 4, error bars). However, the scale of these changes in relation to the base case values is relatively small—typically amounting to under 15%. Emissions associated with fish caught in the Atlantic display the largest potential variation reflecting the fact that average fuel inputs amongst the three Atlantic-based vessels were most varied—mean 442 l/tonne and a standard deviation of 80 l/tonne. As a result, in five of the seven impact categories the range of emission values associated with Indian Ocean-based fishing falls within the range of values associated with Atlantic-based fishing. In no case, however, did the range of values associated with Pacific-based vessels fall within the range of emissions associated with either Atlantic or Indian Ocean-based vessels (Fig. 4).

Although we used data from a large, detailed study of real-world emissions from ships to characterize the direct emissions from the fishing operations analyzed here, uncertainties remain. To explore the effect of applying alternative emission factors, we substituted values derived from two alternative sources, the International Maritime Organization's regulations that stipulate the maximum allowable emission rates from ships (The MARPOL 73/78 Annex VI) that is set to come into force on May 2005 (IMO, 2004) and Wärtsilä, one of the leading manufacturers of marine diesel engines (Hellén, 2003) (Table 5). As neither the IMO regulations nor Wärtsilä data provide as wide a range of emissions factors as those used in the base case analysis, our sensitivity analysis was limited to only those

Table 5
Alternative emission factors used in sensitivity analysis (all values in grams per kilogram of fuel burned)

Data source	NO_x	SO_x	CO_2	CO	HC
IMO regulations[a]	66.0	33.0	3626	–	–
Wartsila[b]	44.0	11.0	3297	0.5	–
Lloyd's register[c]	57.0	4.0	3170	7.4	2.4

[a] *Source*: MARPOL 73/78 Annex VI 1997.
[b] *Source*: Wärtsilä Corporation (2003).
[c] *Source*: Engineering Services Group (1995).

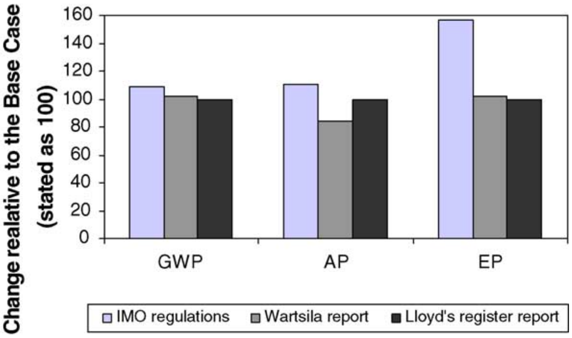

Fig. 5. Results of sensitivity analysis of alternative emission factors.

impact categories most directly affected, namely global warming, acidification and eutrophication potentials. In all instances save one, the real-world emission data used in our base case analysis resulted in lower impacts (Fig. 5). The one exception being the Wärtsilä emission factor data resulted in lower acidification potentials.

4. Discussion

4.1. Fuel consumption

In burning just under 440 l of fuel per tonne of tuna landed, Spanish purse seiners targeting Skipjack and Yellowfin tuna are relatively energy efficient when compared with many other fisheries for human consumption (Tyedmers, 2004). While no data are available from other contemporary tuna purse seine fleets, data from U.S. and Japanese purse seiners operating in the 1970s and 1980s provide contrast. U.S.-based vessels fishing in the eastern tropical Pacific in the mid-70s burned about 1700 l/tonne of all tunas landed (Rawitscher and Mayer, 1977) while Japanese purse seiners fishing in the mid-1980s burned about 1200 l of fuel per tonne of tuna caught (Watanabe and Okubo, 1989). Although the data may not be directly comparable, the lower average fuel consumption rates amongst contemporary tuna fishing operations is heartening if somewhat surprising given the extent to which global fisheries have become dependant on this finite resource (Pauly et al., 2003; Tyedmers et al., in press) and the widespread trend to generally poorer energy performance over time in many fisheries (Tyedmers, 2004). While lower average fuel inputs could result from a general increase in the abundance of Yellowfin and Skipjack stocks, given the widespread declines in predatory fish communities that have been described (Myers and Worm, 2003), this seems unlikely. An alternative explanation for the apparent reduction in average fuel inputs associated with tuna purse seining is that it results from a combination of technical efficiency improvements. In addition to the wide array of fish finding technologies currently available, over the last 30 years major improvements have been made in hull and propeller design and the efficiency of marine diesel engines (Corbett, 2004).

The fact that tuna caught in the Pacific entail higher average fuel inputs and relatively long post-harvest transport distances, both factors that translate directly into higher costs of production when compared to fish caught in other oceans, is well known within the industry (Mr. Antonio Cuevas, Conservas Calvo, June 2004, pers. commun.). As a result, an increasing fraction of Pacific caught tuna are being partially processed at plants in Central-America so that only those portions of the fish suitable for canning are transported to Galicia for final processing. While this variant of the harvest-processing system has not been modelled, it has the potential to reduce the overall environmental impacts associated with Pacific caught fish ceteris paribus.

4.2. Major contributions to environmental impacts

One of the most important uses of LCA is the identification of environmental “hot spots” or activities that contribute disproportionately to the total environmental impact of the system under study, so that steps can be taken to address them either proactively by environmentally concerned producers or through regulation. Here, both fishing-related inputs of diesel fuel (its production and its use) and the use of anti-fouling paint emerge as hot spots of concern. Our finding that fuel inputs have a major impact on the overall environmental performance of tuna fishing echoes results of earlier work in other fisheries (Ziegler et al., 2003). Reducing the fuel intensity of contemporary Spanish tuna fisheries could, in theory, be achieved in a number of ways. Further technological advances, for example in the areas of long-range target identification or the thermal efficiency of engines, are both possible. Alternatively, increasing the general abundance and availability of the targeted species could also result in lower fuel inputs as we explored in our Scenario 1.

Unfortunately, many technologically driven pathways to improved energy performance can work against the stock rebuilding option, ceteris paribus, as they often reduce the economic costs of fishing making it possible to fish longer and harder. Moreover, opportunities to effect substantial reductions in fuel use, regardless of means, may be limited given the already comparatively low fuel use intensity of these fisheries when compared to comparable tuna fisheries as explored above and other fisheries for high value species (Tyedmers, 2004).

The seeming importance of anti-fouling paint has not previously been described as an important hot spot in fishing systems and as such deserves wider consideration. Moreover, losses of anti-fouling paint had the largest apparent impact on marine eco-toxicity, the most problematic impact category quantified from a global perspective (Figs. 3 and 4). It should be noted, however, that the methods used for establishing toxicity factors for non-ferrous metals are currently being reviewed and a clear consensus is lacking (Mr. Alain Dubreuil. Government of Canada, December 2004, pers. commun.). In our analysis, toxicity factors for both human and marine toxicity potentials were taken from the list included in the CML methodology as originally defined by Huijbregts (1999, 2000). And although this list does not include a toxicity factor for Cu(I), the species of copper that enters the water when anti-fouling paint breaks down, from discussions with Mark Huijbregts (September 2004, pers. commun.) it was assumed to be the same as Cu(II) or the equivalent of 1.5E6 kg 1,4DCB/kg (for MTP). It should be noted, however, that in an April 2004 meeting of LCA and related specialists, it was recommended that the toxicity characterization factor applied to essential metals, such as zinc and copper, in marine waters be set at zero as the oceans are deficient in these metals and additional inputs will probably not lead to toxic effects (Aboussouan et al., 2004). Although this perspective overlooks the fact that most anti-fouling paint is likely lost in harbours and other high traffic coastal environments where they are known to cause toxic effects (Alzieu, 1998; Matthiessen and Law, 2002), and it remains, for the present, only a recommendation, if it is widely adopted the modelled marine eco-toxicity associated with tuna fishing, and all other activities that use anti-fouling paint, would be greatly reduced.

Interestingly, while not as large a process chain hot spot as fuel consumption (Fig. 3), the post-harvest transport of carcasses potentially provides greater scope to effect environmental performance improvements as suggested by the results of our two modelled scenarios. This is because the differences in the minimum transport distances associated with operations in the Atlantic, Pacific and Indian Oceans, conservatively estimated at just over 4500, 9100 and 10,100 km, respectively, are much larger than the differences in the corresponding direct fuel inputs to those operations at 440, 525 and 370 l/tonne. Consequently, any set of circumstances, from stock rebuilding efforts, as we suggest in our Scenario 2, to changes in international fisheries management arrangements that results in Spanish purse seiners once again operating exclusively in the Atlantic Ocean would result in the effective halving of the environmental impacts associated with post-harvest transport and overall emission reductions of up to 26% (Table 4). To achieve a comparable scale of improvement in at least one impact category exclusively through reductions in fuel use intensities, average inputs would have to be reduced to around 250 l/tonne—fully 40% below the current average of almost 440 l/tonne.

In contrast to the above noted hot spots, our novel consideration of the impacts associated with solid and liquid wastes generated by crew members indicates that this aspect of the fisheries considered does not warrant immediate attention.

5. Conclusions

We used data from nine large purse seiners that targeted Skipjack and Yellowfin tuna, three in each of the Atlantic, Pacific and Indian Oceans, to evaluate the environmental performance of these important contemporary Spanish tuna fisheries. As purse seining accounts for roughly 90, 88 and 60% of Spanish, European and Global tuna landings, respectively, and the nine vessels inventoried account for approximately one-quarter of Spain's and over 15% of total European tuna landings (308,469 and 507,772 tones in 2003), our results should be broadly representative (FAO, 2005). Overall, the provision and direct combustion of fuel along with anti-fouling paint use while fishing had the biggest impacts on all the life cycle emissions modelled. Consequently, efforts to improve the environmental performance of Spanish tuna fishing operations should focus on these aspects of the fishery first. Comparing the performance of fisheries based in the three oceans, Pacific-based operations resulted in the highest emissions across all impact categories modelled. This was largely the result of markedly higher fuel consumption rates together with relatively long post-harvest transport distances. Efforts to rebuild stocks, particularly in the Atlantic Ocean would not only help reverse the decline of aquatic ecosystems but could result in marked improvements in the environmental performance of the Spanish tuna fishery.

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