ENERGY EFFICIENCY OF THE PURSE SEINE FISHERY: FAD VS FREE SWIMMING SCHOOLS STRATEGY

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SUMMARY

This study aims to evaluate the energy efficiency of the purse seine fishery and to determine the differences between fishing strategies (FAD vs FSC) in the Atlantic Ocean within a FAD closure period, for an isolated assessment of the free-swimming school fishing and for providing carbon footprint indicators in line with Rec. 2022-13. The analysis has been performed with data provided ANABAC and OPAGAC on purse seiner and supply vessels (i.e., vessel specifications, departure and entry date to port, miles navigated by trip, fuel levels at departure and entry to port, bunkering at sea, catch by set type (FAD and FSC) including species and size composition and reference sale prizes. Fuel consumption (L), FUI (L/t) and profitability indicators were estimated for pure FAD, pure FSC and mixed trips. On average, Atlantic purse seiners have a FUI of 856 L fuel/t catch. By fishing strategy, FAD trips (675 L/t) are more efficient and show lower carbon footprint (1839.6 ± 839.6 kgCO_2/t) than FSC trips (FUI: 2044 L/t; 5569.9 ± 5176.4 kgCO_2/t).

KEYWORDS

Tropical tunas, FAD closure, purse-seiners, energetic efficiency, fuel

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1. Introduction

The relationship between climate change and fisheries is complex. Greenhouse Gas (GHG) emissions from fisheries (mainly generated by burning fuel oil) contribute to climate change and, at the same time, climate change is affecting the distribution, abundance and size of species. Commercial fisheries are energy-intensive (Parker et al., 2018a), and fuel costs represent a large part of their operative costs. It is therefore of utmost importance to find solutions to make fleets more energy efficient and thus reduce their impact on the environment. Energy efficiency in fisheries is usually measured by the FUI indicator (*Fuel Use Intensity*) expressed in terms of litres of fuel burned per tonne landed, $FUI = L\ fuel / t\ catch$. The carbon footprint on the other hand measures the GHG emissions created per tonne landed, i.e. $Carbon\ Footprint = kg\ CO_2 / t\ catch$, and it is usually calculated by multiplying the fuel consumption by the emission factor of the fuel used, 3.206 t CO_2/t diesel-gasoil (IMO, 2009; Basurko et al., 2013). Although energy efficiency is not generally considered in the ecosystem management of fisheries, it can be useful to complete the assessment of the sustainability of fisheries. Indeed, ICCAT has adopted the Rec 22-13 to assess the impacts of climate change and other associated environmental degradation on target and non-target species. This includes efforts undertaken by CPCs to reduce the carbon footprint within the ICCAT fisheries.

Several authors state that in general terms tropical tuna purse seine fishing is more energy efficient than other fishing gears targeting tuna fisheries such as longline, driftnet or pole and line fishing (Parker et al., 2015). But few are, however, the ones assessing the differences between FAD and FSC fishing (Basurko et al., 2022; Chassot et al., 2021). Basurko et al (2022) suggested that FAD fishing seems to be slightly more energy demanding than FSC in relation to FUI and carbon footprint, due to the greater distance travelled in FAD fishing, in contrast, FAD has higher success rates per set. The conclusions drawn, present some limitations, since they are based on a detailed onboard engine monitoring of a single tuna freezer vessel operating in the Indian Ocean, and the fuel consumption estimates for the other vessels covered in the study are calculated based on fuel consumption pattern of the monitored vessel and the distance travelled by the other vessels regardless of the ocean in which they operate as fuel consumption data were not available at the time of the study. Recognising that fuel consumption is particular to each vessel since it depends on the engine on board, the skipper's skills, the ocean in which they operate and the fishing strategy employed, it is of utmost importance to carry out a more detailed analysis of the fuel consumption of tropical tuna purse seine fishing and define the real differences between FAD and FSC based on measured data. Besides, in the fishing scenario in which the studies of Basurko et al (2022) and Chassot et al. (2021) were conducted (i.e. the Indian Ocean where there was no closure to FAD fishing), the skipper could choose to operate with a given fishing strategy (FSC or FAD fishing) according to the information received (i.e., eco-sounder buoys, fishing prediction programmes, fishing reports from other colleagues) or encounters of fish schools at sea, maximising their fishing efficiency. Thus, in a scenario with no closure to FADs, the free school search period is always limited and based in the revenue. That is to say, the FSC fishing is conducted while the skippers have the opportunity to fish in FSC and would change to FADs modality when FSC signal is loss, balancing the efficiency during a given trip and of the fishery. In this sense, the FAD closure in the Atlantic presents a unique scenario for assessing the efficiency and carbon footprint of the FSC fishery, as it allows an isolated assessment.

Therefore, to provide indicators of the green-house gas emission of the purse seine fishery (Res 22-13), the overall objective of this work is to evaluate the energy efficiency of the purse seine fishery and to determine the differences between fishing strategies (FAD vs FSC) in the Atlantic Ocean within a FAD closure period.

2. Material and methods

2.1. Data Collection

Data collection templates were developed to collect information on fuel consumption and other operational variables from all the tuna companies belonging to OPAGAC and ANABAC, for the study period 2019-2021. Templates are included in the (Annex A). To ensure that the templates were clear to the tuna companies, meetings were held with all the ones who showed interest to review the tables and the required information together. Data to be collected included:

(i) Fuel consumption by trip and vessel (including supply vessels which support fishing activities and especially in activities with FADs for tuna vessels), including date of entry and departure from port, litres on the tank in the entry and departure, and detail of the bunkering operations made at sea (date and volume).

(ii) Relationship between the tuna purse seiners and their supply vessels.

(iii) Miles navigated per trip and VMS files of the vessels.

(iv) For the vessels having an on-board energy consumption monitoring device, the monitored variables for each of the engines monitored (the main, auxiliaries) and the monitoring frequency. The CSV files with high resolution data were also requested.

(v) Specification of the vessels: year of construction, length (LOA), gross tonnage, number of wells.

(vi) Data on catches from logbooks; in particular, the reported catch by set type (FAD or FSC) of target species stratified by size range. Likewise, reference sale prices by species and size range, and fuel prices were also requested.

2.2. Data Analysis

The FUI indicator was calculated by trip. This allowed the comparison between different fishing strategies (FAD and FSC). From all the trips provided by the tuna companies, only the trips which had a measured record of the fuel consumption per trip was considered in the study. By fuel consumption data per trip we mean, information on measured fuel consumption by on-board monitoring devices or the fuel quantities in fuel tanks measured at the entry and departure, and bunkering at sea.

2.2.1. Analysis of fuel consumption

Only one company confirmed having an on-board energy monitoring system on their fleet; this included devices on-board all tuna vessels and some of the supply vessels. Despite the data provided by the on-board monitoring system are more accurate for the analysis, only the main engines of their vessels were monitored by these devices; hence no information was collected in relation to the auxiliary engines' consumption. To bridge this gap and have a better understanding on the total fuel consumption per trip, data provided on the fuel tanks (entry and departures as well as bunkering at sea) were used as the baseline to calculate the total fuel consumption of each vessel per trip by applying the following equation (EC.1):

$$Consumption_{trip}[L] = L_{departure}[L] + T_{loaded}[tn] * \frac{1000\ L}{0.85\ tn} - L_{arrival}[L] \qquad [EC.1]$$

Where,

- Fuel at departure date ($L_{departure}$): Amount of fuel (litres) that the vessel had before the start of the fishing trip.

- Fuel at arrival date ($L_{arrival}$): Amount of fuel (litres) that the vessel had on the date of the end of the fishing trip.

- Fuel bunkered of loaded at sea (T loaded): Amount of fuel (tonnes) loaded at sea. Note that in this case the data provided by the company were in units of mass (kg), so for its conversion to volume (litres), a fuel density of 0.85 kg/L was considered.

The information provided by the on-board energy monitoring devices was also used to calculate the fuel consumption of auxiliary engines. For this purpose, the following equation was applied:

$$Consumption_{auxiliaries\ per\ trip}[L] = EC._{1}\ [L] - L_{trip\ estimated}[L]$$

Please note that the consumption of vessels in port were excluded from the FUI estimation.

Although the FUI values were only calculated using the fuel consumptions of the tuna vessels, the fuel consumption of supply vessels were also studied. To do this, the average daily consumption of each supply vessel per year was calculated by dividing the consumption of each vessel by the number of days at sea per trip and averaging it over the year. The number of purse seine vessels assisted by each supply each year (2019-2021 period) was also taken into account. Assigning a ratio between supply vessels and the number of tuna vessels assisted is not straightforward. But in order to have a first indication of the percentage that could be involved, it was considered that the consumption of each supply vessel is proportional to the tuna vessel's days at sea. For this purpose, the daily consumption of each supply was multiplied by the days at sea for each trip of the assisted tuna vessel.

$$CM_{d,at,a} = {}_{a=2019}^{2021}\left[\frac{CM_{m,a}/N_{m\,i}}{N_{at}}\right]$$

Where,

- $CM_{d,at,a}$daily consumption (d) per supply vessel (at) for each year (a) of study (2019, 2020, 2021), [unit L/d].
- $CM_{m,a}$average consumption (L) of the supply vessel per trip and study year.
- N_mNumber of days per trip (m) for each year of study (a)
- N_{at}Number of tuna vessels (at) assisted by each supply vessel by year

The proportion of the consumption of the supply vessels was calculated as follows:

$$\%CM = \frac{\sum \frac{CM_{d,at,a} * d_{at}}{CA_m} * 100}{n_m}$$

Where,

- $\%CM$: % that the consumption of the supply vessels represents in relation to the consumption of the tuna vessel
- $CM_{d,at,a}$daily consumption of supply vessel per assisted tuna vessel for each year of the study (in L/d)
- d_{at} duration of the trip in days (day at sea)
- CA_mTuna vessel consumption per fishing trip
- $n_m$number of trips

2.2.2. Catch

The catches during the fishing trips were derived from the data provided by the companies. The catches of the different tuna species were calculated for each trip by taking into account the date of departure and entry of each trip and the vessel studied in each case. Likewise, the number of sets and tuna catch made by set type (i.e. FAD and FSC) were calculated by trip, so were the species composition and the revenue (considering a reference sale prize by size classes and species).

The variables used in the calculations are as follows:

- **Date of capture:** Day of the catch.

- **Time of capture**: Time of the catch.

- **Vessel:** Vessel names.

- **Number of sets:** Number of sets by trip.

- **Species:** Specie composition of the set: skipjack tuna, bigeye tuna, yellowfin tuna, frigate tuna (*Auxis thazard thazard*) and other species whose catch amounts are small compared to the previous species, so they have been grouped under "others". For the calculations of the economic indicators, only the target species of these fisheries (skipjack, bigeye and yellowfin tuna) were considered.

- **Size class:** The size category (>10 kg and <10 kg) of the species skipjack tuna, bigeye tuna, yellowfin tuna, frigate tuna and other species.

- ***Catch:*** Kilograms of fish caught in each set (kg).

- ***Set type:*** Sets were classified in FADs or FSC sets.

Error! Reference source not found.1 *s*hows the flowchart of the procedure followed to estimate the catch for each set type (FAD vs FSC) and per trip; **Error! Reference source not found.** the procedure for calculating the catch of different species by trip.

2.2.3. Assessment of FUI and other indicators

The FUI (L/tonnes) indicator was calculated by dividing the total fuel consumption by the catch for each trip per trip. Furthermore, the average values of FUI indicator (per trip) were calculated per vessel, fishing strategy (FAD, FSC or mixed) and by grouping of vessels with similar characteristics (Group A and Group B).

It must be noted that in order to classify a trip according to their fishing strategy (i.e. FAD, FSC or mixed trips), the following was considered: we considered that a trip followed a FAD strategy when more than 90% of the sets were made on FAD, a FSC strategy when more than 90% of the sets were made on FSC, and the third group (mixed trips) included the rest.

The study years included closure seasons where FAD fishing was forbidden partially or totally depending on the year (Table 1). In order to study the effect of the closure on fishing efficiency, the fishing trips were further classified into 2 groups: "closure" included fishing trips performed entirely during the closure, and "non-closure" included the rest.

As a complementary indicator, the profitability of fishing trips was assessed applying the indicator (€ catch/€ fuel and 1000 € catch/t fuel) by considering the fuel cost and the income related to catches per trip.

For this purpose, the reference prices of the Table 2 and a reference fuel cost of 1270€/Mt were applied, provided as an indication by the consulted tuna companies.

3. Results

3.1. Description of data available

Out of the 95 trips received, only 50 trips (52.6 % of the trips) were selected for the FUI calculation (**Error! Reference source not found.**). These trips were performed by 7 tuna vessels (**Error! Reference source not found.**). The vessels were grouped according to their characteristics (gross tonnage and engine power) (Table 4). Group A represented a cluster of smaller vessels in size, and Group B larger vessels. The names and specific characteristics of the vessels will remain confidential for concealing the ship owners.

Regarding supply vessels, out of the 80 trips provided, only 40 (48%) could be used. The rest of the trips were omitted from the analysis due to lack of information.

As an average, close to 500 tonnes per trip and vessel are consumed by the fleet operating in the Atlantic (Table 5). Adopting a particular strategy seems to reduce the fuel consumption, since FAD or FSC trips show lower fuel consumption than the average of mixed trips combining FAD and FSC sets (495.6 t mixed trips). However, these mixed trips have large variability, reaching both the lowest and the highest fuel consumption values of all the trips.

Vessels with higher gross tonnage (e.g. B_7) show, on average, higher fuel consumption; this may be related to the higher power installed in these vessels. As an exception, vessel B_4 has shown a relatively high average consumption having a small gross tonnage. This may be due to the characteristics of the trips evaluated that corresponded to long trips or with high number of sets. Nonetheless, it should be noted that there were only 3 trips monitored for this vessel.

Supply vessels have an average consumption of 114,167 ± 70,414 L per trip, their trips have an average duration of 59.4 ± 31.6 days, and they can assist between 1-3 tuna vessels. The consumption of supply vessels can represent 3.0% in mixed trips, 5.0% in FAD trips and 2.7% in FSC trips, which are similar to those estimates found by Chassot et al. (2021) for the Indian Ocean (3-7%). The consumption of supply vessels has not been, however, considered in the present calculation of fuel consumption of Table 5.

For catches by trip, there is also a relationship between the vessels size and catch level, with higher catches by trip in larger vessels. However, the standard deviation is high, and thus, high FUI values have been observed in large vessels with low catches by trip.

Regarding the fishing strategies used, the catch is lower in the case of FSC trips compared to FAD or mixed trips. This can be observed both in the average and in their minimum and maximum values.

3.2. Description of FUI and economic indicators

The results of the FUI and economic indicators by vessel type (Group A and B) and fishing strategy (FSC, FAD and mixed trips) are included in Table 6.

FAD trips last longer than FSC counterparts, with higher mean and minimum and maximum values. As an average, the vessels following FAD strategy cover larger distance than the ones following a FSC strategy. In contrast, FSC trips show significantly higher FUI average values than those of FAD or mixed trips (also observable in the box plot shown in Figure 3). However, it must be noted that some FSC trips present lower FUIs than other FAD-only trips, revealing large variability in the observed FSC-only trips (Figure 3). An example of this is that the minimum FUI observed for FSC trips (318 L/t) is half of the average found for FAD trips (675 L/t).

In relation to the economic indicators, mixed trips have shown to be economically the most efficient (2.36 € catch / € fuel). The possibility of combining both fishing strategies should be reflected in a higher overall catch yield. In contrast, FAD and FSC trips have shown lower averages (1.99 and 1.98 € catch/€ fuel respectively), making them slightly less profitable than mixed trips.

Regarding the groups of vessels according to their dimensions (Group A and B), in general terms, the larger vessels (Group B) present longer trips, they cover larger distance, and they present larger FUI values. However, when large catches per trip occurred, large vessels resulted to be much more efficient (lower FUI indices) than the smaller vessels (Group A). This is also visually reflected in the **Error! Reference source not found.** where the distribution the trips is shown as a function of the GT of the associated vessels.

In terms of economic performance, Group B vessels appear to be slightly more profitable than Group A vessels (the averages of the two indicators are slightly higher).

3.3. Relationship of FUI and economic indicators

Despite having high FUI scores, if species with higher prices are fished during a fishing trip, a trip can result highly profitable. In order to analyse this phenomenon, Figure 5 plots the 50 fishing trips in relation to their economic indicator "€ catch/€ fuel" versus the associated FUI.

As the FUI scores increase, the economic indicator "€ catches/ € fuel" decrease, i.e. the higher the economic index, the lower the FUI. This relationship fits a potential function, with an R^2 coefficient of 0.91 showing a high level of fit with respect to the selected potential function.

Half of the FSC trips are found on the right-hand side of the plot, presenting relatively high FUI values and low economic indicators. It is also worth mentioning that the second highest economic score corresponds to an FSC-only trip. Therefore, although it is observed that FSC trips may have lower economic indicators (they are less profitable) because of their low catch per trip, when fish schools are found, they become the most profitable (highest economic indicator scores) and most energy efficient (very small FUIs).

The FAD trips are mostly found on the left side of the plot, where the FUI values are less than 1000 L/t and the economic indicators are around 2 € catch/€ fuel. Given the high level of fit presented by the potential function, it is possible to calculate the potential FUI score where the economic indicator would be €1 catch/€ fuel, i.e. €1 spent on fuel gives you €1 catch. Values below this point would imply that the fuel cost incurred on the trip would exceed the economic gain derived from the catches. If the potential function (Figure 5) is used and substituting the term $\frac{€_{catch}}{€_{fuel}}$ by 1, it returns that FUI values above 1333.47 L/t would indicate that trips showing FUI values higher than this value will not cover fuel costs with catches, regardless of the species caught. Note that this study has limited to the fuel costs, which can account for 20% of the operational costs of an Indian tuna vessel (Miyake et al., 2010); hence no other operative costs have been considered. If other operation costs were also to be considered, for an index of $\frac{€_{catch}}{€_{fuel}}$ above 2, the maximum possible FUI value would be 616.07 L/t.

3.4. Carbon footprint assessment

Table 7 shows the results obtained for the carbon footprint assessment, listing both the equivalent CO_2 emissions per trip in tonnes and the carbon footprint in ($\frac{kg_{CO2}}{t_{catch}}$) for the different fishing strategies. Since for the GHG emission calculation only fuel consumption has been considered, the results obtained for fuel consumption and FUI scores for FAD versus FSC can be directly applied for the GHG emissions and carbon footprint discussion.

3.5. Effect of closure

Out of the 50 trips studied, 7 of them (14%) took place entirely within the closure period. From those, 5 were selected as FSC trips, i.e. 4 were pure to FSC and in one 87.93% of sets were done to FSC which was carried out in 2019 in which the usage of FADs was restricted in the areas mentioned in Table 1. **Error! Reference source not found.** summarises the average values of duration, distance covered, FUIs and economic indicators for the trips considered within and outside the closed season. Annex C presents all the information of the trips.

The average values of the distance travelled, and the duration of the trips are similar inside and outside the closure period, with few exceptions such as the 174-day trip outside the closure period. In relation to FUI scores, the trips within the closure period presented higher mean, minimum and maximum values than those outside the closed period. Similarly, the economic indicators of the trips in the closure period are lower than the counterparts outside this period. Furthermore, while the minimum observed value of the € catch/€ fuel indicator remains close to 1 outside the closure period (being at least able to afford the fuel cost with the catches), the minimum of this index during closure is 0.33, representing an unprofitable tide in terms of fuel cost and gain per catch.

4. Discussion and Conclusions

Since the 90s the use of FADs has been increasing, due to the development of associated technologies, such as echo-sounder buoys that allow fishermen to know in real time the location of these devices and estimation of the aggregated biomass underneath (Lopez et al., 2014; Maufroy et al., 2016; Torres-Irineo et al., 2011; Wain et al., 2020), which makes this strategy highly efficient. As such, nowadays FAD fishing is the principal fishing strategy of purse seine fishing vessels in the Atlantic.

However, from an energy point of view, several studies focused in the Indian Ocean observed that the FAD fishery present higher fuel consumption per tonne of tuna than the free school fishery, shown by Table 9 (Basurko et al., 2022; Chassot et al., 2021). However, these conclusions have to be considered with caution, as in the scenario in which the study was conducted the two strategies (FAD and FSC) could be carried out at the choice of the skipper. That is, the skipper had free choice to make sets to FAD or FSC, depending on the information available, and optimising efficiency. Thus, the FSC search time was limited and dependent on the profitability. The change from FSC strategy to FAD could be made whenever the skipper did not obtain benefits. However, this strategy change is not an option in periods of total FAD closure, and the industry has experienced a significant reduction in catches, which affects to the energetic efficiency of the fishing activity.

Thus, in order to evaluate the energy efficiency of the FSC fishery in the absence of a FAD fishery and provide estimates to evaluate the carbon footprint of the fishery (Rec 2022-13), the Atlantic Ocean provides a suitable scenario. As such, this study estimates the FUI levels (L/t) for the two types of fishing strategy (FAD and FSC) and their relationship with vessel characteristics and an economic indicator is explored (€ catch/€ fuel). In addition estimates for GHG emissions and carbon footprint are given.

Over the decades, purse seine vessels have been increasing in length and capacity. Our analysis show that larger vessels generally have higher consumption. This pattern was also observed by Chassot et al. (2021). This increase in vessel size requires a high catch to offset consumption costs. Therefore, vessels have made increasing use of FADs and have opted for the development of FAD-associated buoy technology. With the change in fishing strategy brought about by the increased use of FADs, the area of activity of purse seiners has increased (ICCAT, 2022). Vessels now spend more time moving from one buoy to another (while in the displacement they also actively search for other FADs or free schools), than doing a pure searching activity (with the exception of FAD closure period). Thus, in this study it has been found that the distance navigated are related to the percentage of catches to FADs and the number of sets to FADs. This explains why previous works has attributed higher fuel consumption to the FAD fishery (Chassot et al., 2021; Basurko et al., 2022). However, the high efficiency of sets on FADs (Wain et al., 2020), may compensate for this fuel expenditure, thus showing a relatively lower FUI when trips are made to FADs rather than to FSC. Thus, this work also shows that in the absence of the FAD fishery the FUI is triggered by the lack of catches. Except for specific FSC trips in which low FUIs have been observed (which are isolated trips where high FSC catches have occurred in a short period of time and are made by the choice of the skipper), it is the FAD fishery what sustains the fishery.

On average, the Atlantic purse seiners has a FUI of 856 L fuel/t catch. By fishing strategy, it is observed that FAD trips (675 L/t) are more efficient than FSC trips (2044 L/t), although small FUIs have been also observed when trips combine FAD with FSC (711 L/t). The averages of the economic indicators (€ catch/€ fuel) of the fleet studied are in the range 2-2.4, with FSC trips presenting the lowest and mixed trips (trips in which FAD and FSC sets has been register) the highest scores. Regarding to carbon footprint, FAD (1839.6 ± 839.6 $kgCO_2/t$) and mixed trips (1937.5 ± 1015.6 $kgCO_2/t$) show lower levels than FSC trips (5569.9 ± 5176.4 $kgCO_2/t$).

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References

Avadí, A., Bolaños, C., Sandoval, I., Ycaza, C., 2015. Life cycle assessment of Ecuadorian processed tuna. The International Journal of Life Cycle Assessment 20, 1415-1428.

Basurko, O.C., Gabiña, G., Uriondo, Z., 2013. Energy performance of fishing vessels and potential savings. Journal of Cleaner Production 54, 30-40.

Basurko, O.C., Gabiña, G., Lopez, J., Granado, I., Murua, H., Fernandes, J.A., Krug, I., Ruiz, J., Uriondo, Z., 2022. Fuel consumption of free-swimming school versus FAD strategies in tropical tuna purse seine fishing. Fisheries Research 245, 106139.

Chassot, E., Antoine, S., Guillotreau, P., Lucas, J., Assan, C., Marguerite, M., Bodin, N., 2021. Fuel consumption and air emissions in one of the world's largest commercial fisheries. Environmental Pollution 273, 116454.

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges⋆. Aquat. Living Resour. 26, 37-48.

Fonteneau, A., Pascual Alayón, P.J., Marsac, F., 2017. Exploitation of large yellowfin tuna caught in free schools concentrations during the 2013 spawning season (December 2012-May 2013). Collect. Vol. Sci. Pap. ICCAT 73, 868-882.

Hospido, A., Tyedmers, P., 2005. Life cycle environmental impacts of Spanish tuna fisheries. Fisheries Research 76, 174-186.

ICCAT, 2022a. Report of the 2021 Bigeye stock assessment meeting. https://www.iccat.int/Documents/Meetings/Docs/2021/REPORTS/2021_BET_SA_ENG.pdf.

ICCAT, 2022b. Report of the 2022 Skipjack stock assessment meeting. https://www.iccat.int/Documents/Meetings/Docs/2022/REPORTS/2022_SKJ_SA_ENG.pdf.

IMO, 2009. Interim guidelines on the method of calculation of the Energy Efficiency Design Index for new ships. IMO.

IMO, 2009. Report of the Marine Environment Protection Committee on its Fifty-Ninth Session. IMO, p. 245.

Lopez, J., Moreno, G., Sancristobal, I., Murua, J., 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fisheries Research 155, 127-137.

Maufroy, A., Kaplan, D.M., Bez, N., De Molina, A.D., Murua, H., Floch, L., Chassot, E., 2016. Massive increase in the use of drifting Fish Aggregating Devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. ICES Journal of Marine Science 74, 215-225.

Miyake, M., Guillotreau, P., Sun, C.-H., Ishimura, G., 2010. FAO Fisheries and Aquaculture Technical Paper. No. 543. Rome, FAO. 2010. 125p.

Parker, R., Blanchard, J., Gardner, C., Green, B., Hartmann, K., Tyedmers, P., Watson, R., 2018a. Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change 8, 333-337.

Parker, R.W.R., Blanchard, J.L., Gardner, C., Green, B.S., Hartmann, K., Tyedmers, P.H., Watson, R.A., 2018b. Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change 8, 333-337.

Parker, R.W.R., Tyedmers, P.H., 2015. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish and Fisheries 16, 684-696.

Parker, R.W.R., Vázquez-Rowe, I., Tyedmers, P.H., 2015. Fuel performance and carbon footprint of the global purse seine tuna fleet. Journal of Cleaner Production 103, 517-524.

Torres-Irineo, E., Gaertner, D., de Molina, A.D., Ariz, J., 2011. Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators. Aquat. Living Resour. 24, 337-350.

Wain, G., Guéry, L., Kaplan, D.M., Gaertner, D., 2020. Quantifying the increase in fishing efficiency due to the use of drifting FADs equipped with echosounders in tropical tuna purse seine fisheries. ICES Journal of Marine Science 78, 235-245.

Tables

Table 1. Period of closure considered in the study

Year	Closure area	Closure period
2019	4ºS to 5ºN and African coast at 20ºW	1/1/2019 - 28/2/2019
2020	The entire ICCAT area	1/1/2020 - 28/2/2020
2021	The entire ICCAT area	1/1/2021 - 31/3/2021

Table 2. Indicative price by species and size (€ per Mt)

Species	Size	Selling price (€/Mt)
Skipjack (*Katsuwonus pelamis*)	-	1191
Yellowfin tuna (*Thunnus albacares*)	-10	1207
	+10	1907
Bigeye tuna (*Thunnus obesus*)	-10	1162
	+10	1337

Table 3. Number of fishing trips selected for each year and fishing strategy.

year	Mixed	FAD	FSC
2019	9	10	1
2020	7	6	1
2021	7	5	4
Total	23	21	6

Table 4. General characteristics of the vessels studied.

Group	**Vessel**	**Year of construction**	**Length (m)**	**Beam (m)**	**Gross Tonnage (GT)**	**Nº of cubes**	**Load capacity (m^3)**	**Main engine power (kW)**
A	B_1	80s	85	13	2000	18	1800	4000
A	B_2	90s	80	13	2000	18	1800	3000
A	B_3	2010s	80	13	2000	20	1700	4000
A	B_4	80s	80	13	2000	16	1300	3000
B	B_5	2010s	95	15	3000	22	1900	6000
B	B_6	80s	85	15	3000	18	2000	4000
B	B_7	90s	105	17	4000	26	3300	5000

Table 5. Average, minimum and maximum values for fuel consumption and fish catches by fishing strategy and analysed vessels

	Gross Tonnage (GT)	Main engine power (kW)	Fuel consumption per trip and vessel (t)			Catches per trip and vessel (t)		
			Average ± SD	**Min.**	**Max.**	**Average ± SD**	**Min.**	**Max.**
				By fishing strategy				
Fleet*	2673	4223	494.7 ± 288.4	214.7	2094.1	930.7 ± 672.0	153	4032.3
FAD	2729	4387	495.2 ± 184.5	246.5	935.7	1013.7 ± 600.3	365	2910
FSC	3062	4851	489.6 ± 155.5	265.1	664.6	556.0 ± 381.7	153	1100
Mixed	2787	4387	495.6 ± 378.8	214.7	2094.1	952.6 ± 755.9	260	4032.3
				By vessel				
B_1	2000	4000	472.2 ± 147.5	264.5	591.8	741.7 ± 77.2	635	815
B_2	2000	3000	319.7 ± 45.1	273.7	404.9	647.9 ± 233.9	260	970.2
B_3	2000	4000	338.9 ± 93.2	249.7	542.9	709.7 ± 178.7	365	980.0
B_4	2000	3000	538.2 ± 106.9	446.6	658.1	808.3 ± 44.8	765	870.0
B_5	3000	6000	474.1 ± 172.3	214.7	809.8	803.5 ± 254	248	1140.0
B_6	3000	4000	437.9 ± 169.3	246.5	658.1	490.7 ± 261.5	153	790.0
B_7	4000	5000	755.7 ± 454.6	309.2	2094.1	1644.2 ± 1099.9	195	4032.3

* Fleet: The seven studied vessels

DS: Standard Deviation

Table 6. Average, minimum and maximum values for FUI, days at sea, miles navigated and economic indices

Fishing strategy	**Days per trip**	**Distance covered (nm)**	**FUI (L/t)**	**Economic indicators** €1000 catch/ t fuel	€ catch / € fuel
AVERAGE VALUES (± Standard Deviation)					
Fleet	42 ± 23	6580 ± 463	856 ± 816	2.74 ± 1.58	2.16 ± 1.24
FAD	44 ± 14	7529 ± 2324	675 ± 308	2.53 ± 1.22	1.99 ± 0.96
FSC	35 ± 14	5156 ± 2566	2044 ± 1899	2.51 ± 2.55	1.98 ± 2.0
Mixed	43 ± 31	6085 ± 2330	711 ± 373	3.0 ± 1.60	2.36 ± 1.26
Group A	35 ± 9	6057 ± 1960	683 ± 300	2.68 ± 1.29	2.11 ± 1.01
Group B	47 ± 28	6959 ± 2741	981 ± 1031	2.79 ± 1.78	2.20 ± 1.40
MINIMUM VALUES					
FAD	23	4167	256	0.99	0.78
FSC	16	1786	318	0.42	0.33
Mixed	21	3260	181	1.10	0.87
Group A	16	1786	318	1.06	0.83
Group B	21	2894	181	0.42	0.33
MAXIMUM VALUES					
FAD	83	13380	1295	5.44	4.28
FSC	53	8574	5060	7.03	5.53
Mixed	174	11799	1771	7.75	6.10
Group A	53	10381	1304	7.03	5.53
Group B	174	13380	5060	7.75	6.10

Table 7. Carbon footprint by fishing strategy per trip

	Fuel consumption per trip (t)			Equivalent CO_2 emissions per trip (t)			Carbon footprint ($\frac{kg_{CO2}}{t_{catch}}$)		
	Average ± DS	Min.	Max.	Average ± DS	Min.	Max.	Average ± DS	Min.	Max.
By fishing strategy									
Fleet*	494.7 ± 288.4	214.7	2094.1	1586.1 ± 924.7	688.2	6713.6	2332.3 ± 2223.9	493.22	13789.78
FAD	495.2 ± 184.5	246.5	935.7	1587.8 ± 591.5	790.3	2999.9	1839.6 ± 839.6	697.5	3528.2
FSC	489.6 ± 155.5	265.1	664.6	1569.5± 498.4	850.0	2130.6	5569.9 ± 5176.4	867.3	13789.78
Mixed	495.6 ± 378.8	214.7	2094.1	1588.9 ± 1214.3	688.2	6713.6	1937.5 ± 1015.6	493.21	4826.6

Table 8. Average, minimum and maximum values of FUI, days at sea, miles navigated and economic indices

PERIOD	**Days per trip**	**Distance covered (nm)**	**FUI (L/t)**	**Economic indicators** €1000 catch/ t fuel	€ catch / € Fuel
AVERAGE VALUES (± standard deviation)					
Closed period	39 ± 13	5,928 ± 2,297	2365 ± 1734	2.29 ± 2.47	1.80 ± 1.94
Out of season	42 ± 24	6,652 ± 2,442	688 ± 332	2.79 ± 1.42	2.20 ± 1.11
MINIMUM VALUES					
Closed period	16	1,786	318	0.42	0.33
Out of season	21	2,894	181	0.99	0.78
MAXIMUM VALUES					
Closed period	53	8,574	5,060	7.03	5.53
Out of season	174	13,380	1,771	7.75	6.10

Table 9. FUIs of tuna freezer vessels reported by other reports in different oceans

	FUI (L/t)	Reference
Indian Ocean		
Average (Spanish fleet)	373	(Hospido and Tyedmers, 2005).
Average	424	(Chassot et al., 2021).
Average	630	(Basurko et al., 2022).
FAD only	544	(Basurko et al., 2022).
FSC only	439	(Basurko et al., 2022).
Pacific Ocean		
Average (Ecuadorian fleet)	709	(Avadí et al., 2015).
Average (Spanish fleet)	527	(Hospido and Tyedmers, 2005).
Atlantic Ocean		
Average	442	(Hospido and Tyedmers, 2005).
Average	856	Present study
Mixed trips	711	Present study
FAD only	675	Present study
FSC only	2044	Present study
Closed period	2365	Present study
Period outside the closed period	688	Present study

Figures

Figure 1

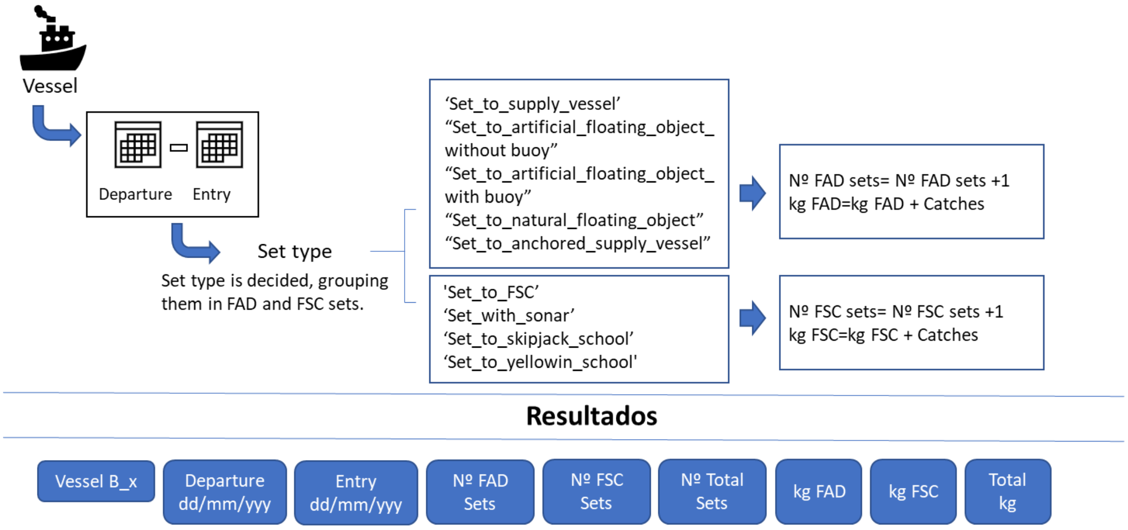

Figure 1 Flowchart of the accounting of catches by trip from haul data

Figure 2

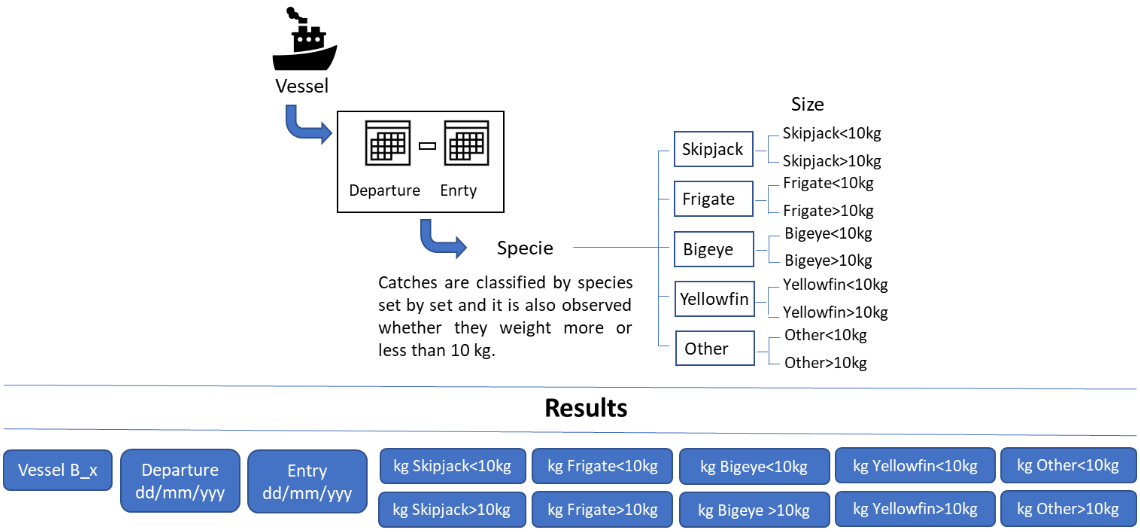

Figure 2 Flowchart of the accounting of catch of the different species by trip

Figure 3

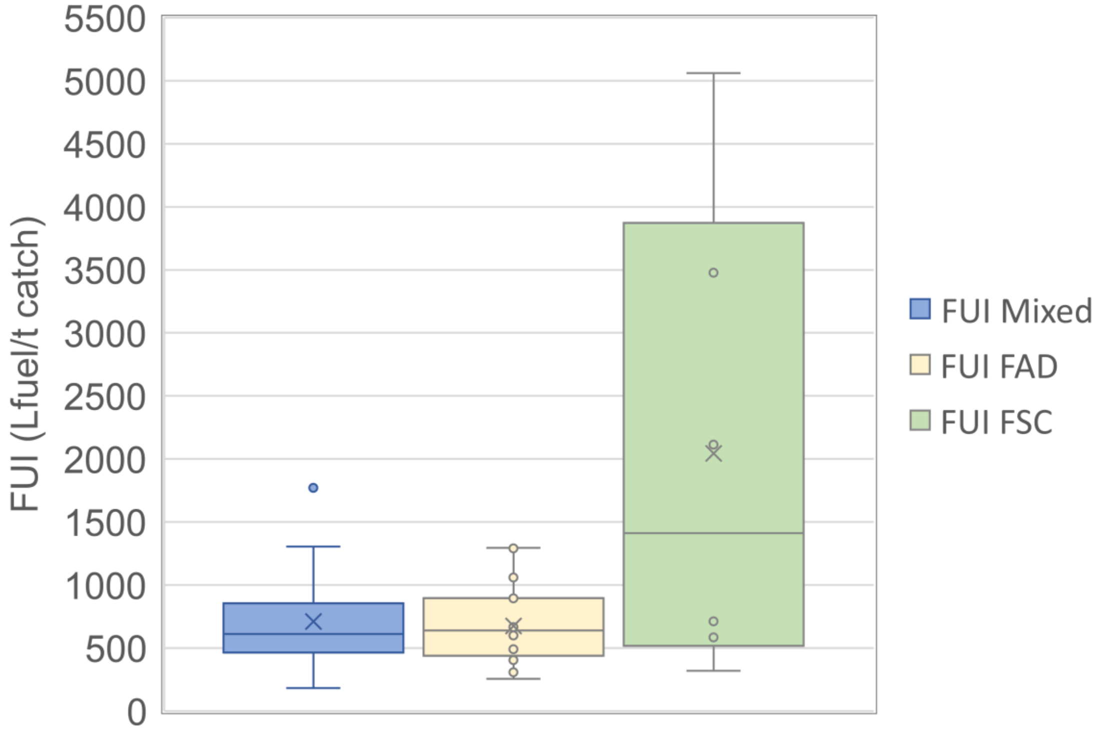

Figure 3. Distribution of observed FUI values for the different fishing strategies.

Figure 4

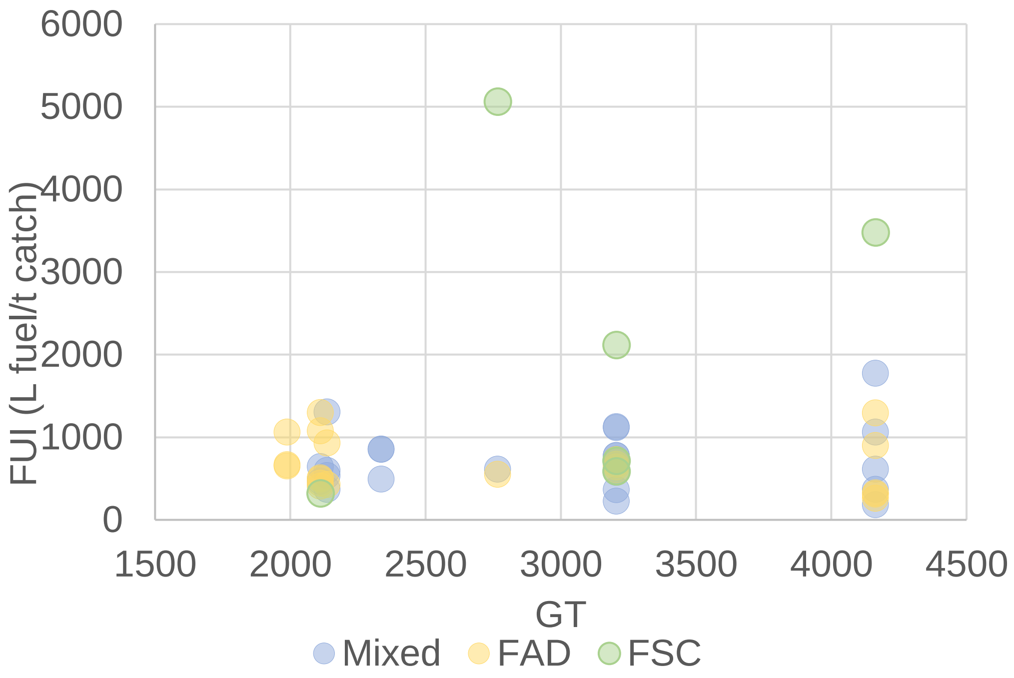

Figure 4. FUI values of the analysed trips as a function of the GT of the tuna vessel that made the trip. The labels B_# refer to the coding of the tuna vessels in Table 4.

Figure 5

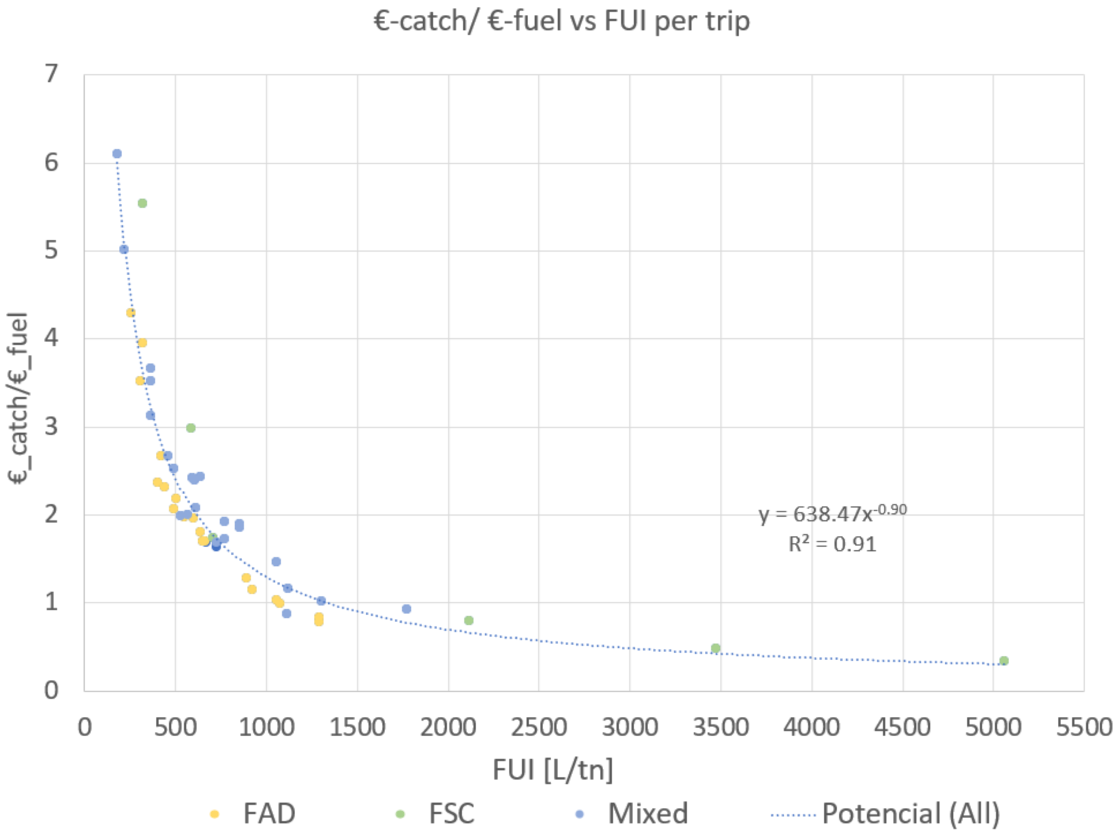

Figure 5. Relationship between economic indicators vs. FUI results for the analysed trips

ANNEX A - Data collection tables

The tables used for data collection were as follows. The explanatory text for each table is shown after each table in a box.

Table A1a. Ship data (top) and explanation (bottom)

Facts about the ship		*General facts about the tide*						
Company	Vessel name (tuna vessel or auxiliary)	Date of departure from port	Date of entry into port	Distance covered (nautical miles)	Litres of fuel at departure date	Litres of fuel at date of entry	At-sea bunkering date	Litres of fuel loaded at sea

Data Typology	Data to be collected	Description
Information about the ship	Company	Choose the company from the drop-down menu
	Name of ship	Choose the ship from the drop-down menu
General information on the tide	Date of departure from port	Port departure date in dd/mm/yyyy format (e.g. 15/02/2022)
	Date of entry into port	Date of port entry in dd/mm/yyyy format (e.g. 15/03/2022)
	Distance covered (nautical miles)	Total distance covered over the tidal range in nautical miles
	Litres of fuel at departure date	Total litres of fuel on board at the time of departure from port
	Litres of fuel at date of entry	Total litres of fuel on board at the time of port entry
	At-sea bunkering date	If fuel has been taken at sea, indicate date in dd/mm/yyyy format (e.g. 03/03/2022).
	Litres of fuel loaded at sea	Total litres of fuel received at sea

Table A1b. Tidal data and daily consumptions (top) and their explanation (bottom)

Facts about the ship		*Tide data*		*Daily consumption data*		
Company	Vessel name (tuna vessel or auxiliary)	Date of departure from port	Date of entry into port	Date of verification	Time to check	Fuel volume on board (L) (at time of check)

Data Typology	**Data to be collected**	**Description**
Information about the ship	Company	Choose the company from the drop-down menu
	Name of ship	Choose the ship from the drop-down menu
Daily consumption data	Date of departure from port	Date of departure to port in format dd/mm/yyyy (e.g. 15/02/2022)
Tidal data	Date of entry into port	Date of port entry in dd/mm/yyyy format (e.g. 15/03/2022)
Daily consumption data	Date of verification	Date on which the fuel volume check is performed. The date in dd/mm/yyyy format (example 10/03/2022).
	Time to check	Time at which the fuel volume on board is checked. GMT time in hh:mm format (example: 15:30)
	Fuel volume on board (L)	Total litres of fuel on board at the time of checking

Table A2 Data on supply vessels and the relationship with tuna vessels (top) and their explanation (bottom)

Relationship between supply vessel and tuna vessel								
Company	Year	Name of supply vessel	Name of tuna vessel	Name of tuna vessel	Name of tuna vessel	Name of tuna vessel	Name of tuna vessel	Name of tuna vessel

Data Typology	**Data to be collected**	**Description**
Relationship between auxiliary and supply	Company	Choose the company from the drop-down menu
	Year	Year of activity of vessels
	Name of supply vessel	Choose name of supply vessel from the drop-down menu
	Name of tuna vessel	Name of the tuna vessel supported by the supply vessel. Choose the name of the tuna vessel from the drop-down menu. If working with more than one tuna vessel include one in each column.

Table A3. Data on the ship monitoring system (top) and explanation (bottom)

Facts about the ship		*On-board consumption monitoring system data*				
Company	Vessel name (tuna vessel or auxiliary)	Year	Monitored engine	Frequency of registration	Measuring device	Variables recorded

Data Typology	**Data to be collected**	**Description**
Information about the ship	Company	Choose the company from the drop-down menu
	Name of ship	Choose the ship from the drop-down menu
On-board consumption monitoring system data	Year	Year from which monitoring is being carried out with specific equipment
	Engine	Type of engine on which the monitoring has been performed. Choose an option from the drop-down menu: main or auxiliary.
	Frequency of registration	Frequency at which each recording is made by the monitoring system. Indicate in seconds (e.g. 10 seconds, 60 seconds).
	Measuring device	Device with which the measurement is made Choose an option from the drop-down list: flowmeter or torque meter
	Variables recorded	Include list of variables to be recorded: e.g. date, time, latitude, longitude, SFOC, kg/h, FOC, rpm, speed boat, kW, kWh

Table A4. Vessel characteristics (top) and explanation (bottom)

Data on the characteristics of the ship														
Company	Vessel name (tuna vessel or auxiliary)	Years of construction	Length (m)	Beam (m)	Gross Tonnage (GT)	Main engine power (kW)	Auxiliary engine power 1 (kW)	Auxiliary engine power 2 (kW)	Auxiliary engine power 3 (kW)	Auxiliary engine power 4 (kW)	Auxiliary engine power 5 (kW)	Number of vats	Vat capacity	Operational deep-freezing (yes/no)

Data to be collected	Description
Years of construction	Year of construction of the tuna vessel or supply vessel
Length (m)	Length of boat in metres
Beam (m)	Beam of the boat in metres
Gross Tonnage (GT)	Gross registered tonnage of the vessel in GT
Main engine power (kW)	Main engine power in kW
Auxiliary engine power 1 (kW)	Power of the first auxiliary engine in kW. If more than one auxiliary engine is available, include the power in the following columns (as many columns as engines)
Auxiliary engine power 2 (kW)	Potential of the second auxiliary engine in kW. If two auxiliary engines are not available, leave this field empty.
Auxiliary engine power 3 (kW)	Potential of the third auxiliary engine in kW. If three auxiliary engines are not available, leave this field empty.
Auxiliary engine power 4 (kW)	Potential of the fourth auxiliary engine in kW. If four auxiliary engines are not available, leave this field empty.
Auxiliary engine power 5 (kW)	Potential of the fifth auxiliary engine in kW. If five auxiliary engines are not available, leave this field empty.
Number of vats	Number of vats on the tuna vessel
Vat capacity	Tank capacity in m3
Operational deep-freezing (yes/no)	Indicate whether you have an operational deep-freezing system. Choose the option from the drop-down menu (yes/no).

ANNEX B - ACRONYMS

EEDI	Energy efficiency operational index
FAD	Fish Aggregating Devices
FOC	Fuel oil consumption (L/h)
FSC	Free school - free school fishing
FUI	Fuel use intensity (L fuel/t capture)
GHG	Greenhouse gas emissions
ICCAT	International Commission for the Conservation of Atlantic Tunas
IMO	International Maritime Organisation
RPM	Revolutions per minute
SFOC	Specific fuel oil consumption (g/kWh)
VMS	Vessel monitoring system

ANNEX C - FUI SCORES FOR ALL TRIPS

Vessel	Date of departure from port	Date of entry into port	Within closed season (Y/N)	Fishing strategy	FAD(FSC)	Trip duration (days)	Distance covered [nm].	FUI [L/t]	Economic index [€1000 catch/ t fuel]	€ catch / € Fuel
B_1	02/09/2021	15/10/2021	No	FAD	174(14)	43	7,153	424	3.39	2.67
B_1	15/10/2021	27/11/2021	No	FAD	170(6)	43	8,057	925	1.45	1.14
B_7	27/08/2019	18/11/2019	No	FAD	527(22)	83	13,380	321	5.02	3.95
B_7	18/11/2019	27/12/2019	No	FAD	167(0)	39	7,189	256	5.44	4.28
B_7	14/03/2020	04/05/2020	No	FAD	345(3)	51	8,756	307	4.46	3.52
B_7	10/11/2020	20/12/2020	No	FAD	139(6)	40	5,869	1291	0.99	0.78
B_7	06/03/2021	13/05/2021	No	FAD	172(7)	68	10,478	894	1.62	1.28
B_3	22/05/2019	09/07/2019	No	FAD	222(19)	48	10,208	1073	1.25	0.99
B_3	03/08/2019	02/09/2019	No	FAD	213(16)	30	5,016	490	2.62	2.07
B_3	02/09/2019	25/09/2019	No	FAD	202(0)	23	4,167	403	3.00	2.36
B_3	25/09/2019	24/10/2019	No	FAD	144(0)	29	6,240	438	2.93	2.31
B_3	24/10/2019	28/11/2019	No	FAD	89(2)	35	6,925	1295	1.06	0.83
B_3	28/11/2019	02/01/2020	No	FAD	189(0)	35	6,721	506	2.76	2.18
B_6	05/06/2019	07/07/2019	No	FAD	71(3)	32	5,019	548	2.50	1.97
B_4	26/08/2019	27/09/2019	No	FAD	276(1)	32	4,646	649	2.15	1.69
B_4	17/08/2020	09/10/2020	No	FAD	144(12)	53	10,381	665	2.16	1.70
B_4	09/10/2020	16/11/2020	No	FAD	200(0)	38	7,379	1058	1.30	1.02
B_5	25/10/2020	05/12/2020	No	FAD	118(8)	41	6,299	638	2.29	1.80
B_5	05/12/2020	16/01/2021	No	FAD	150(5)	42	5,999	600	2.49	1.96
B_5	05/03/2021	05/05/2021	No	FAD	165(17)	61	9,905	727	2.07	1.63
B_5	09/11/2021	31/12/2021	No	FAD	198(4)	52	8,324	667	2.14	1.69
				Average trip scores at FAD		44 ± 14	7529 ± 2324	675 ± 308	2.53 ± 1.22	1.99 ± 0.96

Vessel	Date of departure from port	Date of entry into port	Within closed season (Y/N)	Fishing strategy	FAD(FSC)	Trip duration (days)	Distance covered [nm].	FUI [L/t]	Economic index [€1000 catch / t fuel]	€ catch / € Fuel
B_7	12/01/2021	06/03/2021	Yes	FSC	0(20)	53	8,574	3477	0.60	0.47
B_3	12/01/2019	28/01/2019	Yes	FSC	0(17)	16	1,786	318	7.03	5.53
B_6	08/01/2021	12/02/2021	Yes	FSC	0(21)	35	5,551	5060	0.42	0.33
B_5	19/09/2020	25/10/2020	No	FSC	0(46)	36	4,852	584	3.79	2.98
B_5	16/01/2021	05/03/2021	Yes	FSC	0(20)	48	7,280	2113	1.01	0.80
B_5	05/05/2021	27/05/2021	No	FSC	0(100)	22	2,894	711	2.20	1.73
				Average trip scores at FSC		35.0 ± 14	5156 ± 2566	2044 ± 1899	2.51 ± 2.55	1.98 ± 2.0

Vessel	Date of departure from port	Date of entry into port	Within closed season (Y/N)	Fishing strategy	FAD(FSC)	Trip duration (days)	Distance covered [nm]	FUI [L/t]	Economic index [€1000 catch / t fuel]	€ catch / € Fuel
B_2	26/01/2019	11/03/2019	Yes	Mixed	7(51)	44	6,452	854	2.40	1.89
B_2	11/03/2019	11/04/2019	No	Mixed	96(20)	31	5,036	490	3.20	2.52
B_2	11/04/2019	11/05/2019	No	Mixed	26(23)	30	5,035	851	2.35	1.85
B_1	06/05/2021	14/06/2021	No	Mixed	78(58)	39	4,955	365	3.96	3.12
B_1	14/06/2021	27/07/2021	No	Mixed	38(27)	43	5,836	593	3.06	2.41
B_1	27/07/2021	02/09/2021	No	Mixed	137(23)	37	5,676	533	2.52	1.98
B_1	27/11/2021	30/12/2021	No	Mixed	43(14)	33	5,476	1304	1.29	1.01
B_7	07/01/2019	26/02/2019	No	Mixed	61(37)	50	9,368	365	4.66	3.67
B_7	26/02/2019	29/03/2019	No	Mixed	40(27)	31	4,664	1057	1.85	1.46
B_7	27/07/2019	27/08/2019	No	Mixed	66(12)	31	4,419	181	7.75	6.10
B_7	03/01/2020	14/03/2020	No	Mixed	26(22)	71	11,799	1771	1.17	0.93
B_7	20/05/2020	10/11/2020	No	Mixed	452(95)	174	11,400	611	2.64	2.08
B_3	28/01/2019	27/02/2019	No	Mixed	22(17)	30	5,967	640	3.08	2.43
B_3	09/07/2019	03/08/2019	No	Mixed	86(13)	25	4,090	463	3.39	2.67
B_6	26/02/2019	08/04/2019	No	Mixed	23(44)	41	7,767	609	3.03	2.39
B_5	19/03/2020	02/05/2020	No	Mixed	45(7)	44	8,195	1123	1.48	1.16
B_5	02/05/2020	19/06/2020	No	Mixed	101(14)	48	7,394	1112	1.10	0.87
B_5	19/06/2020	17/07/2020	No	Mixed	8(102)	28	3,490	774	2.18	1.72
B_5	17/07/2020	12/08/2020	No	Mixed	32(41)	26	3,260	363	4.47	3.52
B_5	12/08/2020	19/09/2020	No	Mixed	11(75)	38	6,649	729	2.13	1.68
B_5	27/05/2021	17/06/2021	No	Mixed	63(13)	21	3,324	222	6.37	5.01
B_5	04/08/2021	07/09/2021	No	Mixed	37(24)	34	4,690	772	2.44	1.92
B_5	07/09/2021	07/10/2021	No	Mixed	97(13)	30	5,012	570	2.54	2.00
					Mixed trip averages	43 ± 31	6085 ± 2330	711 ± 373	3.0 ± 1.60	2.36 ± 1.26