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Fuel consumption of free-swimming school versus FAD strategies in tropical tuna purse seine fishing

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ABSTRACT

Different fishing strategies have been adopted in the last decades by tropical tuna purse seiners fleet, including fish aggregating device (FAD) and free-swimming school (FSC) fishing strategies, which has raised issues about the different carbon footprint of those fishing modes. Here we show the activity and energy patterns of a Spanish tuna purse seiner operating in the tropical Indian Ocean, based on the monitoring of energy consumption over 10 consecutive fishing trips; and we also assess the fuel use intensity of FAD versus FSC fishing by analysing 14 further trips of different tropical tuna purse seiners. The average time of a fishing trip lasted 33.1 ± 11 days. The dominant activity during the fishing trip was cruising (with 68.5% of the time), followed by inactive period at sea (15.6%), fishing (7.7%), and in port (8.1%). The vessel consumed 381 ± 113 t fuel/trip, of which 90.4% was spent in cruising, 4.3% in fishing, 3.7% during the inactive period at night and 1.6% while staying in port. The main engine consumed 75% of the total fuel, while the auxiliary engines the remaining 25%. Furthermore, our results demonstrated that FAD fishing (543.6 L/t) is more fuel intensive, than FSC fishing (439.4 L/t). However, FADs fishing successful rates are higher, around 95.7 ± 3.8%, than FSC rates (around 80.6% ± 5.8). It is worth noting that the differences may be driven by seasonality and FSC availability, number of FADs in an area, vessel characteristics and equipment, and skipper skills rather than the adopted fishing strategy. Nonetheless both FAD and FSC fishing are more energy efficient than longline (1069 L/t), trolling (1107 L/t), or pole and line (1490 L/t) fisheries for Atlantic tuna, but similar or slightly less efficient than Maldivian pole and liners.

1. Introduction

Fisheries generate direct impact on fish stocks, and ecosystem structure and functioning (Brown et al., 1998; Garcia and Grainger, 2005; Hilborn et al., 2003; Sibert et al., 2006). Most fisheries are heavily fuel dependent (Suuronen et al., 2012), and the emissions of fuel combustion is one of the drivers of climate change that is impacting species distribution, abundance and size (Baudron et al., 2020; Lotze et al., 2019; Queirós et al., 2018). However, the fuel consumption has been largely excluded from any ecosystem-based analysis and management.

Energy for propulsion and onboard consumers is mainly supplied by marine diesel engines, which are globally used for shipping and fishing alike vessels. As a whole, they burn about 60 million barrels of crude oil a year (Reitz, 2013), resulting in 1 billion tonnes of greenhouse gas (GHG) emissions (i.e. CO_2 eq.) (Smith et al., 2014), and representing 60–70% of annual costs of a vessel activity (Rojon and Smith, 2014). Recent studies estimated the total fuel consumption of global fisheries in 40 billion litres of fuel, and GHG emissions into the atmosphere in 179 million tonnes, which represents an increment of 21% in emissions intensity (per fish landed) during the last two decades (Parker et al., 2018). Such amounts together with the increase of the fuel price have prompted analyses of energy performance and environmental impacts for all kind of fisheries. Examples include fisheries from Australia (Thomas et al., 2010); Norway (Jafarzadeh et al., 2016; Schau et al., 2009), Portugal (Parente et al., 2008), Italy (Sala et al., 2011), Denmark (Thrane, 2004), Sweden (Ziegler and Hansson, 2003), USA (Driscoll and

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Tyedmers, 2010; McKuin et al., 2021), Spain (Basurko et al., 2013; Ramos et al., 2011), considering a wide range of fishing gears, from artisanal fleet operating with long lines, trolling and hand lines, to more industrialised purse seine and trawling.

In the specific case of tuna fisheries, fuel accounts for 30–75% of the total annual costs (Parker et al., 2015), and consume approximately 19 million barrels of fuel (6.3 million is due to tuna purse seiners), releasing 9 million tonnes of CO_2 (3.14 million tonnes due to purse seiners) into the atmosphere (Parker et al., 2015; Tyedmers and Parker, 2012). The tropical tuna purse seine fishery targeting skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye tuna (*Thunnus obesus*) is one of the most technologically developed fishery in the world (Scott and Lopez, 2014), with a world fleet of around 700 vessels (Justel-Rubio and Recio, 2020). Their annual catch of tropical tuna by this fishing gear is about 34.5 million tonnes worldwide (ISSF, 2020), of which 50–60% of the catch is done setting on drifting fish aggregating devices (dFADs) (Fonteneau et al., 2013). DFADs are man-made surface floating objects deployed in the ocean that attract a number of marine species, including tunas (Castro et al., 2002). These dFADs are usually equipped with satellite linked echo-sounder buoys, which provide fishers with accurate geo-location information and rough estimates of the biomass associated underneath (Davies et al., 2014; Lopez et al., 2014). The rest of the catch comes from: (1) setting on free-swimming schools (FSC), which refers to big aggregations of large tunas on the surface or subsurface of the ocean, detected by fishing crews using different means (visuals, breezes, bird radars, etc.), and (2) set associated to dolphins (i.e., dolphin observations in the surface may indicate tuna associated underneath), the latter only occurring in the Easter Pacific Ocean.

The demand for international shipping is predicted to grow in the forthcoming decades (Smith et al., 2015; Traut et al., 2018), estimating that their GHG emissions global share will presumably increase from 2.7% in 2007 up to 20–60% in 2050 (Haji et al., 2014). Under this likely scenario, marine environmental regulations have become stricter. For example, the International Maritime Organization (IMO) has intensified the regulations on energy efficiency for ships –measured in CO_2 emissions per ship's capacity-mile, g CO_2 eq./t-nm (IMO, 2009a)– to guarantee GHG emission reduction, this also applies to some fishing vessels. One of these regulations is the Energy Efficiency Operational Index 'EEOI'. Despite its voluntary nature, it is one of the most representative monitoring tools that allow the calibration and comparison of the effect of any improvement or changes in ship operation in the use of energy. In contrast, energy efficiency in fisheries has been mainly approached by presenting their Fuel Use Intensity (FUI) index, originally proposed by Tyedmers in early 2000s (Tyedmers, 2001, 2004). Recent studies corroborate the use of this index in the assessments of energy efficiency in fishing vessels (Damalas et al., 2015). In addition, the FUI can be estimated for fish species or fishing gear (Parker et al., 2015), or even for fishing region and evaluate the fishing effort (Greer et al., 2019). The FUI index measures the fuel consumption to catch 1 tonne of target species, and it is commonly expressed in litres of fuel per tonne of fish landed (L/t).

Given the importance of tropical tuna purse seine fishery in the world and considering its fuel consumption and resulting carbon footprint, the current contribution aims to investigate the energy efficiency of this fishery comparing the two fishing strategies employed by the fleet: FAD and FSC fishing. Furthermore, it studies the activity and energy consumption patterns of a tuna purse seiner operating in the Indian Ocean and identifies the vessel and engine performance variables that can be used to classify the different vessel activities.

2. Materials and methods

2.1. Energy consumption monitoring

The vessel and engines performances of a tuna purse seine vessel (hereinafter "Vessel A") were monitored during 10 consecutive fishing trips. The acquired data were used to define the activity and energy patterns of an "average" tuna purse seiner. Vessel A (Table 1) operates in the tropical waters of the Indian Ocean and is equipped with a set of sensors to monitor vessel's performance. Data from the sensors were registered every 10 s. Due to the large amount of data, only the most relevant variables related to the activity and energy patterns of the vessel (e.g., date and time *hh/mm/ss dd/mm/yyyy*, vessel speed *kn*, engine speed *RPM*, shaft power *kW*, propeller pitch *%*, thrust *kN*, main and auxiliary engines fuel consumption *kg/h*) were considered for the present study (Table S1).

Vessel A was monitored between June 2014 and May 2015 (11 months). Table S2 of Supplementary Material lists the details of the fishing trips, including the periods in port. Although time in port is not usually considered as part of the fishing trip in this fishery, it was included in the analysis to better understand the effect of the time spent during fish offloading in port over the total fuel consumption of the vessel. The time in port was allocated to the precedent fishing trip because most of this time is the consequence of the fishing activities during that fishing trip (i.e., landing of the catch).

2.2. Classification of vessel's activity

Fishing activities (cruising, fishing, searching for schools, cruising to a FAD, etc.), when they are not collected by observers, are usually inferred and classified based on vessel's speed and turning angle obtained through Vessel Monitoring System (VMS) (Bez et al., 2011) or even main engine speed (Basurko et al., 2013). However, these sources of information may not result optimal to define the energy pattern of this type of vessels. Instead, in our study, Vessel A's activity was classified into 4 main categories that represent the activities and energy patterns

Table 1
Details of Vessel A and the Vessels associated to the 14 trips.

Ship ID	Vessel A	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7
Associated trips	VesselA #1–10	FAD#1	FAD#2 FAD#3 FSC#1	FAD#4 FAD#6 FAD#7 FSC#2 FSC#6	FAD#5	FSC#3	FSC#4 FSC#5	FSC#7
Flag	Seychelles	Spain	Cape Verde	Spain	Curacao	Curacao	Spain	Cape Verde
Construction year	2014	1983	2009	1991	1990	1976	2014	2014
Length (m)	88.6	52.3	87.0	75.6	105.00	76.7	78.0	91.1
Beam (m)	14	NA	14.2	13.6	16.8	13.5	14.2	14.7
Draught (m)	6.7	4.95	6.51	6.62	7.19	6.01	6.3	6.95
Max. speed (kn)	18.2	NA	16.2	NA	NA	12.1	19	19.2
Deadweight (t)	2467	650	2358	1600	1905	1567	2182	2255
Gross tonnage	2755	912	2548	2101	4164	1897	2591	2863
Fish hold capacity (m^3)	1900	721	1700	1700	3500	1400	1750	2200
Power main engine (kW)	4564	1491	4474	2941	6083	2983	4543	5966

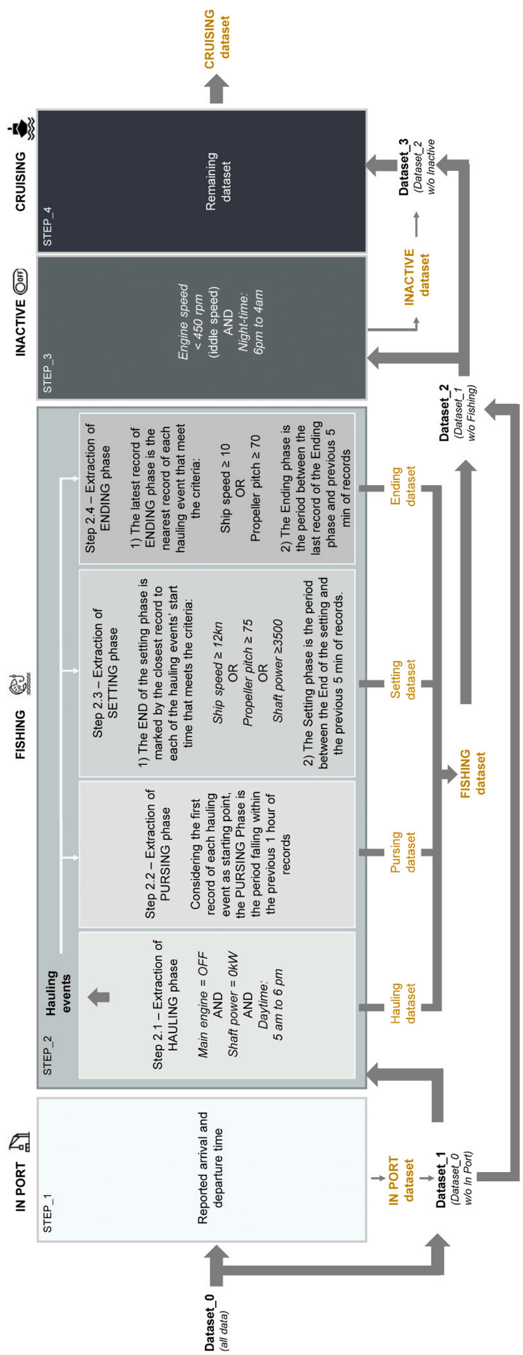

Fig. 1. Ranges of Vessel speed, engine speed and Shaft power for analysed Vessel A trips.

of a tropical tuna purse seiner, i.e. *cruising*, *fishing*, *inactivity at sea*, and *in port*, based on the classification followed by fishing vessels related energy audits (Basurko et al., 2013) and emission factors determination studies for shipping (Corbett and Koehler, 2003). *Cruising* included the time the vessel was steaming, considering also periods leaving or returning to port to/from fishing grounds, the period dedicated to navigating to different fishing locations/FADs in fairly steady course. *Fishing* included data normally associated with periods related to fish tracking and the fishing operations (i.e., fishing sets). The *inactivity at sea* was considered as the time the vessel was neither fishing or cruising, and the main engine was stopped overnight. *In port* consisted of the period the vessel was at port since the arrival from a fishing trip to the departure of the next.

The classification of the 4 classes of activities were defined by the methodology shown graphically in Fig. 1 (furthered described in Supplementary Materials), which threshold values were defined by a group of researchers (co-authors) in collaboration with onboard observers (not published).

Other clustering approaches, based on supervised learning, were applied to define the classes (e.g., k-means) but this approach was neither successful nor useful since the four activities could not be determined. Therefore, the methodology presented in Fig. 1 was followed as best approach.

2.3. Energy efficiency simulations for FAD and FSC

The fishing strategy (FAD or FSC) of a tuna purse seiner is highly variable and may depend on many factors, such as seasonality and FSC availability, number of FADs in an area, vessel characteristics and equipment, and skipper skills (Scott and Lopez, 2014). Therefore, any comparison between FAD and FSC fishing will require large amount of data to ensure the representativeness of results. Likewise, tuna purse seiners usually combine different fishing strategies within the same fishing trip, moving from FAD to FSC sets (Fonteneau et al., 2013), which complicates the comparison between them. Therefore, to evaluate the energy efficiency between FAD and FSC another 14 fishing trips were selected for the study (associated vessels are detailed in Table 1). The selection and classification of the fishing trips was made based on recorded fishing activity by observers onboard to guarantee good quality of data regarding vessel's activities. Most of the sets of those trips were performed exclusively on FAD or FSC and, therefore, allowed the identification of fully FAD and FSC fishing trips. Seven of the 14 trips were classified as FAD-dominated trips and the remainder as FSC-dominated trips, because more than the 90% of the sets of a given trip were conducted either on FADs or on FSC (Table 2). These trips were undertaken in years 2013–2015 by different Spanish-owned tuna purse seiners operating in the Atlantic Ocean. Originally, trips from vessels operating in the Indian Ocean were sought to present similar activity patterns as Vessel A. However, due to data reliability issues and limited presence of observers onboard the Indian Ocean fleet due to piracy threat, the trips selected were conducted by vessels operating in the Atlantic Ocean. The information provided by these fishing trips was limited to the duration of the trip, number of FAD and FSC sets, distance navigated (nautical miles), and catch composition.

It was assumed that the vessels undertaking the 14 fishing trips presented similar energy pattern as Vessel A, although the authors acknowledge that they may present different activity and energy consumption patterns as a result of having different engine powers and usage, derived from differences in their installed power and fishing strategies employed in different Oceans. In a pre-analysis of the data, the distance covered, and the duration of the trip were found to be the most sensitive variables regarding fuel consumption of the main and auxiliary engines of Vessel A. Likewise, good correlations were found between total fuel consumption and distance navigated per trip (r = 0.99), and between trip duration and fuel consumption (r = 0.97). Following the best correlation, the 'estimated fuel consumption of the 14 trips' was

Table 2
Selected fishing trips with dominance of sets using FADs and FSC.

Fishing trip code	Ship ID[a]	Start (date)	End (date)	Trip duration[a] (days/trip)	Dominance of fishing strategy (>90% of sets)[2]	Nº sets FAD (FSC)[3]
VesselA#1	VesselA	04/06/2014	27/07/2014	49	FAD/FSC	13(25)
VesselA#2	VesselA	01/08/2014	05/09/2014	35	FAD/FSC	9(4)
VesselA#3	VesselA	07/09/2014	02/10/2014	25	FAD	19(2)
VesselA#4	VesselA	04/10/2014	24/10/2014	20	FAD	19(1)
VesselA#5	VesselA	26/10/2014	04/12/2014	39	FAD	36(3)
VesselA#6	VesselA	06/12/2014	16/01/2015	40	FAD/FSC	12(31)
VesselA#7	VesselA	21/01/2015	04/02/2015	14	FAD/FSC	11(3)
VesselA#8	VesselA	07/02/2015	07/03/2015	27	FAD	25(2)
VesselA#9	VesselA	10/03/2015	07/04/2015	28	FAD/FSC	19(4)
VesselA#10	VesselA	09/04/2015	08/05/2015	28	FAD	30(3)
FAD#1	1	15/02/2014	09/03/2014	23	FAD	17(3)
FAD#2	2	02/10/2014	27/10/2014	26	FAD	18(2)
FAD#3	2	25/03/2015	20/04/2015	27	FAD	23(3)
FAD#4	3	06/12/2013	07/01/2014	33	FAD	17(2)
FAD#5	4	22/05/2015	18/06/2015	28	FAD	18(2)
FAD#6	3	03/05/2015	22/05/2015	20	FAD	16(0)
FAD#7	3	02/12/2015	28/12/2015	27	FAD	21(1)
FSC#1	2	07/01/2013	31/01/2013	25	FSC	1(20)
FSC#2	3	01/02/2015	20/03/2015	48	FSC	2(39)
FSC#3	5	24/01/2015	16/02/2015	24	FSC	4(33)
FSC#4	6	27/12/2014	20/01/2015	25	FSC	4(19)
FSC#5	6	26/02/2015	22/03/2015	25	FSC	4(17)
FSC#6	3	01/02/2015	20/03/2015	48	FSC	1(28)
FSC#7	7	15/12/2015	02/01/2016	19	FSC	2(17)

[a] The scores include all the activities: stays in port, cruising, fishing, and inactive periods.

calculated by multiplying the ratio "total fuel consumption (t) per distance travelled (nm)" determined as an average value from Vessel A by the distance navigated by each of the 14 trips.

2.4. Energy efficiency indicators

Both the FUI (L/t) and carbon footprint (g CO_2/t) were calculated for the Vessel A's 10 fishing trips and the 14 FAD and FSC-dominated fishing trip, to compare the fuel usage and energy efficiency differences between FAD/FSC oriented trips; the first ones were derived from the variables measures, the second ones were calculated considering 'estimated fuel consumption of the 14 trips'. In all cases, the conversion factor 3.206 t CO_2/t diesel (IMO, 2009b) was used to calculate the CO_2 emissions related to the fuel consumption. Similarly, the economic index '€ of catch landed/t fuel' was also calculated. The value of the landings for each trip was derived from multiplying the catch landed by the tuna prices provided by Thai Customs (Bangkok) for different species (average for year 2014, tuna price data source: Thai Customs data www.customs.go.th): *Katsuwonus pelamis*: 1457 US$/t, *Thunnus obesus*: 1457 US$/t, *Thunnus albacares*: 2418 US$/t, *Thunnus alalunga*: 2876 US$/t. Due to data limitation, same price was applied to all size ranges of a same species.

An additional energy efficiency indicator was calculated for Vessel A, the EEOI. For the specific case of fishing vessels, the EEOI may be calculated as follows:

$$EEOI = \frac{\sum_i \sum_j FC_{ij} \times C_{Fj}}{\sum_i m_{cargo,\,i} \times D_i}$$

Where, *j* is the type of fuel; *i* is the number of trips; FC_{ij} is the mass fuel consumption *j* in trip *i*; C_{Fj} is the CO_2 content in the fuel *j* employed; $m_{cargo,i}$ is the cargo transported per trip *i* (i.e., for fishing vessels this can be understood as the catch landed in tonnes); D_i is the distance navigated (in nautical miles) during trip *i*.

This indicator was only applied to Vessel A's trips, because the fuel consumption of the 14 trips was estimated from the rate of fuel consumed per distance travelled of the Vessel A due to data availability. Hence, the indicator would end up showing a result directly related to the FUI values.

To complement the FAD and FSC energy efficiency indicators, the success rates of the FAD and FSC sets done by Vessel A over the last year of activity was also analysed.

3. Results

3.1. Activity and energy pattern of a tuna purse seiner

3.1.1. Vessel A's performance

A typical fishing day for a tuna purse seiner at sea commences at sunrise, when the main engine is started on. Electricity and hydraulic supply are provided by the auxiliary engines. A fishing day usually includes one or, in the best cases, two fishing sets. In the nightfall, the main engine stops, and auxiliary engines supply the electricity onboard. At night, the vessel is usually adrift, unless immersed in navigation to different fishing location (e.g., a geo-referenced FAD or area with fish availability).

The most dominant ranges for Vessel A were vessel speed between 12 and 14 kn or below 2 kn when the vessel was stopped or adrift at night; engine speed from 740 to 750 rpm, followed by the range between 680 and 700 rpm; shaft power from 220 to 2800 kW (Fig. 2). Bearing in mind that the vessel has a variable pitch propeller, a classification by the engine speed based on engine monitoring fails to provide good insight for the classification of onboard activities. Instead, the shaft power, pitch propeller, engine speed, and the vessel's speed enabled the detection of clusters of data. These clusters resulted to be good indicators to identify and classify data from registered variables in different vessel activities, as well as to define variable ranges for such vessel activities.

A more detailed explanation of both vessel's activity (i.e., cruising, fishing and inactivity at sea) and engines performances while at these activities are presented as Supplementary Material. This includes the values of the vessel speed, the power and speed of main and auxiliary engines, the shaft power, and the propeller pitch at each activity. The profile also includes a description of the different phases occurring during a fishing set.

3.1.2. Activity and energy pattern

According to the activity pattern of Vessel A (Table 3), a typical tuna purse seiner trip lasted 33.1 ± 10.8 days, of which 68.5% (22.7 ± 7.2

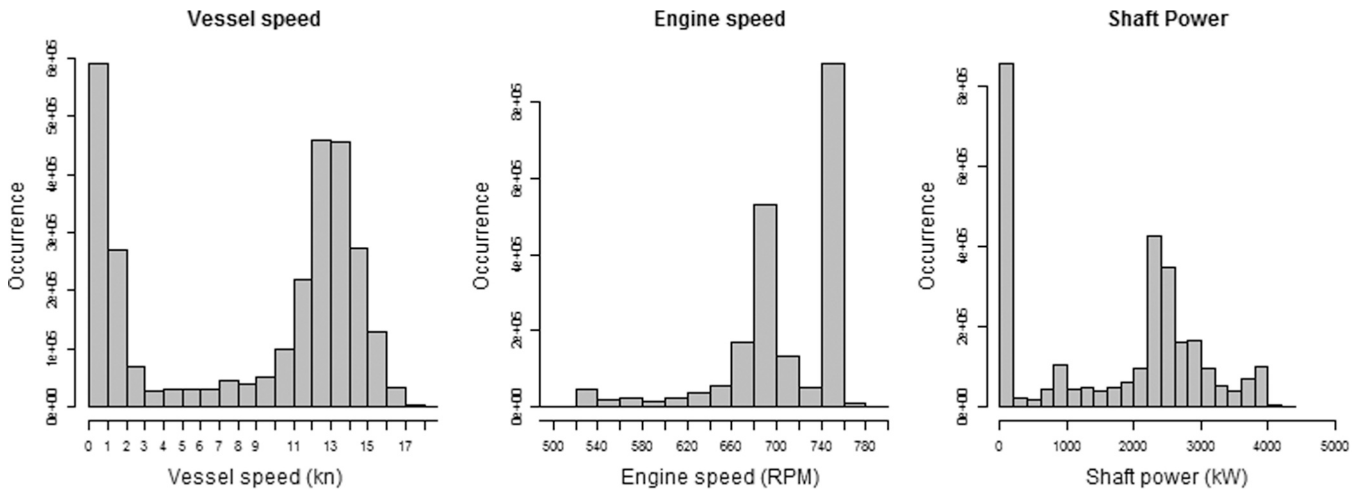

Fig. 2. Methodology followed to classify the vessels activity in Cruising, Fishing, Inactive and In Port modes.

Table 3
Main engine performance variables with their average values and standard deviations for Vessel A.

		Cruising	Fishing	Inactive at sea	In port
Engine speed	rpm	706.4±15.2	157.5±34.0	0.2±0.0	14.9±13.6
Propeller pitch	%	74.5±1.6	6.2±0.8	2.0±0.1	2.0±0.1
Shaft power	kW	2423.3±129.8	293.8±44.9	0.4±0.9	8.6±10.9
Main engine's fuel consumption	kg/h	512.6±24.5	72.4±11.9	0.9±0.3	3.0±3.0
Aux. engines' fuel consumption	kg/h	121.8±12.7	190.8±10.9	119.7±17.1	91.1±6.2
Vessel's speed	kn	12.2±0.3	1.9±0.2	1.1±0.2	0.0±0.0
Nº auxiliaries ON	nº	1.2±0.1	2.8±0.2	1.2±0.1	1.1±0.1
Power auxiliary engines	kW	535.4±72.8	853.7±60.3	513.7±100.2	373.2±97.0
Trip duration	days/trip	22.7±7.3	2.6±1.0	5.2±2.8	2.7±1.5
	% per trip	68.5	7.7	15.6	8.1
Distance navigated	nm/trip	6606.5±2034.1	114.9±43.5	139.4±72.6	3.6±3.14
	% per trip	96.2	1.7	2.0	0.1

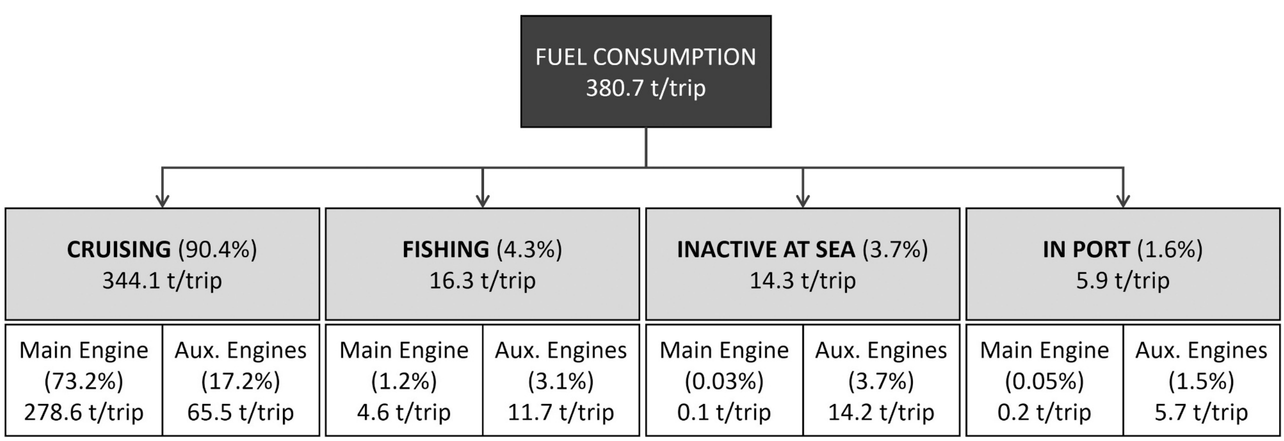

Fig. 3. Energy pattern of Vessel A, including fuel consumption in cruising, fishing, inactivity at sea and in port: values are presented in total, and per engine type.

days per trip) was dedicated to cruising, 7.7% fishing (2.6 ± 1.0 days), 15.6% (5.2 ± 2.8 days) inactive at sea, and the remaining 8.1% (2.7 ± 1.5 days) in port. The energy pattern (Fig. 3) explains that the vessel consumed on average 380.6 ± 112.8 t of fuel per trip, of which more than 90.4% was consumed while cruising, 4.3% during fishing operations, 3.8% while inactive at sea, and 1.5% while staying in port. The main engine consumed 75% (283.6 ± 88.8 t) of the fuel, being the remaining 25% used by the auxiliary engines (96.9 ± 25.7 t). The fishing activity consumed less fuel than the inactive periods at sea and in port together. Cruising was the responsible for the 96.2% of the total distance navigated per trip; nonetheless, fishing accounted for the 1.7%, and the inactive at sea the 2.0%.

3.2. *Energy efficiency indices for FAD and FSC fishing*

Energy efficiency indices of Vessel A and the selected 14 trips of other vessels are listed in Table 4. For Vessel A the energy efficiency values for the trips with FAD dominance (FAD#3, FAD#4, FAD#5, FAD#8, and FAD#10) were used to estimate Vessel A's FAD trip average values. The trip FAD#7 was slightly irregular in comparison to other FAD trips due to it presented very high fishing efficiency (large catch with very little distance navigated during the trip); however, no

Table 4
Energy efficiency indices for the analysed fishing trips with FAD and FSC sets dominance, including stays in port, cruising, fishing, and inactive phases.

Fishing trip code	Fuel cons.[a] (t/trip)	Catch (t)	Duration[a] (days/trip)	Distance sailed (nm/trip)	Catch per distance sailed (t/nm)	Energy efficiency indices			Economic index[c] 1000US$ catch landed / t fuel
						FUI (L/t)	Carbon footprint (t CO_2/ trip)	EEOI (g CO_2/ t·nm)	
VesselA#1	538.1	941.4	49	9898	0.10	635.1	1762.4	185.1	3.4
VesselA#2	423.5	328.3	35	8057	0.04	1433.1	1373.7	513.2	1.1
VesselA#3	362.0	707.0	25	6573	0.11	569.0	1177.1	249.8	2.6
VesselA#4	254.8	680.3	20	4601	0.15	416.1	829.5	261.0	5.0
VesselA#5	493.9	675.9	39	9087	0.07	811.9	1598.9	257.8	2.3
VesselA#6	470.4	1059.7	40	8619	0.12	493.2	1538.6	165.1	3.9
VesselA#7	178.0	908.2	14	2961	0.31	217.8	571.0	212.3	9.0
VesselA#8	354.0	1305.7	27	6498	0.20	301.2	1161.0	133.8	5.1
VesselA#9	326.8	368.6	28	6494	0.06	984.9	1056.8	437.6	2.0
VesselA#10	346.3	884.3	28	5822	0.15	435.2	1132.0	215.7	4.1
FAD#1	243.9	355.8	23	4463	0.08	761.9	795.7	NA	2.5
FAD#2	330.5	459.1	26	6047	0.08	800.0	1078.2	NA	2.5
FAD#3	296.1	1105.2	27	5417	0.20	297.7	965.8	NA	6.2
FAD#4	366.0	395.2	33	6697	0.06	1029.1	1194.1	NA	1.7
FAD#5	271.2	2579.7	28	4962	0.52	116.8	884.7	NA	14.0
FAD#6	113.6	430.2	20	2078	0.21	293.4	370.5	NA	5.9
FAD#7	103.3	2317	27	1890	1.23	NA	337.0	49.5	34.8
VesselA (FAD)[b]	362.2	850.6	28	6516	0.13	506.7	1179.7	NA	3.8
FSC#1	248.4	769.2	25	4545	0.17	358.8	810.4	NA	7.4
FSC#2	429.5	470.0	48	7859	0.06	1015.5	1401.2	NA	2.6
FSC#3	176.9	500.0	24	3236	0.15	393.0	577.0	NA	6.7
FSC#4	127.6	597.0	25	2335	0.26	237.5	416.3	NA	11.2
FSC#5	119.8	552.0	25	2191	0.25	241.0	390.6	NA	10.2
FSC#6	213.9	470.0	48	3914	0.12	505.7	697.9	NA	5.2
FSC#7	98.1	336.0	19	1795	0.19	324.4	320.0	NA	7.5
Average ± Standard Deviation									
VesselA	374.8±110.1	785.9±299.4	30.0±10.4	6861.0±2119.9	0.13±0.08	629.8±363.3	1220.1±361.5	263.1±120.4	3.8±2.2
FAD	250.7±103.9	887.2±875.1	26.5±3.8	4758.8±1870.2	0.31±0.40	543.6±330.6	850.7±335.9	NA	8.9±11.2
FSC	202.0±113.9	527.7±134.1	30.6±12.1	3696.4±2083.3	0.17±0.07	439.4±270.4	659.1±371.5	NA	7.2±2.9

[a] The scores include all the activities: stays in port, cruising, fishing, and inactive periods.
[b] The data correspond to the average values of only those sets with clear dominance of using FADs (nº sets using FADs per trip > 90%).
[c] Source of tuna sp. prices (USD/metric tonne): Thai Customs data www.customs.go.th Union, Bangkok, average for 2014.

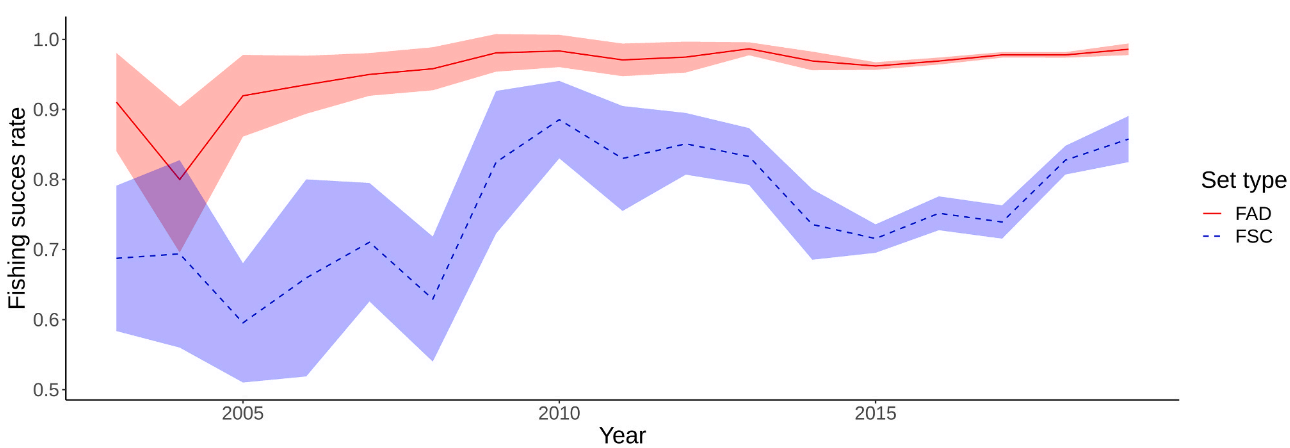

Fig. 4. Comparison of fishing success rate using FAD (solid line) or FSC (dashed line) strategy from 2003 to 2019. The lines represent the mean fishing success rate, whereas the rectangles indicate the 95% confident interval limits.

statistically significant difference was observed among other FAD trips that could make it an outlier, therefore it was considered in the calculations.

FAD fishing appeared to be more energy demanding than FSC in terms of FUI and carbon footprint (t CO_2/t fish) scores. FAD trips required travelling longer distances (1.4% more) than FSC type trips (Table 4); however, the differences were not statistically significant (*t*-test) due to the high variance across trips and the small sample size. Thus, considering that cruising consumed 90.4% of the total fuel of a trip, it seems logical to obtain larger FUI indices for FAD than for FSC.

In contrast, the index catch per set was higher in FAD sets than in FSC (43.3 ± 42.9 and 20.7 ± 8.7 of tonnes of catch/set respectively). Likewise, FAD strategy (of Vessel A over the last 10 years) showed higher and more regular success rates than FSC sets (Fig. 4). However, FAD sets resulted less cost-efficient than FSC sets with 5.2–7.2 1000US$/t fuel respectively (Table 4).

Yet it must be noted, that both fishing strategies presented efficient and not very efficient fishing trips and that the considered sample size was small.

4. Discussion

Most of studies use the FUI indicator to compare the energy consumption among fisheries. Despite sometimes the indicator has been used by mass (Schau et al., 2009), or transformed to economic value of the annual fuel bill (€) (Davie et al., 2014) or by edible protein (i.e. EROI) (Tyedmers et al., 2005) or carbon forcing (i.e. kg CO_2 per kg fish protein) (McKuin et al., 2021), the common procedure has been to compare the absolute value of fuel consumption related to the catch of a whole year for each fleet (Parker et al., 2015; Tyedmers and Parker, 2012). Fuel consumption is a critical variable to study but is often overlooked as few researchers calculate the FUI indicator per trip or based on monitored instantaneous fuel consumption, as done in the present study and elsewhere (Basurko et al., 2013).

According to Tyedmers and Parker (2012), tuna purse seine fisheries has been the most efficient tuna fisheries (386 L/t), when compared to longline, pole and line or trolling fisheries (1069 L/t, 1485 L/t, 1107 L/t respectively). However, Maldivian pole and line fishery have reported very low FUI values of between 197 L/t and 328 L/t (Miller et al., 2017). Our study shows higher average FUI scores 439 L/t and 544 L/t for FSC and FAD accordingly, and 630 L/t for Vessel A. These values are larger than those observed by Hospido and Tyedmers (2005) (373 L/t for Galician purse seine fleet operating in the Indian Ocean), but smaller than those from Ecuadorian large tuna purse seiners (709 L/t) (Avadí et al., 2015). It must be also considered that one of the FAD trips showed a very low FUI of 49.5 L/t. Considering the small sample (10 trips) we cannot know if it is a real outlier or very efficient trips occur from time to time. Current research shows that the use of decision support system based on machine learning and mathematical optimisation could half routing time and fuel consumption when fishing with FADs, whereas FSC has not yet been tested in such systems (Granado et al., 2021). Moreover, FADs successful fishing rates have been increasing, whereas FSC successful fishing rates are more variable (Fernandes et al., 2021). As shown here historical successful fishing rates for FADs are around 95.7 $\pm$ 3.8%, whereas for FSC 80.6% $\pm$ 5.8. Further work is needed to understand the sources of the differences considering that these studies are in a diversity of regions with different vessels not targeting the same species and covering different years of operations. For example, some studies have provided performance indicators for different vessel groups based on the classification on their gross tonnage (Guillotreau et al., 2011) or the length (Jafarzadeh et al., 2016), as it seems likely that the main and auxiliary engine powers vary with these variables. Nonetheless, the vessels used in the present study (Table 1) corroborate the good correlation between total length and installed power and ($r = 0.9$), in opposite to that between gross tonnage and install power ($r = 0.7$), highlighting the preference of using length in energy-related studies for classification of vessels.

Parker et al. (2018) concluded also that the pelagic fisheries are more fuel efficient (430 L/t, fish size >30 cm) than the demersal fisheries (539 L/t). Differences can also be found between target species and among oceans (i.e., Atlantic, Indian and Pacific), being the purse seiners operating in the Atlantic and Indian Ocean the least efficient according to FUI (Tyedmers and Parker, 2012). These differences may be due to variations in the productivity of the oceans and in the fishing strategy, but also to other factors such as to the fact that the Pacific Ocean is the largest and the distance travelled by vessels is higher. The Pacific Oceans is widely known as being more productive than Indian and Atlantic Oceans, in terms of tuna catches, despite worst FUIs are observed in the Pacific Ocean (527 L/t) in comparison to Indian (373 L/t) and Atlantic (442 L/t) Oceans (Hospido and Tyedmers, 2005). The differences are also assessed by region, being Asia (without China), Oceania and China the least efficient regions in terms of FUI (554 L/t, 636 L/t, 809 L/t respectively); in global terms, same authors estimated FUI index for global fisheries in 489 L/t (Parker et al., 2018), which are close to the FUI values obtained in the present contribution (543.6 L/t and 439.4 L/t for FAD and FSC respectively).

Vessel A presents an average FUI higher than the values presented elsewhere for tuna purse seiners but lower than other gear types such as longline, pole and line, and trolling (Tyedmers and Parker, 2012). Nonetheless, the main engine power (4500 kW) alone is larger than that of the main and auxiliary engines together presented in the mentioned article. Thus, considering the power of its main engine, one would expect that the FUI of analysed FAD and FSC trips of Vessel A, which is a vessel with primarily FAD-oriented fishing strategy, be greater. Yet, published studies fail to differentiate between fishing strategies, and the only reference discussing it is the work by Chassot et al. (2021) who observed differences in fuel consumption based on not only fishing strategy (FAD versus FSC) but also in relation to vessel size, fishing effort, period of the vessel construction (being the ones built in the 1990–2000 the most efficient, due to the absence of storing of the catch at ultra-low temperature to improve fish quality). This approach highlights the need to have a good definition of the fishing activity and energy patterns of tuna purse seiners by fishing strategies (FAD or FSC) to compare the energy usage and efficiency between FAD and FSC.

The activity pattern of fishing vessels has been approached from different angles. The classification of the activities has been strongly related to the fishing gear employed and the objective of the study. The normal classification for tuna purse seiners activities using VMS data differentiate between *cruising*, *fishing* and *searching*, by only focusing on the period the vessel is active during daytime (Bez et al., 2011). In that particular case, fish searching was the most dominant activity of a tuna purse seiner (i.e., 59% of the time) (Bez et al., 2011). However, due to one of the objectives of the present study was to define the activity and energy patterns of the fishing vessels, more detailed categories were necessary. In the current study, fish tracking was considered as part of fishing activity, unlike in Bez et al. (2011) where it was considered as an independent vessel activity. Likewise, both the active and the inactive periods of the vessels were studied in this work, as energy is not only consumed while the vessel is active but also when inactive and in port. The key limitation of doing a classification by main engine and vessel performance is related to the activity classification accuracy; that is, to be sure that a vessel is indeed involved in a certain activity. In that sense, determining the thresholds and ranges of values that help identifying whether a vessel is *cruising* or *fishing* may result complicated in occasions. One way to improve the analysis would be to make the observers onboard keep a comprehensive and high frequency registry of all the activities happening onboard. This could allow contrasting monitored data of the vessel and engines with the vessel's activity provided by the observer. The use of this information would facilitate the classification of the engine data on *cruising* and *fishing*, proposing more accurate criteria to classify these activities, and optimising the models. Despite these limitations, results obtained in the present study are good indicators of the energy peculiarities of FAD and FSC fishing.

Tunas are highly migratory species (Hallier, 2005) and fishing vessels address fish availability dynamics with their adaptive fishing strategies (Dagorn et al., 2013; Fonteneau et al., 2013; Lopez et al., 2014). Indeed, surface tuna availability determines, among other factors, the fishing strategy used by a given vessel. For instance, the greater surface tuna school availability between December and February in some areas of the Indian Ocean, makes the vessel strategy to be more oriented to FSC fishing than in the rest of the year (Guillotreau et al., 2011). When the fishing strategy is more oriented to use FADs, the vessels tend to navigate non-stop and further than when the fishing strategy is FSC oriented (Delgado de Molina et al., 2012a, 2012b), especially since the introduction of echo-sounder buoys in their fishing strategy (Lopez et al., 2014). Fig. 5 illustrates examples of the trajectories of two common fishing trips, including locations with the positive sets conducted during the fishing trip: a FAD-oriented fishing trip (left) and a FSC-oriented one (right). The trajectory of FSC trip (Fig. 5, right) highlights the irregularities and sinuosity of the FSC oriented fishing trip, where most of the sets are conducted in concentrated areas, and longer distance navigated to find the fish schools and the relative

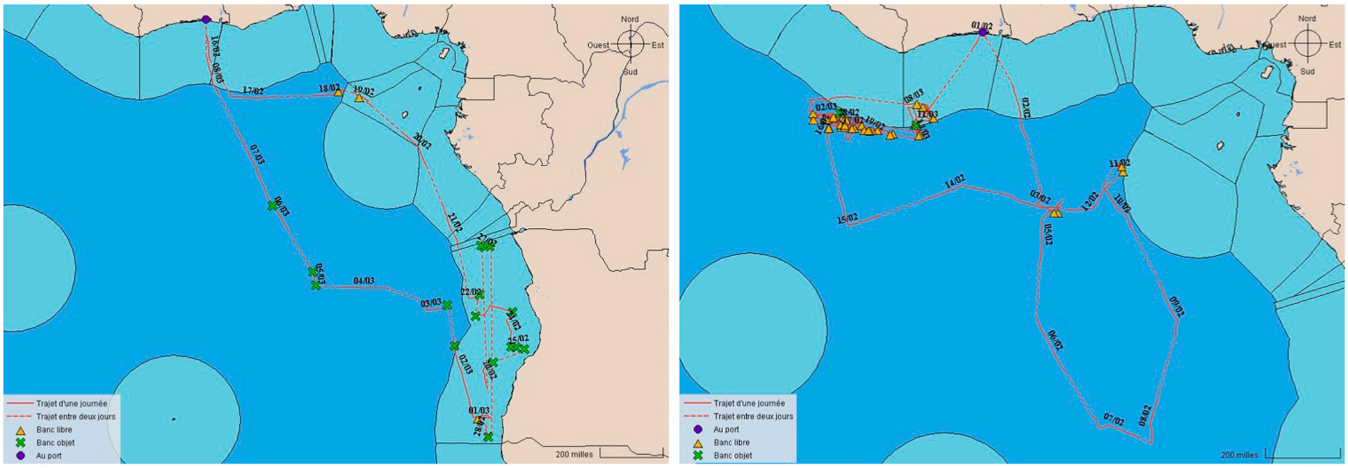

Fig. 5. Example of a trip with high dominance of FAD sets (left) and with FSC sets (right). The left figure corresponds to trip FAD#1 and the right to FSC#6.

proximity to shore. This may also be due to the season of the year which affects the tuna migration (Bez et al., 2011).

FAD and FSC fishing not only differ in energy efficiency indices; FAD-related catch is more diverse in species, including both target and no-target species, and usually include smaller size individuals (Chumchuen et al., 2016; Guillotreau et al., 2011). The species composition for FAD sets include target tuna species and rarely small tunas, such as little tunny (*Euthynnus alletteratus*), and frigate species (*Auxis sp.*), along with juveniles of yellowfin and bigeye tuna (Guillotreau et al., 2011; Hare et al., 2015). In contrast, FSC fishing sets mainly catch adult yellowfin tuna, and they are usually of larger size (>30 kg), except for skipjacks FSC fishing sets. The regular use of FADs has required larger fishing vessels, and additional technology and infrastructure onboard, such as satellite-buoys equipped with echo-sounders and the use of supply vessels (Lopez et al., 2014, 2015; Scott and Lopez, 2014). All this technology and the adaptive nature of the fleet have led vessels to be able to increase their catches when setting on FADs. The fishing efficiency with FADs (270.9 t/trip) is higher than in FSC (202.0 t/trip), which usually includes a larger number of null sets (as proved by Chumchuen et al. (2016)); in contrast, FSC are more cost efficient (6.3 1000€/t fuel) than FAD sets (4.4 1000€/t fuel) as a result of the distance navigated and the species composition. However, and despite all these differences, results of the analysed trips indicated that FSC (439.4 L/t) are less energy intensive than FAD fishing (543.6 L/t) (also observed by Chassot et al., 2021), likely related to the amount of total distance travelled during the whole trip to obtain the final catch.

Tuna purse seiners, on average, are much more inefficient than any merchant type ship. Their scores are placed in between train and road transport mode, being closer to road transport values but yet far from those of shipping (Buhaug et al., 2009). To do this comparison, the EEOI results (Table 4) have been transformed to distance in kilometres, instead of nautical miles. The average values of EEOI of FAD, FSC and Vessel A trips (considering all 10 trips) are 167.8 g CO_2/t·km, 189.5 g CO_2/t·km and 142.1 g CO_2/t·km, respectively. The minimum EEOI values found for FAD (36.7 g CO_2/t·km) fit well in the range for shipping in general, excluding larger tankers and bulk carriers which are the most efficient. As the minimum values of Vessel A (72.2 g CO_2/t·km) obtained in a FAD dominated fishing trip, corresponds to similar ranges of Ro-Ro ships; it is worth mentioning that this positive trend is not identified for FSC fishing, which minimum values are still considerably high (123.0 g CO_2/t·km) in comparison to those of shipping.

5. Conclusions

Tuna purse seiners are one of the most fuel intensive fishing fleet operating in our oceans due to, among other things, their installed power, technology onboard, catch size, and distance covered (4759 ± 1870 nm/trip with FAD and 3696 ± 2083 nm with FSC strategy) and long duration of their fishing trips (33.1 days). In terms of duration a fishing trip lasts 33.1 days, of which 68% of a trip is dedicated to cruising, 8% fishing, 16% of the time the vessel is inactive and adrift at sea, and the remaining 8% the vessel is in port. A total of 381 tonnes of fuel are consumed on average in a fishing trip, of which 90% is due to cruising, 4% to fishing, 4% to the inactive period at sea mainly at night, and 2% to stays in port. The main engine consumes the 75% of the total fuel consumption of a trip, while the 25% is used by the auxiliary engines.

Different fishing strategies can be adopted by the purse seiners (i.e., FAD o FSC), each presenting different characteristics. FSC appear to be less energy intensive than FAD (in terms of L/t). However, FADs present higher set success rates, meaning that there are technically more efficient. Both FAD and FSC are less energy intensive (in terms of L/t) that other tuna fishing gears such as longline and trolling. Comparing energy efficiency in terms of IMO's EEOI index, tropical tuna purse seiners are on average less energy efficient in comparison to different ship types, and their scores can be comparable with those of average road transportation, highlighting their inefficiency. But the good scores found in some of the FAD trips, which were similar to those of RoRo vessels, suggest that FAD fishing can present much improved EEOI values than FSC, for which this value is quite constant and high. Further studies are necessary to compare the energy efficiency of FSC and FAD fishing under different seasons and oceans.

CRediT authorship contribution statement

Oihane C. Basurko: Experimental design, Data analysis and writing up. **Gorka Gabiña**: Experimental design and intellectual contribution on engine monitoring and energy efficiency indices. **Igor Granado**: Data modelling and statistical analysis, Editing. **Jon Lopez, Hilario Murua**: Intellectual contribution on tropical tuna purse seine fishery and FAD/FSC sets, Contribution to writing up and editing. **Jose A. Fernandes**: Supervision of data modelling and statistical analysis, Review, Editing. **Jon Ruiz**: Intellectual contribution on FAD and FSC fishing sets and data acquisition. **Iñigo Krug**: Intellectual contribution on tropical tuna purse seine activities selling prices. **Zigor Uriondo**: Intellectual contribution on engine monitoring for topical tuna purse seiners.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2021.106139.

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