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Fuel consumption and air emissions in one of the world's largest commercial fisheries

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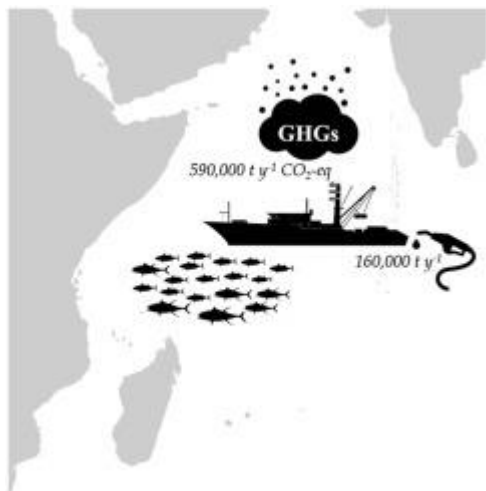
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Abstract :

The little information available on fuel consumption and emissions by high seas tuna fisheries indicates that the global tuna fleet may have consumed about 2.5 Mt of fuel in 2009, resulting in the production of about 9 Mt of CO₂-equivalent greenhouse gases (GHGs), i.e., about 4.5–5% of the global fishing fleet emissions. We developed a model of annual fuel consumption for the large-scale purse seiners operating in the western Indian Ocean as a function of fishing effort, strategy, and vessel characteristics based on an original and unique data set of more than 4300 bunkering operations that spanned the period 2013–2019. We used the model to estimate the total fuel consumption and associated GHG and SO₂ emissions of the Indian Ocean purse seine fishery between 1981 and 2019. Our results showed that the energetic performance of this fishery was characterized by strong interannual variability over the last four decades. This resulted from a combination of variations in tuna abundance but also changes in catchability and fishing strategy. In recent years, the increased targeting of schools associated with fish aggregating devices in response to market incentives combined with the IOTC management measure implemented to rebuild the stock of yellowfin tuna has strongly modified the productivity and spatio-temporal patterns of purse seine fishing. This had effects on fuel consumption and air pollutant emissions. Over the period 2015 to 2019, the purse seine fishery, including its support vessel component, annually consumed about 160,000 t of fuel and emitted 590,000 t of CO₂-eq GHG. Furthermore, our results showed that air pollutant emissions can be significantly reduced when limits in fuel composition are imposed. In 2015, SO₂ air pollution exceeded 1500 t, but successive implementation of sulphur limits in the Indian Ocean purse seine fishery in 2016 and 2018 have almost eliminated this pollution. Our findings highlight the need for a routine monitoring of fuel consumption with standardized methods to better assess the determinants of fuel consumption in fisheries and the air pollutants they emit in the atmosphere.

Graphical abstract



Highlights

► We modelled the annual fuel consumption in tuna purse seiners of the Indian Ocean. ► Days at sea, numbers of operations, vessel length and age affect fuel consumption. ► Fuel Use Intensity and consumption showed strong variability over 1981 to 2019. ► Greenhouse gas emissions were about $600,000 \text{ t y}^{-1}$ of $\text{CO}_2\text{-eq}$ over 2015 to 2019. ► Sulphur limits reduced annual SO_2 emissions from $>1500 \text{ t}$ to almost none since 2018.

Keywords : Air pollution Fish aggregating device (FAD), Energy use Greenhouse gas (GHG), Sulphur dioxide, Tuna purse seine fisheries

46 **Introduction**

47 Oceangoing ships constitute a significant source of air pollution through the emission of
48 greenhouse gases (GHGs) such as carbon dioxide (CO₂) and nitrous oxide (N₂O), and other air
49 pollutants such as sulphur dioxide (SO₂) (Corbett and Fischbeck, 1997; Corbett et al., 1999).
50 Global shipping emissions have major effects on the environment, including ocean acidification
51 and contribution to climate change, and on human health (Corbett et al., 2007; Jägerbrand et
52 al., 2019; Tian et al., 2013). With about 2.5 million motorized vessels out of 4.6 million vessels in
53 operation (FAO, 2018; Rousseau et al., 2019), the global fishing fleet annually consumes about
54 30-40 million tonnes (Mt) of fuel and accounts for more than 1% of the global marine fuel
55 demand (Parker et al., 2018; Tyedmers et al., 2005). Global emissions from fuel combustion by
56 fishing vessels have been estimated at about 180-200 Mt of CO₂-equivalent GHGs every year
57 (Parker et al., 2018). Furthermore, total emissions related to fishing go beyond the direct
58 emissions of fuel combustion because of indirect effects of upstream and downstream
59 activities, e.g., emissions generated during fuel processing and refining, fish product packaging
60 and transport (Winebrake et al., 2007). Fishing and water transport are therefore considered
61 among the most air-polluting industries, per unit of wealth created, in particular for CO₂ and
62 SO₂ (Bagoulla and Guillotreau, 2020). To improve air quality and global health, global sulphur
63 limits of 0.5% (mass/mass) in fuel oil have been recently imposed by the International Maritime
64 Organization (IMO) under the MARPOL convention (Annex VI) to reduce the emissions of both
65 sulphate aerosols and sulphur-containing particles (Chu Van et al., 2019).

66 Industrial tuna fisheries are one of the most highly capitalized fisheries in the world (Miyake et
67 al., 2010). High seas fishing vessels, typically longer than 25 m, travel long distances to search

68 and catch highly migratory tuna and billfish widely distributed across the world's oceans
69 (Fonteneau, 2010). Energy costs make up to 20% or more of total running costs in the high seas
70 fishing industry (Miyake et al., 2010). However, little information is available on fuel
71 consumption and emissions by high seas tuna fisheries. This said, a survey-based study
72 indicated that the global tuna fleet may have consumed about 2.5 Mt of fuel in 2009, resulting
73 in the production of about 9 Mt of CO₂-equivalent GHGs, i.e., about 4.5-5% of the global fishing
74 fleet emissions (Tyedmers and Parker, 2012). Although large-scale purse seiners represent a
75 very small component of the global tuna fleet (~700 vessels in 2020; Justel-Rubio and Recio
76 (2020)), they accounted for more than two thirds of the global catch of tuna since the late
77 2000s. In 2009, the global tuna purse seine fishery was responsible for the release of more than
78 3 Mt of CO₂-equivalent GHGs into the atmosphere (R. W. R. Parker, Hartmann, et al., 2015).

79 The global tuna purse seine fishery has significantly changed over the last decade. The purse
80 seine catches of tropical tuna increased from about 2.8 Mt in the late 2000s to more than 3.2
81 Mt in the late 2010s, with about two thirds of the catch coming from fish aggregating devices
82 (FAD) and the rest from free-swimming schools (FSC) and schools associated with dolphins
83 (Taconet et al., 2018). In the Indian Ocean, the catch of the tuna purse seine fishery, composed
84 of about 50 vessels larger than 65 m, increased from 280,000 t in the late 2000s to almost
85 500,000 t in 2018 (Fiorellato et al., 2019). In particular, the advent and increasing use of echo-
86 sounder buoys attached to the FADs deployed at sea has greatly increased the efficiency and
87 catchability of purse seiners over the last decade (Lopez et al., 2014; Wain et al., 2020).

88 Furthermore, 20 support vessels assist the purse-seine fishing fleet by maintaining a network of
89 FADs. These support vessels have proved to be instrumental in increasing fishing success,

90 although they consume additional fuel energy and produce more GHG emissions (Assan et al.,
91 2015; Ramos et al., 2010). Over the last decades, an increasing proportion of FAD-caught tuna
92 has been observed in the Indian Ocean purse seine fishery. Since 2017, the use of FADs has
93 been further accentuated by a shift in the fishing strategy to target more skipjack tuna
94 (*Katsuwonus pelamis*) (Assan et al., 2019; Baez et al., 2018; Floch et al., 2019). This change
95 occurred following the implementation of a total allowable catch on yellowfin tuna (*Thunnus*
96 *albacares*) by the Indian Ocean Tuna Commission (IOTC) with the aim of rebuilding the
97 yellowfin tuna stock. Yellowfin tuna compose the large majority of FSCs while tuna schools
98 associated with FADs are dominated by skipjack tuna (Fonteneau et al., 2013). Such a change in
99 fishing strategy may have affected the fuel consumption and air pollutant emissions as purse
100 seiners targeting schools associated with FADs have been shown to consume more fuel per ton
101 landed than purse seiners targeting FSCs at global scale (R. W. R. Parker, Vázquez-Rowe, et al.,
102 2015).

103 In this context, the overarching objective of the present study was to estimate with more
104 accuracy the GHG and SO₂ emissions of the tuna purse seine fishery of the Indian Ocean over
105 the period 1981 to 2019 and assess how they vary with fleet structure, fishing strategy and
106 productivity. First, we developed a model of fuel consumption of tropical tuna purse seiners
107 based on a unique large data set of bunkering operations that took place in the Seychelles
108 between 2013 and 2019. Secondly, we used the model to estimate the direct total fuel
109 consumption and associated GHGs and SO₂ emissions for the western Indian Ocean purse seine
110 fishery over the last four decades (1981-2019), including the fuel consumed by the fleet of

111 support vessels. Finally, we assessed the extent of the reduction in SO₂ emissions following the
112 mandated reduction in sulphur content of the marine diesel oil delivered in the Seychelles.

113 **Materials & Methods**

114 **Fuel data**

115 All bunkering operations in Port Victoria are recorded by the Seychelles Petroleum Company
116 (SEYPEC) and include the vessel name, type of gasoil (i.e., sulphur content), volume (l) and
117 weight (t) delivered, and the date and location of delivery. All purse seiners and support vessels
118 considered in the study use the same marine diesel oil, a marine fuel composed of various
119 blends of distillates and heavy fuel oil. Except for sulphur, the general composition of the
120 marine fuel delivered in Port Victoria has not varied much over the last four decades. The
121 storage capacity of fuel varies with vessel size, i.e., between 370-1,000 m³ and 90-160 m³ for
122 purse seiners and support vessels, respectively. The data set available for the study covered the
123 period 2013 to 2019 and included a total of 3,676 and 703 bunkering operations for 52 purse
124 seiners and 29 support vessels, respectively. Sulphur content in the fuel delivered to the purse
125 seiners and support vessels calling on Port Victoria was reduced from 0.5% to 0.05% on the 1st
126 of March 2016 and from 0.05% to 0.005% on the 15th of May 2018.

127 **Fisheries data**

128 The purse seine fleet based in Port Victoria, Seychelles, represents more than 90% of the total
129 purse seine catch of the Indian Ocean over the period 1981 to 2019 (Assan et al., 2019; Baez et
130 al., 2018; Floch et al., 2019; Kawol et al., 2019). The activities of the purse seiners operating in
131 the western Indian Ocean have been monitored since the early 1980s by the Seychelles Fishing

132 Authority (SFA) in collaboration with the French national Research Institute for Sustainable
133 Development (IRD) and the Spanish national Institute of Oceanography (IEO). The monitoring
134 consists of the collection and processing of fisher' logbooks, landings and sales notes, and
135 sampling of the catch at unloading. Information on landings is recorded for each trip. All purse
136 seiners are equipped with a Vessel Monitoring System (VMS) and monitored at sea by their
137 respective national fisheries administrations. For each fishing operation, the catch by species
138 and type of tuna school association (i.e., FSC and FAD) are recorded in the logbook. Days at sea
139 constitute the standard effort unit to monitor purse seine fishing effort (FAO, 1997). Purse
140 seiner logbook data constitute the basis of the aggregated catch-effort data reported to the
141 IOTC and were assumed to be comprehensive and accurate in this study. By contrast, support
142 vessel logbooks were incomplete or missing, preventing the computation of the annual number
143 of days at sea for this component of the purse seine fishery.

144 **Vessel fuel consumption**

145 The fishing activities of purse seiners that operated in the western Indian Ocean from 2013 to
146 2019 were linked with the bunkering operations that took place at Port Victoria, Seychelles,
147 during the same period. We selected a subset of purse seiners that unloaded and transshipped
148 all their catch in Port Victoria, assuming that the vessels did not purchase fuel elsewhere. In
149 most cases, the vessels take the opportunity to refuel during unloading operations. We
150 considered that the fuel delivered in a given year was representative of the landings of the year
151 although a few fishing trips may span two years.

152 We used generalized additive models (GAMs) to examine the relationship between the annual
153 quantity of fuel (F ; t) delivered to the subset of selected purse seiners as a function of vessel
154 length overall (LOA ; m), annual number of days at sea (D) and number of fishing sets on FSCs
155 (S_{FSC}) and FADs (S_{FAD}) in order to account for differences in fishing effort and strategy. By
156 using local smoothers, GAMs make no *a priori* assumptions about the nature of the associations
157 between predictors and response variables (Hastie and Tibshirani, 1990). The period of
158 construction (C) of each purse seiner was included in the model as a categorical covariate (i.e.,
159 1970-1980s, 1990-2000s and 2010s) to account for technological improvements in diesel
160 engines and vessel design. Year (Y) was finally included as a categorical covariate to account for
161 changes in tuna abundance and accessibility, e.g., changes in access opportunities related to
162 fisheries agreements. The general form of the model fitted to the fuel data was:

$$163 \quad F_{v,Y} = s(LOA_v) + C_v + s(D_{v,Y}) + s(S_{FAD_{v,Y}}) + s(S_{FSC_{v,Y}}) + Y + \epsilon_{v,Y}$$

164 Where v and Y indicate vessel and year, respectively and the model residuals $\epsilon_{v,Y}$ were
165 assumed to be independent and identically distributed normal random variables with mean
166 zero and constant variance. Model fitting and the automatic selection of degrees of freedom
167 for the regression splines were performed using the generalized cross-validation method
168 (Wood, 2011). Assumptions of homoscedasticity and Gaussian distribution were checked
169 through the residuals.

170 Effects of vessel size were assessed by comparing predictions of annual fuel consumption for
171 the smallest purse seiner ($LOA = 67.3$ m), a purse seiner of mean length ($LOA = 89.7$ m), and the
172 largest purse seiner of the fleet ($LOA = 116$ m), all built in the 1990s, having operated over 273

173 days and having made 223 and 51 sets on FAD and FSC, respectively, corresponding to the
174 mean values observed in the data set. Model predictions were also performed to assess the
175 influence of the fishing strategy (i.e., FSC vs. FAD) on purse seiner's annual fuel consumption.
176 For these simulations, we considered a purse seiner built in the 1990s of mean length 89.7 m in
177 operation for 273 days at sea (i.e. the mean value observed in the data set) for a number of sets
178 varying between 0 and 141 made either on FADs or FSCs and corresponding to the range of
179 values observed for FSCs in the data set.

180 Statistical analyses were performed in R version 3.6.3 (R Core Team 2020).

181 **Energetic performance**

182 The Fuel Use Intensity (FUI), i.e., annual volume of fuel (l) consumed per ton of wet weight
183 landings, was used to describe and assess the environmental performance of the purse seine
184 fishery (Parker et al., 2018; R. W. R. Parker, Hartmann, et al., 2015). The annual value of FUI was
185 computed for all purse seiners to describe the variability between vessels. The fuel consumed
186 by the support vessels could not be included in the individual FUI of the purse seiners as they
187 were generally assisting several vessels and this information was not available for most years of
188 the study period. To account for this additional fuel consumption, the annual FUI values were
189 scaled up by the FUI of the support vessels computed as the ratio between the total annual
190 quantity of fuel consumed by this fleet segment and the total landings of the fishery.

191 **GHG and SO₂ emissions**

192 Emissions of GHGs and SO₂ from marine fuel combustion are considered to be mostly
193 dependent on fuel contents while engine and combustion technology may have more influence

194 on the release of other pollutants such as nitrogen oxides (Holloway et al., 2006; Winnes and
195 Fridell, 2009). GHGs emitted from water-borne navigation include CO₂, N₂O, methane (CH₄),
196 carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), particulate matter
197 (PM), and oxides of nitrogen (NO_x) (Waldron et al., 2006). There is currently little information
198 available about the emissions of each GHG by large-scale purse seiners and their associated
199 support vessels. Recently, Parker et al. (2015) estimated a total GHG-to-fuel ratio of 3.1 kg CO₂-
200 eq per litre of fuel consumed for the purse seine fishery. This emission factor reflects both the
201 direct emissions of the marine distillate fuel used by the vessels (2.8 kg CO₂-eq l⁻¹) and the life
202 cycle emissions from mining, processing, and transporting, to packaging (0.3 kg CO₂-eq l⁻¹)
203 (Hospido and Tyedmers, 2005; Hospido et al., 2006; Parker and Tyedmers, 2015). This emission
204 factor is very similar to that of other studies (Dalsøren et al., 2009; Ziegler and Hansson, 2003)
205 and it has been used for a large range of fisheries worldwide (Parker et al., 2018; R. W. R.
206 Parker, Hartmann, et al., 2015).

207 In absence of detailed information, we followed the approach of Parker et al. (2015) and
208 considered a mean emission factor of 3.7 t of CO₂-eq per t of fuel consumed based on the mean
209 density of 0.835 of the fuel delivered in Port Victoria between 2013 and 2019. To account for
210 variability in GHG emissions, we considered a coefficient of variation of 10% for the emission
211 factor, i.e., we assumed that 95% of the values of the emission factor were comprised between
212 3 and 4.4 t of CO₂-eq per t of fuel consumed. While the variance of the CO₂ emission factor is
213 considered small for marine diesel (Waldron et al., 2006), emissions associated with the
214 transport of tuna from the fishing grounds to the processing factories are expected to vary due
215 to their location all over the world (Miyake et al. 2010). Furthermore, the variability in

216 emissions may stem from differences in packaging since tuna caught with purse seine can be
217 processed in different products: canned chunks and flakes, loins, and steaks. Confidence
218 intervals around GHG estimates were computed by bootstrap resampling ($n = 500$) in the
219 distributions of fuel predictions and emission factor assuming that they were normally
220 distributed.

221 For SO_2 , emissions were assumed to be directly proportional to the sulphur content in the fuel,
222 i.e., 0.01, 0.001, and 0.0001 t per t of fuel consumed for 0.5%, 0.05%, and 0.005% sulphur,
223 respectively (Corbett et al., 1999). Since the model of fuel consumption was based on annual
224 data, the successive changes in sulphur content were assumed to have taken place in January
225 2016 and 2018, respectively. The reduction in sulphur was also assumed to have occurred in the
226 other fishing ports of call of the Port Victoria-based purse seiners, i.e., Diego Suarez
227 (Madagascar) and Port-Louis (Mauritius). The landings made at these ports represented less
228 than 2.5% of the landings of the fleet over the period 2016 to 2019. Information on fishing
229 effort and operations was available for all large-scale purse seiners that operated in the
230 western Indian Ocean and were based in Port Victoria over the last four decades (1981-2019).
231 We used the model of annual vessel fuel consumption to predict the total fuel consumed and
232 associated GHG and SO_2 emissions for all Port Victoria-based purse seiners from 1981 to 2019.
233 We included the fuel consumed by the support vessels from 2013 to 2019, assuming they
234 bunkered only in Port Victoria during that period. Statistical analyses were performed in R
235 version 3.6.3 (R Core Team 2020).

236 **Results**

237 **Fuel delivery in Port Victoria**

238 From 2013 to 2019, mean total weights of 139,000 t (SD=20,000 t) and 8,000 t (SD=3,000 t) of
239 fuel were delivered annually to the purse seiners and support vessels calling on Port Victoria,
240 Seychelles, respectively (**Table 1**). Over that period, the support vessels represented 5.4% of the
241 total fuel purchased in Port Victoria. For purse seiners, the mean fuel quantity delivered during
242 an operation was 264 t and the maximum was 858 t (**Table 1**). For support vessels, the mean
243 was 79 t and the maximum was 176 t.

244 **Selected data set**

245 More than 95% of all fish caught by the purse seine fishing fleet operating in the western Indian
246 Ocean from 2013 to 2019 were landed at Port Victoria, Seychelles. We found 168 annual
247 records of 44 purse seiners that exclusively unloaded and transshipped in Port Victoria,
248 providing an opportunity to link fishing effort and activities with fuel consumption. This data set
249 represented 63% of all days at sea, 65% of fishing sets, and 67% of landings of the Port Victoria
250 based-purse seine fishing fleet over the period 2013 to 2019.

251 The mean annual fishing effort for the selected vessels decreased between 2013-2016 and
252 2017-2019 following the implementation of the rebuilding plan for the Indian Ocean yellowfin
253 tuna stock (**Table 2**). Between the two periods, the mean annual number of fishing sets
254 remained stable but the proportion of sets on FADs increased from 77% to 86% in 2017 to
255 2019. The mean weight of fuel consumed annually by one purse seiner decreased from about
256 4,000 t in 2013 to about 3,000 t in 2019 (**Table 2**).

257 Variability in fuel consumption

258 We found that vessel size, fishing effort, and fishing sets for both types of tuna school
259 associations as well as the period of vessel construction significantly explained the variability in
260 purse seiners' fuel consumption while there were no significant differences between years of
261 activity. The final model explained 88.5% of the total variance of the annual fuel consumed by
262 purse seiners and each effect was significant (**Table 3**). After accounting for differences in vessel
263 length, we found that purse seiners built throughout the 1970s and 1980s had the highest fuel
264 consumption. They consumed 943 t more fuel annually than vessels built in the 1990s-2000s
265 and 212 t more than vessels built after the 2010s. Hence, the most recent vessels were found to
266 annually consume 731 t more fuel than the ones built during the 1990s-2000s. This is explained
267 by the increased requirements in energy to store part of the catch at ultra-low temperature to
268 improve fish quality. Some purse seine fishing companies have recently developed new markets
269 of higher value (e.g., loins, sashimi) based on improved handling and storage practices. Besides,
270 the annual fuel consumption was found to linearly increase with the number of fishing
271 operations on FADs, i.e., by 3.8 t of fuel for each additional set on FADs, while the positive
272 effects of length overall, days at sea, and number of sets on FSCs on fuel consumption were
273 found to be non-linear (**Fig. 1**).

274 Vessel length substantially increased the annual quantity of fuel consumed by a purse seiner.
275 Considering the mean annual values of 273 days spent at sea, 223 sets on FADs and 51 sets on
276 FSCs observed in the data set, the mean annual fuel consumption (lower and upper bounds of
277 the 95% confidence interval) was estimated at 2,044 t (1,792–2,297 t) for small-sized purse

278 seiners, 2,682 t (2,392–2,971 t) for medium-sized purse seiners, and 4,360 t (4,097–4,623 t) for
279 large-sized purse seiners built in 2001 (**Fig. 2**).

280 The fishing strategy defined by the type of school association targeted was found to affect fuel
281 consumption, with FAD-fishing resulting on average in more fuel consumed than FSC-fishing.
282 For 60 fishing sets made either on FSC- or FAD-associated schools, model predictions indicated
283 that the annual fuel consumption would be 1,868 t (1,515 – 2,221 t) for FSC sets and 2,135
284 (1,746 – 2,523 t) for FAD sets (**Fig. 3**). Nevertheless, the difference was found to be not
285 significant as the confidence intervals of the predictions overlapped, showing the large
286 variability in fuel consumption estimates between vessels.

287 **Fuel Use Intensity**

288 The FUI in the western Indian Ocean purse seine fishery showed a large variability over the last
289 four decades. The median FUI was larger than 1,000 l t⁻¹ in the early 1980s during the initial
290 phase of development of the fishery and then showed an overall decreasing trend until 2003
291 when it reached a minimum of 364 l t⁻¹ (**Fig. 4**). The FUI showed large interannual variability
292 during the 2000s and 2010s and had median values lower than 500 l t⁻¹ in 2018 and 2019. The
293 support vessels contributed to between 3% and 7% of the FUI of the purse seine fishery
294 between 2013 and 2019.

295 The annual estimates of FUI were found to differ highly between purse seiners. For instance, in
296 2015, the standard deviation of the FUI in the fleet was 210 l t⁻¹, with values ranging from less
297 than 500 l t⁻¹ to more than 800 l t⁻¹. Furthermore, the purse seiners showed some major
298 changes in FUI over time. For instance, a purse seiner that was present in the fishery between

299 1984 and 2019 was described by a standard deviation of 132 l t^{-1} for a mean value of FUI of 436
300 l t^{-1} over the period, i.e., a coefficient of variation of 30%.

301 **Historical changes in the fishery**

302 After an initial period of exploration in the very early 1980s, a large number of purse seiners
303 arrived in the Indian Ocean from the Atlantic Ocean in 1984, rapidly increasing the fishing effort
304 and the number of fishing operations. These were mainly conducted on FSC tuna at that time
305 (**Fig. 5a-c**). The annual effort of the fishery increased with some variability to more than 15,000
306 days at sea in 1997, before decreasing to about 12,000 days in 2004 (**Fig. 5a,c**). Between 1984
307 and 1997, the FAD component of the fishery steadily developed. The fishery experienced a
308 major decrease in effort and sets on FSCs due mainly to the piracy threat in 2008 to 2010 (**Fig.**
309 **5a,c**). The effort increased again in 2016 to almost 14,000 days at sea while the sets on FADs
310 showed a massive increase, from about 7,500 annually over the period 2013 to 2015 to more
311 than 10,000 from 2016 to 2018 (**Fig. 5b**). In the last years (2017 to 2019), the yellowfin tuna
312 catch limit on the purse seine fishery resulted in a decrease in the number of days spent at sea
313 combined with a drop in the targeting of FSC tuna (**Fig. 5a,c**).

314 In addition to changes in fishing effort and operations, the purse seine fishery showed some
315 major changes in vessel technical characteristics that affected fuel consumption throughout the
316 whole period. In particular, larger vessels consumed more fuel (see section [Variability in fuel](#)
317 [consumption](#)) and the fishery showed a steady increase in vessel size over the last four
318 decades. The mean vessel length increased from less than 60 m in the early 1980s to more than
319 90 m in 2019 (**Fig. 5d**). In addition, the period of construction was found to affect fuel

320 consumption (see section [Fuel Consumption](#)), which is likely due to technological
321 improvements in vessel and engine design over the last decades. The mean year of
322 construction, used as a metric of age of the vessels, steadily increased over time from a mean
323 of 1978 in the 1980s to 1999 in the 2010s (**Fig. 5e**). These changes reflected an aging of the
324 fleet from about 5-6 years old at the inception of the fishery in the early 1980s to about 15
325 years old on average in the 2000s and early 2010s. Some new vessels came into the fleet in
326 2015, reducing the mean age from a maximum of 16.2 years old in 2013 to 13.5 years in 2015
327 (**Fig. 5f**).

328 **Total fuel consumption and air emissions**

329 The estimated quantity of fuel consumed by the purse seine fishery in operation in the western
330 Indian Ocean showed strong interannual variability over the last four decades (1981-2019) in
331 relation to major changes in the fishing effort and activities (**Fig. 6a**). GHG and SO₂ emissions
332 were assumed to be proportional to fuel consumption and therefore showed similar temporal
333 patterns as fuel consumption over the last decades (**Fig. 6b-c**). The development of the fishery
334 in the 1980s resulted in a rapid increase of the fleet fuel consumption to about 110,000-
335 125,000 t over the decade between 1985 and 1994 (**Fig. 6**). In the meantime, the annual GHG
336 and SO₂ emissions increased to about 425,000 t of CO₂-eq (SD = 31,522 t) and 1,100 t (SD = 86
337 t), respectively. Fuel consumption and emissions then increased with some variability to reach a
338 peak in 2006 at about 165,000 t of fuel, 610,000 t of CO₂-eq GHG and 1,700 t of SO₂ (**Fig. 6**). The
339 high values of fuel consumption and emissions observed during 2003 to 2006 seemed to mainly
340 be driven by the large number of fishing sets on FSCs during that period (**Fig. 5c**). Fuel
341 consumption and associated emissions then showed major declines to 106,000 t of fuel,

342 428,000 t of CO₂-eq GHG and 1,100 t of SO₂ in 2010 in relation to a sharp decline in the overall
343 effort and activities of the purse seine fleet. When the piracy risk was reduced, the vessels
344 came back to the fishery and increased their overall fishing effort, in particular towards a
345 massive use of FADs and support vessels. Consequently, the air emissions increased to reach
346 more than 660,000 t of CO₂-eq in 2016. In recent years, fuel consumption and GHG emissions
347 decreased following the implementation of the yellowfin tuna catch limit. Meanwhile, SO₂
348 emissions dropped to about 180 t in 2016 and 15 t in 2019 following the successive reductions
349 in the sulphur content of fuel imposed in 2016 and 2018.

350 **Discussion**

351 Our results provide a four decade perspective on the air pollutant emissions of one of the
352 world's largest commercial fisheries, the Indian Ocean purse seine fishery, responsible for
353 about half a Mt of tropical tuna catch in 2018. Based on an original and unique data set of more
354 than 4,300 bunkering operations spanning the period 2013-2019, we developed a model of
355 annual fuel consumption for a subset of large-scale purse seiners based in Port Victoria,
356 Seychelles, as a function of fishing effort, strategy and vessel characteristics. Based on our
357 model that explained almost 90% of the variability in purse seiners' annual fuel consumption,
358 our findings are threefold. First, we showed that the energetic performance of the Indian Ocean
359 purse seine fleet quantified with the FUI showed strong interannual variability. This is mainly
360 explained by the variability in fishing success due to a combination of variations in tuna
361 abundance and catchability, changes in accessibility and changes in fishing grounds, and
362 changes in fishing strategy. In particular, the increased targeting of FAD-associated schools in

363 response to market incentives (e.g., sale price of skipjack tuna) combined with the IOTC
364 management measure that was implemented to rebuild the stock of yellowfin tuna have
365 strongly modified the productivity and spatio-temporal patterns of the purse seine fishery with
366 recent effects on both catch and fuel consumption. Second, we estimated the past and current
367 levels of fuel consumption and GHG emissions of the Indian Ocean purse seine fishery over four
368 decades. We showed how emissions varied from the inception of the fishery to its evolution as
369 described by changes in the fleet structure (i.e., age and size of the vessels), technology, and
370 the effects of the environment on tuna catchability and management measures. The whole
371 fishery, including its support vessel component, annually consumed about 160,000 t of fuel and
372 emitted about 590,000 t of CO₂-eq GHG from 2015 to 2019. Finally, we demonstrated the
373 efficiency of the implementation of sulphur limits in the Indian Ocean purse seine fishery. These
374 limits resulted in the sharp reduction of the SO₂ air pollution which had exceeded 1,500 t in
375 2015.

376 **GHG emissions**

377 Considering annual estimates of GHG emissions available from the literature, our results
378 indicate that the Indian Ocean purse seine fishery represented about 0.37% of the global
379 fisheries emissions in 2000 (Tyedmers et al., 2005), 0.24% in 2011 (Parker et al., 2018) and
380 0.32% in 2016 (Greer et al., 2019). Emissions from this highly industrial fishery are overall low
381 due to the small number of active vessels (~50 purse seiners) and despite their large size (~90 m
382 length overall) and the wide spatial extent of their fishing grounds. Tuna fisheries of the Indian
383 Ocean represented about 20% of the global tuna catch over the last decades (Taconet et
384 al. 2018). The importance of coastal fisheries has steadily increased over time and they now

385 contribute to about 70% of the total tuna catch (Fiorellato et al. 2019). In this context, it seems
386 essential to extend such analysis to the other industrial components of the tuna fisheries
387 (i.e. longliners and pole and liners) but also to the thousands of small fishing vessels that target
388 tunas and other pelagic fishes with a large variety of fishing gears (e.g. handline, gillnets,
389 driftnets) to better assess the multiple sources of air pollution by fisheries across the Indian
390 Ocean.

391 **Purse seiners' characteristics and fuel consumption**

392 Vessel characteristics (e.g., hull design, propeller, auxiliary engine and cold storage capacity) as
393 well as fishing strategies and tactics affect the distance travelled and fuel consumption
394 (Guillotreau et al., 2011; Sala et al., 2011). Our results showed that size and age explain a
395 significant part of the differences observed in annual fuel consumption between vessels. Purse
396 seiners' length increased steadily over the last four decades. Some fishing companies invested
397 in very large boats (>90 m) throughout the 1990s and 2000s to reduce the fuel to catch ratio
398 and increase profit (Campling, 2012). Economic incentives explain the increasing size of purse
399 seiners to a large extent as the economies of scale are high for this highly capitalized industry
400 characterized by heavy fixed costs. Fuel costs represent on average 20% of the total operating
401 costs of a purse-seine vessel fishing in the Indian Ocean (Miyake et al., 2010). However, the
402 business model of purse seine fishing companies became more dependent on fuel price rises
403 during the oil crisis of 2008 when the energy costs reached more than 50% of the running costs
404 (Miyake et al., 2010). Even for smaller vessels such as Japanese longliners, fuel costs rose from
405 7 up to 23% of total running costs between 1994 and 2006 (Miyake et al., 2010). When it is not
406 possible to implement a slow-steaming strategy, one way of dealing with such a dependency is

407 to increase the size of vessels to reduce unit costs (Cariou, 2011). This strategy is only possible
408 because the environmental costs of carbon emission externalities are not included in oil price
409 (Lvovsky et al., 2000). Furthermore, government subsidies for vessel construction and tax
410 exemption of fuel consumption may have supported the development of larger vessels and
411 buffered the effects of increased oil price to some extent (Sumaila et al., 2008).

412 In recent years, several new purse seiners were built and equipped with diesel-electric
413 propulsion systems that optimize the use of energy according to power demand. As such, fuel
414 consumption and associated air pollutant emissions are reduced (Hideki et al., 2011).
415 Nevertheless, the adoption of these mixed systems was mainly driven by the development of
416 ultra-freezing capacities onboard these vessels to store part of the catch at temperatures
417 between -40°C and -60°C and target markets of higher value than canned tuna. The high power
418 required to maintain these cold storage conditions actually resulted in the increase of the
419 overall fuel consumption of the purse seine fleet. This was shown by the effect of construction
420 period in our model that indicated that vessels built in the 2010s consume more than vessels
421 built throughout the 1990s-2000s.

422 **Fishing strategy and fuel consumption**

423 Fuel consumption varies with purse seine fishing strategy which depends on several factors
424 driven by resource availability, market demand and costs, and are affected by innovation and
425 technological changes (Guillotreau et al., 2011; Torres-Irineo et al., 2014). In particular, the
426 advent of satellite-tracked buoys equipped with accurate positioning systems in the early 2000s
427 supported the development of FAD-fishing that has become increasingly prevalent over the

428 years (Fonteneau et al., 2013; Maufroy et al., 2015). The profitability of the very large purse
429 seiners (>90-100 m) relied on an increasing number of GPS-tracked FADs and the association
430 with support vessels that manage the array of FADs, while smaller, less-costly purse seiners
431 (<80 m) generally used less FADs and seasonally targeted FSCs of large yellowfin tuna
432 (Guillotreau et al., 2011; Maufroy et al., 2017). Since the early 2010s, buoys attached to the
433 FADs include acoustic units that provide real-time information on the biomass of tuna occurring
434 in the vicinity of the drifting rafts (Lopez et al., 2014). This has led to increasing fishing efficiency
435 and success and enables further FAD-fishing throughout the year (Wain et al., 2020). The
436 increasing use of FADs has substantially modified the spatial extent and movement patterns of
437 the purse seiners. These vessels spend less time searching for tuna and more time steaming
438 towards the FADs where fish appear to be present. This may explain that the fuel consumption
439 increased more on average for a FAD set than a FSC set in our model although this was a
440 marginal effect and was not significant considering the large variability between vessels and
441 years. It should be noted however that vessels targeting FAD-associated schools make more
442 sets per day than when fishing on FSCs (Floch et al., 2019). The FUI for purse seiners targeting
443 FADs would then increase through increased number of fishing sets and associated fuel
444 consumption but decrease through increased catch per set enabled by better selection of the
445 FADs (Wain et al., 2020).

446 At short time scales, fishing tactics depend on the technical skills and different sources of
447 information available to the skipper, e.g., location of oceanographic features and acoustic
448 estimates of tuna abundance around GPS-tracked FADs (Baidai et al., 2020; Gaertner et al.,
449 1999). In addition, cooperative fishing is an essential component of purse seine fishing as FAD

450 position information can be shared between vessels and some skippers work in groups
451 (Lennert-Cody et al., 2020; Snouck-Hurgronje et al., 2018). Cooperative behaviour may
452 significantly reduce searching time and associated fuel costs, and this could explain the non-
453 linear pattern observed for the number of FSC sets in our model, i.e., the initial reduction in fuel
454 consumed when the number of FSCs increased from 0 to 60. The transfer of information on
455 tuna presence between vessels explains the spatio-temporal co-occurrence of several purse
456 seiners in the same fishing area observed. For instance, this has been observed in the cases
457 where there are large concentrations of tuna and all purse seiners were found in the same
458 concentrated fishing grounds (Fonteneau et al., 2008). Further work is required to study how
459 collaborative fishing may affect fishing success, the relationship between fuel consumption and
460 catch measured by the FUI and more generally the use of purse seine catch rates as indices of
461 tuna abundance (Lennert-Cody et al., 2020).

462 **Emissions's variability**

463 GHG emissions of the Indian Ocean purse seine fishery showed a general increasing trend over
464 the last four decades described by some strong interannual variability and a mean annual value
465 of 590,000 t of CO₂-eq from 2015 to 2019. Our estimates are conservative as they do not
466 include emissions from support vessels prior to 2013 nor from purse seiners that operated in
467 the northwest and eastern parts of the Indian Ocean. Information on vessels' characteristics
468 and fishing operations for these vessels was not available for the present study. However, we
469 assume that their contribution to the total air pollutant emissions of the Indian Ocean purse
470 seine fishery is on the order of magnitude of their catch, i.e., less than 6% of the total purse
471 seine catch for the whole period. Support vessels appeared in the late 1980s in the purse seine

472 fishery but their role has increased since the late 1990s. Their number varied between 10 and
473 15 over 1997 to 2012 (Chassot et al., 2015), and likely would represent an additional 3-4% of
474 the total fuel consumed by purse seiners' activity during that period.

475 Our results showed that fuel consumption and associated emissions varied strongly over time
476 as a result of several intricate factors, including changes in fleet characteristics and strategy,
477 changes in accessibility to fishing grounds and tuna abundance and catchability. In the Indian
478 Ocean, annual catch rates are strongly related to the extent of favourable feeding habitats for
479 tuna, i.e., good environmental conditions result in fishery contraction (Druon et al., 2017).
480 Although the reduction in the size of fishing grounds, supported by collaborative fishing, might
481 suggest a reduction in fuel consumption, we found that increased catchability may actually
482 result in increased numbers of fishing sets and eventually higher fuel consumption. In
483 particular, the period 2003 to 2005 was characterized by an exceptional abundance of mantis
484 shrimp *Natosquilla investigatoris*, a major prey of tuna that occurred in large swarms near the
485 surface and substantially increased the catchability of tuna schools (Potier et al., 2007;
486 Romanov et al., 2015). During that period, the total landings of the fishery were larger than
487 385,000 t per year. GHG emissions showed a major increase and reached almost 500,000 t of
488 CO₂-eq per year. Our study also showed that GHG emissions declined by 30% over 2009 to 2011
489 due to the piracy threat, which resulted in a major decline of overall purse seine effort and
490 reduction in the extent of the fishing grounds (Chassot et al., 2012). Although too early to
491 assess, preliminary information suggests a major decrease in purse seiners' effort and GHG
492 emissions in 2020 in relation with the COVID-19 pandemic, possibly of the same magnitude as
493 observed during the main period of the Somali piracy threat.

494 Energetic and environmental performance

495 FUI is used to describe and compare the environmental performance of fisheries and fishing
496 gears in terms of output and efficiency (Parker et al., 2018; R. W. R. Parker, Vázquez-Rowe, et
497 al., 2015). Based on a global survey among purse seine fishing companies, Tyedmers and Parker
498 (2012) found that the FUI of the purse seine fishery in 2009 was lower in the Indian Ocean (454
499 l t^{-1}) than in the Atlantic (513 l t^{-1}) but higher than in the Pacific Ocean (354 l t^{-1}). Our mean FUI
500 predictions of 496 l t^{-1} in 2009 are slightly higher than their estimate, possibly due to the
501 difference in methodology and sample size (i.e., nine purse seiners in the sample of Tyedmers
502 and Parker (2012) and 46 in this study). The review of historical values of FUI in purse seine
503 fisheries shows a range of $200\text{-}2,500 \text{ l t}^{-1}$ and a more restricted range ($200\text{-}527 \text{ l t}^{-1}$) since 2000
504 (R. W. R. Parker, Hartmann, et al., 2015). Our results showed that the mean annual FUI of the
505 Indian Ocean purse seine fishery exceeded this range in the last decade, reaching more than
506 650 l t^{-1} in 2015, while the same fleet showed a FUI of less than 420 l t^{-1} in 2018. This illustrates
507 the large temporal variability in FUI linked to the main factors described above (see [Fishing](#)
508 [strategy and fuel consumption](#)). In this context, developing and implementing routine
509 monitoring of fuel consumption using standardized methods is required to provide more
510 accurate assessment of fisheries energetic performance.

511 The economic drivers and consequences of the FUI were beyond the scope of this study.

512 Nonetheless, it would be interesting in future research to look at the impact of heavy fuel oil
513 and marine diesel oil prices on fishing strategies, fuel consumption and the level of emissions.

514 In particular, if the fishing companies were deemed sensitive to price signals, incentive-based
515 policies such as tax instruments could be implemented as complements to the new standards

516 of sulphur content, at least for catches taking place within the exclusive economic zones of
517 coastal countries.

518 Air pollutant emissions from fuel combustion constitute one component of the environmental
519 performance of a fishery. The status of the stocks that are targeted as well as the impact of
520 fishing on habitat and species that are taken as bycatch should also be scrutinised when it
521 comes to assessing the sustainability of a fishery as is done for eco-labels such as the Marine
522 Stewardship Council (MSC) fisheries standard. In recent years, most purse seine fisheries have
523 entered into the process of MSC certification through Fishery Improvement Projects (Crona et
524 al., 2019) which do not include any constraint related to emissions of air pollutants. Quantifying
525 the magnitude and composition of air pollutant emissions should be an integral component to
526 monitoring sustainability of fisheries.

527 **Conclusion**

528 Our model of purse seiner fuel consumption allowed us to reconstruct the history of air
529 pollutant emissions of the Indian Ocean purse seine fishery over four decades. The FUI
530 predicted by our model is in line with that found in earlier studies, but it also shows a great
531 inter-annual variability according to environmental and fishing conditions that should be taken
532 into greater consideration. The shifting structure of the fleet towards larger vessels assisted by
533 support vessels and more intensive use of FADs tend to increase fuel consumption, hence air
534 pollution in the fishery. GHGs now reach some 600,000 t of CO₂-eq yearly. This high level of air
535 pollutant emissions should certainly be a concern to the eco-label schemes promoting

536 sustainable fisheries, responding to the Sustainable Development Goal #14 of the United
537 Nations.

538 Further work is required to better account for the additional air pollution linked to the global
539 tuna supply chain: transportation of raw tuna material to the processing factories located all
540 over the world and of processed tuna products to the consumer markets that are dominated by
541 the EU and the USA (Miyake et al., 2010). The model will also be useful to predict the expected
542 effects of changes in fleet capacity and fishing activities on the Seychelles national economy,
543 e.g., to quantify the decrease in revenues for the government linked to the stop of vessels due
544 to the COVID-19 pandemic.

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556 and two anonymous referees who greatly helped improving the article.

557 *Table 1: Description of the fuel data set. Number of vessels and bunkering operations with*
 558 *mean, maximum and total weight (t) of fuel delivered annually to the purse seiners (PS) and*
 559 *support vessels (SV) that called on Port Victoria, Seychelles, during 2013-2019.*

Year	VesselType	Vessels	Operations	MeanWeight	MaxWeight	TotalWeight
2013	PS	38	390	269	858	104,731
2013	SV	10	50	72	151	3,613
2014	PS	42	465	260	672	120,883
2014	SV	15	68	81	135	5,526
2015	PS	49	534	279	792	149,043
2015	SV	18	96	84	176	8,099
2016	PS	47	606	274	777	166,227
2016	SV	21	120	84	176	10,103
2017	PS	45	557	263	713	146,588
2017	SV	20	135	79	166	10,611
2018	PS	44	580	247	729	143,095
2018	SV	18	121	74	152	8,932
2019	PS	45	544	261	605	141,735
2019	SV	16	113	79	172	8,889

560

561 **Tables**

562 *Table 2: Description of the fisheries data set selected for modelling fuel consumption. Number*
563 *of vessels (N) and mean annual values of length overall (LOA; m), fishing effort (days at sea),*
564 *numbers of sets on schools associated with fish aggregating devices (SetsFAD) and on free*
565 *swimming schools (SetsFSC), landings (t) and fuel consumed (t) for the purse seiners that*
566 *called exclusively on Port Victoria, Seychelles, during 2013-2019.*

Year	N	LOA	DaysAtSea	SetsFAD	SetsFSC	Landings	Fuel
2013	8	94.1	298	254	63	11,463	3,989
2014	19	89.6	300	205	52	7,593	3,568
2015	23	90.9	267	170	72	6,672	3,465
2016	31	88.8	300	228	61	7,207	3,605
2017	29	92.7	270	231	66	8,283	3,499
2018	30	91.5	258	259	14	11,064	3,494
2019	28	89.8	245	219	41	8,384	3,014

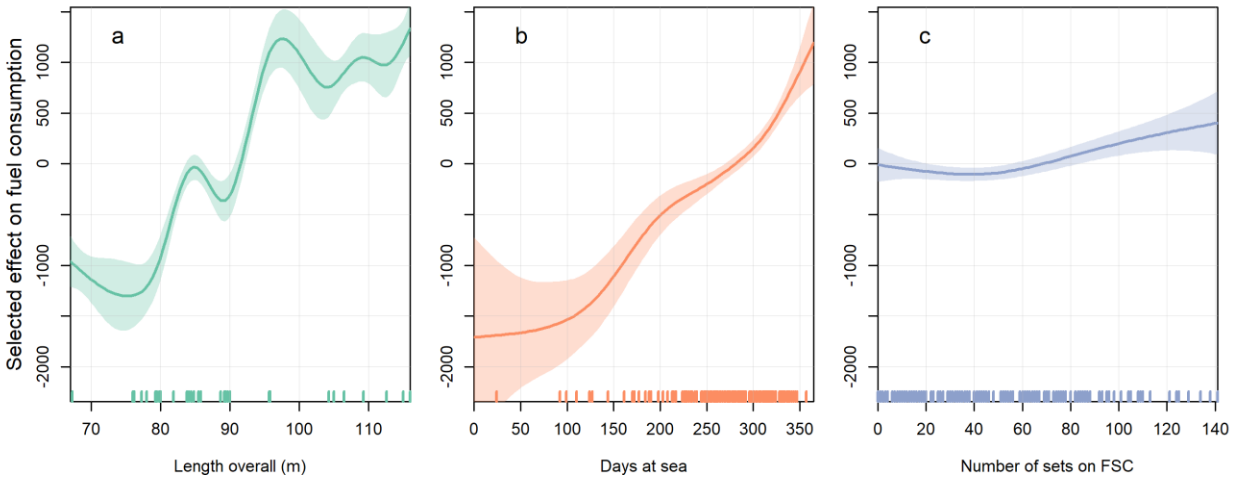
567

568 *Table 3: Analysis of variance outputs for the annual quantity of fuel consumed (t) by large-*
 569 *scale purse seiners. YOC = Year of construction; SetsFAD = number of sets on schools*
 570 *associated with fish aggregating devices; LOA = Length overall; SetsFSC = number of sets on*
 571 *free swimming schools; s = smooth function; edf = effective degrees of freedom; F = Test*
 572 *statistic.*

Source of variation	edf	F value	p-value
DecadeYOC	2.00	22.2	<0.001
SetsFAD	1.00	36.2	<0.001
s(LOA)	8.64	32.1	<0.001
s(DaysAtSea)	4.94	22.4	<0.001
s(SetsFSC)	2.58	5.2	0.0014

573

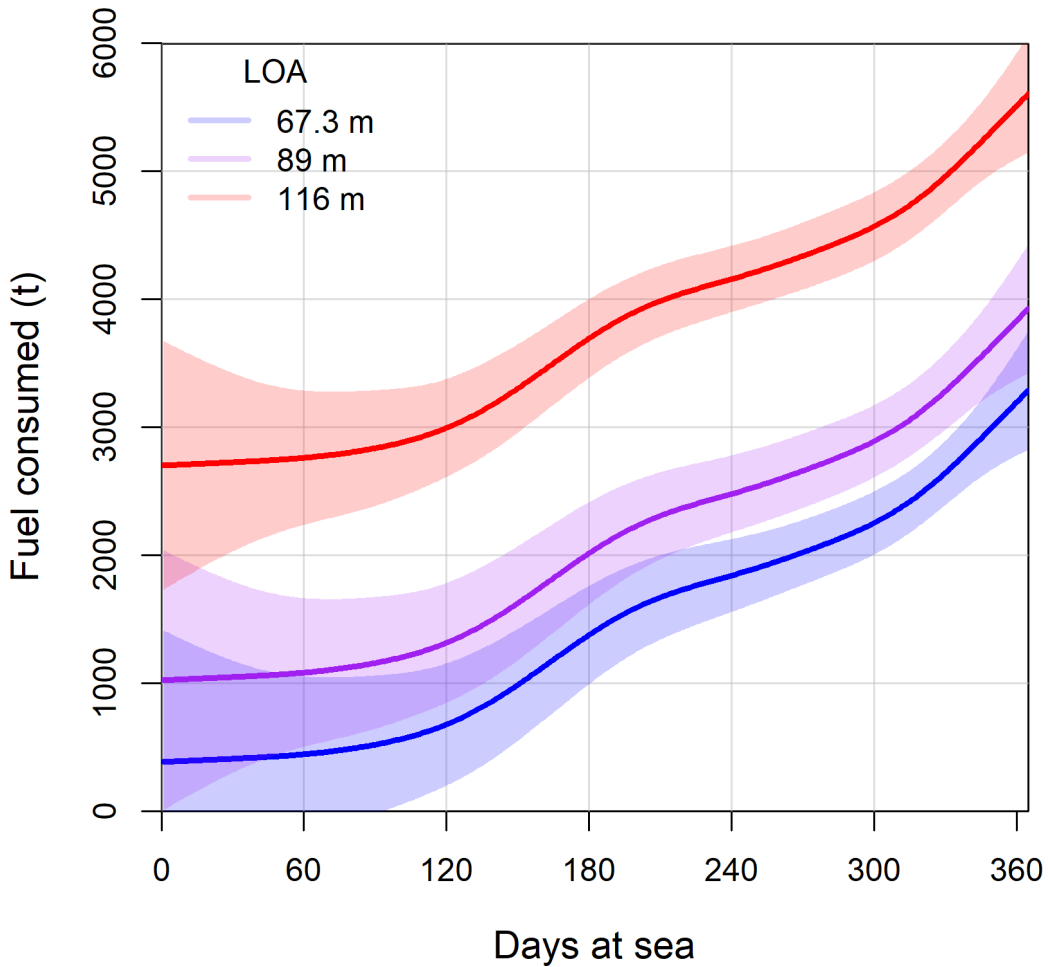
574 **Figures**



575

576 *Figure 1: Variability in annual fuel consumption of large-scale purse seiners operating in the*
577 *western Indian Ocean. Predictions for the three continuous variables included in the model of*
578 *annual fuel consumption: (a) length overall (m), (b) days a sea, (c) number of sets on tuna*
579 *free-swimming schools (FSC).*

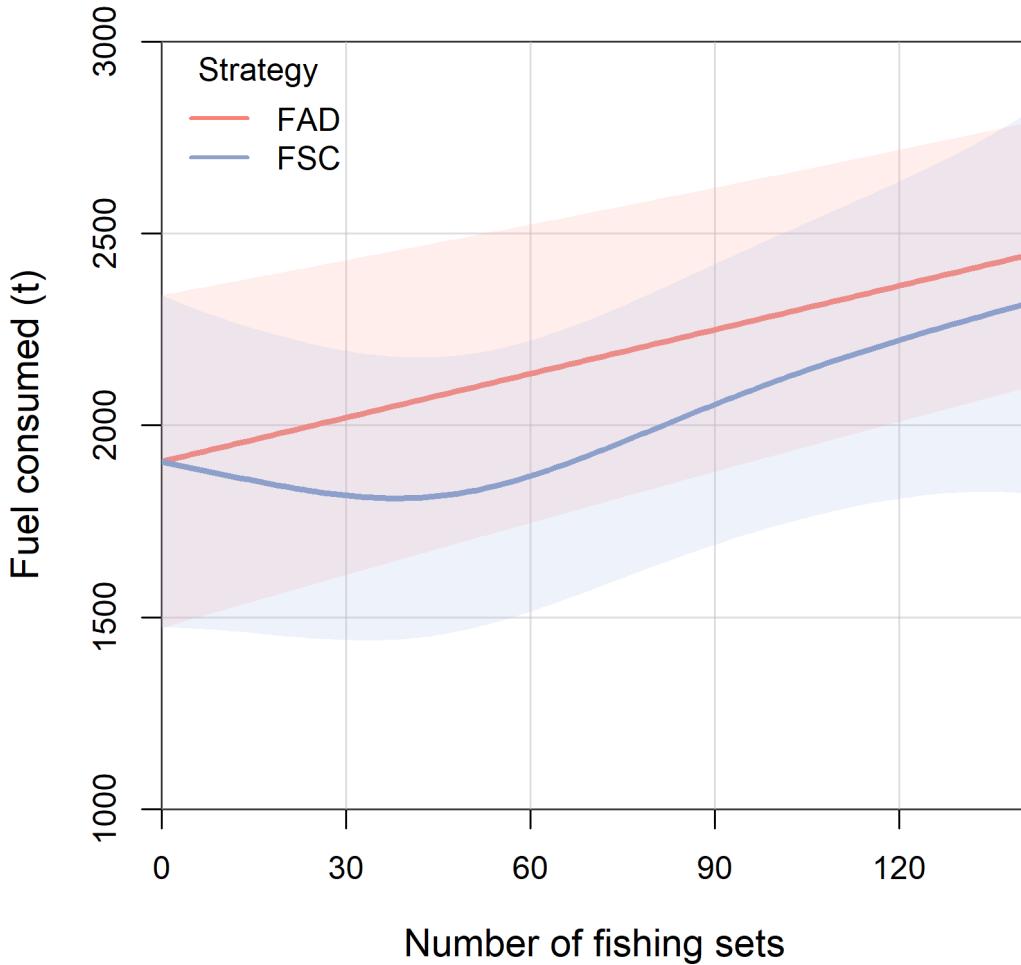
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581

582 *Figure 2: Effect of fishing effort and vessel length on fuel consumption of large-scale purse*
 583 *seiners of the Indian Ocean. Predictions of quantity of fuel consumed (t) by purse seiners of*
 584 *different length overall (LOA; m) as a function of the annual number of days spent at sea.*
 585 *Solid lines are the mean predictions with 95% confidence intervals for the smallest (67.3 m),*
 586 *medium-sized (89.7 m) and largest (116 m) vessels of the purse seine fishery.*

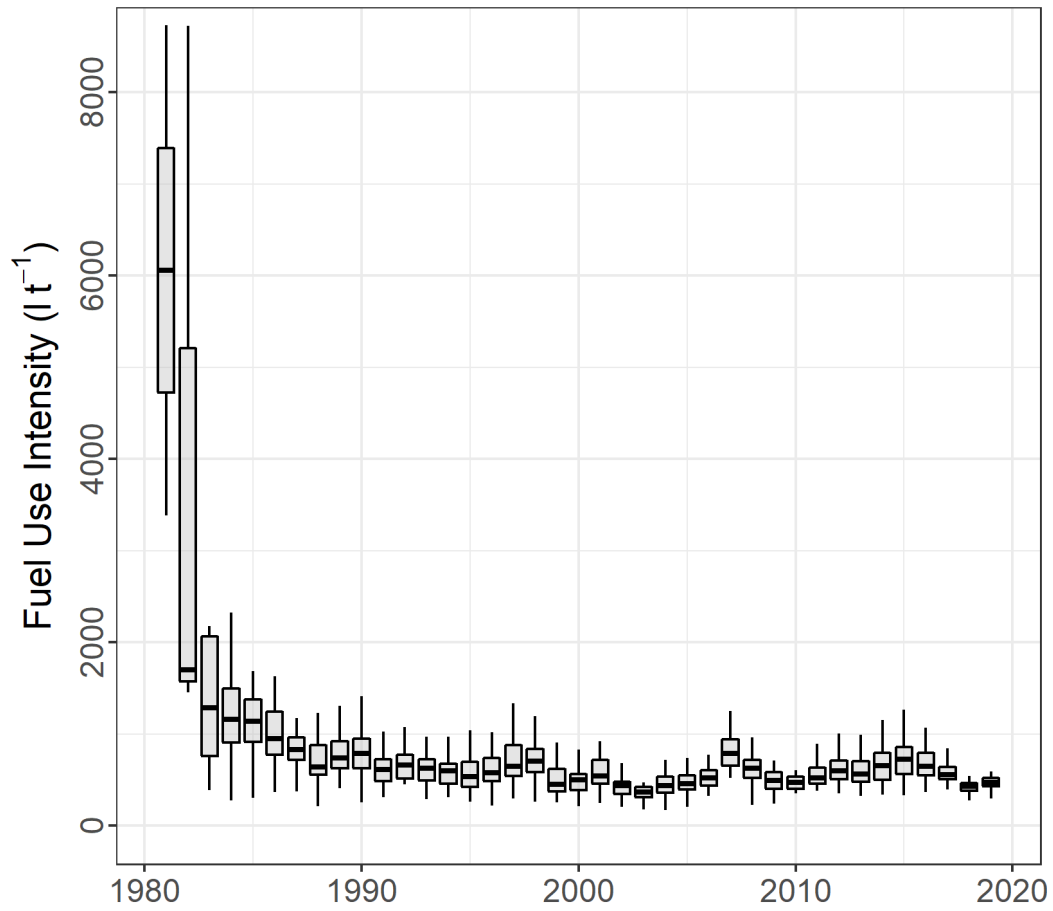
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588

589 *Figure 3: Effect of fishing strategy on fuel consumption of large-scale purse seiners of the*
 590 *Indian Ocean. Predictions of quantity of fuel consumed (t) by a medium-sized purse seiner*
 591 *(89.7 m) as a function of the annual number of fishing sets that would have been made*
 592 *exclusively on schools associated with fish aggregating devices (FADs) or on free-swimming*
 593 *schools (FSCs). Solid lines are the mean predictions with 95% confidence intervals.*

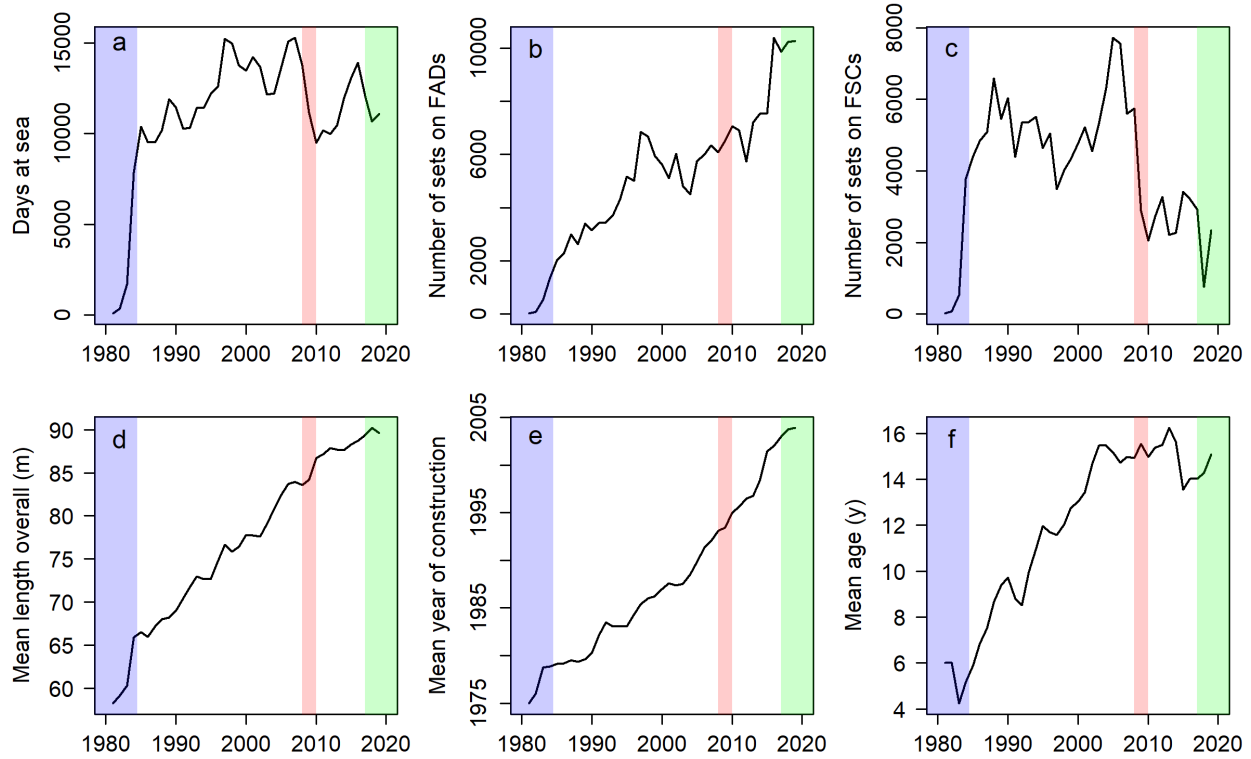
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596 *Figure 4: Temporal variability in environmental performance of the Indian Ocean purse seine*
597 *fishery from 1981 to 2019 as described by the annual distribution of Fuel Use Intensity (l t⁻¹).*

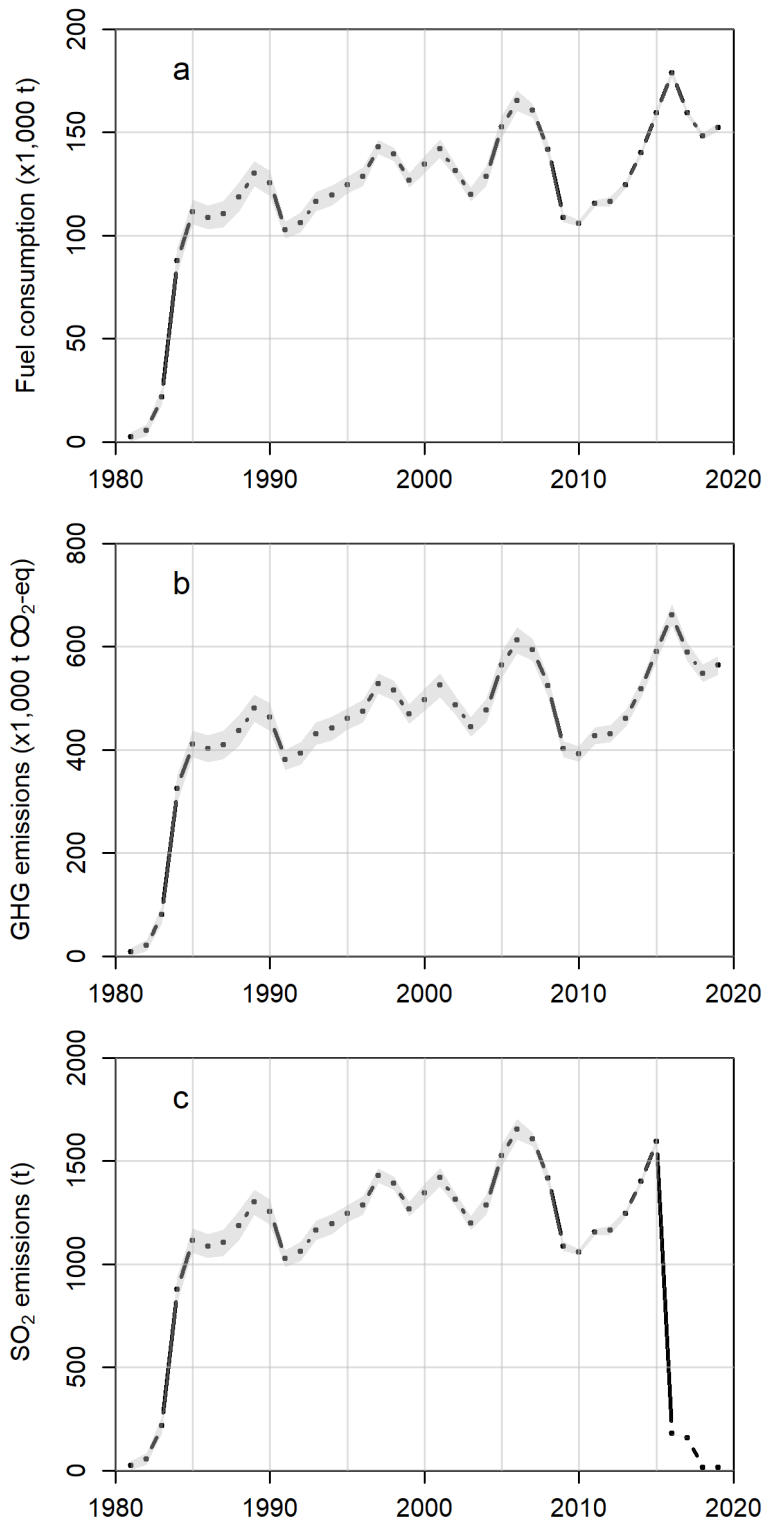
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599

600 *Figure 5: Annual changes in fishing effort, activities, and main technical characteristics of the*
 601 *western Indian Ocean purse seine fishery from 1981 to 2019. Annual time series of (a) days at*
 602 *sea, (b) number of sets on tuna schools associated with Fish Aggregating Devices (FADs), (c)*
 603 *number of sets on free swimming schools (FSCs), (d) mean length overall (m), (e) mean year*
 604 *of construction and (f) mean age of the purse seiners that operated in the western Indian*
 605 *Ocean during 1981-2019. Blue polygon = Onset of the fishery; Red polygon = Piracy threat and*
 606 *worldwide financial crisis; Green polygon = Yellowfin tuna catch limit.*

607



608

609 *Figure 6: Temporal variability in fuel consumption, greenhouse gas and sulphur dioxide*
 610 *emissions of the western Indian Ocean purse seine fishery from 1981 to 2019. Annual time*
 611 *series of (a) fuel consumption (t), (b) GHG emissions (x1,000 t CO₂-eq) and (c) SO₂ emissions*

612 *(t) as derived from model predictions of fuel annually consumed by the fleet of purse seiners*
613 *and support vessels based in Port Victoria, Seychelles, during 1981-2019.*
614

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