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

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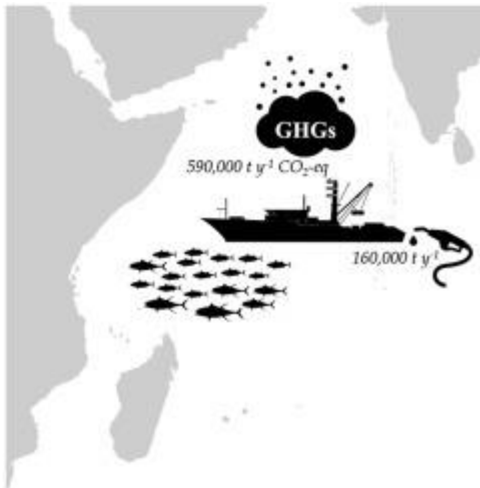
Abstract :

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 CO_2-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 SO_2 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 CO_2-eq GHG. Furthermore, our results showed that air pollutant emissions can be significantly reduced when limits in fuel composition are imposed. In 2015, SO_2 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 t y^{-1} of CO_2-eq over 2015 to 2019. ► Sulphur limits reduced annual SO_2 emissions from >1500 t to almost none since 2018.

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

Introduction

Oceangoing ships constitute a significant source of air pollution through the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and nitrous oxide (N_2O), and other air pollutants such as sulphur dioxide (SO_2) (Corbett and Fischbeck, 1997; Corbett et al., 1999). Global shipping emissions have major effects on the environment, including ocean acidification and contribution to climate change, and on human health (Corbett et al., 2007; Jägerbrand et al., 2019; Tian et al., 2013). With about 2.5 million motorized vessels out of 4.6 million vessels in operation (FAO, 2018; Rousseau et al., 2019), the global fishing fleet annually consumes about 30-40 million tonnes (Mt) of fuel and accounts for more than 1% of the global marine fuel demand (Parker et al., 2018; Tyedmers et al., 2005). Global emissions from fuel combustion by fishing vessels have been estimated at about 180-200 Mt of CO_2-equivalent GHGs every year (Parker et al., 2018). Furthermore, total emissions related to fishing go beyond the direct emissions of fuel combustion because of indirect effects of upstream and downstream activities, e.g., emissions generated during fuel processing and refining, fish product packaging and transport (Winebrake et al., 2007). Fishing and water transport are therefore considered among the most air-polluting industries, per unit of wealth created, in particular for CO_2 and SO_2 (Bagoulla and Guillotreau, 2020). To improve air quality and global health, global sulphur limits of 0.5% (mass/mass) in fuel oil have been recently imposed by the International Maritime Organization (IMO) under the MARPOL convention (Annex VI) to reduce the emissions of both sulphate aerosols and sulphur-containing particles (Chu Van et al., 2019).

Industrial tuna fisheries are one of the most highly capitalized fisheries in the world (Miyake et al., 2010). High seas fishing vessels, typically longer than 25 m, travel long distances to search and catch highly migratory tuna and billfish widely distributed across the world's oceans (Fonteneau, 2010). Energy costs make up to 20% or more of total running costs in the high seas fishing industry (Miyake et al., 2010). However, little information is available on fuel consumption and emissions by high seas tuna fisheries. This said, a survey-based study indicated 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 CO_2-equivalent GHGs, i.e., about 4.5-5% of the global fishing fleet emissions (Tyedmers and Parker, 2012). Although large-scale purse seiners represent a very small component of the global tuna fleet (~700 vessels in 2020; Justel-Rubio and Recio (2020)), they accounted for more than two thirds of the global catch of tuna since the late 2000s. In 2009, the global tuna purse seine fishery was responsible for the release of more than 3 Mt of CO_2-equivalent GHGs into the atmosphere (R. W. R. Parker, Hartmann, et al., 2015).

The global tuna purse seine fishery has significantly changed over the last decade. The purse seine catches of tropical tuna increased from about 2.8 Mt in the late 2000s to more than 3.2 Mt in the late 2010s, with about two thirds of the catch coming from fish aggregating devices (FAD) and the rest from free-swimming schools (FSC) and schools associated with dolphins (Taconet et al., 2018). In the Indian Ocean, the catch of the tuna purse seine fishery, composed of about 50 vessels larger than 65 m, increased from 280,000 t in the late 2000s to almost 500,000 t in 2018 (Fiorellato et al., 2019). In particular, the advent and increasing use of echo-sounder buoys attached to the FADs deployed at sea has greatly increased the efficiency and catchability of purse seiners over the last decade (Lopez et al., 2014; Wain et al., 2020). Furthermore, 20 support vessels assist the purse-seine fishing fleet by maintaining a network of FADs. These support vessels have proved to be instrumental in increasing fishing success, although they consume additional fuel energy and produce more GHG emissions (Assan et al., 2015; Ramos et al., 2010). Over the last decades, an increasing proportion of FAD-caught tuna has been observed in the Indian Ocean purse seine fishery. Since 2017, the use of FADs has been further accentuated by a shift in the fishing strategy to target more skipjack tuna (*Katsuwonus pelamis*) (Assan et al., 2019; Baez et al., 2018; Floch et al., 2019). This change occurred following the implementation of a total allowable catch on yellowfin tuna (*Thunnus albacares*) by the Indian Ocean Tuna Commission (IOTC) with the aim of rebuilding the yellowfin tuna stock. Yellowfin tuna compose the large majority of FSCs while tuna schools associated with FADs are dominated by skipjack tuna (Fonteneau et al., 2013). Such a change in fishing strategy may have affected the fuel consumption and air pollutant emissions as purse seiners targeting schools associated with FADs have been shown to consume more fuel per ton landed than purse seiners targeting FSCs at global scale (R. W. R. Parker, Vázquez-Rowe, et al., 2015).

In this context, the overarching objective of the present study was to estimate with more accuracy the GHG and SO_2 emissions of the tuna purse seine fishery of the Indian Ocean over the period 1981 to 2019 and assess how they vary with fleet structure, fishing strategy and productivity. First, we developed a model of fuel consumption of tropical tuna purse seiners based on a unique large data set of bunkering operations that took place in the Seychelles between 2013 and 2019. Secondly, we used the model to estimate the direct total fuel consumption and associated GHGs and SO_2 emissions for the western Indian Ocean purse seine fishery over the last four decades (1981-2019), including the fuel consumed by the fleet of support vessels. Finally, we assessed the extent of the reduction in SO_2 emissions following the mandated reduction in sulphur content of the marine diesel oil delivered in the Seychelles.

Materials & Methods

Fuel data

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

Fisheries data

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

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

Vessel fuel consumption

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

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

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

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

Effects of vessel size were assessed by comparing predictions of annual fuel consumption for the smallest purse seiner (LOA = 67.3 m), a purse seiner of mean length (LOA = 89.7 m), and the largest purse seiner of the fleet (LOA = 116 m), all built in the 1990s, having operated over 273 days and having made 223 and 51 sets on FAD and FSC, respectively, corresponding to the mean values observed in the data set. Model predictions were also performed to assess the influence of the fishing strategy (i.e., FSC vs. FAD) on purse seiner's annual fuel consumption. For these simulations, we considered a purse seiner built in the 1990s of mean length 89.7 m in operation for 273 days at sea (i.e. the mean value observed in the data set) for a number of sets varying between 0 and 141 made either on FADs or FSCs and corresponding to the range of values observed for FSCs in the data set.

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

Energetic performance

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

GHG and SO_2 emissions

Emissions of GHGs and SO_2 from marine fuel combustion are considered to be mostly dependent on fuel contents while engine and combustion technology may have more influence on the release of other pollutants such as nitrogen oxides (Holloway et al., 2006; Winnes and Fridell, 2009). GHGs emitted from water-borne navigation include CO_2, N_2O, methane (CH_4), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), particulate matter (PM), and oxides of nitrogen (NO_x) (Waldron et al., 2006). There is currently little information available about the emissions of each GHG by large-scale purse seiners and their associated support vessels. Recently, Parker et al. (2015) estimated a total GHG-to-fuel ratio of 3.1 kg CO_2-eq per litre of fuel consumed for the purse seine fishery. This emission factor reflects both the direct emissions of the marine distillate fuel used by the vessels (2.8 kg CO_2-eq l^{-1}) and the life cycle emissions from mining, processing, and transporting, to packaging (0.3 kg CO_2-eq l^{-1}) (Hospido and Tyedmers, 2005; Hospido et al., 2006; Parker and Tyedmers, 2015). This emission factor is very similar to that of other studies (Dalsøren et al., 2009; Ziegler and Hansson, 2003) and it has been used for a large range of fisheries worldwide (Parker et al., 2018; R. W. R. Parker, Hartmann, et al., 2015).

In absence of detailed information, we followed the approach of Parker et al. (2015) and considered a mean emission factor of 3.7 t of CO_2-eq per t of fuel consumed based on the mean density of 0.835 of the fuel delivered in Port Victoria between 2013 and 2019. To account for variability in GHG emissions, we considered a coefficient of variation of 10% for the emission factor, i.e., we assumed that 95% of the values of the emission factor were comprised between 3 and 4.4 t of CO_2-eq per t of fuel consumed. While the variance of the CO_2 emission factor is considered small for marine diesel (Waldron et al., 2006), emissions associated with the transport of tuna from the fishing grounds to the processing factories are expected to vary due to their location all over the world (Miyake et al. 2010). Furthermore, the variability in emissions may stem from differences in packaging since tuna caught with purse seine can be processed in different products: canned chunks and flakes, loins, and steaks. Confidence intervals around GHG estimates were computed by boostrap resampling (n = 500) in the distributions of fuel predictions and emission factor assuming that they were normally distributed.

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

Results

Fuel delivery in Port Victoria

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

Selected data set

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

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

Variability in fuel consumption

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

Vessel length substantially increased the annual quantity of fuel consumed by a purse seiner. Considering the mean annual values of 273 days spent at sea, 223 sets on FADs and 51 sets on FSCs observed in the data set, the mean annual fuel consumption (lower and upper bounds of the 95% confidence interval) was estimated at 2,044 t (1,792–2,297 t) for small-sized purse seiners, 2,682 t (2,392–2,971 t) for medium-sized purse seiners, and 4,360 t (4,097–4,623 t) for large-sized purse seiners built in 2001 (**Fig. 2**).

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

Fuel Use Intensity

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

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

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

Historical changes in the fishery

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

In addition to changes in fishing effort and operations, the purse seine fishery showed some major changes in vessel technical characteristics that affected fuel consumption throughout the whole period. In particular, larger vessels consumed more fuel (see section Variability in fuel consumption) and the fishery showed a steady increase in vessel size over the last four decades. The mean vessel length increased from less than 60 m in the early 1980s to more than 90 m in 2019 (**Fig. 5d**). In addition, the period of construction was found to affect fuel consumption (see section Fuel Consumption), which is likely due to technological improvements in vessel and engine design over the last decades. The mean year of construction, used as a metric of age of the vessels, steadily increased over time from a mean of 1978 in the 1980s to 1999 in the 2010s (**Fig. 5e**). These changes reflected an aging of the fleet from about 5-6 years old at the inception of the fishery in the early 1980s to about 15 years old on average in the 2000s and early 2010s. Some new vessels came into the fleet in 2015, reducing the mean age from a maximum of 16.2 years old in 2013 to 13.5 years in 2015 (**Fig. 5f**).

Total fuel consumption and air emissions

The estimated quantity of fuel consumed by the purse seine fishery in operation in the western Indian Ocean showed strong interannual variability over the last four decades (1981-2019) in relation to major changes in the fishing effort and activities (**Fig. 6a**). GHG and SO_2 emissions were assumed to be proportional to fuel consumption and therefore showed similar temporal patterns as fuel consumption over the last decades (**Fig. 6b-c**). The development of the fishery in the 1980s resulted in a rapid increase of the fleet fuel consumption to about 110,000-125,000 t over the decade between 1985 and 1994 (**Fig. 6**). In the meantime, the annual GHG and SO_2 emissions increased to about 425,000 t of CO_2-eq (SD = 31,522 t) and 1,100 t (SD = 86 t), respectively. Fuel consumption and emissions then increased with some variability to reach a peak in 2006 at about 165,000 t of fuel, 610,000 t of CO_2-eq GHG and 1,700 t of SO_2 (**Fig. 6**). The high values of fuel consumption and emissions observed during 2003 to 2006 seemed to mainly be driven by the large number of fishing sets on FSCs during that period (**Fig. 5c**). Fuel consumption and associated emissions then showed major declines to 106,000 t of fuel, 428,000 t of CO_2-eq GHG and 1,100 t of SO_2 in 2010 in relation to a sharp decline in the overall effort and activities of the purse seine fleet. When the piracy risk was reduced, the vessels came back to the fishery and increased their overall fishing effort, in particular towards a massive use of FADs and support vessels. Consequently, the air emissions increased to reach more than 660,000 t of CO_2-eq in 2016. In recent years, fuel consumption and GHG emissions decreased following the implementation of the yellowfin tuna catch limit. Meanwhile, SO_2 emissions dropped to about 180 t in 2016 and 15 t in 2019 following the successive reductions in the sulphur content of fuel imposed in 2016 and 2018.

Discussion

Our results provide a four decade perspective on the air pollutant emissions of one of the world's largest commercial fisheries, the Indian Ocean purse seine fishery, responsible for about half a Mt of tropical tuna catch in 2018. Based on an original and unique data set of more than 4,300 bunkering operations spanning the period 2013-2019, we developed a model of annual fuel consumption for a subset of large-scale purse seiners based in Port Victoria, Seychelles, as a function of fishing effort, strategy and vessel characteristics. Based on our model that explained almost 90% of the variability in purse seiners' annual fuel consumption, our findings are threefold. First, we showed that the energetic performance of the Indian Ocean purse seine fleet quantified with the FUI showed strong interannual variability. This is mainly explained by the variability in fishing success due to a combination of variations in tuna abundance and catchability, changes in accessibility and changes in fishing grounds, and changes in fishing strategy. In particular, the increased targeting of FAD-associated schools in response to market incentives (e.g., sale price of skipjack tuna) combined with the IOTC management measure that was implemented to rebuild the stock of yellowfin tuna have strongly modified the productivity and spatio-temporal patterns of the purse seine fishery with recent effects on both catch and fuel consumption. Second, we estimated the past and current levels of fuel consumption and GHG emissions of the Indian Ocean purse seine fishery over four decades. We showed how emissions varied from the inception of the fishery to its evolution as described by changes in the fleet structure (i.e., age and size of the vessels), technology, and the effects of the environment on tuna catchability and management measures. The whole fishery, including its support vessel component, annually consumed about 160,000 t of fuel and emitted about 590,000 t of CO_2-eq GHG from 2015 to 2019. Finally, we demonstrated the efficiency of the implementation of sulphur limits in the Indian Ocean purse seine fishery. These limits resulted in the sharp reduction of the SO_2 air pollution which had exceeded 1,500 t in 2015.

GHG emissions

Considering annual estimates of GHG emissions available from the literature, our results indicate that the Indian Ocean purse seine fishery represented about 0.37% of the global fisheries emissions in 2000 (Tyedmers et al., 2005), 0.24% in 2011 (Parker et al., 2018) and 0.32% in 2016 (Greer et al., 2019). Emissions from this highly industrial fishery are overall low due to the small number of active vessels (~50 purse seiners) and despite their large size (~90 m length overall) and the wide spatial extent of their fishing grounds. Tuna fisheries of the Indian Ocean represented about 20% of the global tuna catch over the last decades (Taconet et al. 2018). The importance of coastal fisheries has steadily increased over time and they now contribute to about 70% of the total tuna catch (Fiorellato et al. 2019). In this context, it seems essential to extend such analysis to the other industrial components of the tuna fisheries (i.e. longliners and pole and liners) but also to the thousands of small fishing vessels that target tunas and other pelagic fishes with a large variety of fishing gears (e.g. handline, gillnets, driftnets) to better assess the multiple sources of air pollution by fisheries across the Indian Ocean.

Purse seiners' characteristics and fuel consumption

Vessel characteristics (e.g., hull design, propeller, auxiliary engine and cold storage capacity) as well as fishing strategies and tactics affect the distance travelled and fuel consumption (Guillotreau et al., 2011; Sala et al., 2011). Our results showed that size and age explain a significant part of the differences observed in annual fuel consumption between vessels. Purse seiners' length increased steadily over the last four decades. Some fishing companies invested in very large boats (>90 m) throughout the 1990s and 2000s to reduce the fuel to catch ratio and increase profit (Campling, 2012). Economic incentives explain the increasing size of purse seiners to a large extent as the economies of scale are high for this highly capitalized industry characterized by heavy fixed costs. Fuel costs represent on average 20% of the total operating costs of a purse-seine vessel fishing in the Indian Ocean (Miyake et al., 2010). However, the business model of purse seine fishing companies became more dependent on fuel price rises during the oil crisis of 2008 when the energy costs reached more than 50% of the running costs (Miyake et al., 2010). Even for smaller vessels such as Japanese longliners, fuel costs rose from 7 up to 23% of total running costs between 1994 and 2006 (Miyake et al., 2010). When it is not possible to implement a slow-steaming strategy, one way of dealing with such a dependency is to increase the size of vessels to reduce unit costs (Cariou, 2011). This strategy is only possible because the environmental costs of carbon emission externalities are not included in oil price (Lvovsky et al., 2000). Furthermore, government subsidies for vessel construction and tax exemption of fuel consumption may have supported the development of larger vessels and buffered the effects of increased oil price to some extent (Sumaila et al., 2008).

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

Fishing strategy and fuel consumption

Fuel consumption varies with purse seine fishing strategy which depends on several factors driven by resource availability, market demand and costs, and are affected by innovation and technological changes (Guillotreau et al., 2011; Torres-Irineo et al., 2014). In particular, the advent of satellite-tracked buoys equipped with accurate positioning systems in the early 2000s supported the development of FAD-fishing that has become increasingly prevalent over the years (Fonteneau et al., 2013; Maufroy et al., 2015). The profitability of the very large purse seiners (>90-100 m) relied on an increasing number of GPS-tracked FADs and the association with support vessels that manage the array of FADs, while smaller, less-costly purse seiners (<80 m) generally used less FADs and seasonally targeted FSCs of large yellowfin tuna (Guillotreau et al., 2011; Maufroy et al., 2017). Since the early 2010s, buoys attached to the FADs include acoustic units that provide real-time information on the biomass of tuna occurring in the vicinity of the drifting rafts (Lopez et al., 2014). This has led to increasing fishing efficiency and success and enables further FAD-fishing throughout the year (Wain et al., 2020). The increasing use of FADs has substantially modified the spatial extent and movement patterns of the purse seiners. These vessels spend less time searching for tuna and more time steaming towards the FADs where fish appear to be present. This may explain that the fuel consumption increased more on average for a FAD set than a FSC set in our model although this was a marginal effect and was not significant considering the large variability between vessels and years. It should be noted however that vessels targeting FAD-associated schools make more sets per day than when fishing on FSCs (Floch et al., 2019). The FUI for purse seiners targeting FADs would then increase through increased number of fishing sets and associated fuel consumption but decrease through increased catch per set enabled by better selection of the FADs (Wain et al., 2020).

At short time scales, fishing tactics depend on the technical skills and different sources of information available to the skipper, e.g., location of oceanographic features and acoustic estimates of tuna abundance around GPS-tracked FADs (Baidai et al., 2020; Gaertner et al., 1999). In addition, cooperative fishing is an essential component of purse seine fishing as FAD position information can be shared between vessels and some skippers work in groups (Lennert-Cody et al., 2020; Snouck-Hurgronje et al., 2018). Cooperative behaviour may significantly reduce searching time and associated fuel costs, and this could explain the non-linear pattern observed for the number of FSC sets in our model, i.e., the initial reduction in fuel consumed when the number of FSCs increased from 0 to 60. The transfer of information on tuna presence between vessels explains the spatio-temporal co-occurrence of several purse seiners in the same fishing area observed. For instance, this has been observed in the cases where there are large concentrations of tuna and all purse seiners were found in the same concentrated fishing grounds (Fonteneau et al., 2008). Further work is required to study how collaborative fishing may affect fishing success, the relationship between fuel consumption and catch measured by the FUI and more generally the use of purse seine catch rates as indices of tuna abundance (Lennert-Cody et al., 2020).

Emissions's variability

GHG emissions of the Indian Ocean purse seine fishery showed a general increasing trend over the last four decades described by some strong interannual variability and a mean annual value of 590,000 t of CO_2-eq from 2015 to 2019. Our estimates are conservative as they do not include emissions from support vessels prior to 2013 nor from purse seiners that operated in the northwest and eastern parts of the Indian Ocean. Information on vessels' characteristics and fishing operations for these vessels was not available for the present study. However, we assume that their contribution to the total air pollutant emissions of the Indian Ocean purse seine fishery is on the order of magnitude of their catch, i.e., less than 6% of the total purse seine catch for the whole period. Support vessels appeared in the late 1980s in the purse seine fishery but their role has increased since the late 1990s. Their number varied between 10 and 15 over 1997 to 2012 (Chassot et al., 2015), and likely would represent an additional 3-4% of the total fuel consumed by purse seiners' activity during that period.

Our results showed that fuel consumption and associated emissions varied strongly over time as a result of several intricate factors, including changes in fleet characteristics and strategy, changes in accessibility to fishing grounds and tuna abundance and catchability. In the Indian Ocean, annual catch rates are strongly related to the extent of favourable feeding habitats for tuna, i.e., good environmental conditions result in fishery contraction (Druon et al., 2017). Although the reduction in the size of fishing grounds, supported by collaborative fishing, might suggest a reduction in fuel consumption, we found that increased catchability may actually result in increased numbers of fishing sets and eventually higher fuel consumption. In particular, the period 2003 to 2005 was characterized by an exceptional abundance of mantis shrimp *Natosquilla investigatoris*, a major prey of tuna that occurred in large swarms near the surface and substantially increased the catchability of tuna schools (Potier et al., 2007; Romanov et al., 2015). During that period, the total landings of the fishery were larger than 385,000 t per year. GHG emissions showed a major increase and reached almost 500,000 t of CO_2-eq per year. Our study also showed that GHG emissions declined by 30% over 2009 to 2011 due to the piracy threat, which resulted in a major decline of overall purse seine effort and reduction in the extent of the fishing grounds (Chassot et al., 2012). Although too early to assess, preliminary information suggests a major decrease in purse seiners' effort and GHG emissions in 2020 in relation with the COVID-19 pandemic, possibly of the same magnitude as observed during the main period of the Somali piracy threat.

Energetic and environmental performance

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

The economic drivers and consequences of the FUI were beyond the scope of this study. Nonetheless, it would be interesting in future research to look at the impact of heavy fuel oil and marine diesel oil prices on fishing strategies, fuel consumption and the level of emissions. In particular, if the fishing companies were deemed sensitive to price signals, incentive-based policies such as tax instruments could be implemented as complements to the new standards of sulphur content, at least for catches taking place within the exclusive economic zones of coastal countries.

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

Conclusion

Our model of purse seiner fuel consumption allowed us to reconstruct the history of air pollutant emissions of the Indian Ocean purse seine fishery over four decades. The FUI predicted by our model is in line with that found in earlier studies, but it also shows a great inter-annual variability according to environmental and fishing conditions that should be taken into greater consideration. The shifting structure of the fleet towards larger vessels assisted by support vessels and more intensive use of FADs tend to increase fuel consumption, hence air pollution in the fishery. GHGs now reach some 600,000 t of CO_2-eq yearly. This high level of air pollutant emissions should certainly be a concern to the eco-label schemes promoting sustainable fisheries, responding to the Sustainable Development Goal #14 of the United Nations.

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

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Table 1: Description of the fuel data set. Number of vessels and bunkering operations with mean, maximum and total weight (t) of fuel delivered annually to the purse seiners (PS) and 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

Tables

Table 2: Description of the fisheries data set selected for modelling fuel consumption. Number of vessels (N) and mean annual values of length overall (LOA; m), fishing effort (days at sea), numbers of sets on schools associated with fish aggregating devices (SetsFAD) and on free swimming schools (SetsFSC), landings (t) and fuel consumed (t) for the purse seiners that 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

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

Figures

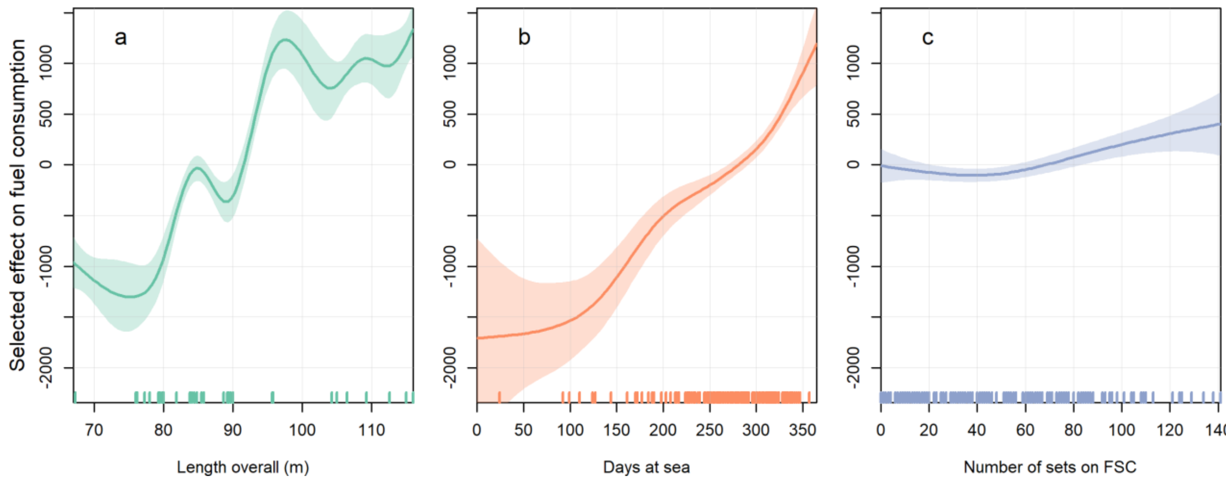

Figure 1: Variability in annual fuel consumption of large-scale purse seiners operating in the western Indian Ocean. Predictions for the three continuous variables included in the model of annual fuel consumption: (a) length overall (m), (b) days a sea, (c) number of sets on tuna free-swimming schools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

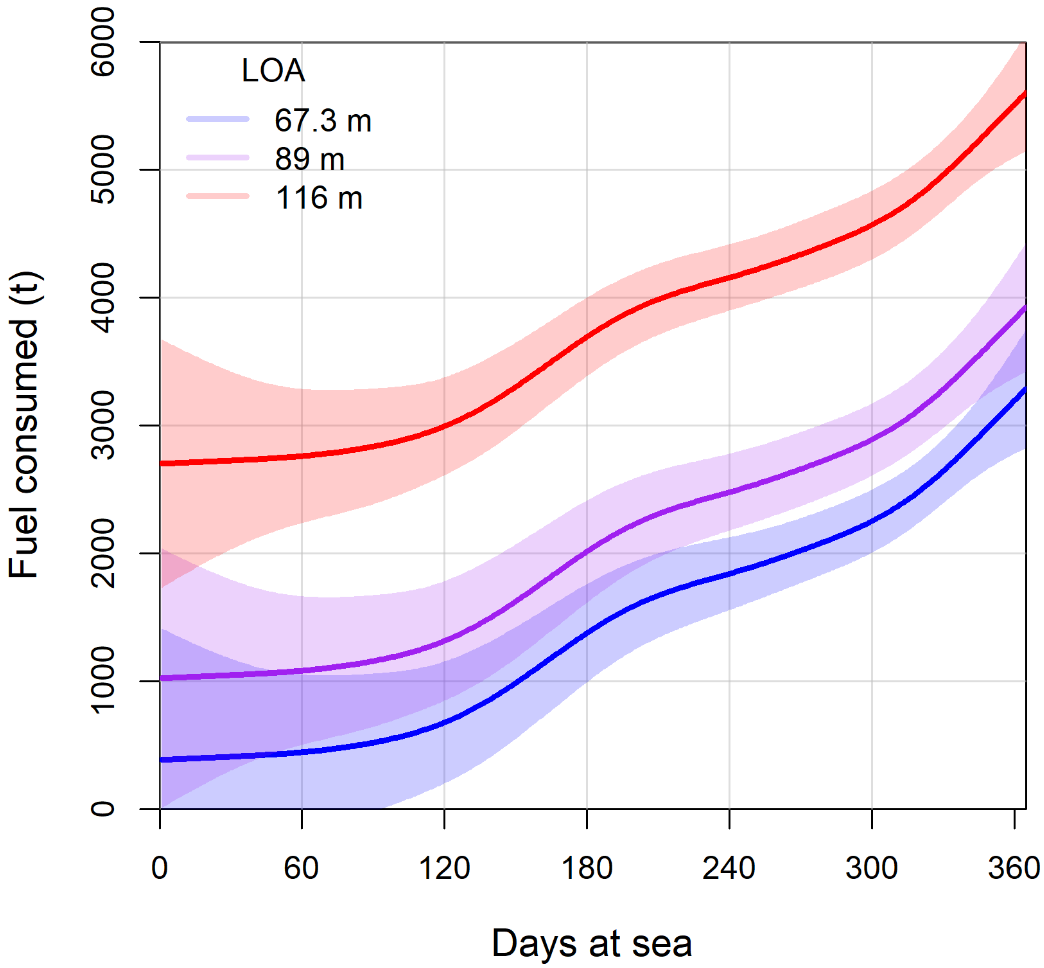

Figure 2: Effect of fishing effort and vessel length on fuel consumption of large-scale purse seiners of the Indian Ocean. Predictions of quantity of fuel consumed (t) by purse seiners of different length overall (LOA; m) as a function of the annual number of days spent at sea. Solid lines are the mean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

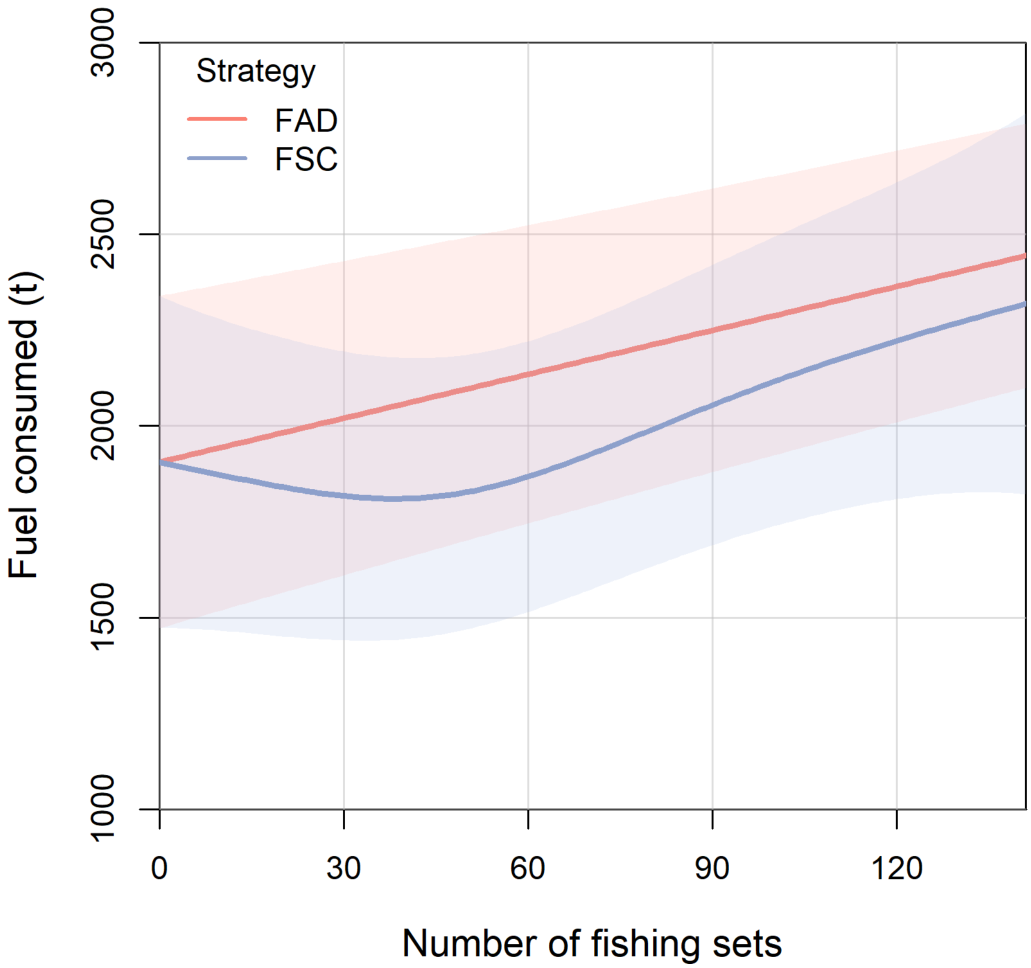

Figure 3: Effect of fishing strategy on fuel consumption of large-scale purse seiners of the Indian Ocean. Predictions of quantity of fuel consumed (t) by a medium-sized purse seiner (89.7 m) as a function of the annual number of fishing sets that would have been made exclusively on schools associated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

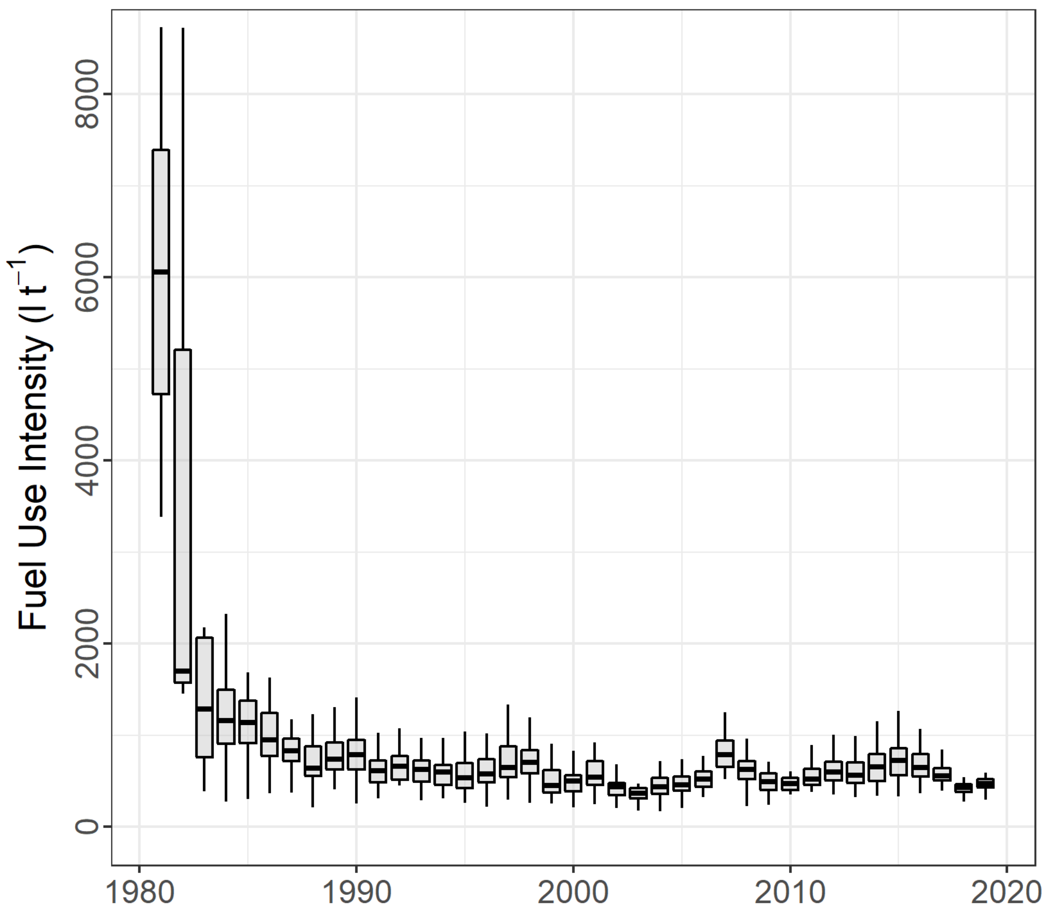

Figure 4: Temporal variability in environmental performance of the Indian Ocean purse seine fishery from 1981 to 2019 as described by the annual distribution of Fuel Use Intensity ($l\ t^{-1}$).

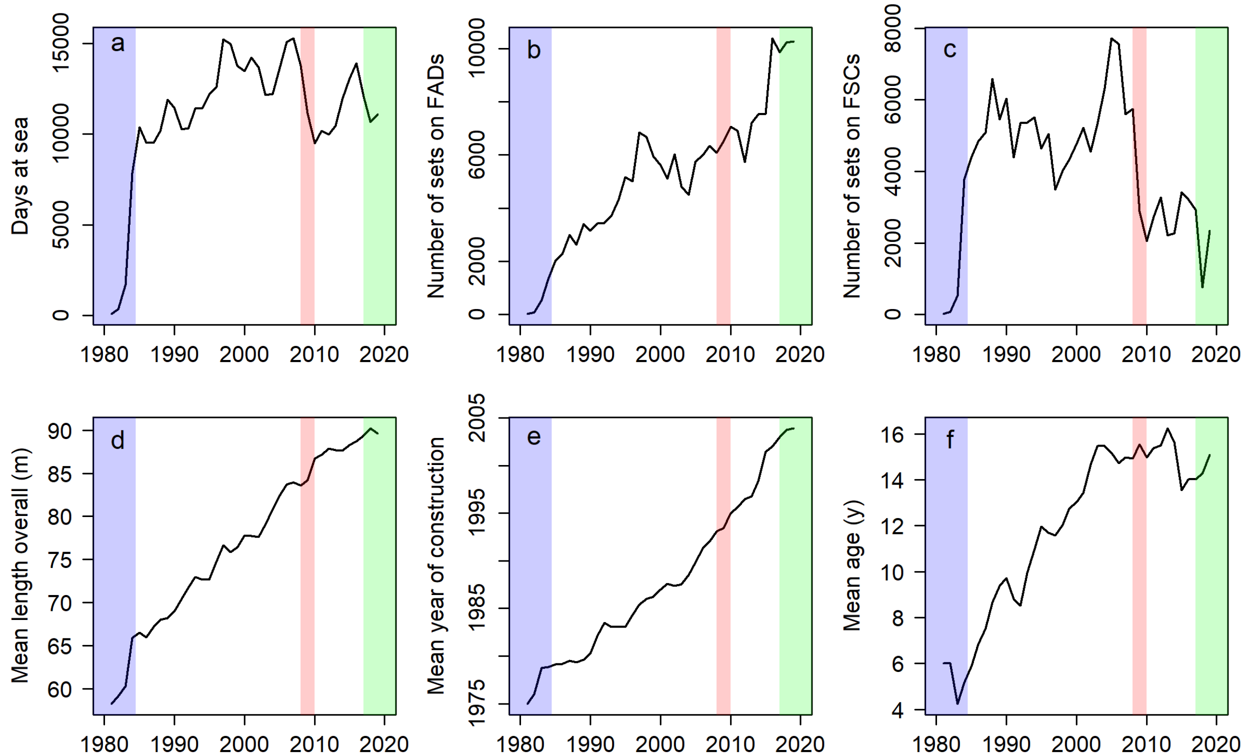

Figure 5: Annual changes in fishing effort, activities, and main technical characteristics of the western Indian Ocean purse seine fishery from 1981 to 2019. Annual time series of (a) days at sea, (b) number of sets on tuna schools associated with Fish Aggregating Devices (FADs), (c) number of sets on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

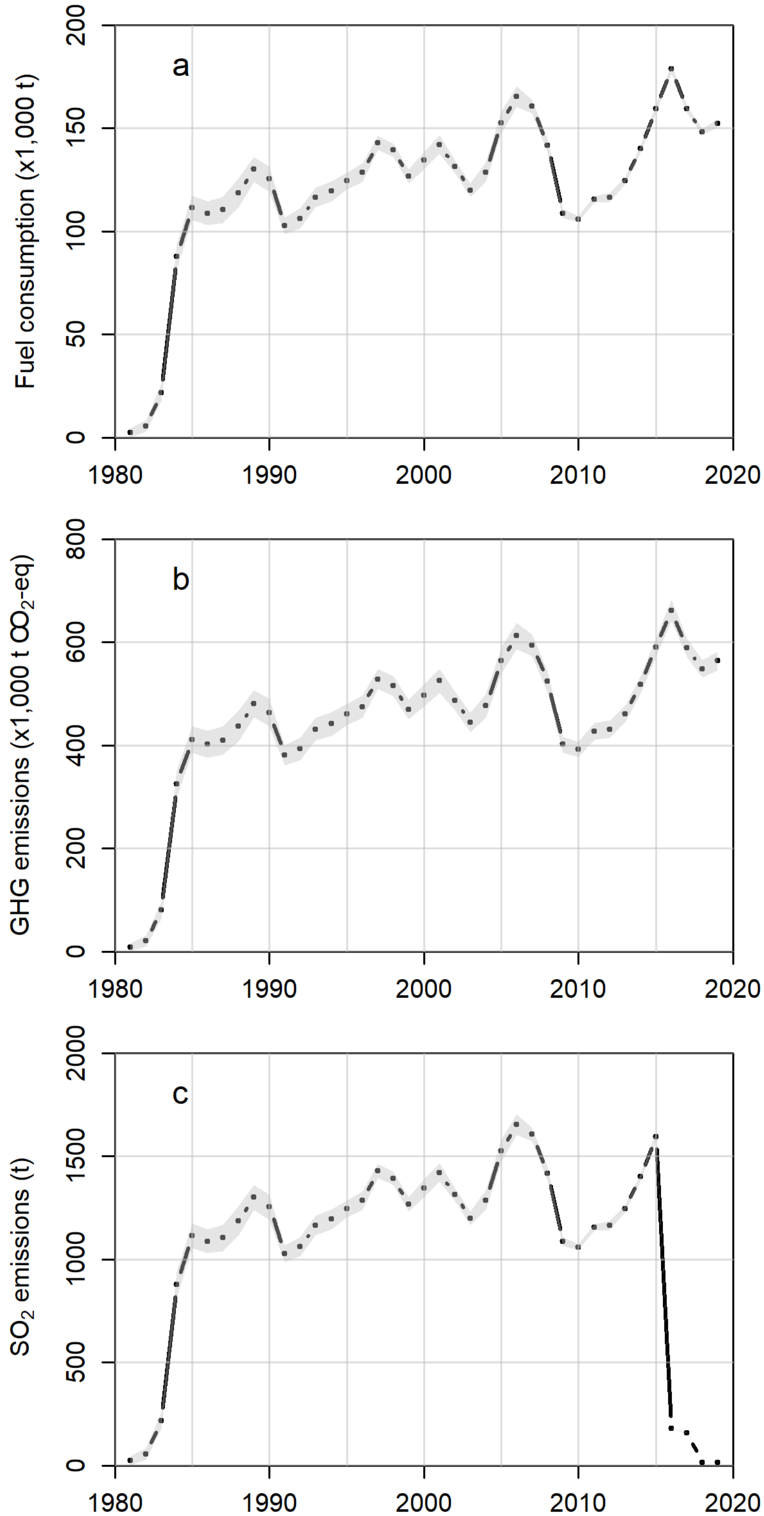

Figure 6: Temporal variability in fuel consumption, greenhouse gas and sulphur dioxide emissions of the western Indian Ocean purse seine fishery from 1981 to 2019. Annual time series of (a) fuel consumption (t), (b) GHG emissions (x1,000 t CO_2-eq) and (b) SO_2 emissions

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

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