Distant water industrial fishing in developing countries: A case study of Madagascar

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Table 1: Explanatory variables used as fixed effects in models of industrial fishing effort from 2012-2020 around Madagascar.

Variable	Range	Description	Source
Year	2012-2020		
Julian day	1-365		
Dipole index	(-1.37) – (+2.15)	Indian Ocean Dipole (IOD) is an index that shows the changes in the difference between the sea surface temperature of the tropical western and eastern Indian Ocean. Positive numbers correlate with weakened westerly winds and warmer than average waters shifting towards Africa (50°E to 70°E)	2021 Australian Bureau of Meteorology (Bom.Gov.Au, 2020)
Global oil price	(-54.2942) – (248.1612)	USD/bbl	("IMF Primary Commodity Prices," 2020)
Global fish prices	4.35 - 8.06	USD per kilogram	("IMF Primary Commodity Prices," 2020)
Cyclone events	Presence or absence on any given day	Presence of any cyclone within the Madagascar EEZ with a cyclone defined as any form of sustained wind speed above 15 knots (Tropical Cyclone Climatology 2015)	NOAA IBTrACS Version 4

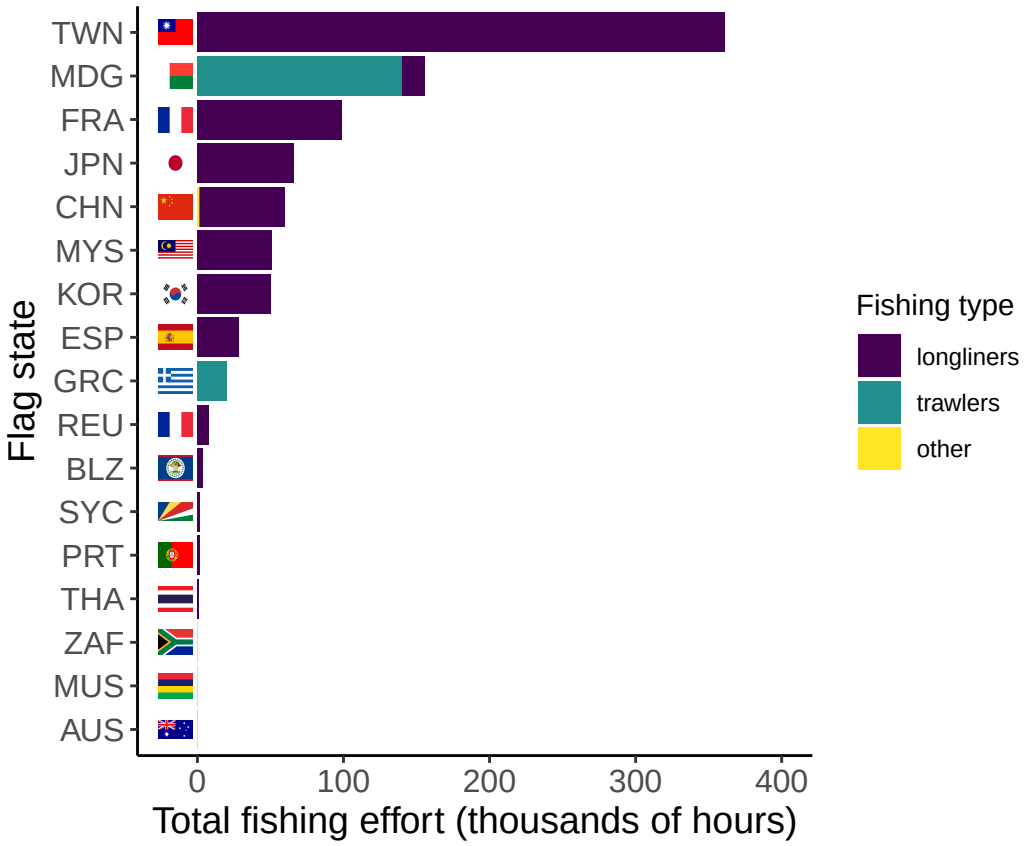

Figure 1: Total fishing effort (in hours) for the entire Madagascar EEZ from 2012-2020 by flag state

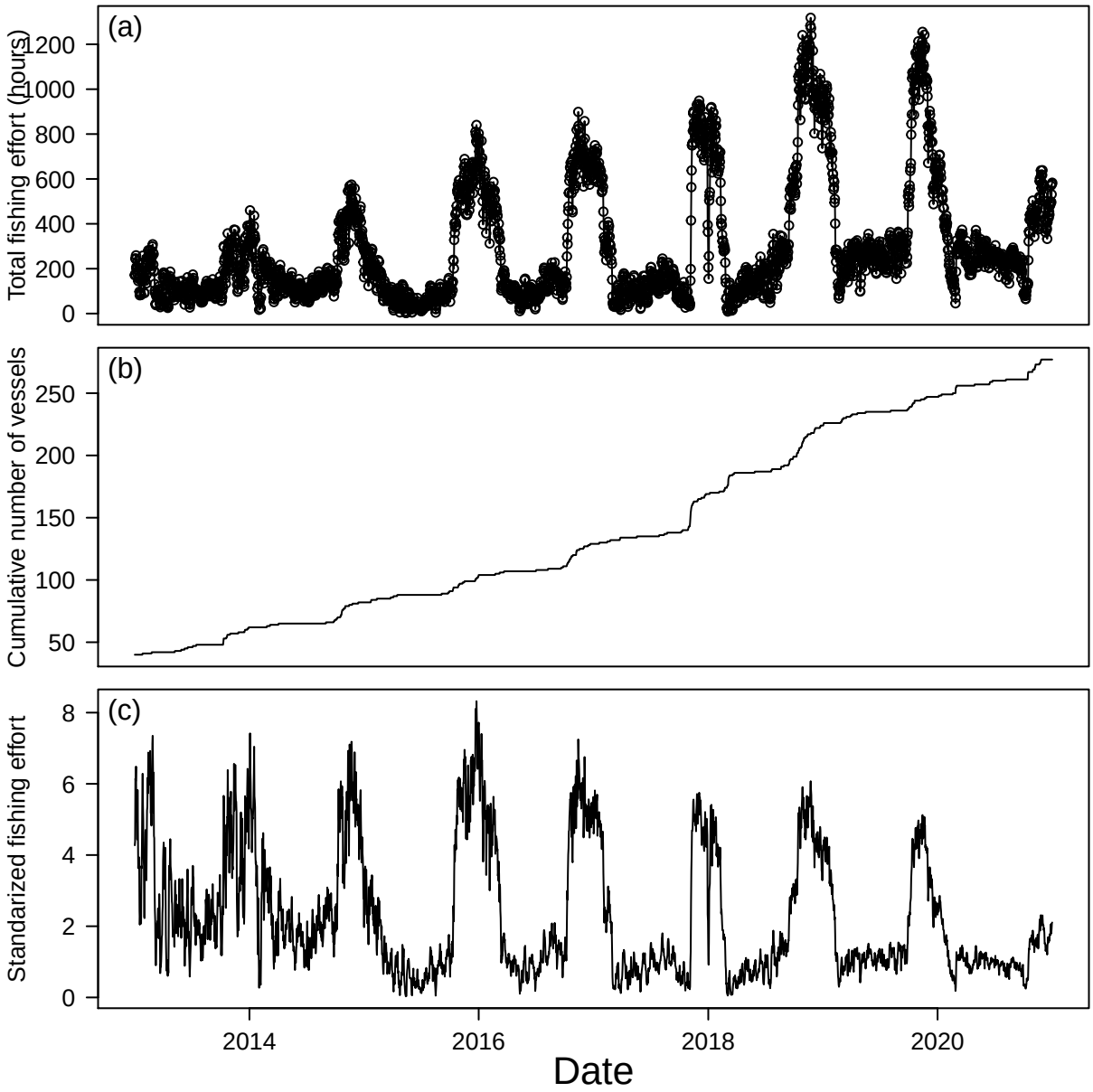

Figure 2: (a) Total fishing effort within the Madagascar EEZ per day. (b) Cumulative number of vessels observed within the Madagascar EEZ per day. (c) Standardized fishing effort which is the total fishing effort (in hours) divided by the cumulative number of vessels observed. Effort from 2012 not shown due to low number of vessels recorded.

Table 2: Model estimates (and standard errors) for the average of the best fitting models (AIC < 2) using a GLM framework with a Gaussian error structure. Fishing effort (from 2012-2019) is the total daily fishing effort within the Madagascar EEZ for only the vessels seen during all nine years of the data set (n = 51). Sine and cosine terms denote seasonal variables as a function of the julian day of the year.

	Fishing effort
(Intercept)	27115.652^{***}
	(1475.293)
sine	-22.906^{***}
	(1.369)
cosine	45.095^{***}
	(1.287)
year	-13.468^{***}
	(0.733)
Dipole index	28.620^{***}
	(4.108)
Fish price index (USD)	20.356^{***}
	(1.113)
Oil price (USD)	-0.359^{***}
	(0.056)
Cyclone event	-2.347
	(4.564)
Num. obs.	2610

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

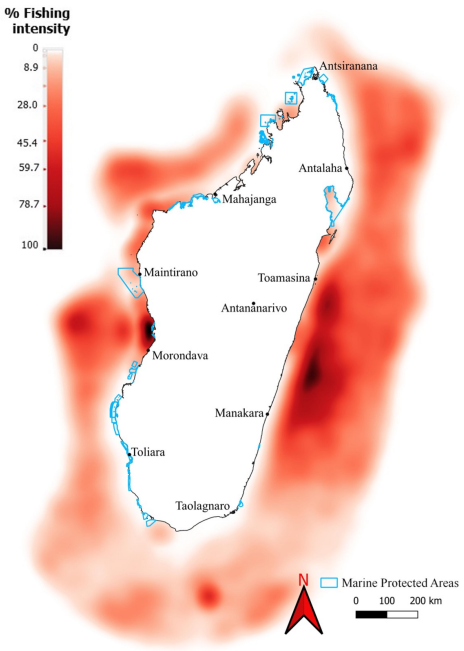

Figure 3: Total fishing effort (in hours) across the entire Madagascar EEZ from 2012-2020 with darker areas indicated more effort and lines denoting marine protected areas.

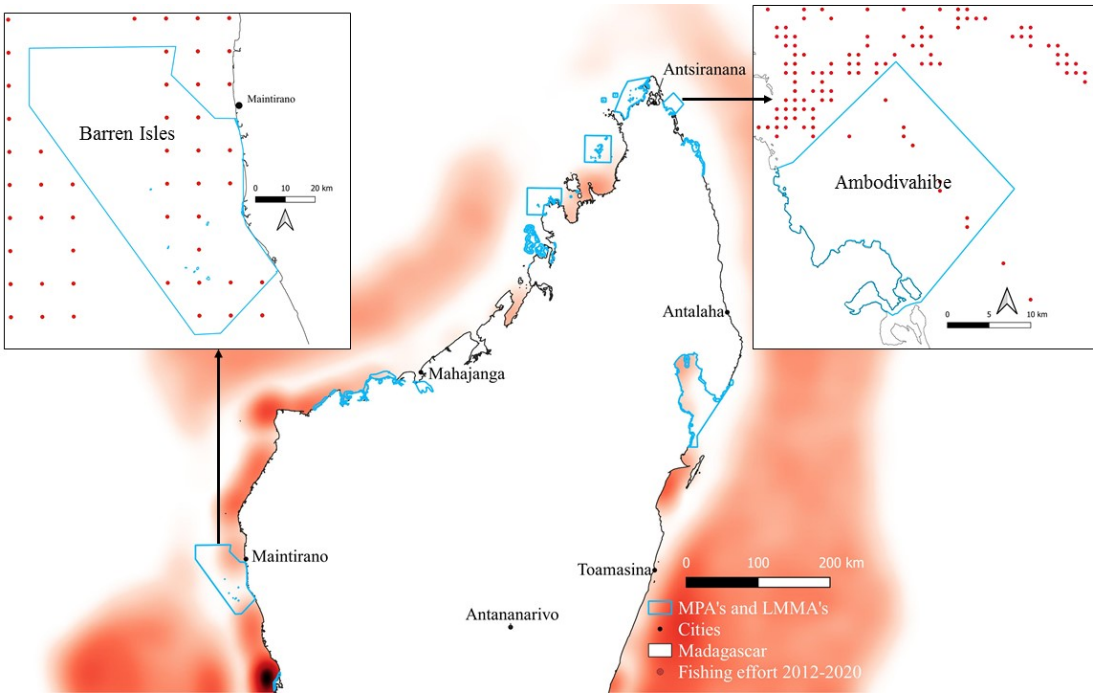

Figure 4: (larger map) Total fishing effort from 2012-2020 with darker areas indicated more effort and lines denoting marine protected areas. (smaller maps) Fishing vessel movement in two marine protected areas: Barren Islands and Ambodivahibe.

Results text

Temporal dynamics

Between 2012-2020, there were 907,643 documented hours of fishing within the Madagascar EEZ. This does not include all industrial fishing efforts as vessels were added to the database during the course of the study and some vessels were likely not included. In total, there were 277 vessels recorded fishing from a total of 17 different countries (Fig. 1). Taiwan accounted for 39.8 percent of all fishing effort, with other distant water fishing nations (France, Japan, China, Korea, Malaysia, and Spain), constituting the bulk of other longlining activity (Fig. 1). Madagascar accounted for 17.2 percent of all fishing effort, led by shrimp trawlers, which were first recorded in 2018. Greece vessels were the only other major source of trawling within the EEZ (Fig. 1).

The vast majority of fishing activity was drifting longlines (82.1%) and trawlers (17.7%) with vessels mostly in the 25-30 meter and 50-150 tonnage range (Figs. 1, S1). Fishing effort was highly seasonal and peaks between November-January each year (Fig. 2). When standardized by cumulative number of vessels recorded, fishing effort was similar between years (Fig. 2). Thus, given the nature of the data, it is not possible to determine if the total fishing effort is truly changing over time or if it is actually the number of vessels included in the data (Fig. 2).

Temporal covariates

In addition to being highly seasonal, fishing effort was also strongly correlated with a number of economic and environmental covariates (Table 2). We found that fishing effort was higher with a positive dipole index, indicating more fishing during periods of warmer waters, increased wind speeds and increased precipitation (Table 2, Figs. S6). Fishing effort was not strongly correlated with the presence of cyclone events (Table 2, Figs. S6,S5). In addition, fishing effort increased with higher fish prices (Table 2, Fig. S4). Conversely, fishing effort was not strongly correlated with global oil prices (Table 2, Fig. S3).

Spatial dynamics

The exact distribution of fishing effort changed over time, but fishing was generally concentrated on the east coast, south of the island, and on the western coast between Morondava and Mahajanga (Fig. 3). Most of the 2012-2020 fishing effort (82.4%) was 12 nautical miles (22.2 km) or more from shore, however, 17.6% of the fishing effort was closer to shore (Figs. 3,4). This accounts for approximately 170,726 total hours of fishing during the course of the study or 52.7 hours of fishing effort per day. In addition to fishing effort nearshore, we also documented fishing vessels fishing within marine protected areas (Fig. 4). As a pair of case studies, we chose two marine protected areas, Barren Isles Archipelago and Ambodivahibe. Barren Isles is a the largest marine and coastal protected area and was given temporary status

in 2014, and official status in 2017. Our analysis found that between 2013-2020, multiple trawling vessels flagged to Greece operated in the Barren Isles MPA. The Ambodivahibe protected area was first established in 2009 and includes an area of 465.62 km^2. Drifting longline and purse seiners vessels from Seychelles, France and Reunion were observed in this area between 2013-2020. It should be noted that other protected areas had similar incursions such as the Baie de Baly, Mahavavy Kinkony, and Ankivonjy.

Important data points used throughout paper

- Total number of vessels: 277
- Total number of countries fishing in Madagascar's EEZ: 17
- Although fishing effort was noted year-round, approximately 68% of fishing activity occurred between the months of October and February.

Supplemental Material: Distant water industrial fishing in developing countries: A case study of Madagascar

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Vessel characteristics

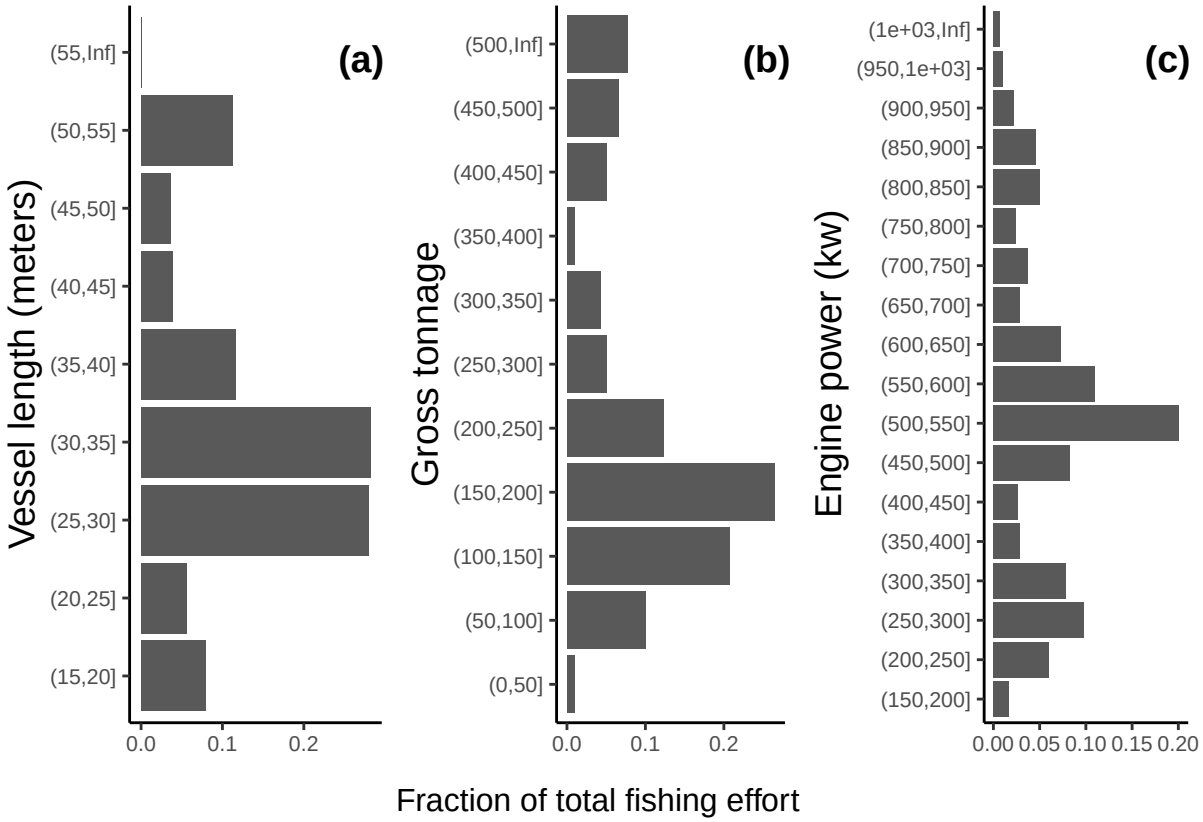

Figure S1: Total fishing effort (hours) versus various vessel characteristics: (a) vessel length (meters), (b) vessel tonnage, and (c) engine power

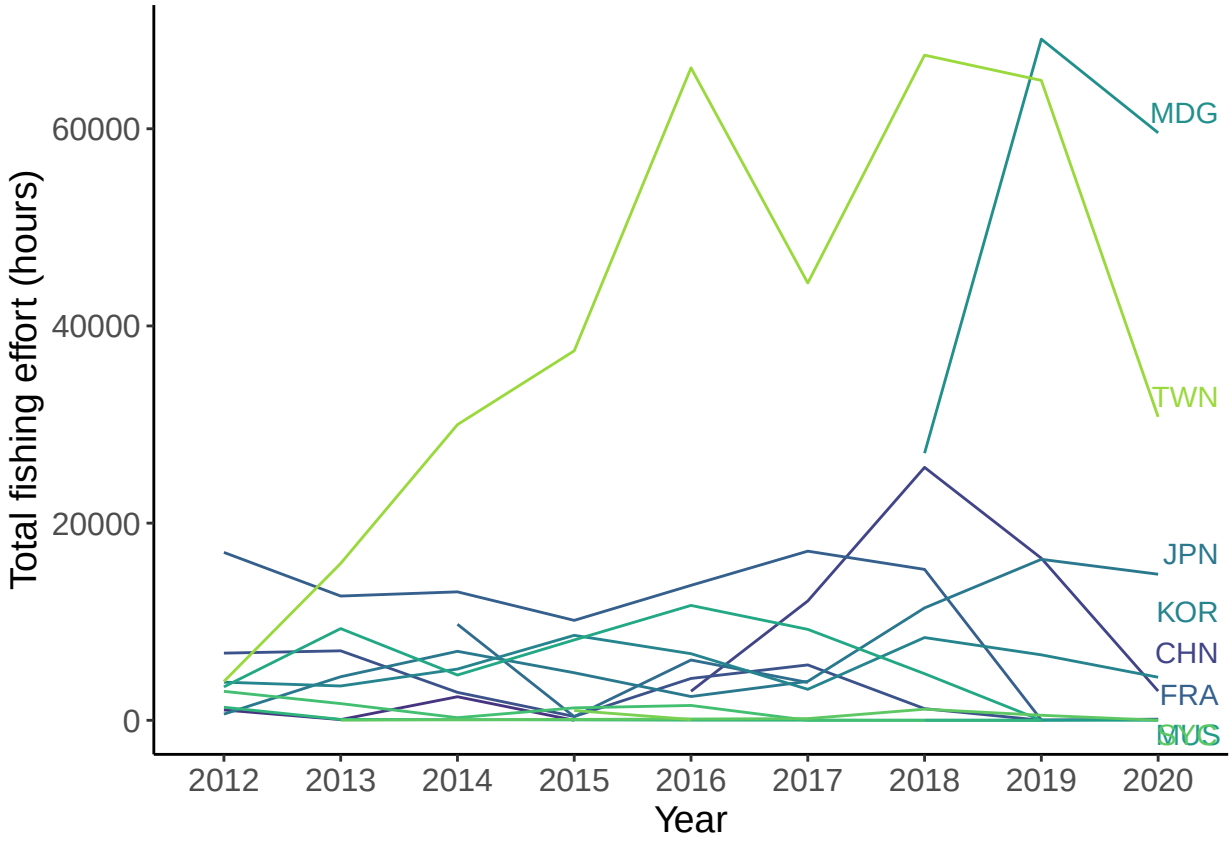

Figure S2: Total fishing effort (hours) for each country over time.

Covariates

Oil Prices

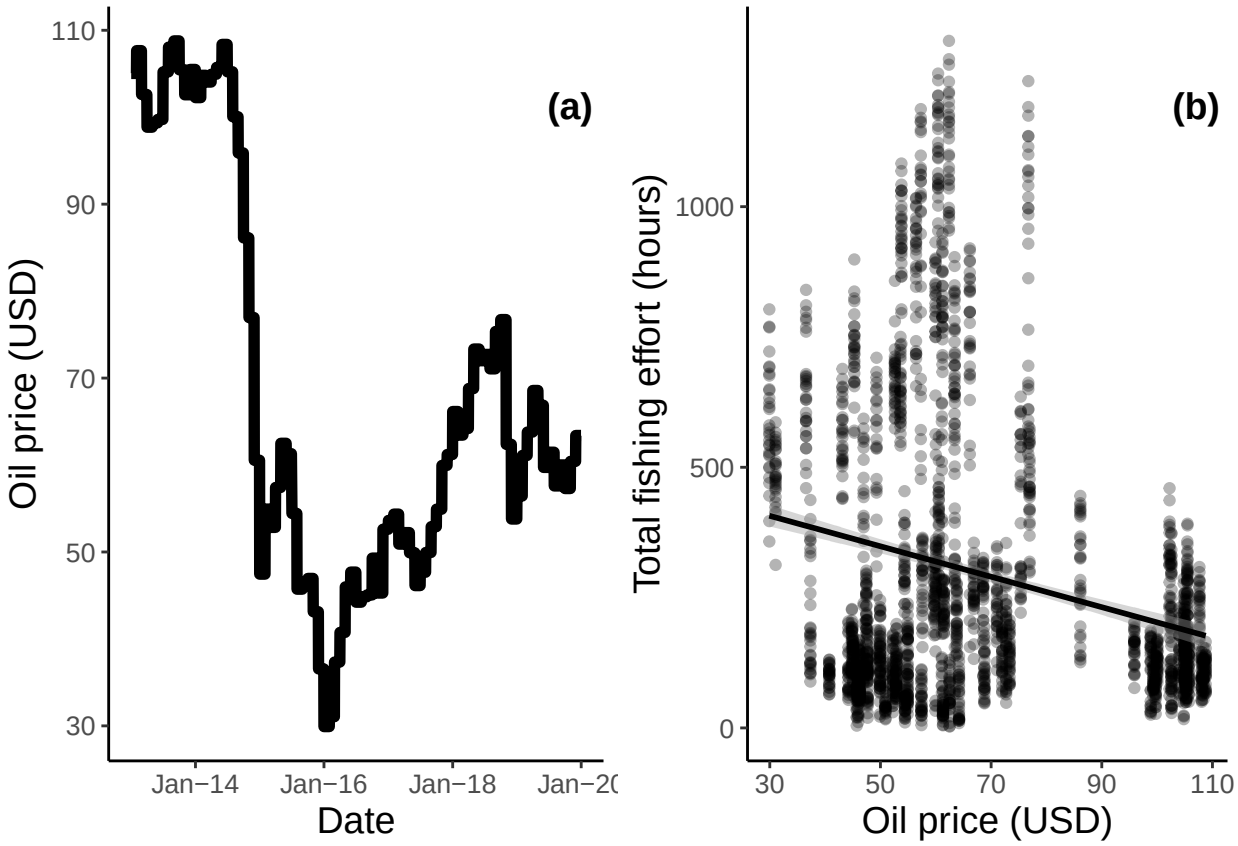

Figure S3: (a) Global oil price (USD) over time and (b) standarized fishing effort versus the global oil price.

Fish prices

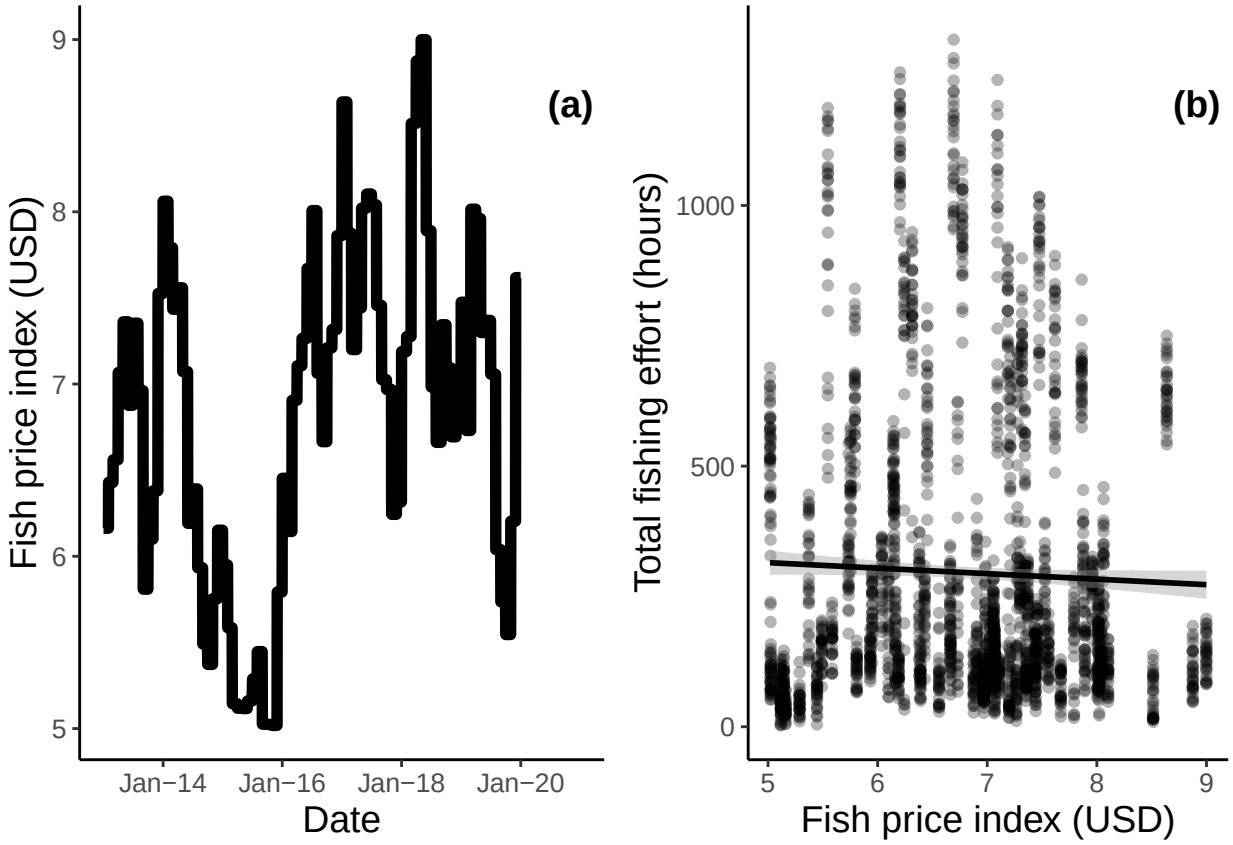

Figure S4: (a) Fish price index (USD) over time and (b) standarized fishing effort versus the fish price index.

Cyclone events

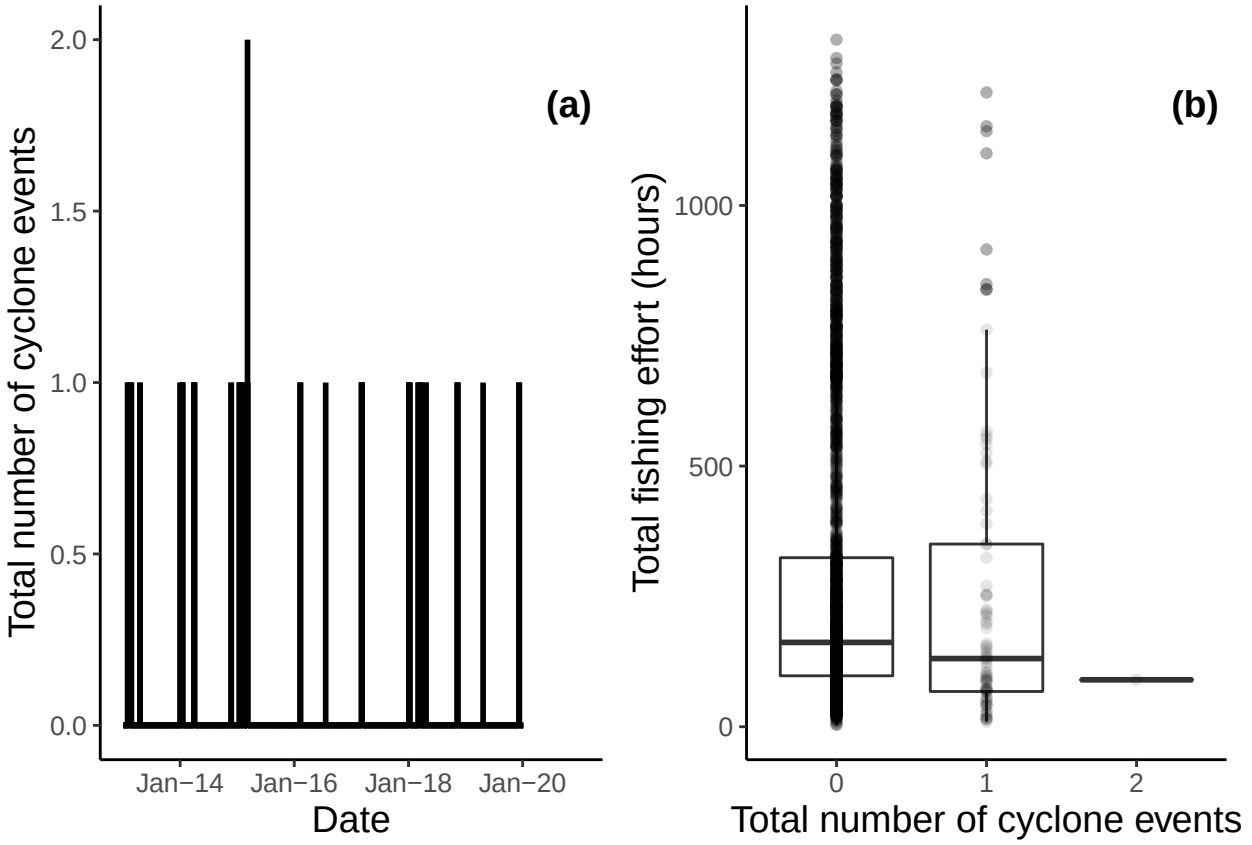

Figure S5: (a) Total number of cyclone events over time and (b) standarized fishing effort versus the total number of cyclone events.

Dipole index

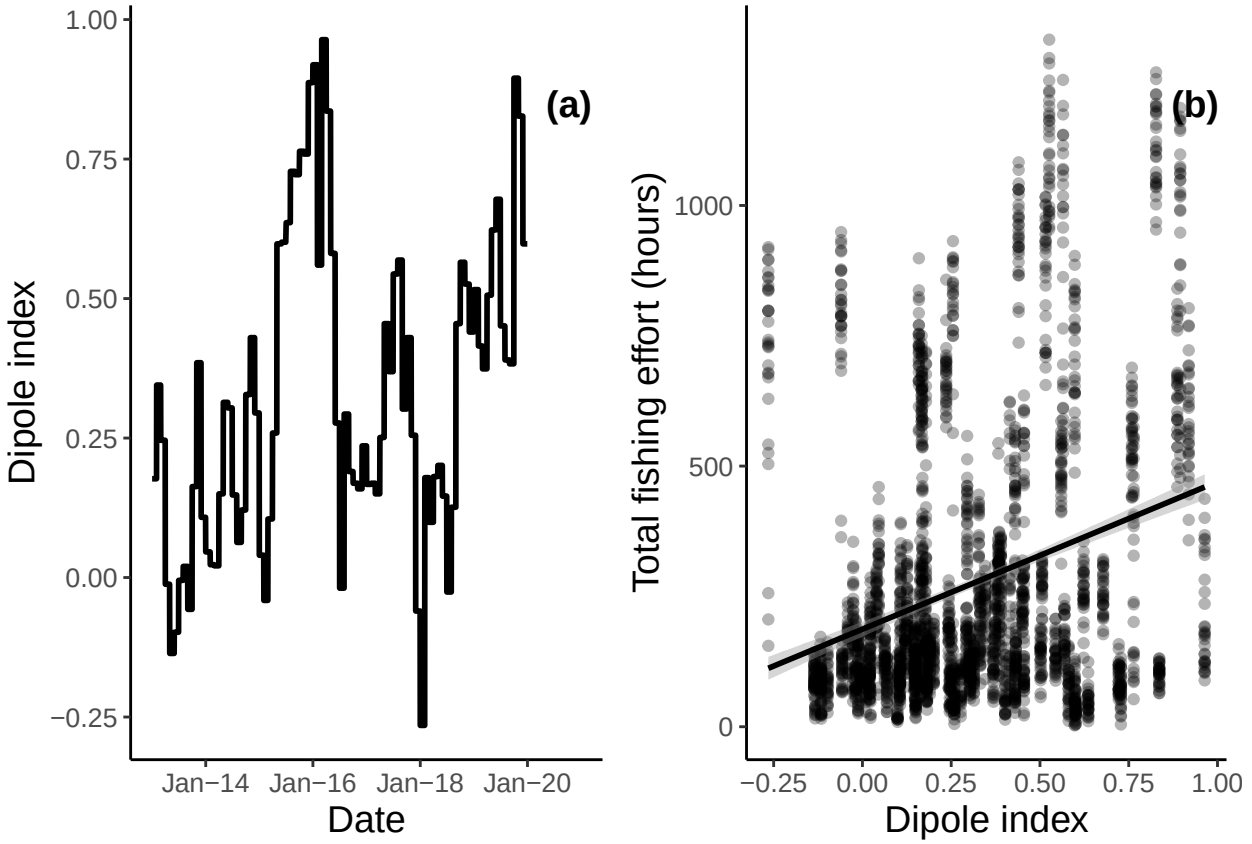

Figure S6: (a) Dipole index over time and (b) standarized fishing effort versus the dipole index.

Diagnostic plots of best fitting model

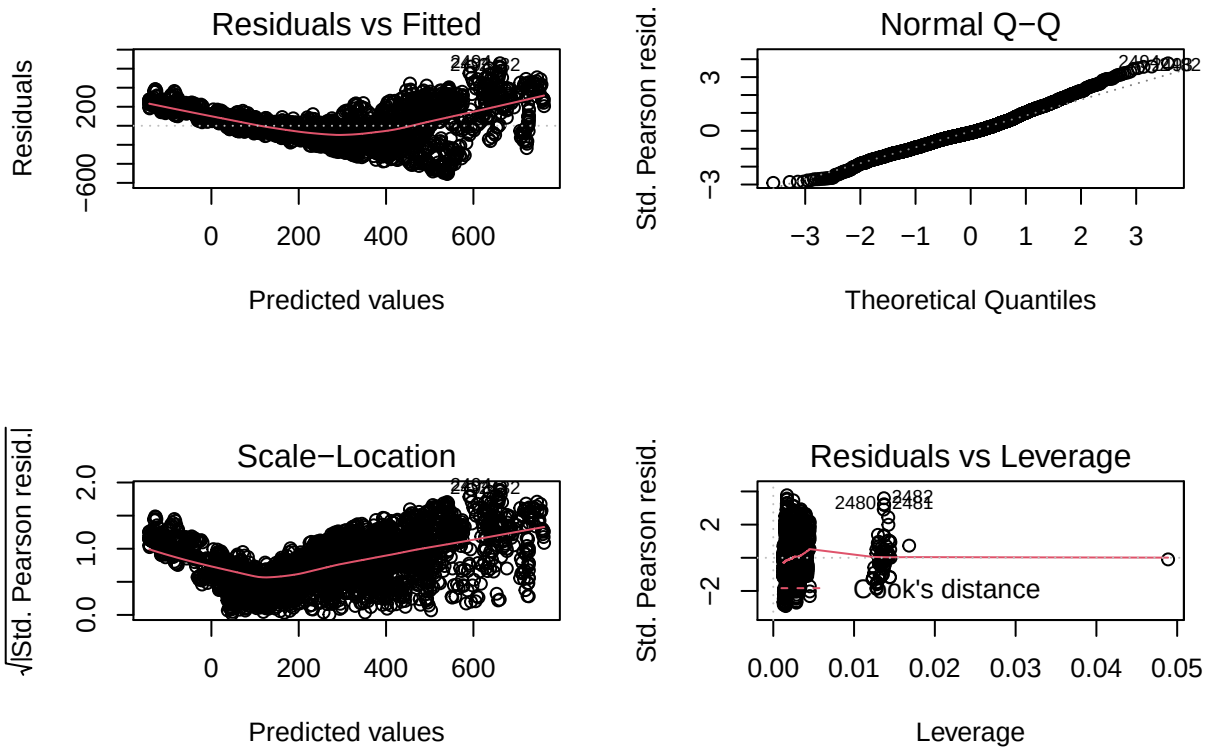

Figure S7: Diagnostic residual plots for the best fitting linear model described in the main text.

Alternative models

In the main text, in our model selection process, we examined the total fishing effort for 2012-2019. Vessels were added to the Global Fishing Watch databases throughout the study making it difficult to evaluate which years of data to include or which vessels. Therefore, we present three additional analyses here with response variables as: fishing effort from 2017-2019, standardized fishing effort from 2017-2019, and only looking at data for vessels that were present every year.

Table S1: Model estimates (and standard errors) for the average of the best fitting models (AIC < 2) using a GLM framework with a Gaussian error structure. Fishing effort (from 2017-2019) is the total daily fishing effort within the Madagascar EEZ divided by the cumulative number of vessels observed. Sine and cosine terms denote seasonal variables as a function of the julian day of the year.

	Fishing effort
(Intercept)	-28643.889
	(27779.515)
sine	-119.333^{***}
	(14.267)
cosine	326.734^{***}
	(8.804)
year	14.229
	(13.771)
Dipole index	359.311^{***}
	(38.526)
Fish price index (USD)	-33.968^{**}
	(12.018)
Oil price (USD)	7.374^{***}
	(1.123)
Cyclone event	-7.736
	(23.317)
Num. obs.	1094

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Table S2: Model estimates (and standard errors) for the average of the best fitting models (AIC < 2) using a GLM framework with a Gaussian error structure. Fishing effort (from 2017-2019) is the total daily fishing effort within the Madagascar EEZ divided by the cumulative number of vessels observed. Sine and cosine terms denote seasonal variables as a function of the julian day of the year.

	Standardized fishing effort
(Intercept)	301.582^{**}
	(116.688)
sine	-0.696^{***}
	(0.057)
cosine	1.686^{***}
	(0.046)
year	-0.149^{**}
	(0.058)
Dipole index	0.759^{***}
	(0.185)
Fish price index (USD)	-0.007
	(0.034)
Oil price (USD)	0.027^{***}
	(0.005)
Cyclone event	-0.453^{*}
	(0.202)
Num. obs.	1094

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Table S3: Model estimates (and standard errors) for the average of the best fitting models (AIC < 2) using a GLM framework with a Gaussian error structure. Fishing effort (from 2012-2019) is the total daily fishing effort within the Madagascar EEZ for all vessels (as opposed to only the vessels seen during all nine years of the data set used in the main manuscript). Sine and cosine terms denote seasonal variables as a function of the julian day of the year.

	Fishing effort
(Intercept)	-121906.271^{***}
	(4774.274)
sine	-95.190^{***}
	(4.954)
cosine	213.735^{***}
	(4.662)
year	60.584^{***}
	(2.373)
Dipole index	110.033^{***}
	(14.962)
Fish price index (USD)	-10.980^{**}
	(3.936)
Oil price (USD)	1.556^{***}
	(0.199)
Cyclone event	-50.379^{*}
	(19.549)
Log Likelihood	-19061.089
AIC	38140.179
Delta	0.000
Weight	1.000
Num. obs.	2897

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Madagascar MPA database

Table S4: Name and year started of areas in Madagascar listed as either a MPA or LMMA

Name	Status.Year
Manombo	1962
Lokobe	1966
Nosy Tanihely	1968
Mananara Nord	1990
Baie de Baly	1997
Masoala Marine Park	1997
Tampolo Marine Park	1997
Tanjona Marine Park	1997
Nosy Ve	1998
Sahamalaza Iles Radama	2001
Loky Manambato	2005
Complexe Zones Humides Mahavavy Kinkony	2006
Velondriake	2006
Antongil Bay	2007
Nosy Hara	2007
Ranobe Bay	2007
Ambohibola	2008
Ambondrolava Mangroves	2008
Beheloke	2008
Itampolo	2008
Maromena/Befasy	2008
Tahosoa	2008
Amboditangena	2009
Ambodivahibe	2009
Antisakivolo	2009
Fimihara/Ankaranjelita	2009
Imorona	2009
Maintimbato	2009
Manjaboaka	2009
Rantohely	2009
Vohitralanana	2009
Ambodiforaha	2011
Analanjahana	2011
Aniribe	2011
Anoromby/Andreba	2011

Mahasoa	2011
Tanandava	2011
Teariake	2011
Tsinjoriake	2011
Vatolava	2011
Ambodimangamaro	2012
Anandrivola	2012
Hoalampano	2012
Seranambe	2012
Antanambe-Malotrandro	2013
Sainte Luce	2014
Ambato Atsinanana	2015
Ankarea	2015
Ankivonjy	2015
Elodrato	2015
Soariake	2015
Itapera	2016
Kirindy Mite	2016
Iles Barren	2017
Site Bioculturel dAntrema	2017
Nosy Ve Androka	2018