

1 Displacement of fishing effort by Large Scale Marine
2 Protected Areas*

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8 **Abstract**

9 Large-scale Marine Protected Areas (LSMPAs) have seen a significant increase over the last
10 years. Fishing effort is effectively eliminated within these protected areas upon implementation.
11 The benefits of reducing effort have been largely studied, and include increases in abundance,
12 biomass, and diversity within the bounded regions. These no-take zones may produce spillover
13 effects, which provide fish for outside areas. However, the economic and ecological implications
14 of displacing fishing effort are not yet fully understood. Novel data products that track fishing
15 effort at the vessel-level allow us to identify changes in fleet- and vessel-level behavior upon
16 the implementation of protected areas, as well as how these redistribute. This paper evaluates
17 the implications of implementing LSMPA, by evaluating changes in fishing hours, showing
18 that vessels in the effected region reduce fishing effort after the implementation of PIPA. Our
19 results are robust to a set of specifications. We also track the relative spatial allocation of
20 fishing events thorough time, and identify that areas closer to PIPA show an increase in relative
21 fishing hourse due to the displacement of PIPA-fishing vessels. Our results not only provide an
22 impact evaluation of the effect of LSMPAs on fishing activity, but provide insights into vessel
23 redistribution dynamics, which may have ecological and economic implications.

*Work in progress, do not circulate

24 1 Introduction

25 Marine Protected Areas (MPAs) are intended to safeguard parts of the ocean from fishing and other
26 extractive activities. Current international goals aim to protect 10% of the ocean environments
27 by 2020. In an effort to meet this target, the world has seen a rapid increase in MPA coverage
28 (Wood et al., 2008; Sala et al., 2018), largely driven by a small number of Large Scale Marine
29 Protected Areas (LSMPA) Singleton and Roberts (2014); Boonzaier and Pauly (2016); Alger and
30 Dauvergne (2017)). Due to weak property rights, limited habitat transformation, and potentially
31 lower management costs, LSMPAs provide an opportunity to safeguard the oceans Game et al.
32 (2009). Today, a small number of LSMPAs make up at least 80% of the managed areas in the ocean
33 Toonen et al. (2013). LSMPAs may be instrumental in helping us achieve the 10% target by 2020
34 (McCauley et al., 2016).

35 Given the relatively recent establishment of most LSMPAs, very little is known about their human
36 dimensions and implication for fisheries (Gray et al., 2017). As with customary MPAs, it is important
37 that we understand the socioeconomic implications of management interventions. One issue of
38 particular importance is that of the displacement or redistribution of fishing effort, which may
39 influence the outcomes of an MPA (Smith and Wilen, 2003). Theoretical models make different
40 assumptions about the way in which fishers will reallocate fishing effort after an area closure. The
41 few empirical works focus on small-scale fisheries and rarely incorporate spatially explicit data.
42 Despite these efforts, marine conservation is yet to identify the response in fishing effort and its
43 management implications.

44 Recent advances in satellite tracking technologies and near real-time identification of fishing activity
45 provide us with an opportunity to tackle increase governance and answer long-lasting questions.
46 Here, we ask, how do fishers respond to the implementation of LSMPA? After a closure, and if they
47 continue to fish, where do they reallocate fishing effort? We use identification of fishing activity via
48 Automatic Identification Systems (AIS) and causal inference techniques to describe the behavioral
49 changes and spatial redistribution of the industrial tuna purse seine fleet due to the implementation
50 of a Large Scale Marine Protected Areas in the Pacific Ocean.

51 Our work is novel in the sense that it provides empirical evidence of the effect of Large Scale Marine
52 Protected Areas in fishing behavior and distribution and can help guide future interventions as
53 countries march towards meeting the targeted 10% of ocean protection. Understanding how effort is
54 displaced from LSMPAs might provide insights into how the industrial fleet would react to a high
55 seas closure.

56 The paper is outlined as follows: Section 2 provides more information on Large Scale Marine
57 Protected Areas and background on empirical studies of effort redistribution. An overview of the
58 Nauru Agreement and associated countries, a description of the fleet that operates in the region,
59 and a brief history of PIPA is also included. Section 3 describes our data and identification strategy.
60 Section 4 presents our results, section 5 provides an extension of our results to other LSMPAs¹ and
61 discusses our results².

¹Not yet. but I think this would be interesting

²I might also include a section, after the background, where I explain the different theoretical models of effort redistribution and behavioral responses

62 2 Background

63 2.1 Large Scale Marine Protected Areas

64 The cutoff at which an MPA is considered to be a LSMPA ranges from areas larger than 30,000
65 km² as defined by De Santo (2013) or areas larger than 250,000 km², as defined by (Toonen et al.,
66 2013). Figure 1 shows LSMPAs that meet the later, and that are fully no take. LSMPAs are often
67 implemented in the pelagic environment, where the dominant human activity is industrial fishing
68 (Gray et al., 2017; Kroodsma et al., 2018). The early literature on LSMPAs focused on the inherent
69 challenges and difficulties that come with a pelagic environment. Kaplan et al. (2010) claimed that
70 very large MPAs would result in excessive opportunity costs and that these would be difficult to
71 enforce. Game et al. (2009) suggested that most of the challenges could be overcome with the
72 incorporation of technology, in what then became known as Dynamic Ocean Management (Maxwell
73 et al., 2015). The effectiveness and difficulties of implementing LSMPAs are not the focus of this
74 paper ³. Instead, we focus on the effect and implications of the ones that *have been* implemented.

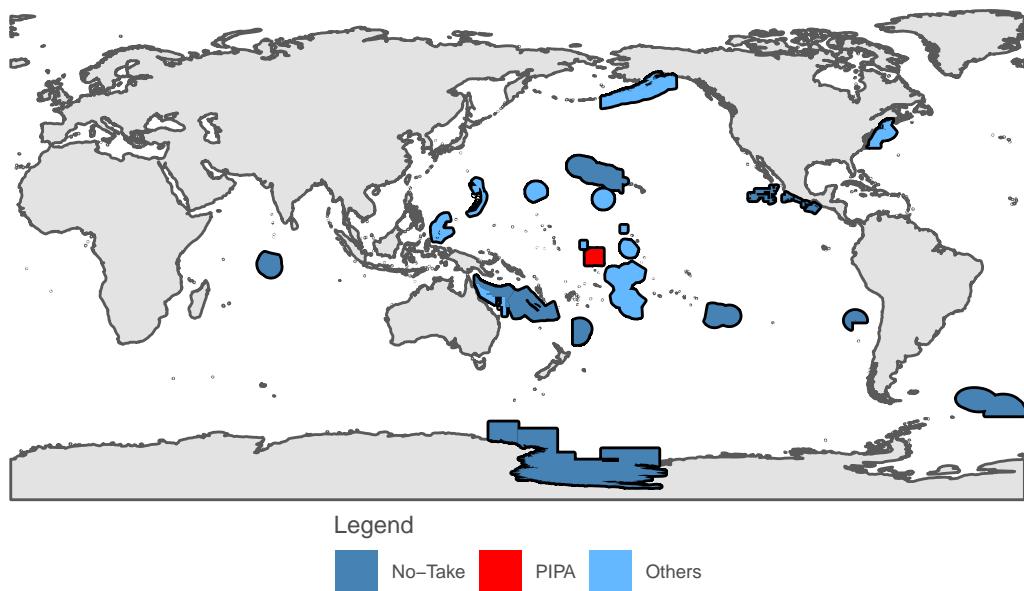


Figure 1: Large Scale Marine Protected Areas. The map shows all areas larger than 250,000 Km². Areas in dark blue meet at least one of these conditions: reported no take area is greater than 0, are categorized as IUCN Ia or Ib, their designated english name is ‘Protected Area’.

75 LSMPAs were erroneously assumed to have little social implications due to their remoteness.
76 However, there have been calls to incorporate the human dimensions into LSMPAs management and
77 evaluation (Agardy et al., 2011; Gray et al., 2017). Most research incorporating these dimensions has
78 focused on governance and enforcement of LSMPAs (*i.e.* Alger and Dauvergne (2017); Christie et al.
79 (2017)), but they are yet to be the focus of economic analyses (Gray et al., 2017). Overall, there has
80 been little empirical work regarding LSMPAs. Recent technological advances in vessel-detection

³But see Singleton and Roberts (2014), who provide an objective discussion of pros and cons of LSMPAs.

systems allows for the discovery and advancement of many important facets of LSMPAs. For example, (McDermott et al., 2018) show that the anticipation of a LSMPA can lead to preemptive overfishing, which can erode or delay the expected benefits of the intervention. White et al. (2017) combine shark tags and vessel-tracking data to demonstrate that the fairly large Palmyra Atoll National Wildlife Refuge (54,000 Km²) protectes two thrids of the tagged grey reef sharks by effectively excluding fishing effort. More recently, (Bradley et al., 2018) use similar data to highlight cases of potential illegal shark fishing *inside* a 2 million km² shark sanctuary. To date, no studies have evaluated the displacement of fishing effort due to LSMPA implementation.

Spatial closures of this magnitude are likely to induce changes in fishers' behavior. Theoretical models of fishing effort redistribution range from the simplistic assumption that effort inside the bounded region disappears, to spatially explicit models that reallocate fishing effort based on habitat characteristics, presence of other vessels, and expected returns (Smith and Wilen, 2003; Hilborn et al., 2006). However, these focus on the long term optimal equilibrium, and redistribution of fishing effort may not always be optimal, especially over the first years (Stevenson et al., 2013).

The empirical research that has been done in customary sized MPAs suggest that resource users may show idiosyncratic responses. For example, Stevenson et al. (2013) show that a network of MPAs displaced fishing effort farther away from ports, resulting in higher *perceived* costs, and increases in catch per unit effort. Cabral et al. (2017) analyse the redistribution of fishing and non-fishing vessels following the implementation of a network of MPAs in California, and find that commercial dive boats follow a fishing-the-line pattern, while some fishing boats follow an ideal free distribution. More recently Elahi et al. (2018) used satellite tracking data to show that a temporal spatial closure caused trawlers to maintain effort but apply it more intensively elsewhere, particularly along the borders and closer to shore. The way in which fishers react to a spatial closure can have major implications in its outcome (Smith and Wilen, 2003; Hilborn et al., 2006) highlighting the need to understand how fishers react to the implementation of LSMPAs, and fishing effort changes and is spatially redistributed. However, all these closures took place within Exlcusive Economic Zones, where other regulations exist. This may not always be the case for LSMPAs, where often the entire EEZ is converted into a LSMPA, leaving fishers with the options of moving to the high seas or other countries' EEZs.

2.2 Nauru agreement and the Phoenix Island Protected Area

The Nauru Agreement was established in 1982 by a select group of Pacific island nations to manage their important tuna resources. PNA Members include Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, and Tuvalu. The Nauru Agreement regulated access of foreign vessels (*i.e.* those from non-PNA countries). Holding ~80% of the historical purse seining grounds within their Exclusive Economic Zones, PNA countries gained bargaining power when providing access to foreign fleets (Havice, 2010).

The cooperation that emerged thanks to the PNA allowed for subsequent agreements that strengthened fisheries management, like the Palau Agreement, which limited the number of purse seiners at 205 vessels from 1995-2007⁴. However, the most notable regulation is their approach to manage fishing effort: a Vessel Day Scheme (VDS) implemented in 2007 (Havice, 2013). This effectively modified how fishing effort was managed, from number of vessels under the Palau Agreement to

⁴See Havice (2010) for a detailed description of the Nauru, Palau, and Federal States of Micronesia agreements, their objectives, and outcomes.

122 fishing hours. The VDS works as follows: Each year, scientific advisors recommend a total number
123 of fishing vessel-days per year. Hours are allocated to each PNA country based on catch history,
124 and they then use or sell fishing rights to other non-PNA countries (Aqorau et al., 2018). While
125 the effectiveness of this scheme has been debated in terms of meeting their fishery management
126 and conservation objectives, the licensing significantly contributes to the economy of these island
127 nations (Havice, 2010).

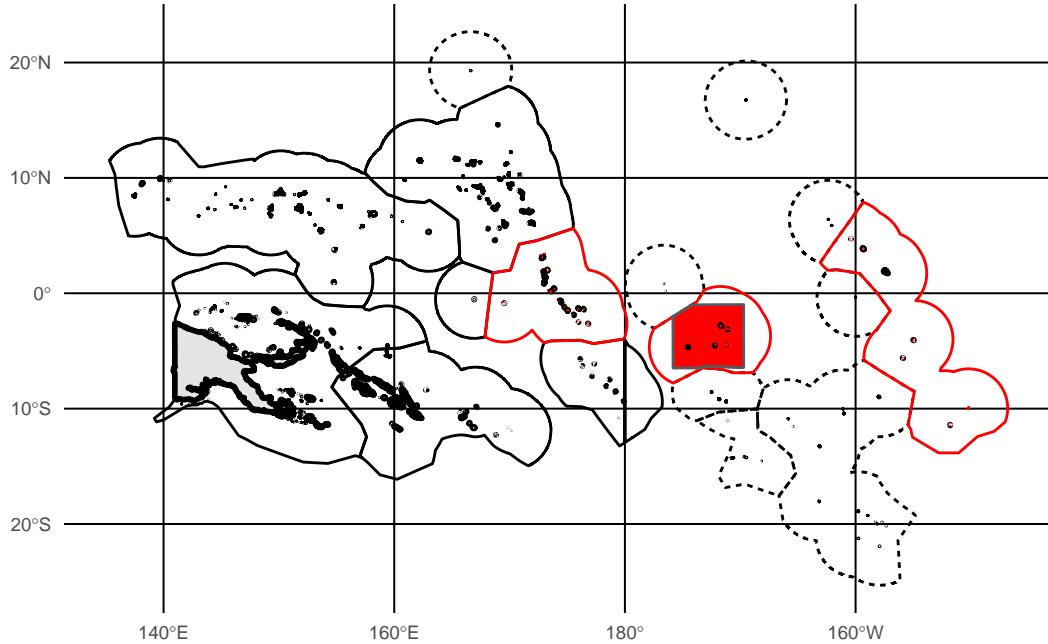


Figure 2: Map of the Exclusive Economic Zones (EEZs) of the region of interest. A solid line indicates countries that belong to the PNA, while a dashed line indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

128 The main tuna species caught in the region are skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus*
129 *albacares*), albacore (*Thunnus alalunga*) and bigeye (*Thunnus obesus*). From these, the first two are
130 amongst the top-10 species represented in global fisheries production statistics, with 2016 catches
131 increasing relative to the 2005-2014 average (FAO, 2018). This region of the Pacific has historically
132 accounted for a large portion of tuna catches (Aqorau and Bergin, 1997). Today, the PNA controls
133 close to 50% of the global skipjack tuna production (PNA, 2018). A large portion of these catches
134 derive from purse seine vessels licensed under the VDS. Fishing vessels from Australia, New Zealand,
135 China, France, Korea, Japan, the Philippines, Taiwan, and the United States participate in the
136 purse-seining VDS.

137 One of the most notable and recent management interventions in the region is the implementation of
138 the Phoenix Island Protected Area (PIPA) by the government of Kiribati. PIPA was first declared
139 in 2006, and established in 2008 with only 4% of it declared as no-take. In January 1st, 2015,
140 the no-take area within PIPA was expanded to a total area of 397,447 km², roughly 1.5 times the
141 size of Ecuador. Figure 4 shows a map of the PNA countries and the Phoenix Island Protected
142 Area.

143 The closure of such a large area in one of the most important fishing regions in the world provides a

144 great opportunity to evaluate the behavioral responses and redistribution of fishing effort by vessels
145 that used to fish there. PIPA has been the focus of previous research, showing that fishing effort is
146 effectively reduced after implementation (McCauley et al., 2016; McDermott et al., 2018). To this,
147 we pose two questions: How do individual vessels respond to the sudden exclusion of such a big
148 area? And where did all the vessels go? In the next sections we describe the data and methods
149 used to answer this questions.

150 3 Methods

151 This section is divided into two main parts. First, we provide a general description of AIS data and
152 the process of identification of vessel-level fishing events done by Global Fishing Watch⁵. Alongside,
153 we describe the subset of data used on our analyses. When relevant, we also point out possible
154 shortcomings in the data, or factors that must be considered in the later analyses. We then move on
155 to explain our empirical strategy for the identification of the behavioral changes and redistribution
156 of fishing effort.

157 3.1 Data

158 Automatic Identification Systems (AIS) are on-board devices that provide at-sea safety and prevent
159 ship collisions by broadcasting vessel position, course, and activity to surrounding vessels. These
160 broadcasted messages can be received by satellites and land-based antennas. GFW uses convolutional
161 neural networks to infer vessel characteristics and whether each broadcasted position represents a
162 fishing event, thus allowing us to estimate near real-time fishing events globally since 2012 (Kroodsma
163 et al., 2018).

164 The amount of data gathered is dependent on the number of antennas and satellites that can pick
165 up the signals. In June 1st 2014 satellite count increased from 3 to 6, and then to 10 in January 1st
166 2016. This causes an increase in the number of *received* AIS messages (*i.e.* points), and therefore
167 an apparent increase in the number of vessels and fishing hours. However, the addition of satellites
168 “affects” all vessels in the same way. The variability in AIS data and ocean conditions require that
169 temporal trends be taken into account. We do that by including specific controls in our identification
170 strategy and using a subset of data that meet a BACI design -which gives us the full tracks for
171 vessels affected and unaffected by the implementation of PIPA.

172 Our analysis focuses on purse seine vessels, the most important fishery for PNA countries⁶. We
173 identify a total of 103 purse seiners that fished in PNA waters at least once before 2015⁷. These
174 vessels represent over 26 million individual observations for the 2012 - 2017 period. We identify
175 65 vessels that have fished inside PIPA at least once since 2012. From these, 62 did so before the
176 announcement (*i.e.* 09/01/2014 *sensu* (McDermott et al., 2018)) but are only able to track 61 for
177 the complete periof of study before and after its implementation⁸. On the other hand, 38 vessels
178 never fished inside PIPA but we only have data for 26 vessels before and after.

⁵Global Fishing Watch: globalfishingwatch.org

⁶We perform some of the same analyses for longliners and include them in the Appendix

⁷New vessels that entered the fishery after 2015 were not exposed to the policy intervention in the pre-treatment period and are therefore exlcuded from our analyses.

⁸1 vessel never fished again after August 18, 2013.

179 Therefore, our treatment group contains all purse seiners ($n = 61$) that fished within PIPA at
180 least once before the announcement, and that continued to fish elsewhere after the January 2015
181 implementation. Vessels in the control group meet the following two conditions: i) vessels never
182 fished within PIPA waters, and ii) vessels have fished in surrounding areas (*i.e.* PNA-countries'
183 EEZ) before and after PIPA closure ($n = 26$).

184 We include three additional definitions of control groups as a robustness check: one with only vessels
185 that belong to PNA countries ($n = 7$), and one that excludes Chinese vessels ($n = 21$). Our third
186 control is made up of Japanese purse seiners that fish in the Pacific but that never fished inside
187 PIPA ($n = 27$)⁹. Our definition of treatment and control groups leaves us with 61 and 21 treated
188 and control vessels, which have just over 22 million observations where about 22% are identified as
189 fishing events.

190 For each vessel we calculate total daily fishing hours and obtain panel data with 37,800 observations.
191 Table 1 shows the number of vessels following a BACI design, as well as the fishing hours, before
192 and after PIPA. Fig. 4 shows that mean fishing hours for purse seiners have an abrupt increase,
193 just before January 1st, 2015. This trend is observed for both treated and control groups. Across
194 all measures, the treatment and control vessels follow similar patterns, confirming our claim that
195 the control group provides a plausible counterfactual. Figure S1 provides a visual representation of
196 the vessel-level fishing events that make up each group through time. We use this data to answer
197 our key questions: How do the 61 purse seiners modify their behavior as compared to the different
198 control groups, and where do they go after the spatial closure? The following section describes our
199 empirical identification strategies.

Table 1: Number of fishing vessels and mean daily fishing hours by group before and after PIPA implementation.

Group	n	Before	After	Change (A / B)
Control	26	11.74	20.13	1.72
Treatment	61	10.67	18.36	1.72

⁹Using Taiwanese vessels was the original idea, but there are only 4 vessels with pre-2015 data. I need to further identify proper Taiwanese vessels, as I am currently using the entire Pacific ocean

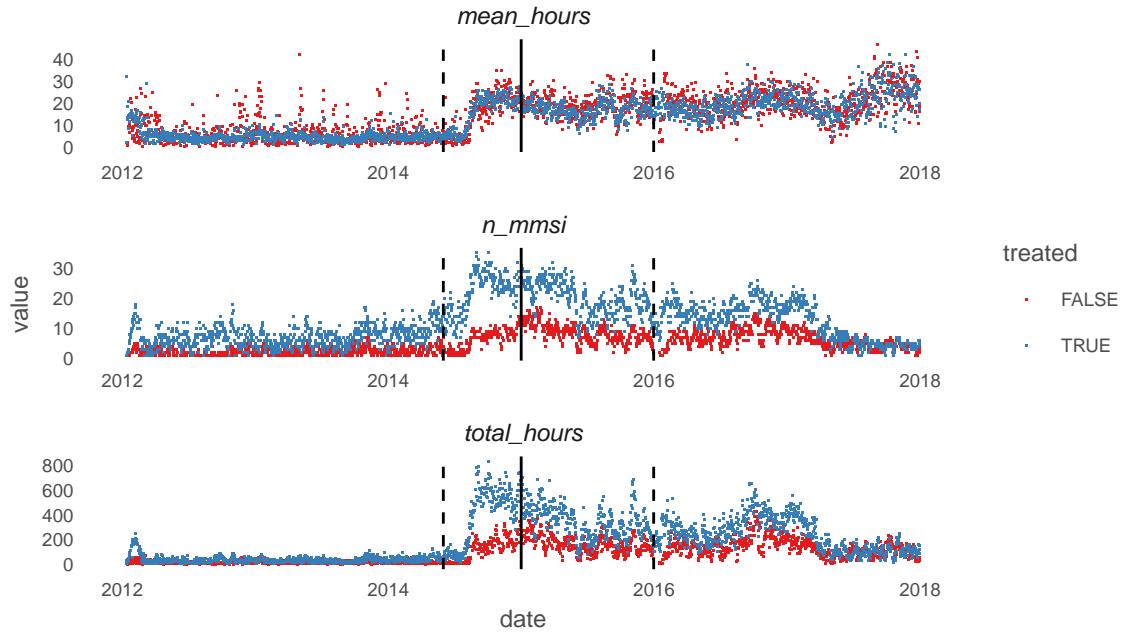


Figure 3: Fishing hours and number of vessels by month for all vessels. Vertical dashed lines indicate dates when satellites were added, solid line indicates PIPA closure.

200 3.2 Analyses

201 The first analysis focuses on identifying the response of fishing vessels to PIPA closure. A spatial
 202 closure might cause fishers to modify their behavior as they adapt to a new state of the world. Some
 203 may have to travel further distances to find new fishing grounds, which would lead them to fish
 204 harder to compensate for the associated extra fuel costs. If fishers had developed experience for
 205 fishing in particular sites, being excluded might impose a learning cost on them, as they identify
 206 new fishing grounds. This would result in increased search times. However, if the area of influence
 207 of a vessel is significantly larger than that of the spatial closure, they might already know other
 208 places and times where to fish. Our variables of interests intend to capture these possible reactions.

209 We use daily fishing hours, daily proportion of fishing vs. non-fishing hours, and daily distance
 210 traveled (km). We compare our variable of interest before and after the implementation of PIPA using
 211 a Difference-in-Differences approach, where we track the variable of interest for vessels described in
 212 the previous section. Our specification is the following:

$$y_{i,t} = \alpha + \beta_1 Post_t + \beta_2 Treat_i + \beta_3 Post_t \times Treat_i + \phi_t + \gamma_i + \epsilon_{i,t}$$

213 Where $y_{i,t}$ is the variable of interest for vessel i in time period t . A dummy variable $Post_t$ takes the
 214 value of 0 for all dates prior to PIPA implementation and a value of 1 for all dates including and
 215 following PIPA implementation. $Treat_i$ is a dummy variable indicating whether a vessel belongs to
 216 the control ($Treat_i = 0$) or treatment ($Treat_i = 1$) group. α is the standard intercept, β_1 captures
 217 the temporal trend change, β_2 captures the difference between treated and control groups, and β_3
 218 is our parameter of interest: de DiD estimate capturing the treatment effect. Finally, ϕ_t and γ_i

²¹⁹ represent month-, and flag-level dummies that account for seasonality or country-level management
²²⁰ interventions¹⁰.

²²¹ Our second part of the analyses focuses on the redistribution of fishing effort. The role of institutions
²²² may play an important role. As stated before, LSMPAs often span the entirety of an EEZ. In the
²²³ case of purse seining in the PNA, vessels purchase access to the fishery at the beginning of the
²²⁴ season. If a vessel decides to fish within the PNA, they've already made the decision to pay for
²²⁵ access, expecting higher returns from fishing there than in the High Seas. In the particular case of
²²⁶ PIPA, one would expect that a vessel holding a permit to fish in I-Kiribati waters would then move
²²⁷ to other fishing grounds within Kiribati after the closure. Alternatively, if a vessel fishes illegally in
²²⁸ I-Kiribati waters before the implementation, one would expect them to reallocate to other regions
²²⁹ with equal or less enforcement. In this case, they might then choose to move to other I-Kiribati
²³⁰ waters, waters of countries that have similar enforcement levels, or the High Seas.

²³¹ We discretize spatial units by using a polygon for PIPA ¹¹ and distinct spatial units for each EEZ
²³² of each country. Some vessels might shift from EEZs into the high seas, but we are interested in
²³³ knowing *where* in the high seas, so we incorporate additional regions by using a 1 degree buffer of
²³⁴ the high seas around each of the EEZ regions. The rest of the high seas are merged into a single
²³⁵ spatial unit. For example, if we were to do this only for Kiribati, we would have 8 spatial units:
²³⁶ PIPA, three EEZs, three 1-degree buffers of high seas around each EEZs, and the rest of the high
²³⁷ seas. Whenever the buffers overlapped between themselves, we randomly clipped one on to the
²³⁸ other. EEZs that had sporadic fishing events were pooled into a group of "others".

²³⁹ To evaluate this change in effort allocation, we regress our variable of interest (*i.e.* fishing hours) on
²⁴⁰ the interaction between a dummy variable indicating the policy intervention and a dummy variable
²⁴¹ for countries. This gives us the by-country change in proportional allocation of fishing effort:

$$y_{i,t} = \alpha + \beta_1 Post + \beta_{2,i} Country + \beta_{3,i} Post_t \times Country_i + \epsilon_{i,t}$$

²⁴² Our variable of interest, $y_{i,t}$ represents the proportion of fishing hours that country i receives at time
²⁴³ t . *Post* also represents a policy dummy that takes the value of 0 for all dates before implementation
²⁴⁴ of PIPA, and 1 otherwise. *Country* is a dummy variable for countries for the spatial units defined
²⁴⁵ above. Our parameter of interest is $\beta_{1,i}$, which captures the country-level change in proportional
²⁴⁶ fishing effort.

²⁴⁷ All regression coefficients were estimated via ordinary least squares, and heteroskedastic-robust
²⁴⁸ standard errors were calculated. All analyses were performed in R version 3.5.1 (R Core Team,
²⁴⁹ 2018). Raw data and code used in this work are available on github.

¹⁰We test for other more complex specifications that interact a quarterly dummy or year-month dummies with the treatment group and find qualitatively the same results.

¹¹we would expect to see a decrease here

Table 2: Changes in the relative allocation of fishing effort by region (EEZ, PIPA, high seas) and gear.

country	change
EEZ COK 1	0.53
EEZ FSM 1	0.81
EEZ KIR 1	-0.16
EEZ KIR 2	4.50
EEZ KIR 3	-2.79
EEZ MHL 1	-0.44
EEZ NRU 1	0.07
EEZ PNG 2	-9.07
EEZ SLB 1	3.18
EEZ TUV 1	1.27
HS	3.93
HS COK 1	0.06
HS KIR 1	2.96
HS KIR 2	1.07
HS KIR 3	2.53
PIPA PIPA 1	-8.25

250 4 Results

251 Our DiD analysis shows an overall increase in purse seine fishing hours, even after accounting for the
 252 introduction of new satellites (Table 3). This coefficient estimate is consistent for different model
 253 specifications and across groups of treatment and controls. These effectively represent the patterns
 254 observed in Figure 4. The β_3 coefficient indicating our treatment effect suggests that, relative to the
 255 control, treated vessels fish less, in the order of 0.5 hours per day. Another way to interpret this is
 256 that the increase in fishing effort by treated vessels has occurred at a lower rate than control vessels.
 257 This result is robust and significant ($p < 0.05$) for all model specifications using our main control
 258 group, with the effect varying between $\beta_3 = -0.515$ and $\beta_3 = -0.934$. These values are equivalent
 259 to a 15 - 28 reduction in fishing hours per month.

260 Regressions coefficients for our DiD analysis are shown in Table 3. Columns 1 - 3 use all data for
 261 controls. Columns 4 - 6 use only PNA vessels as controls, and columns 7 - 9 exclude Chinese vessels.
 262 Columns 10 and 11 use Japanese vessels in the Pacific as controls, and hence don't include flag FEs
 263 to avoid perfect collinearity between Japanese flag and control¹². It must be noted, however, that
 264 when reducing the linear structure of the $Pre \times Post$ design and instead interacting the treatment
 265 dummy with quarterly or year-month combinations we are not able to reject the null hypotheses of
 266 no change (Figures ??).

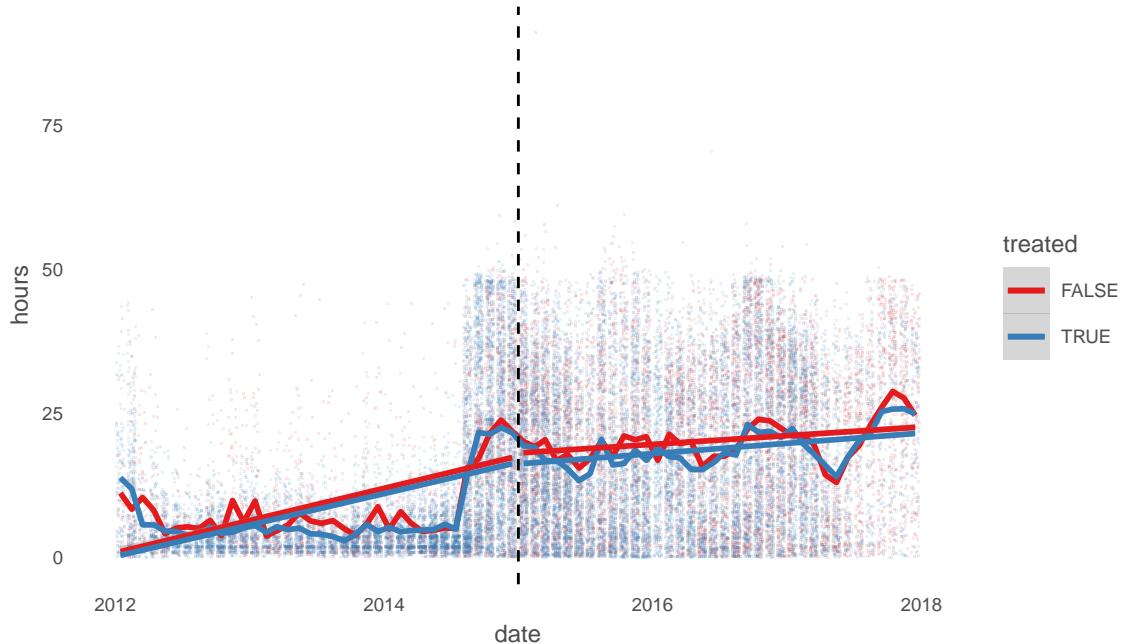


Figure 4: Daily fishing hours for all vessels in our main treatment-control groups. Solid straight lines show a linear trend by period (pre-psot) and treatment. The other red and blue lines show monthly averages. Vertical dashed line indicates PIPA closure.

¹²Results of the same analysis is shown for longliners in S1

Table 3: Difference-in-differences estimates for 3 different controls and 3 different specifications. The first three columns use all data for controls. Columns 4 - 6 use only PNA vessels as controls, and columns 7 - 9 exclude Chinese vessels. Columns 10 and 11 use Japanese vessels in the Pacific as controls, and hence don't include flag FEs. Numbers in parentheses are heteroskedastic-robust standard errors.

	Dependent variable:										
	hours										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Constant	6.345*** (0.186)	7.863*** (0.274)	10.322*** (0.404)	7.124*** (0.265)	9.007*** (0.341)	9.933*** (0.620)	6.057*** (0.193)	7.584*** (0.279)	10.194*** (0.538)	22.625*** (0.629)	24.731*** (0.683)
post	-0.052 (0.303)	1.134*** (0.304)	1.115*** (0.339)	-1.199*** (0.435)	-0.279 (0.429)	0.124 (0.436)	-0.284 (0.318)	1.013*** (0.318)	1.166*** (0.357)	2.330*** (0.890)	3.991*** (0.877)
treated	-1.142*** (0.214)	-0.839*** (0.209)	0.010 (0.281)	-1.977*** (0.284)	-1.675*** (0.274)	0.626 (0.416)	-0.877*** (0.221)	-0.536** (0.215)	0.150 (0.297)	-18.190*** (0.673)	-18.257*** (0.661)
sate2	12.579*** (0.197)	11.589*** (0.199)	11.340*** (0.232)	12.709*** (0.212)	11.850*** (0.213)	11.749*** (0.246)	12.631*** (0.199)	11.599*** (0.201)	11.349*** (0.235)	14.346*** (0.303)	12.967*** (0.309)
sate3	14.675*** (0.260)	13.587*** (0.262)	13.328*** (0.307)	14.799*** (0.286)	13.894*** (0.287)	13.795*** (0.329)	14.958*** (0.264)	13.804*** (0.266)	13.566*** (0.315)	15.187*** (0.402)	13.719*** (0.410)
post:treated	-0.515* (0.281)	-0.833*** (0.276)	-0.934*** (0.310)	0.562 (0.413)	0.373 (0.402)	-0.176 (0.407)	-0.439 (0.293)	-0.814*** (0.287)	-1.084*** (0.326)	-3.209*** (0.811)	-3.715*** (0.799)
Control	All	All	All	PNA	PNA	PNA	-CHN	-CHN	-CHN	JPN	JPN
Month FE	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes
Flag FE	No	No	Yes	No	No	Yes	No	No	Yes	No	No
Observations	37,840	37,840	30,359	30,583	30,583	25,034	36,415	36,415	28,934	34,047	34,047
R ²	0.171	0.200	0.208	0.178	0.208	0.215	0.173	0.203	0.211	0.260	0.280

Note:

*p<0.1; **p<0.05; ***p<0.01

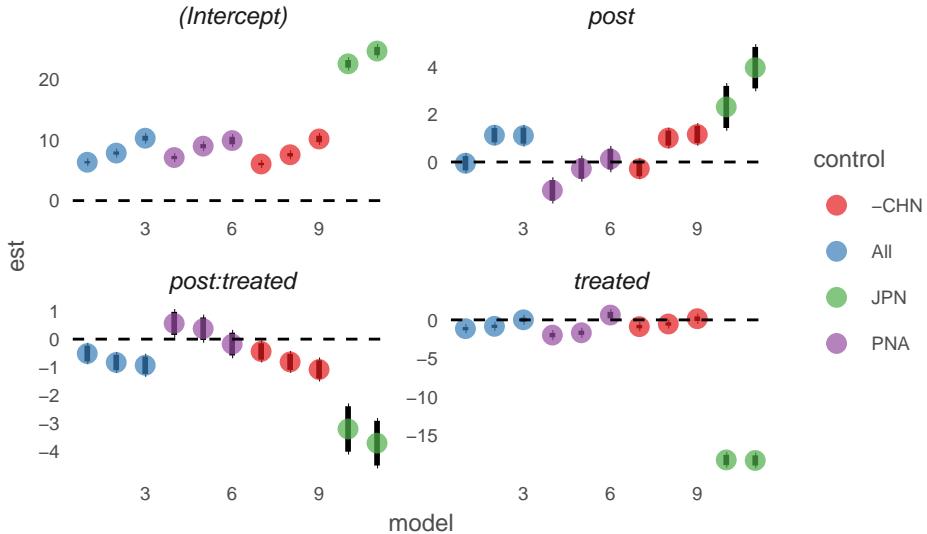


Figure 5: Coefficient estimates for each model. Top pannel indicates variable, x-axis represents model specification, and y-axis coefficient estimate.

Recall that to evaluate the redistribution of fishing effort we only track fishing vessels that belong to the treated group. Figure 6 provides a spatial representation of these changes. Note that 2013 effort distribution is roughly similar across vessels. Then in 2014 there is a sharp increase in fishing hours by treated vessels inside PIPA (blue paradox). In 2015 treated vessels then allocate more effort to the easternmost Kiribati EEZ (see Figure) and the high seas. In 2016 spatial distribution of fishing effort is again similar across groups. It is evident that the increase in relative fishing effort is greater for regions closer to PIPA, and.

Four our empirical identification we calculated the proportion of fishing effort allocated every month to each spatially explicit regions defined in section 3. For purse seiners, these represent 9 main EEZs, PIPA, the high seas, and a group of other EEZs. Figure 7 shows the monthly relative fishing hours that each region received by all 61 treated vessels. The top-left panel shows the change in fishing effort inside PIPA, including the preemptive fishing and immediate reduction previously reported (McDermott et al., 2018). The change in the relative allocation of fishing effort by purse seiners increases in eight of the 12 regions after PIPA implementation (Table 4, fig:map_change_ps). The largest increase is observed for the I-Kiribati EEZ, with an average increase of 0.11 ($p < 0.001$). In other words, the redistribution of treated vessels caused a 10% increase in the *relative* allocation of fishing effort within I-Kiribati waters. The only decrease is observed for Papua New Guinea, but the coefficient is not significant.

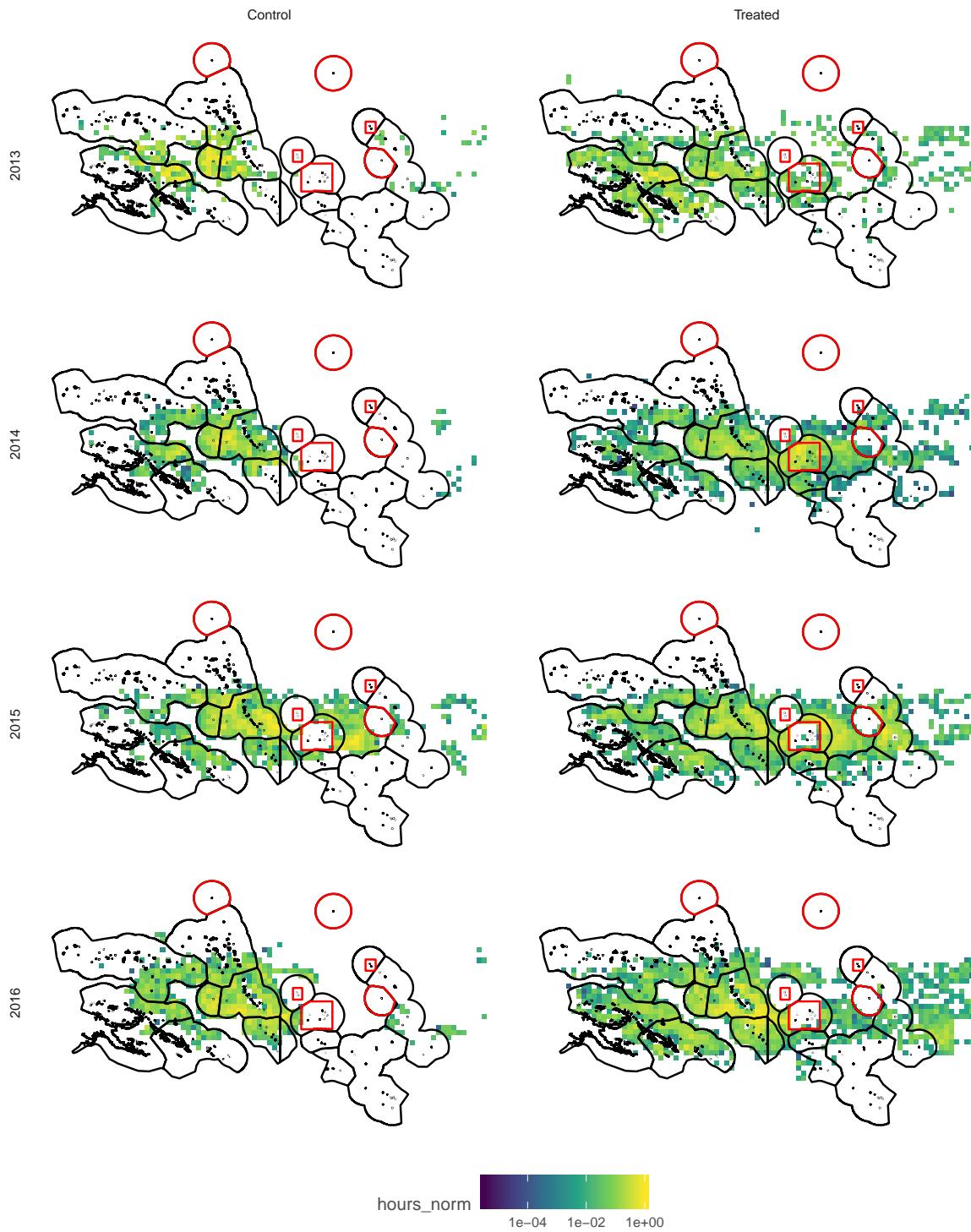


Figure 6: Yearly spatial distribution of fishing effort by treated and control vessels. Colors have been adjusted relative to the maximum observed by group and year.

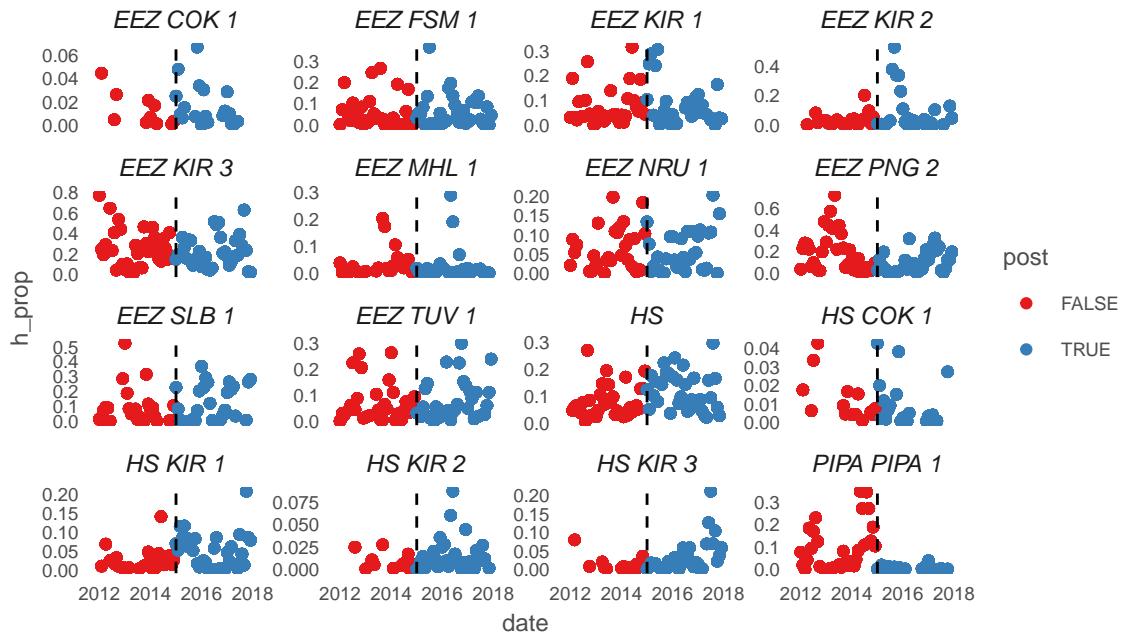


Figure 7: Monthly relative allocation of fishing effort by PIPA-fishing vessels before and after PIPA for 9 EEZs, PIPA, the high seas and ‘other EEZs’.

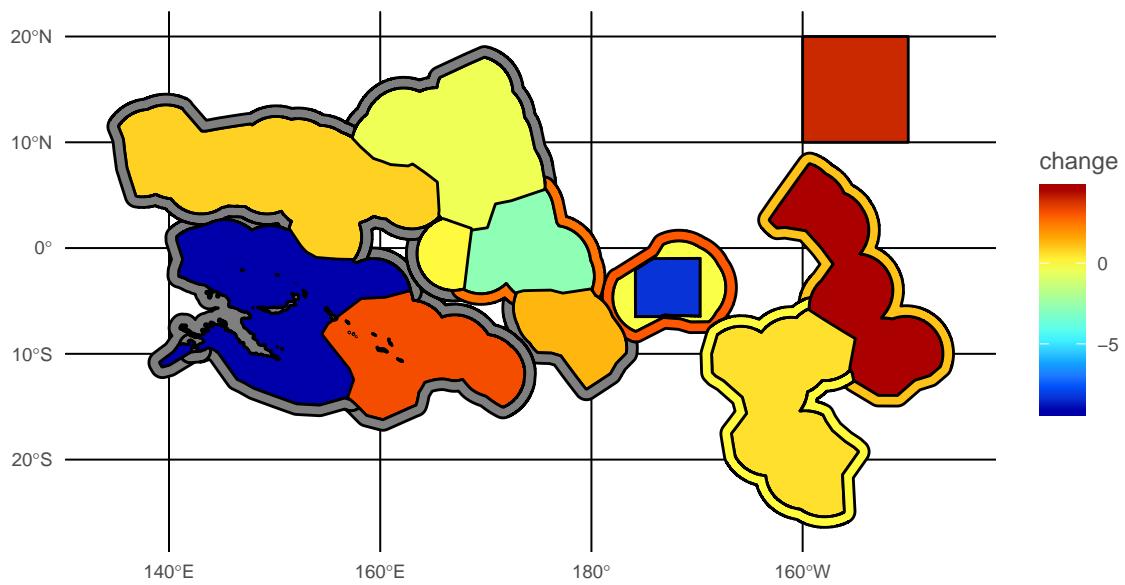


Figure 8: Spatial representation of the mean change in the monthly allocation of fishing effort for purse seiners.

Table 4: Change in the relative allocation of purse seining fishing hours by region ($R^2 = 0.36$, $F(47, 69000) = 961.1$, $p < 0.001$)

term	h_prop
(Intercept)	0.087 (0.002)***
post	-0.081 (0.003)***
sate2	-0.003 (0.001)***
sate3	-0.002 (0.001)
post:countryEEZ COK 1	0.088 (0.002)***
post:countryEEZ FSM 1	0.091 (0.003)***
post:countryEEZ KIR 1	0.081 (0.003)***
post:countryEEZ KIR 2	0.127 (0.004)***
post:countryEEZ KIR 3	0.055 (0.005)***
post:countryEEZ MHL 1	0.078 (0.003)***
post:countryEEZ NRU 1	0.083 (0.003)***
post:countryEEZ PNG 2	-0.008 (0.005)*
post:countryEEZ SLB 1	0.114 (0.004)***
post:countryEEZ TUV 1	0.095 (0.003)***
post:countryHS	0.122 (0.003)***
post:countryHS COK 1	0.083 (0.002)***
post:countryHS KIR 1	0.112 (0.003)***
post:countryHS KIR 2	0.093 (0.002)***
post:countryHS KIR 3	0.108 (0.003)***

285 **5 Discussion**

286 Our findings provide interesting insights into the effect that LSMPAs can have on vessel behavior
287 and the redistribution of fishing effort. These collection of results shows that the implementation of
288 PIPA caused treated vessels to reduce their fishing hours, and that this effect is greater for purse
289 seiners than longliners. Even though treated vessels fish less, their relative allocation of fishing
290 hours increased for all other fishing grounds. This does not imply that there is more fishing effort
291 exerted by treated vessels, but rather that each region receives a greater portion of the post-PIPA
292 fishing effort of these same vessels, which is lower than pre-PIPA levels. In this section we discuss
293 the implications of vessel-level reductions in fishing effort and the increase in relative allocation of
294 the remaining effort through space. We also provide plausible explanations as to why purse seiners
295 seem to be more reactive to the spatial closure.

296 A major shortcoming of our analyses is that we do not observe catches or revenues, which ultimately
297 are the factors that guide the decision making process of profit-maximizing agents. Therefore, it is
298 difficult to know whether the reduction in fishing effort represents a positive or negative impact.
299 A decrease in fishing effort is associated to an increase in catches (and therefore greater CPUE)
300 only when the entire fleet does it, and if previous levels of effort were greater than F_{MEY} (*i.e.* the
301 effort that would yield the maximum economic yield). Therefore, it is plausible that the reduction
302 of fishing hours is not done by choice, but rather results from fishers having to increase search time.
303 Upon being relocated, fishers may not identify the best fishing grounds as easily as before, and
304 therefore invest a greater proportion of their time searching for their catch. Further analysis of
305 temporal trends in non-fishing hours, as well as distance traveled should provide us with insights as
306 to why fishers reduced fishing hours.

307 Previous studies on insular environments suggest that vessels move to distant places, which might be
308 translated as increased costs (Stevenson et al., 2013). Nevertheless, they do not use counterfactuals
309 that could help account for system- or fleet-level changes that occur through time. Others have
310 used similar satellite-tracking systems to show that fishing effort accumulates near the edges of
311 spatial closures, yielding greater catches (Murawski et al., 2005). Yet, these vessel tracks do not
312 cover the pre-reserve period, making it difficult identify the contribution of spatial closures to
313 the observed spatial distribution of fishing vessels. Recent work by Elahi et al. (2018) identified
314 that total fishing effort in a focal region where a short-term MPA was implemented showed little
315 change, likely indicating that fishers redistributed fishing effort to compensate for the reduction in
316 available space. Our data is assembled in a similar way, with fishing positions before and after the
317 implementation of PIPA and vessels grouped into treated and control groups. Our BACI design,
318 along with our difference-in-differences analysis allows us to make causal inferences about the effect
319 that large scale marine protected areas have on fishing effort.

320 The different responses observed between purse seiners and longliners might have two possible
321 explanations. It is likely that PIPA did not contain habitat that longliners would consider optimal.
322 Therefore, the sporadic fishing events that occurred there are of little importance to the fleet, and it
323 is unlikely that the implementation of PIPA has an effect on them. Alternatively, the differences
324 may be due to the nature of each fishing gear. Purse seiners are often constrained by seafloor and
325 termocline depth, and have a smaller spatial footprint (Kroodsma et al., 2018). Tuna purse seiners
326 are known to have greater proportion of null sets (*i.e.* where purse seines effectively cast their nets,
327 but no catch is obtained) during El Niño years, where the termocline deepens in the Eastern Pacific
328 (Dreyfus-Leon, 2015). On the other hand, longliners may be more flexible as to where they can
329 deploy their longlines. Ortúñoz-Crespo et al. (2018) evaluated the ecological niche of the pelagic

³³⁰ longline fleet, and suggest that the fleet may be under-utilizing the ocean, meaning that they can
³³¹ easily redistribute elsewhere.

³³² Our work suggests that the implementation of LSMPAs can have important implications for purse
³³³ seiners, and less so for longliners. We also show that fishing effort is redistributed to areas close
³³⁴ by. Future management interventions that aim to close large portion of the oceans should consider
³³⁵ how fishing effort will change in space and through time, and the ecological implications of this
³³⁶ redistribution to ensure that fishing effort is not just displaced elsewhere, leading to overfishing in
³³⁷ adjacent waters.

³³⁸ Furthermore, a growing body of literature suggests that closing the high seas to all fishing could
³³⁹ increase fishery yields and profitability of fisheries, with negligible costs to food security (White and
³⁴⁰ Costello, 2014; Sumaila et al., 2015; Sala et al., 2018; Schiller et al., 2018).

³⁴¹ **6 Appendix**

³⁴² **6.1 Stream of data by vessel, group, and period**



Figure S1: Stream of fishing events by vessels through time. Each line represents a vessel, with dots indicating months with fishing activity and colors indicating the pre and post periods.

³⁴³ **6.2 Longliners**

³⁴⁴ Longliners show a similar pattern of effort reduction. However, the magnitude of the β_3 coefficient
³⁴⁵ is smaller (ranging from $\beta_3 = -0.98$ to $\beta_3 = -1.125$) and not significant unless including month
³⁴⁶ and flag FEs for the general treatment-control groups, or when excluding Chinese vessels. This,
³⁴⁷ along with higher standard error values suggest that longliners have a smaller and more variable
³⁴⁸ response to the implementation of LSMPAs.

Table S1: Difference-in-differences estimates for 2 different controls and 3 different specifications. The first three columns use all data for controls. Columns 4 - 6 exclude Chinese vessels. Numbers in parentheses are heteroskedastic-robust standard errors.

<i>Dependent variable:</i>						
	hours					
	(1)	(2)	(3)	(4)	(5)	(6)
Constant	39.192*** (0.095)	38.411*** (0.132)	36.520*** (0.169)	39.402*** (0.102)	38.636*** (0.140)	34.402*** (0.236)
post	-1.014*** (0.143)	-0.189 (0.145)	0.710*** (0.158)	-1.400*** (0.163)	-0.574*** (0.165)	0.896*** (0.186)
treated	2.544*** (0.101)	2.570*** (0.101)	2.724*** (0.121)	2.349*** (0.110)	2.391*** (0.110)	3.299*** (0.135)
sate2	-0.495*** (0.099)	-1.488*** (0.105)	-0.898*** (0.110)	-0.561*** (0.104)	-1.497*** (0.110)	-1.015*** (0.114)
sate3	-0.313** (0.129)	-1.150*** (0.132)	0.050 (0.143)	-0.375*** (0.134)	-1.129*** (0.138)	0.001 (0.149)
post:treated	0.098 (0.134)	0.056 (0.134)	-1.125*** (0.148)	0.532*** (0.149)	0.427*** (0.149)	-1.280*** (0.171)
Control	All	All	All	-CHN	-CHN	-CHN
Month FE	No	Yes	Yes	No	Yes	Yes
Flag FE	No	No	Yes	No	No	Yes
Observations	227,873	227,873	217,467	209,135	209,135	198,729
R ²	0.010	0.016	0.022	0.010	0.016	0.023

Note:

*p<0.1; **p<0.05; ***p<0.01

³⁴⁹ **6.3 Other model specifications for purse seiners**

³⁵⁰ We include a second degree polynomial for years as:

$$y_{i,t} = \alpha + \beta_1 Post_t + \beta_2 Treat_i + \beta_3 Post_t \times Treat_i + \phi_t + \gamma_i + \omega Y_t + \Omega Y_t^2 + \epsilon_{i,t}$$

³⁵¹ ³⁵² \begin{table}[!htbp] \caption{Fishing hours from GFW for purse_seiners. Asterisks indicate significance levels. Numbers in parentheses represent heteroskedastic-robust standard errors.}

<i>Dependent variable:</i>				
	hours			
	(1)	(2)	(3)	(4)
post	8.394*** (0.267)	9.334*** (0.254)	14.934*** (0.312)	17.284*** (0.403)
treated	−1.069*** (0.249)	−0.770*** (0.234)	−0.993*** (0.219)	0.259 (0.269)
post:treated	−0.701** (0.308)	−0.899*** (0.295)	−0.530* (0.283)	−0.580** (0.292)
Constant	11.738*** (0.220)	11.281*** (0.292)	7.574*** (0.318)	10.077*** (0.422)
Month FE	No	Yes	Yes	Yes
Year FE	No	No	Yes	Yes
Flag FE	No	No	No	Yes
Observations	37,840	37,840	37,840	37,840
R ²	0.087	0.136	0.179	0.192

Note:

*p<0.1; **p<0.05; ***p<0.01

\end{table}

³⁵⁴

6.3.1 Quarterly DID interactions

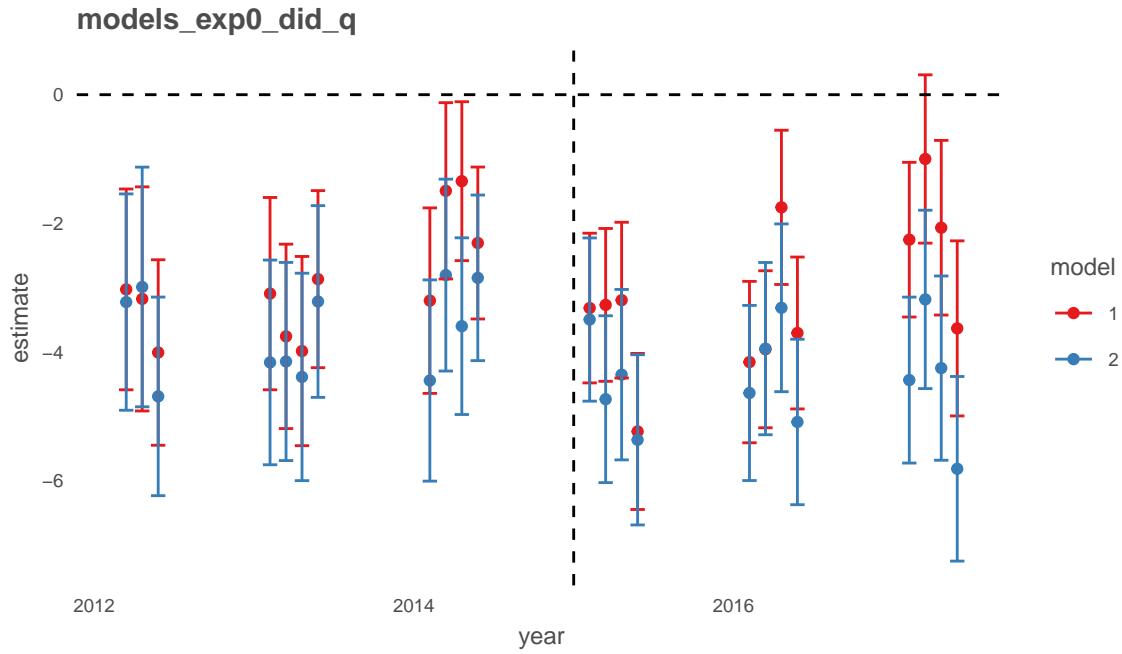


Figure S2: Interaction of quarters and treatment. Control group is all vessels.

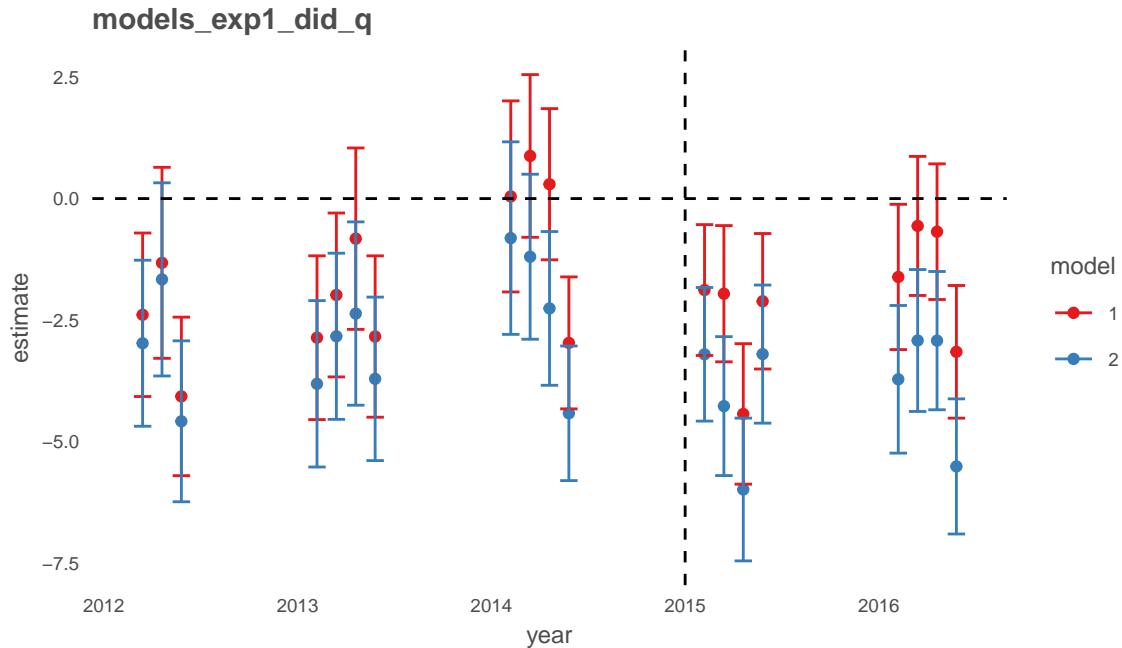


Figure S3: Interaction of quarters and treatment. Control group is vessels from PNA.

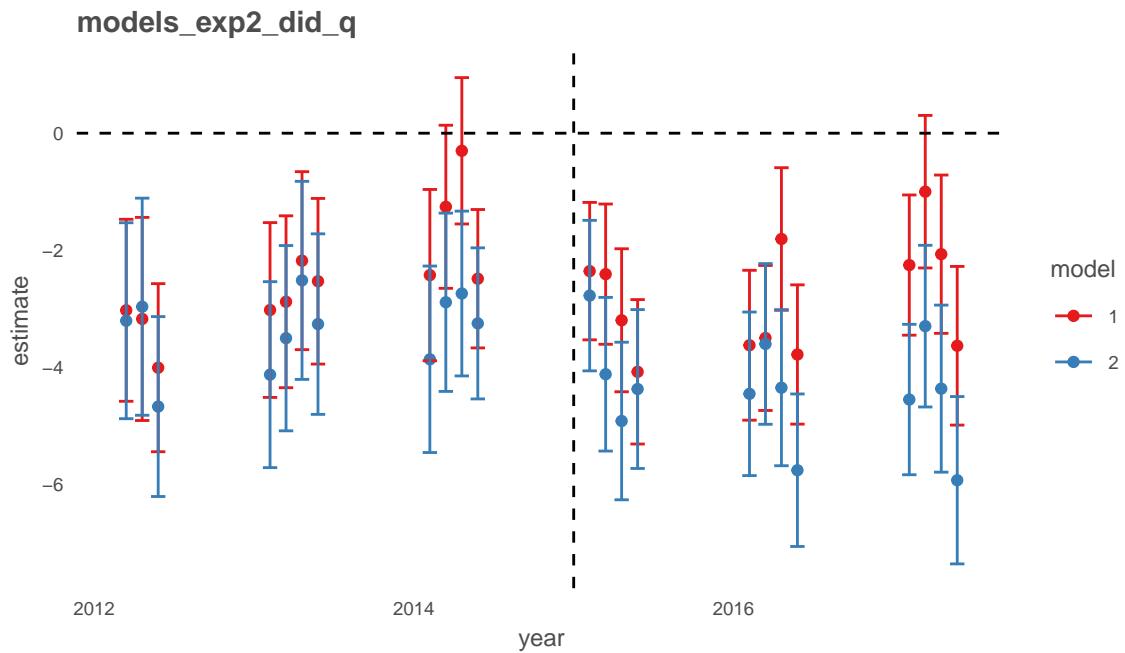


Figure S4: Interaction of quarters and treatment. Control group excludes Chinese vessels.

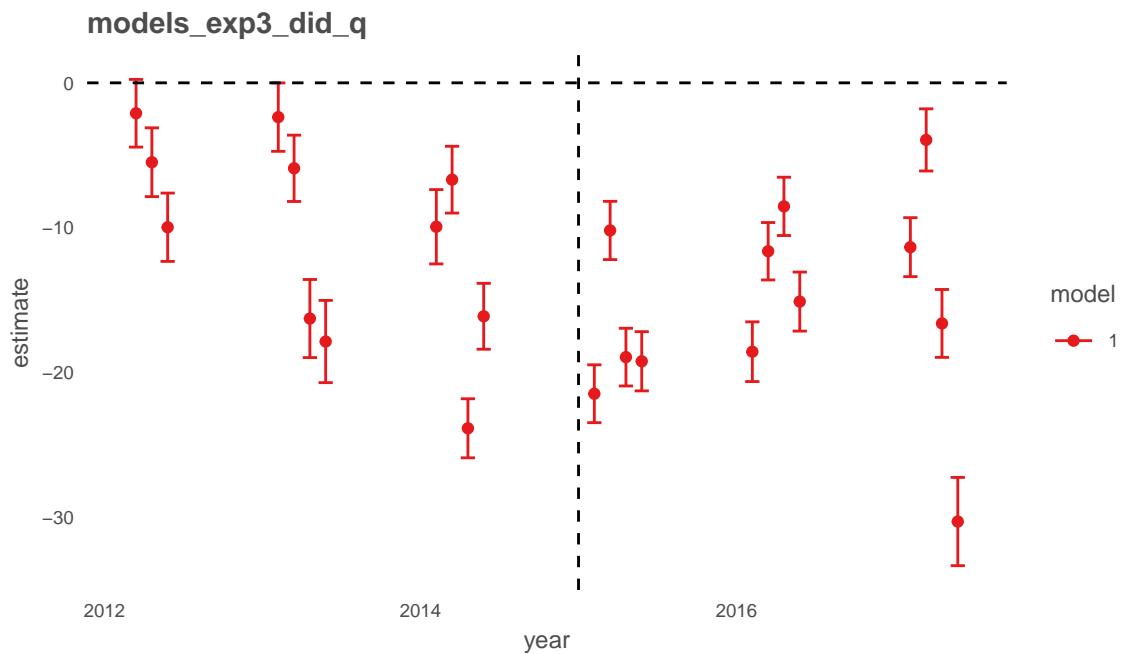


Figure S5: Interaction of quarters and treatment. Control group is Japanese vessels.

6.3.2 Year-month DID interactions

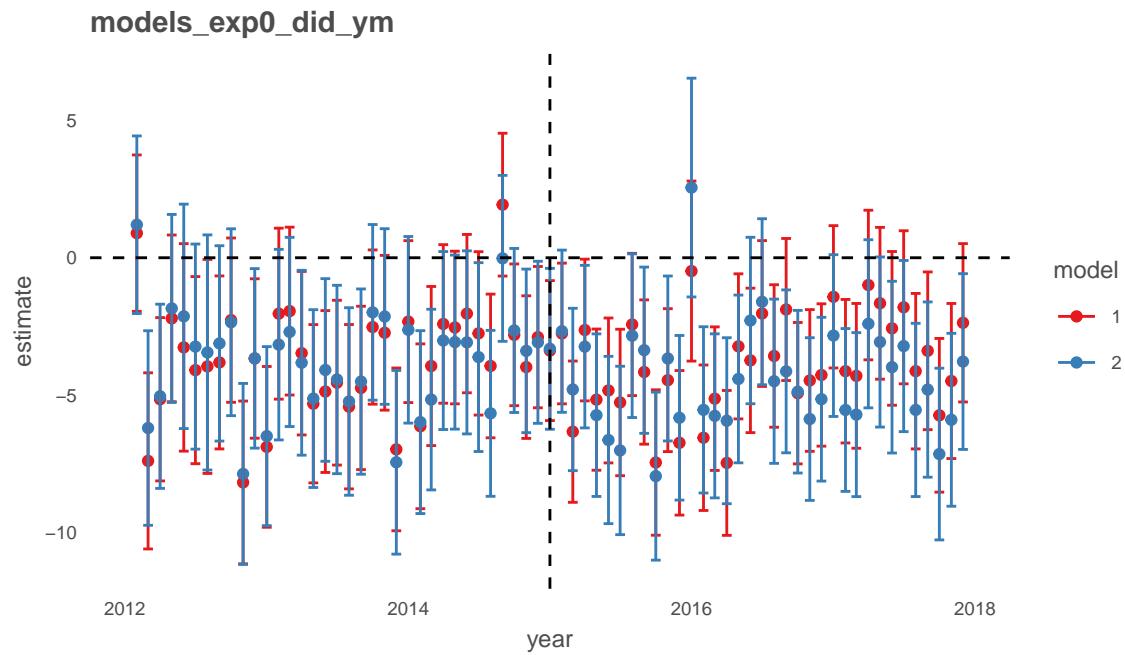


Figure S6: Interaction of year-month and treatment. Control group is all vessels.

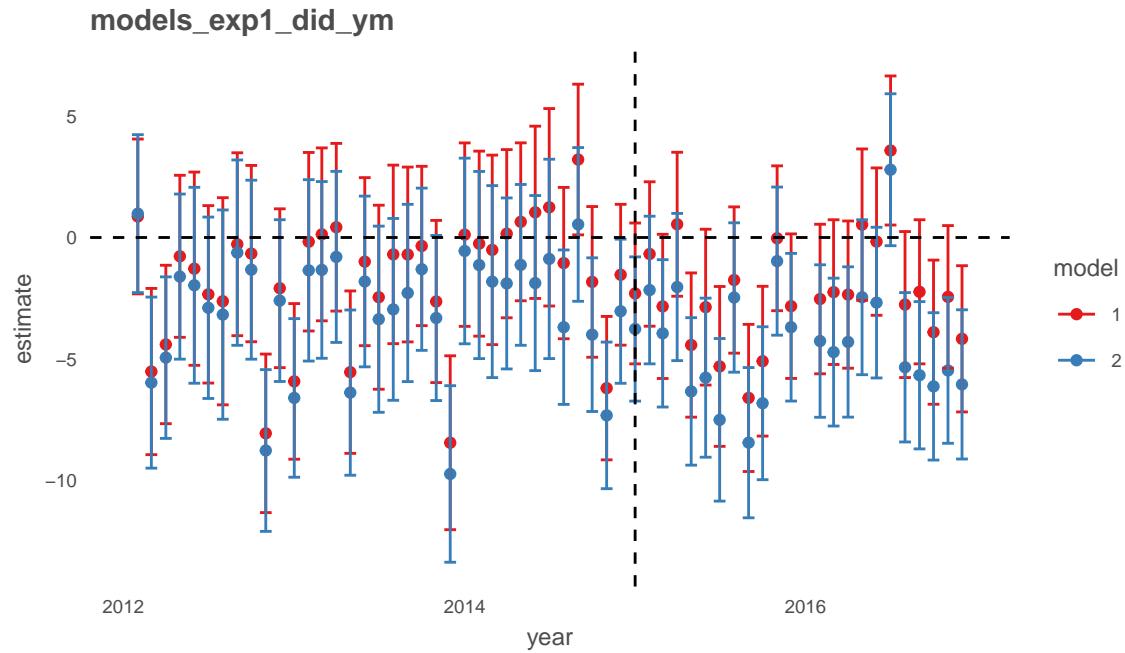


Figure S7: Interaction of year-month and treatment. Control group is vessels from PNA.

models_exp2_did_ym

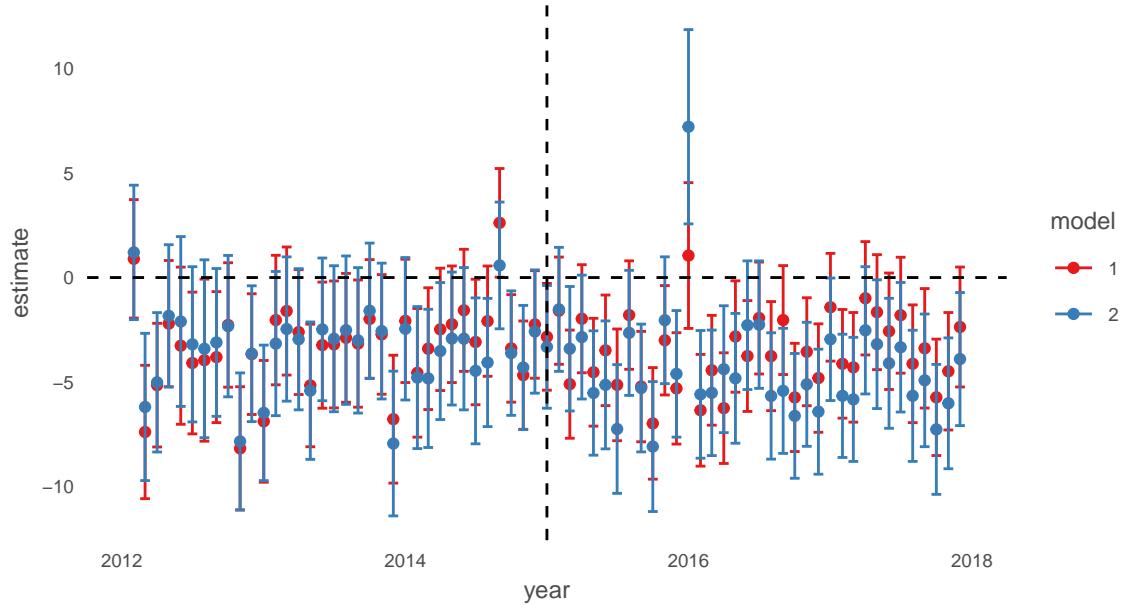


Figure S8: Interaction of year-month and treatment. Control group excludes Chinese vessels.

models_exp3_did_ym

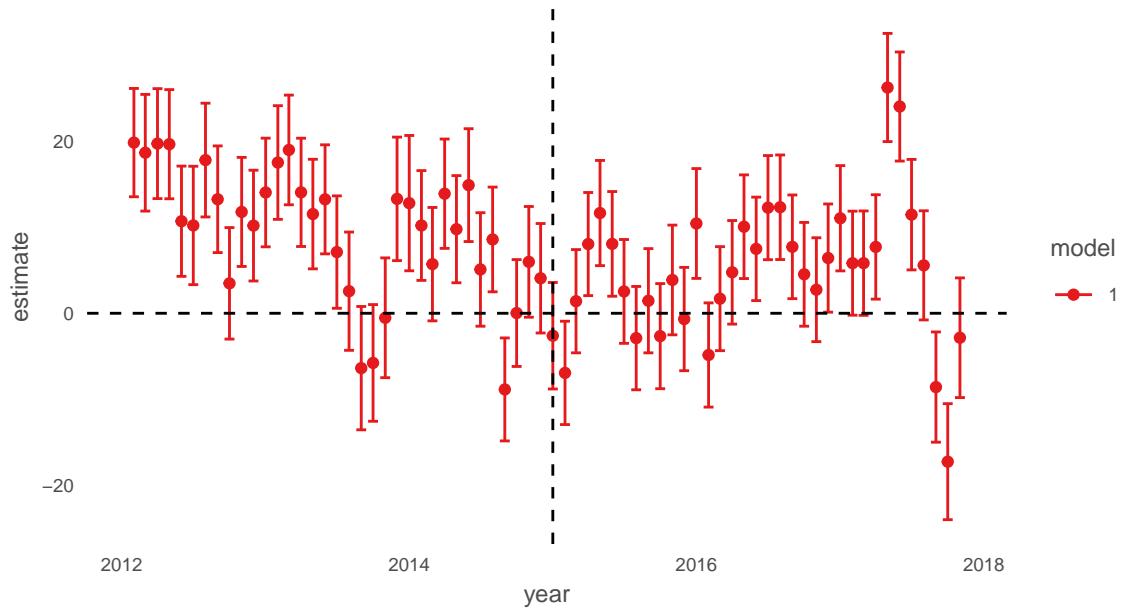
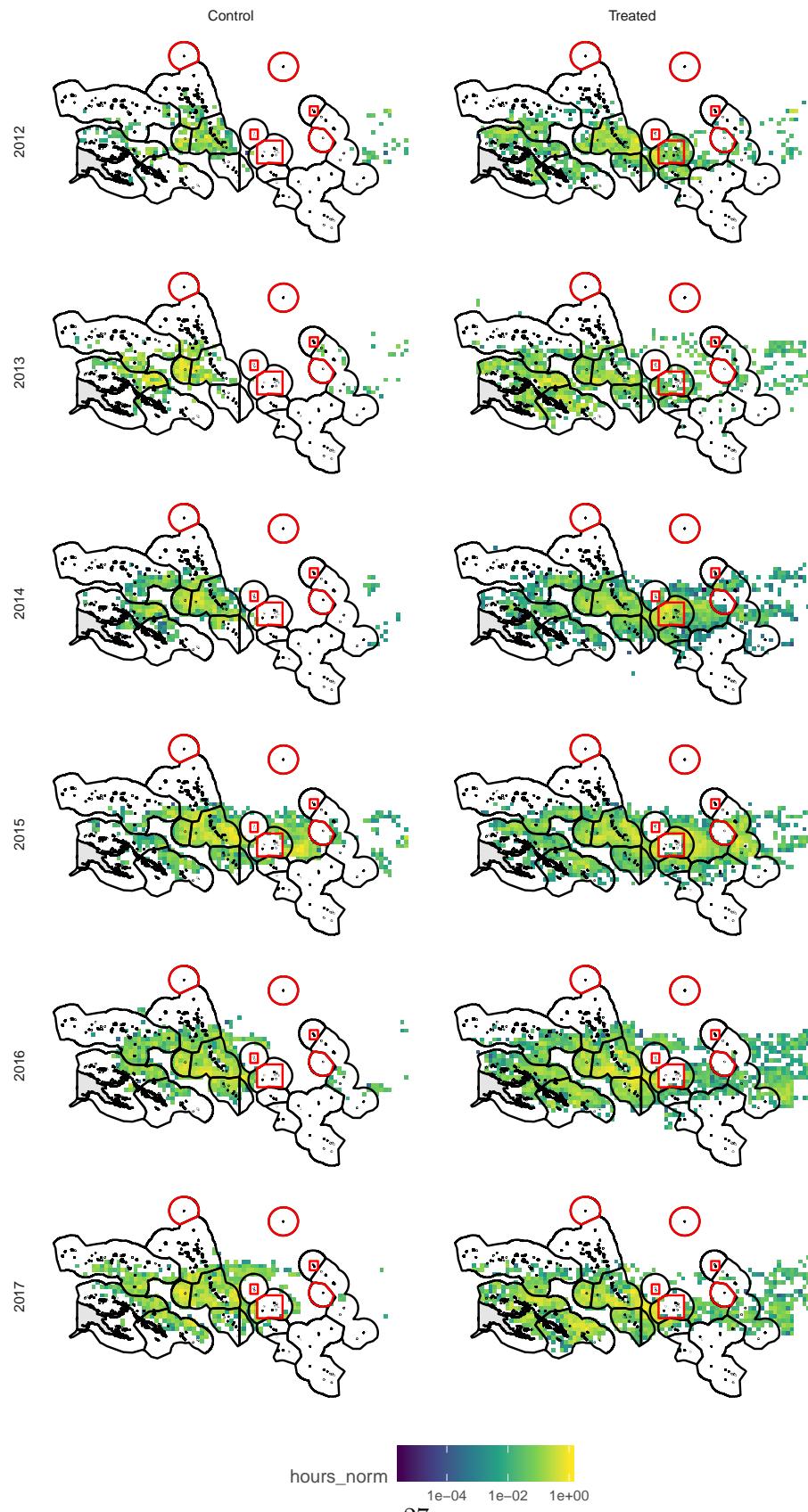


Figure S9: Interaction of year-month and treatment. Control group is Japanese vessels.

6.3.3 Fishing raster



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