

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, but little empirical works evaluate  
12 what happens to the effort after an MPA is created. The economic and ecological implications of  
13 displacing fishing effort are not yet fully understood. We use identification of fishing activity  
14 via Automatic Identification Systems (AIS) and causal inference techniques to provide the  
15 first analyses of behavioral changes and spatial redistribution of tuna purse seiners due to the  
16 implementation of a Large Scale Marine Protected Area in the Pacific Ocean. Our work provides  
17 three main findings: 1) aggregate fishing effort remains relatively unaffected; 2) Vessels that fished  
18 inside the protected area redistribute to adjacent waters; and 3) We observe a crowding effect  
19 for the first years after implementation. Our results not only provide an impact evaluation of  
20 the effect of LSMPAs on fishing activity, but provide insights into vessel redistribution dynamics,  
21 which may have ecological and economic implications. As countries continue to implement  
22 LSMPAs as a way to reach the stated 10% target of ocean protection, managers should consider  
23 how fishing effort will change in space and through time to ensure that fishing effort is not just  
24 displaced elsewhere, leading to overfishing in adjacent waters. While LSMPAs can provide a  
25 wide range of benefits, their implementation must be accompanied with traditional fisheries  
26 management to maximize their effectiveness.

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\*Work in progress, do not circulate

## 27 1 Introduction

28 Marine Protected Areas (MPAs) are intended to safeguard parts of the ocean from fishing and other  
29 extractive activities. Current international goals aim to protect 10% of the ocean environments  
30 by 2020. In an effort to meet this target, the world has seen a rapid increase in MPA coverage  
31 (Wood et al., 2008; Sala et al., 2018), largely driven by a small number of Large Scale Marine  
32 Protected Areas (LSMPA) Singleton and Roberts (2014); Boonzaier and Pauly (2016); Alger and  
33 Dauvergne (2017)). Due to weak property rights, limited habitat transformation, and potentially  
34 lower management costs, LSMPAs provide an opportunity to safeguard the oceans Game et al.  
35 (2009). Today, a small number of LSMPAs make up at least 80% of the managed areas in the ocean  
36 Toonen et al. (2013). LSMPAs may be instrumental in helping us achieve the 10% target by 2020  
37 (McCauley et al., 2016).

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

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

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

59 The paper is outlined as follows: Section 2 provides more information on Large Scale Marine  
60 Protected Areas and background on empirical studies of effort redistribution. An overview of the  
61 Nauru Agreement and associated countries, a description of the fleet that operates in the region,  
62 and a brief history of PIPA is also included. Section 3 describes our data and identification strategy.  
63 Section 4 presents our results, section 5 provides an extension of our results to other LSMPAs<sup>1</sup> and  
64 discusses our results<sup>2</sup>.

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<sup>1</sup>Not yet. but I think this would be interesting

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

## 65 2 Background

### 66 2.1 Large Scale Marine Protected Areas

67 The cutoff at which an MPA is considered to be a LSMPA ranges from areas larger than 30,000  
68 km<sup>2</sup> as defined by De Santo (2013) or areas larger than 250,000 km<sup>2</sup>, as defined by (Toonen et al.,  
69 2013). Figure 1 shows LSMPAs that meet the later, and that are fully no take. LSMPAs are often  
70 implemented in the pelagic environment, where the dominant human activity is industrial fishing  
71 (Gray et al., 2017; Kroodsma et al., 2018). The early literature on LSMPAs focused on the inherent  
72 challenges and difficulties that come with a pelagic environment. Kaplan et al. (2010) claimed that  
73 very large MPAs would result in excessive opportunity costs and that these would be difficult to  
74 enforce. Game et al. (2009) suggested that most of the challenges could be overcome with the  
75 incorporation of technology, in what then became known as Dynamic Ocean Management (Maxwell  
76 et al., 2015). The effectiveness and difficulties of implementing LSMPAs are not the focus of this  
77 paper <sup>3</sup>. Instead, we focus on the effect and implications of the ones that *have been* implemented.

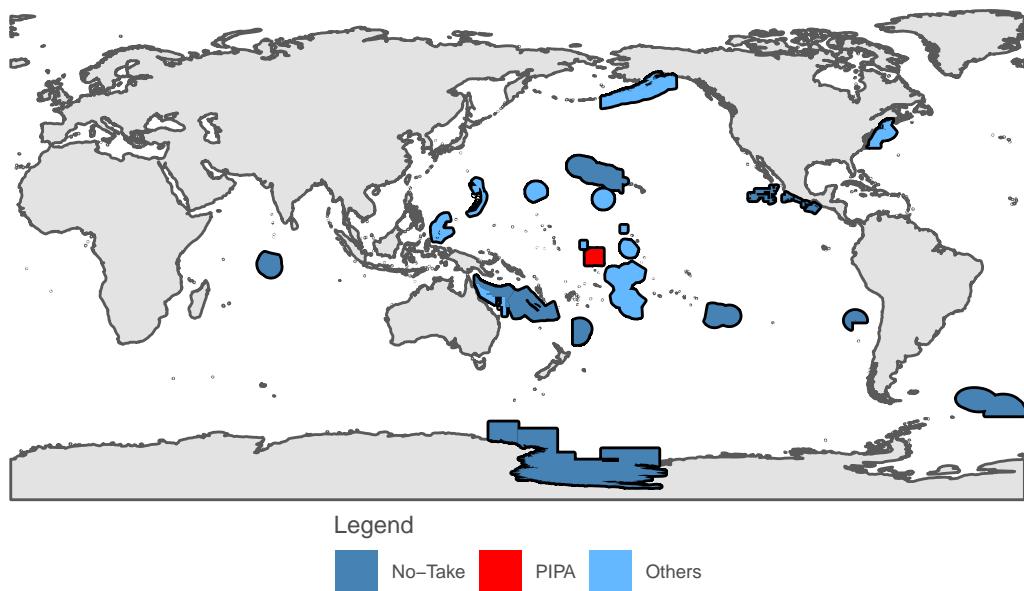


Figure 1: Large Scale Marine Protected Areas. The map shows all areas larger than 250,000 Km<sup>2</sup>. Areas in dark blue meet at least one of these conditions: reported no take area is greater than 0, are categorized as IUCN Ia or Ib, their designated english name is ‘Protected Area’.

78 LSMPAs were erroneously assumed to have little social implications due to their remoteness.  
79 However, there have been calls to incorporate the human dimensions into LSMPAs management and  
80 evaluation (Agardy et al., 2011; Gray et al., 2017). Most research incorporating these dimensions has  
81 focused on governance and enforcement of LSMPAs (*i.e.* Alger and Dauvergne (2017); Christie et al.  
82 (2017)), but they are yet to be the focus of economic analyses (Gray et al., 2017). Overall, there has  
83 been little empirical work regarding LSMPAs. Recent technological advances in vessel-detection

<sup>3</sup>But 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 ( $54,000 \text{ Km}^2$ ) protects two thirds 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  $\text{km}^2$  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 Exclusive 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 1995-2007<sup>4</sup>. 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

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

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

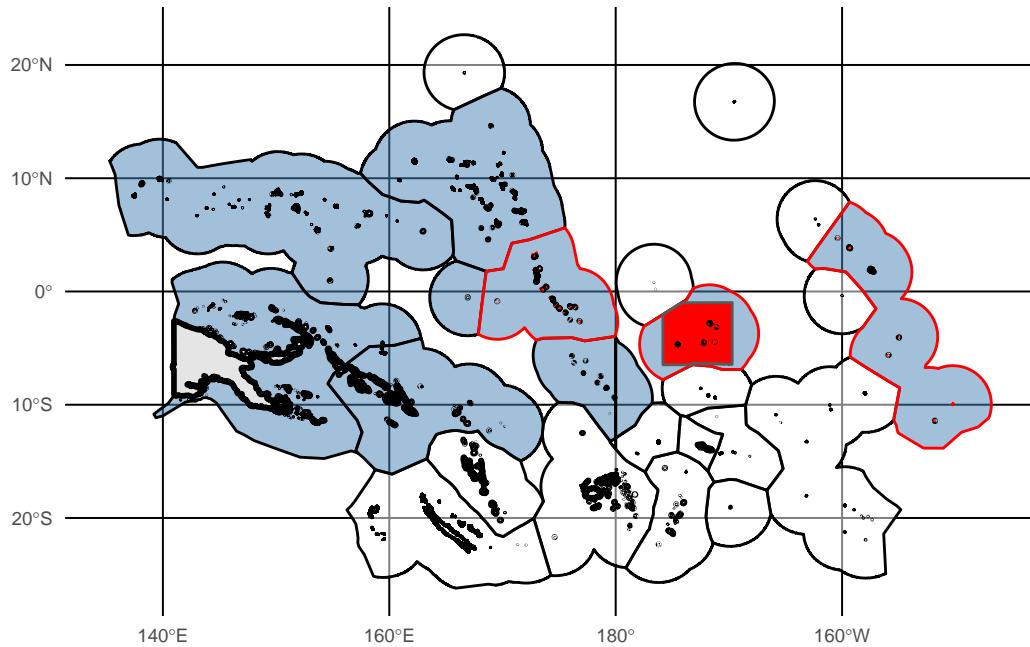


Figure 2: Map of the Exclusive Economic Zones (EEZs) of the region of interest. Countries that belong to the PNA are shown in blue, while empty polygons indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

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

140 One of the most notable and recent management interventions in the region is the implementation of  
141 the Phoenix Island Protected Area (PIPA) by the government of Kiribati. PIPA was first declared  
142 in 2006, and established in 2008 with only 4% of it was declared as no-take. In January 1<sup>st</sup>, 2015,  
143 the no-take area within PIPA was expanded to a total area of 397,447 km<sup>2</sup>, roughly 1.5 times the  
144 size of Ecuador. Figure 4 shows a map of the PNA countries and the Phoenix Island Protected  
145 Area.

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

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

## 153 3 Methods

154 This section is divided into two main parts. First, we provide a general description of AIS data and  
155 the process of identification of vessel-level fishing events done by Global Fishing Watch<sup>5</sup>. Alongside,  
156 we describe the subset of data used on our analyses. When relevant, we also point out possible  
157 shortcomings in the data, or factors that must be considered in the later analyses. We then move on  
158 to explain our empirical strategy for the identification of the behavioral changes and redistribution  
159 of fishing effort.

### 160 3.1 Data

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

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

175 Our analysis focuses on purse seine vessels, the most important fishery for PNA countries<sup>6</sup>. We  
176 identify a total of 103 purse seiners that fished in PNA waters at least once before 2015<sup>7</sup>. These  
177 vessels represent over 26 million individual observations for the 2012 - 2017 period. We identify  
178 65 vessels that have fished inside PIPA at least once since 2012. From these, 62 did so before the  
179 announcement (*i.e.* 09/01/2014 *sensu* (McDermott et al., 2018)) but are only able to track 61 for  
180 the complete period of study before and after its implementation<sup>8</sup>. On the other hand, 38 vessels  
181 never fished inside PIPA but we only have data for 26 vessels before and after.

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<sup>5</sup>Global Fishing Watch: [globalfishingwatch.org](http://globalfishingwatch.org)

<sup>6</sup>We perform some of the same analyses for longliners and include them in the Appendix

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

<sup>8</sup>1 vessel never fished again after August 18, 2013.

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

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

193 For each vessel we calculate total daily fishing hours and obtain panel data with 37,800 observations.  
194 Table 1 shows the number of vessels following a BACI design, as well as the fishing hours, before  
195 and after PIPA. Fig. 4 shows that mean fishing hours for purse seiners have an abrupt increase,  
196 just before January 1st, 2015. This trend is observed for both treated and control groups. Across  
197 all measures, the treatment and control vessels follow similar patterns, confirming our claim that  
198 the control group provides a plausible counterfactual. Figure S1 provides a visual representation of  
199 the vessel-level fishing events that make up each group through time. We use this data to answer  
200 our key questions: How do the 61 purse seiners modify their behavior as compared to the different  
201 control groups, and where do they go after the spatial closure? The following section describes our  
202 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

<sup>9</sup>Using 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

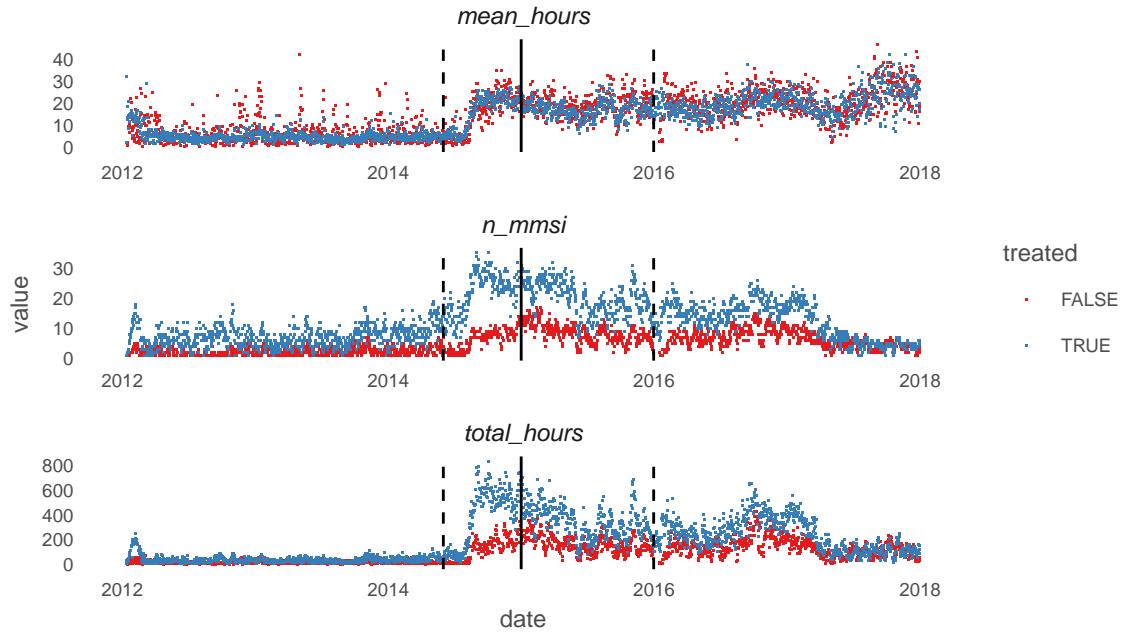


Figure 3: Fishing hours and number of vessels by month for all vessels. Vertical dashed lines indicates dates when satellites were added, solid line indicates PIPA closure.

### 203 3.2 Analyses

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

212 We use daily fishing hours, daily proportion of fishing vs. non-fishing hours, daily distance traveled  
 213 (km), distance from shore (km) and distance from port(km)<sup>10</sup>. We compare our variable of interest  
 214 before and after the implementation of PIPA using a Difference-in-Differences approach, where we  
 215 track the variable of interest for vessels described in the previous section. Our specification is the  
 216 following:

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

217 Where  $y_{i,t}$  is the variable of interest for vessel  $i$  in time period  $t$ . A dummy variable  $Post_t$  takes the  
 218 value of 0 for all dates prior to PIPA implementation and a value of 1 for all dates including and  
 219 following PIPA implementation.  $Treat_i$  is a dummy variable indicating whether a vessel belongs to

<sup>10</sup>Results are presented for fishing hours, but preliminary results for distance from shore and distance from port are shown in Tables S4 and S7

220 the control ( $Treat_i = 0$ ) or treatment ( $Treat_i = 1$ ) group.  $\alpha$  is the standard intercept,  $\beta_1$  captures  
221 the temporal trend change,  $\beta_2$  captures the difference between treated and control groups, and  $\beta_3$   
222 is our parameter of interest: de DiD estimate capturing the treatment effect. Finally,  $\phi_t$  and  $\gamma_i$   
223 represent month- and flag-level dummies that account for seasonality or country-level management  
224 interventions.  $\theta_t$  are dummies to account for the addition of more satellites. <sup>11</sup>.

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

235 We discretize spatial units by using a polygon for PIPA<sup>12</sup> and distinct spatial units for each EEZ  
236 of each country. Some vessels might shift from EEZs into the high seas, but we are interested in  
237 knowing *where* in the high seas, so we incorporate additional regions by using a 1 degree buffer of  
238 the high seas around each of the EEZ regions. The rest of the high seas are merged into a single  
239 spatial unit. For example, if we were to do this only for Kiribati, we would have 8 spatial units:  
240 PIPA, three EEZs, three 1-degree buffers of high seas around each EEZs, and the rest of the high  
241 seas. Whenever the buffers overlapped between themselves, we randomly clipped one on to the  
242 other.

243 We then take this spatial polygons and rasterize them to a 1-degree grid (See Figure S10), which we  
244 then use to rasterize points of fishing activity. For each cell, we calculate the total monthly fishing  
245 hours by treated and control vessels (See Figure 6). Since we are interested in the redistribution of  
246 fishing effort, we use this gridded data to calculate the proportion of fishing hours that each region  
247 receives each month relative to the total fishing hours observed across all regions and all cells in  
248 that month.

249 We use this measure to evaluate the change in effort allocation by regressing it on the interaction  
250 between a year dummy and a dummy for regions:

$$y_{i,t} = \alpha + \beta_1 Year_t + \beta_{2,i} Region_i + \beta_{3,i} Year_t \times Region_i + \epsilon_{i,t}$$

251 Our variable of interest,  $y_{i,t}$  represents the proportion of fishing hours that region  $i$  receives at time  
252  $t$ . Years are modelled as factors ( $Year_t$ ), using 2012 as the reference level.  $Region$  is a dummy  
253 variable for regions defined above. Our parameter of interest is  $\beta_{3,i}$ , which captures the yearly  
254 by-country change in proportional allocation of fishing effort relative to 2012.

255 All regression coefficients were estimated via ordinary least squares, and heteroskedastic-robust  
256 standard errors were calculated. All analyses were performed in R version 3.5.1 (R Core Team,  
257 2018). Raw data and code used in this work are available on github.

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<sup>11</sup>We 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.

<sup>12</sup>we would expect to see a decrease here

## 258 4 Results

259 Regressions coefficients for our DiD analysis are shown in Table 2. Columns 1 -3 use all data for  
260 controls. Columns 4 - 6 use only PNA vessels as controls, and columns 7 - 9 exclude Chinese vessels.  
261 Columns 10 and 11 use Japanese vessels in the Pacific as controls, and hence don't include flag  
262 fixed-effects to avoid perfect collinearity between Japanese flag and control<sup>13</sup>. Our DiD analysis  
263 shows an overall increase in purse seine fishing hours, even after accounting for the introduction of  
264 new satellites (Table 2). This coefficient estimate is consistent for different model specifications and  
265 across groups of treatment and controls, and effectively represents the patterns observed in Figure 4.

266 The  $\beta_3$  coefficient indicating our treatment effect suggests that, relative to the control, treated  
267 vessels fish less, in the order of 0.5 hours per day. Another way to interpret this is that the increase  
268 in fishing effort by treated vessels has occurred at a lower rate than control vessels. The effect  
269 varying between  $\beta_3 = -0.515$  and  $\beta_3 = -0.934$ . These values are equivalent to a 15 - 28 reduction  
270 in fishing hours per month. However, this result is only robust and significant ( $p < 0.01$ ) in the  
271 simplest specification of the Diff-in-Diff. When reducing the linear structure of the *Pre × Post*  
272 design and instead interacting the treatment dummy with quarterly or year-month combinations  
273 we are not able to reject the null hypotheses of no change, suggesting that the total fishing hours  
274 remains similar for the displaced vessels (Figs. S2-S9). Since vessels don't seem to be fishing less  
275 (or at least not much less), an obvious question arises: where are they fishing now?

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

282 Along a similar line, Figure 7 shows a detailed temporal evolution of the relative allocation of fishing  
283 effort<sup>14</sup>. It shows shows the change in fishing effort inside PIPA, including the preemptive fishing  
284 and immediate reduction previously reported (McDermott et al., 2018). I-Kiribati waters in KIR  
285 1 and KIR 2 show an increase in fishing effort for 2015; the same pattern is observed for their  
286 respective High Seas buffers, and the general High Seas. Other regions farther away from PIPA  
287 don't show a clear pattern under visual inspection.

288 We then move on to our regression results, presented as a figure showing the year-region interaction  
289 coefficient estimates for each region as a stream of changes through time (Fig. 8 and Table 3).  
290 As noted before, the marginal change in the relative allocation of fishing effort relative to 2012  
291 increases in 2014 for PIPA. Most coefficients are not statistically significant, but follow the same  
292 trends previously discussed, with a tendency for regions closer to PIPA to show an increase in  
293 the relative allocation of fishing effort in the post-implementation period. The largest increase is  
294 observed for the I-Kiribati EEZ 2, where the redistribution of treated vessels caused a 15% increase  
295 in the *relative* allocation of fishing effort within I-Kiribati waters. This displacement is likely causing  
296 a crowding effect after PIPA-fishing vessels redistribute to other areas.

297 We use the rasterized effort to evaluate if the PIPA closure increased crowding outside the LSMPA.  
298 We count the number of raster cells that had both treated and control vessels each year (Fig. 9A).

<sup>13</sup>Results of the same analysis is shown for longliners in S1

<sup>14</sup>Recall that to evaluate the redistribution of fishing effort we only track fishing vessels that belong to the treated group.

299 The pattern observed here could just be an artifact of satellite detections increasing though time.  
 300 Therefore we also calculate a spatial correlation of presence/absence and observe similar patterns  
 301 (Fig. 9B). While this are at the year level and cannot assure that vessels were in effect at the same  
 302 time in the same vessel, it provides an accurate depiction of what we would expect to find if our  
 303 claims of displacement are true. Spatial overlap increases in 2015 as vessels from PIPA are excluded,  
 304 and that measure slowly returns to its previous state.

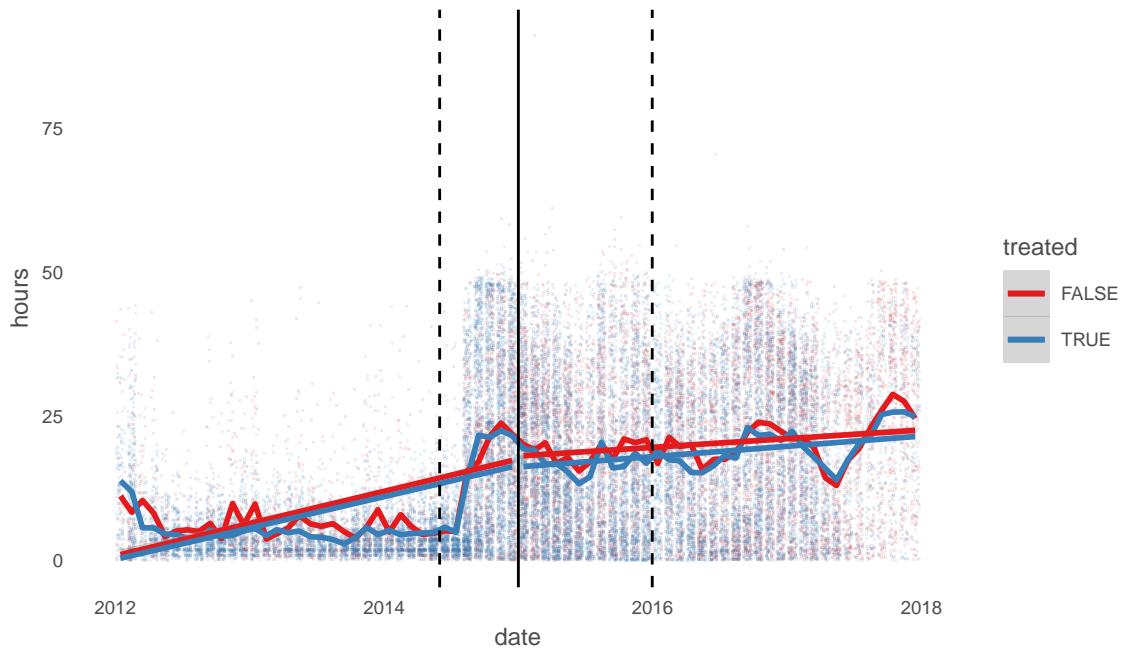


Figure 4: Daily fishing hours for all vessels in our main treatment-control groups. Solid straight lines show a linear trend by period (pre-psot) and treatment. The other red and blue lines show monthly averages. Vertical dashed lines indicates dates when satellites were added, solid line indicates PIPA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

Table 2: 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 <sup>2</sup>	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

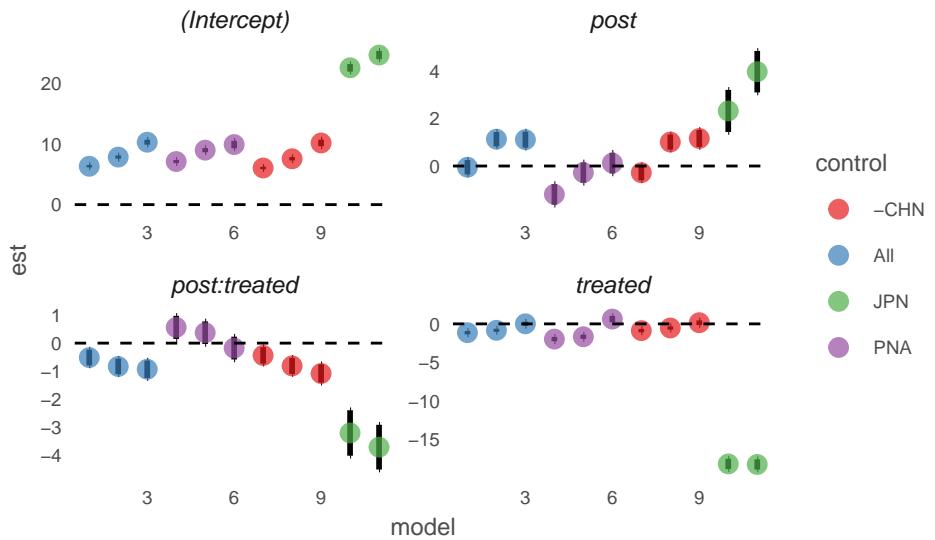


Figure 5: Coefficient estimates for each model. Top pannel indicates variable, x-axis represents model specification, and y-axis coefficient estimate.

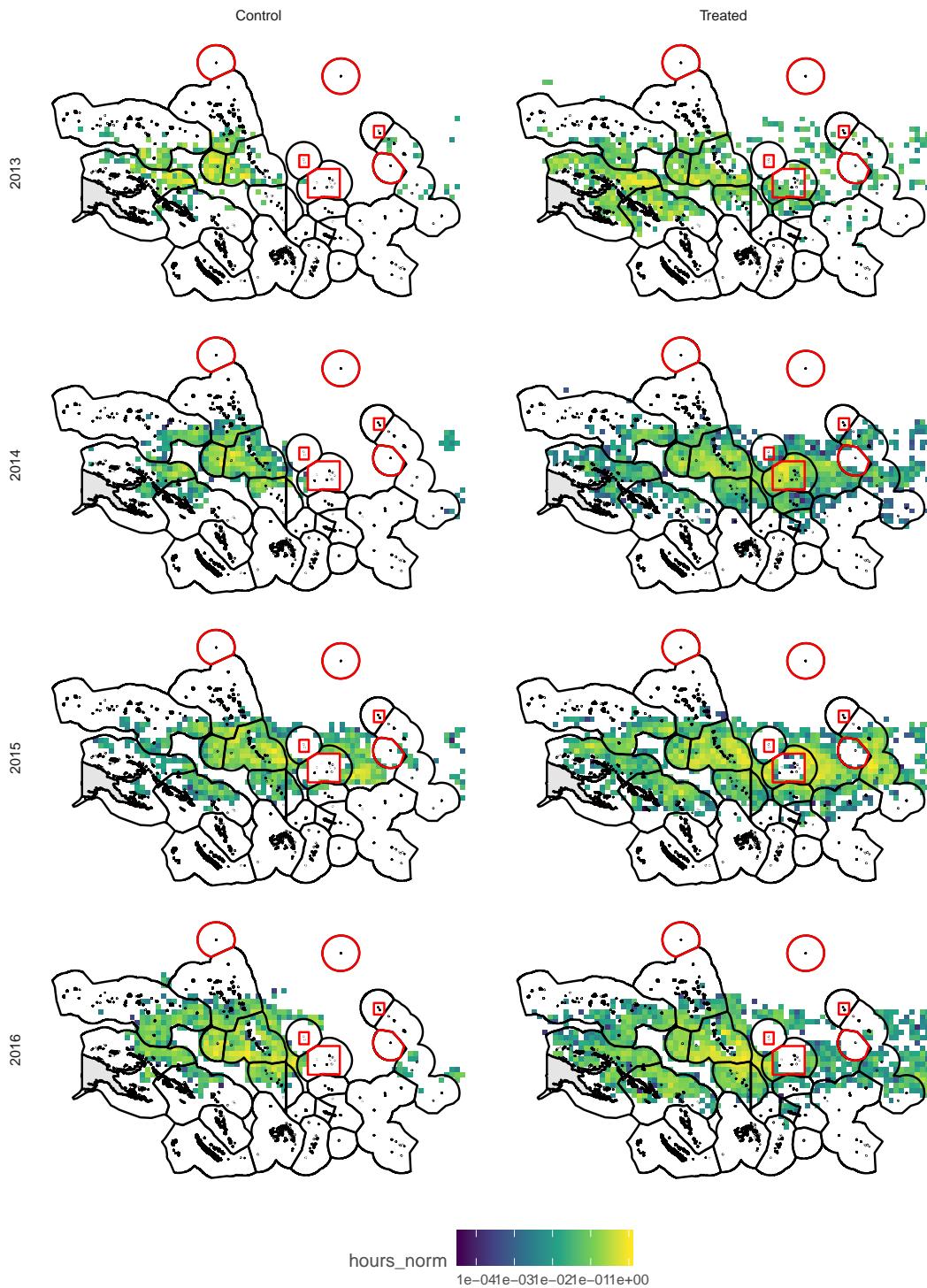


Figure 6: Yearly spatial distribution of fishing effort by treated and control vessels. Colors have been adjusted relative to the maximum observed by group and year. Red polygons show LGMPAs in the region. For visualization purpose only some years are presented, the full 2012 - 2017 period is shown in Figure S11.

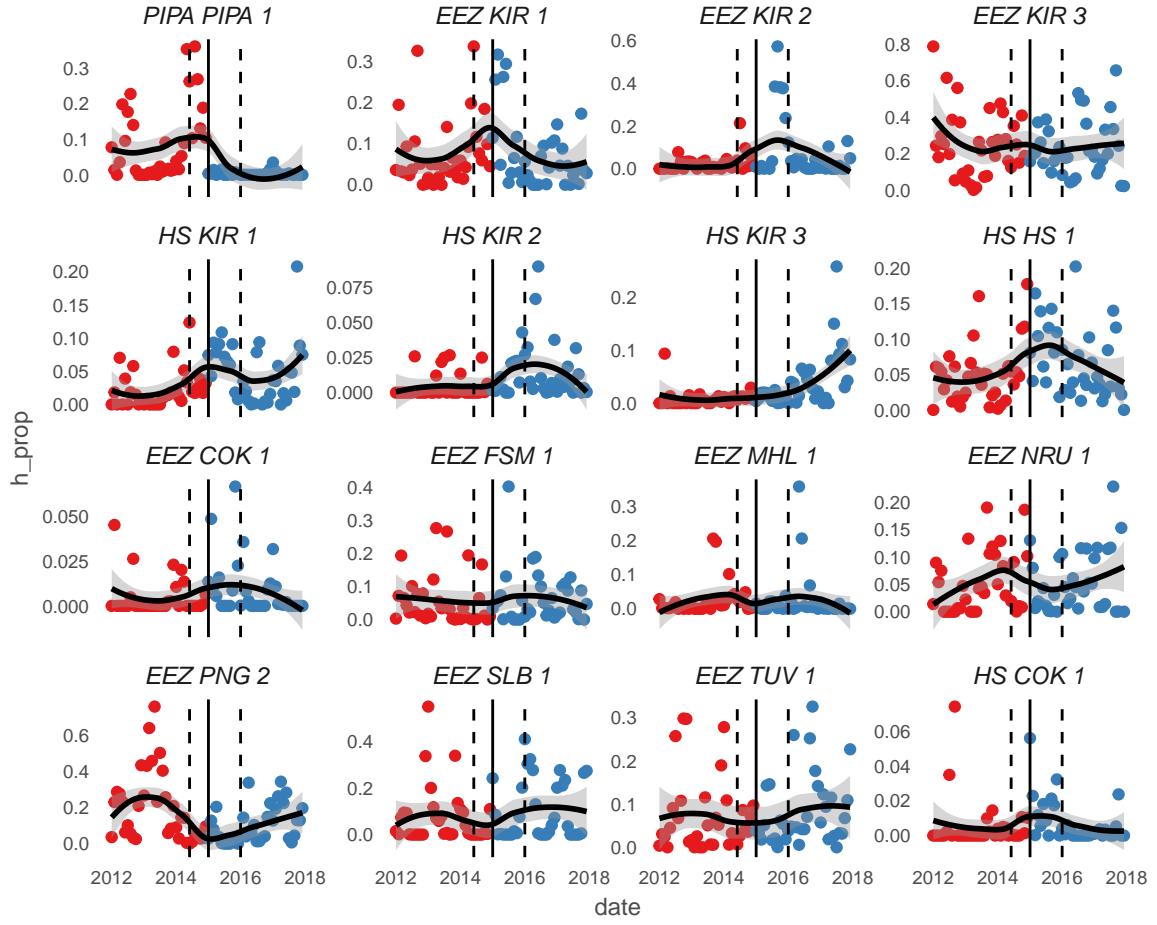


Figure 7: Monthly relative allocation of fishing effort by PIPA-fishing vessels before and after PIPA by region. Colors indicate the pre-post period. Solid line across points shows local mean with a region-specific loess smoother. Vertical dashed lines indicates dates when satellites were added, solid line indicates PIPA closurePIPA closure. Note that inflection points of the loess smoother are not affected by the addition of satellites.

Table 3: Coefficient estimates for the interaction of year and region. Each row represents a region, each color a year. Numbers in parentheses are heteroskedastic-robust standard errors. R2 = 0.47 (F(95, 1056) = 9.99; p < 0.001). \* < 0.1; \*\* p < 0.05; \*\*\*p < 0.01.

term	2013	2014	2015	2016	2017
PIPA PIPA 1	-0.062 (0.026)**	0.085 (0.043)**	-0.086 (0.026)***	-0.079 (0.025)***	-0.074 (0.025)***
EEZ KIR 1	-0.034 (0.030)	0.035 (0.038)	0.042 (0.045)	-0.035 (0.031)	-0.023 (0.032)
EEZ KIR 2	0.001 (0.009)	0.032 (0.019)*	0.142 (0.061)**	0.014 (0.013)	0.014 (0.015)
EEZ KIR 3	-0.188 (0.075)**	-0.061 (0.072)	-0.118 (0.069)*	-0.093 (0.083)	-0.098 (0.083)
HS KIR 1	-0.003 (0.011)	0.016 (0.012)	0.038 (0.013)***	0.004 (0.013)	0.037 (0.018)**
HS KIR 2	0.009 (0.006)	0.004 (0.006)	-0.000 (0.009)	0.022 (0.010)**	0.008 (0.006)
HS KIR 3	-0.002 (0.009)	0.003 (0.009)	-0.008 (0.011)	0.022 (0.011)*	0.064 (0.024)***
HS HS 1	0.021 (0.015)	0.027 (0.017)	0.045 (0.017)***	0.030 (0.017)*	0.014 (0.015)
EEZ FSM 1	0.018 (0.033)	-0.015 (0.025)	0.000 (0.037)	0.012 (0.025)	-0.001 (0.021)
EEZ MHL 1	0.037 (0.022)	0.025 (0.010)**	-0.006 (0.009)	0.052 (0.032)	-0.000 (0.006)
EEZ NRU 1	0.046 (0.021)**	0.044 (0.020)**	0.003 (0.017)	0.033 (0.015)**	0.050 (0.025)**
EEZ PNG 2	0.196 (0.072)***	-0.106 (0.041)***	-0.132 (0.043)***	-0.064 (0.048)	0.001 (0.049)
EEZ SLB 1	0.083 (0.056)	-0.019 (0.032)	-0.009 (0.038)	0.081 (0.053)	0.076 (0.046)*
EEZ TUV 1	-0.055 (0.037)	-0.033 (0.040)	-0.063 (0.037)*	0.018 (0.046)	-0.026 (0.038)
HS COK 1	-0.003 (0.008)	-0.004 (0.008)	-0.003 (0.011)	-0.007 (0.008)	-0.003 (0.008)

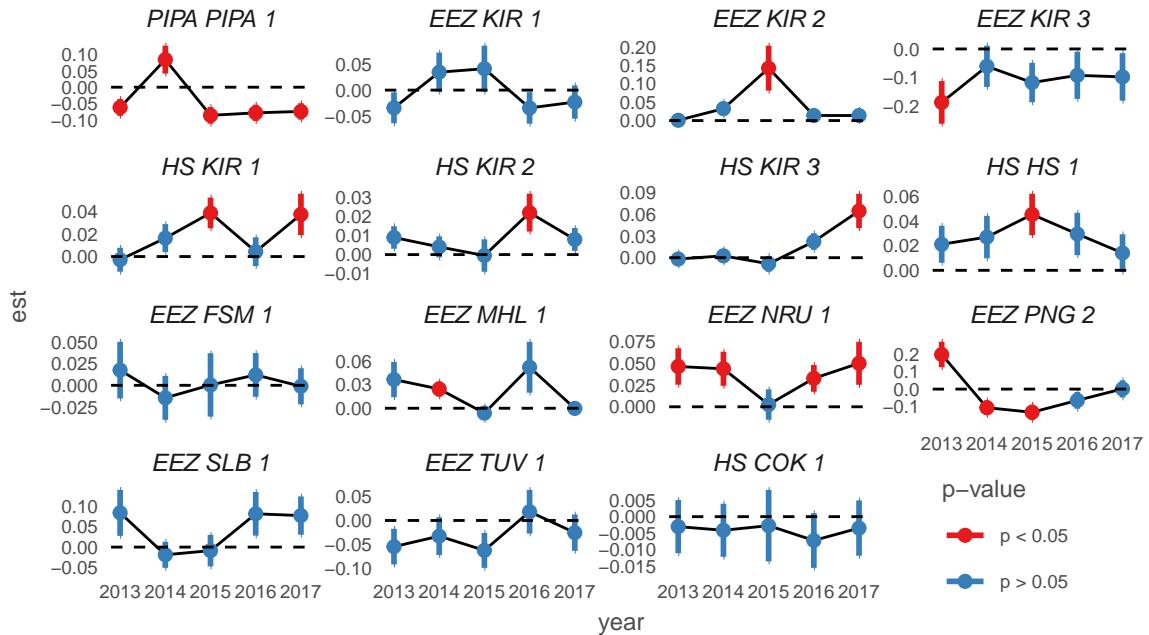


Figure 8: Coefficient estimates for the redistribution regression. Each panel shows the region-specific coefficients, with heteroskedastic-robust standard errors as error bars. The horizontal dashed line represents 0 change relative to the 2012 region-specific levels.

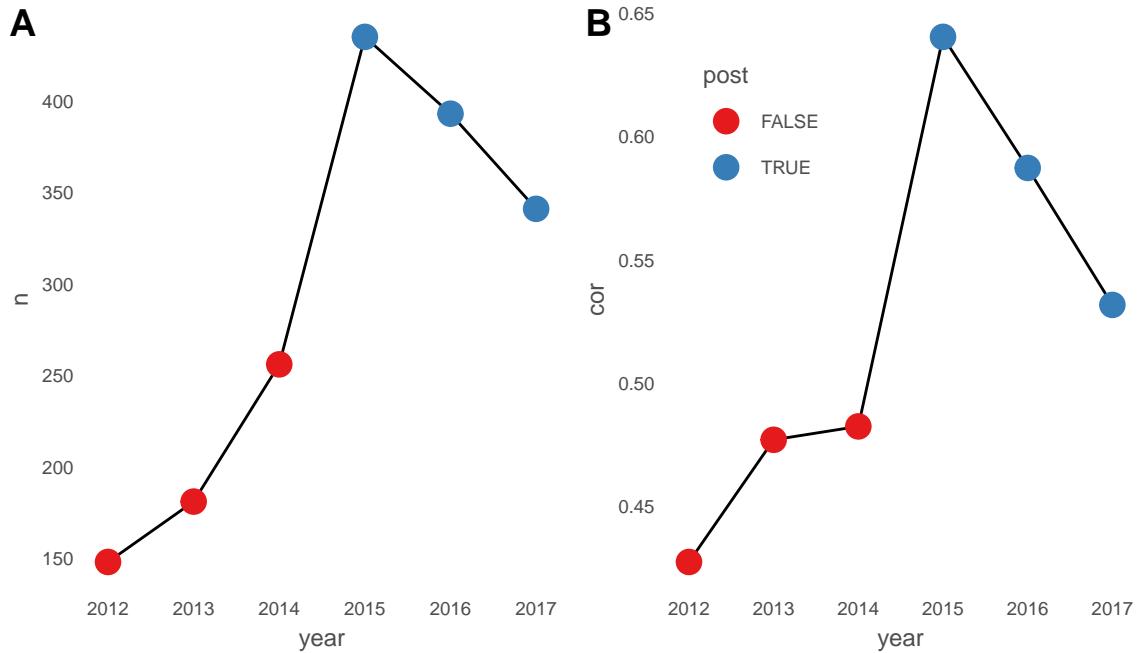


Figure 9: Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B).

305 **5 Discussion**

306 Our findings provide interesting insights into the effect that LSMPAs can have on vessel behavior  
307 and the redistribution of fishing effort. These collection of results show that the implementation of  
308 PIPA had little effect on the effort exerted by purse seiners. However, regions adjacent to PIPA  
309 show an increase in the relative amount of fishing effort, suggesting that effort is simply redisplaced  
310 to closeby areas. This does not imply that there is more fishing effort exerted by treated vessels,  
311 but rather that each region receives a greater portion of the post-PIPA fishing effort of these same  
312 vessels, which is lower than pre-PIPA levels. Additionally, we show that post-PIPA there is a  
313 concentration of effort leading to crowding. In this section we discuss the implications of vessel-level  
314 reductions in fishing effort and the increase in relative allocation of the remaining effort through  
315 space. We also provide plausible explanations as to why purse seiners seem to be more reactive to  
316 the spatial closure.

317 Previous studies on insular environments suggest that vessels move to distant places, which might be  
318 translated as increased costs (Stevenson et al., 2013). Nevertheless, they do not use counterfactuals  
319 that could help account for system- or fleet-level changes that occur through time. Others have  
320 used similar satellite-tracking systems to show that fishing effort accumulates near the edges of  
321 spatial closures, yielding greater catches (Murawski et al., 2005). Yet, these vessel tracks do not  
322 cover the pre-reserve period, making it difficult identify the contribution of spatial closures to the  
323 observed spatial distribution of fishing vessels. Recent work by Elahi et al. (2018) identified that  
324 total fishing effort in a focal region where a short-term MPA was implemented showed little change,  
325 likely indicating that fishers redistributed fishing effort to compensate for the reduction in available  
326 space. Our data, which is assembled in a similar way, allows us to make similar inferences about  
327 the unobserved change in aggregate fishing effort and its spatial redistribution.

328 The role of the institutions at play is evident. Vessels that fished inside PIPA before the imple-  
329 mentation were, ultimately, fishing in I-Kiribati waters likely under a VDS license. Upon the  
330 implementation, some of these redistribute to other areas of the I-Kiribati EEZ and the high seas for  
331 the year immediately after the closure. As stated before, it is reasonable for a vessel holding a license  
332 to fish in I-Kiribati waters to simply reallocate their effort to other parts of that EEZ. However,  
333 the shift to the high seas may not follow the same logic. Instead, it is possible that vessels that  
334 redistribute to the high seas were operating in I-Kiribati illegally, and decide to reallocate in the  
335 high seas to continue fishing without a license. These patterns provide us with interesting insight  
336 into fishing behavior, which may become useful in tackling Illegal, Unreported and Unregulated  
337 (IUU) fisheries.

338 A major shortcoming of our analyses is that we do not observe catches or revenues, which ultimately  
339 are the factors that guide the decision making process of profit-maximizing agents. Therefore, it is  
340 difficult to know whether lack of change in fishing hours represents a positive or negative impact.  
341 An additional thing that we are yet to test is the changes in non-fishing hours spent at sea. It is  
342 plausible that fishing hours remain constant, but vessels have to increase search time. Upon being  
343 relocated, fishers may not identify the best fishing grounds as easily as before, and therefore invest  
344 a greater proportion of their time searching for their catch. Further analysis of temporal trends  
345 in non-fishing hours, as well as distance traveled should provide us with insights as to why fishers  
346 reduced fishing hours. However, the widespread footprint of the treated fleet may suggest that they  
347 are well acquainted with the region (See Fig. 6), and its unlikely that they would need to learn or  
348 identify new fishing grounds.

349 Our work suggests that the implementation of LSMPAs has little impact on purse seiners fishing  
350 effort. We also show that fishing effort is redistributed to areas close by, and that this leads to a  
351 potentially negative crowding effect. A growing body of literature suggests that closing the high  
352 seas to all fishing could increase fishery yields and profitability of fisheries, with negligible costs to  
353 food security (White and Costello, 2014; Sumaila et al., 2015; Sala et al., 2018; Schiller et al., 2018).  
354 Such management interventions should consider how fishing effort will change in space and through  
355 time, and the ecological implications of this redistribution to ensure that fishing effort is not just  
356 displaced elsewhere, leading to overfishing in adjacent waters. While LSMPAs can provide a wide  
357 range of benefits, their implementation must be accompanied with traditional fisheries management  
358 to maximize effectiveness.

## 359 6 Further work

- 360 • Distance traveled
- 361 • Non-fishing hours at sea
- 362 • Monthly crowdnes (same approach as now, but monthly instead of yearly)
- 363 • Number of vessels per cell as another measure of crowdness (this is a more real one)
- 364 • Repeat raster exercise for Revillagigedo and other recently implemented LSMPAs. It would  
365 be great to have a pannel figure of 3 or 4 other LSMPAs that show wher effort was and where  
366 it went to generalize our results.
- 367 • John talked about this being relevant to Palau (their upcoming LSMPA). We might want to  
368 talk about where the vessels that are there would go.

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455 7 Appendix

456 7.1 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.

457 **7.2 Longliners**

458 Longliners show a similar pattern of effort reduction. However, the magnitude of the  $\beta_3$  coefficient  
 459 is smaller (ranging from  $\beta_3 = -0.98$  to  $\beta_3 = -1.125$ ) and not significant unless including month  
 460 and flag FEs for the general treatment-control groups, or when excluding Chinese vessels. This,  
 461 along with higher standard error values suggest that longliners have a smaller and more variable  
 462 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 <sup>2</sup>	0.010	0.016	0.022	0.010	0.016	0.023

Note:

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

<sup>463</sup> 7.2.1 Quarterly DID interactions

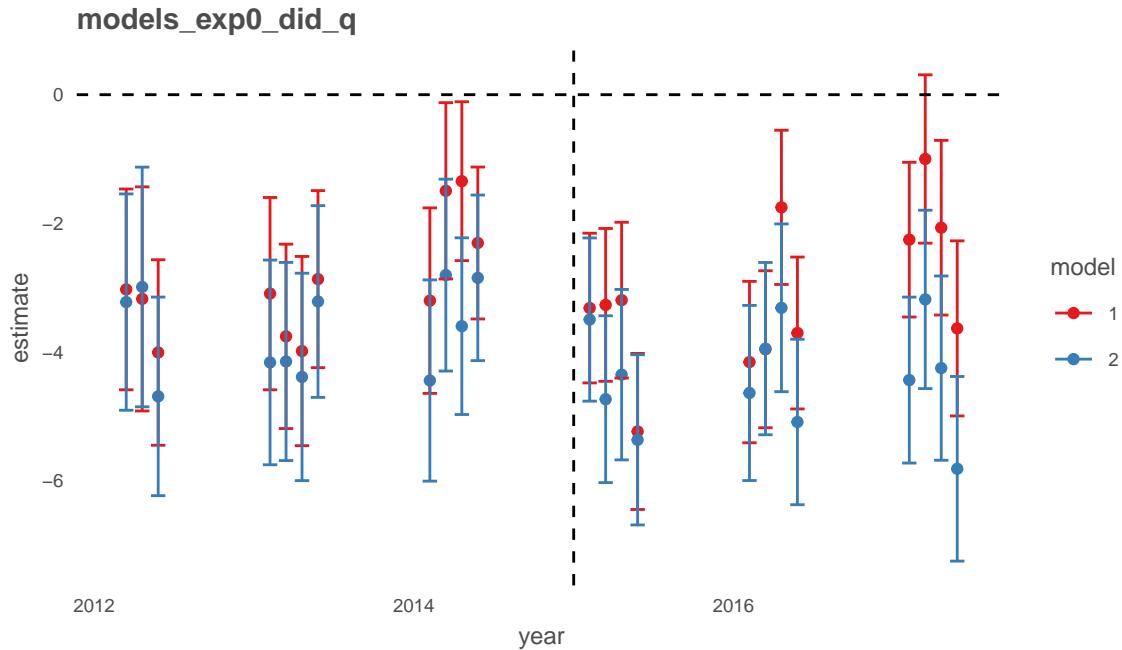


Figure S2: Interaction of quarters and treatment. Control group is all vessels.

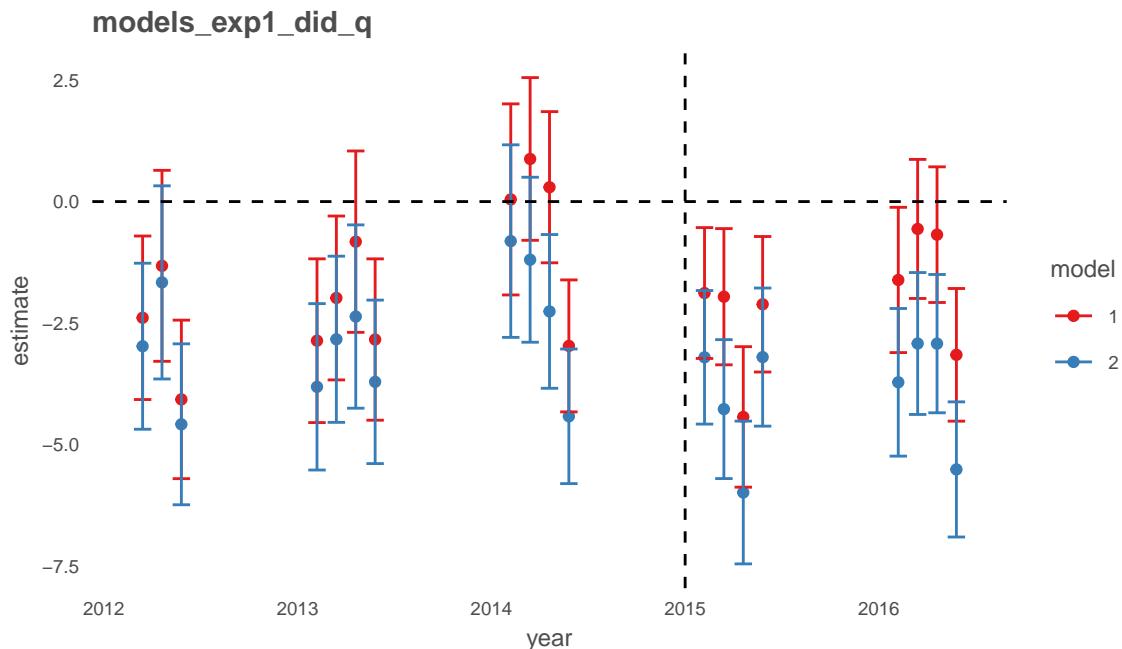


Figure S3: Interaction of quarters and treatment. Control group is vessels from PNA.

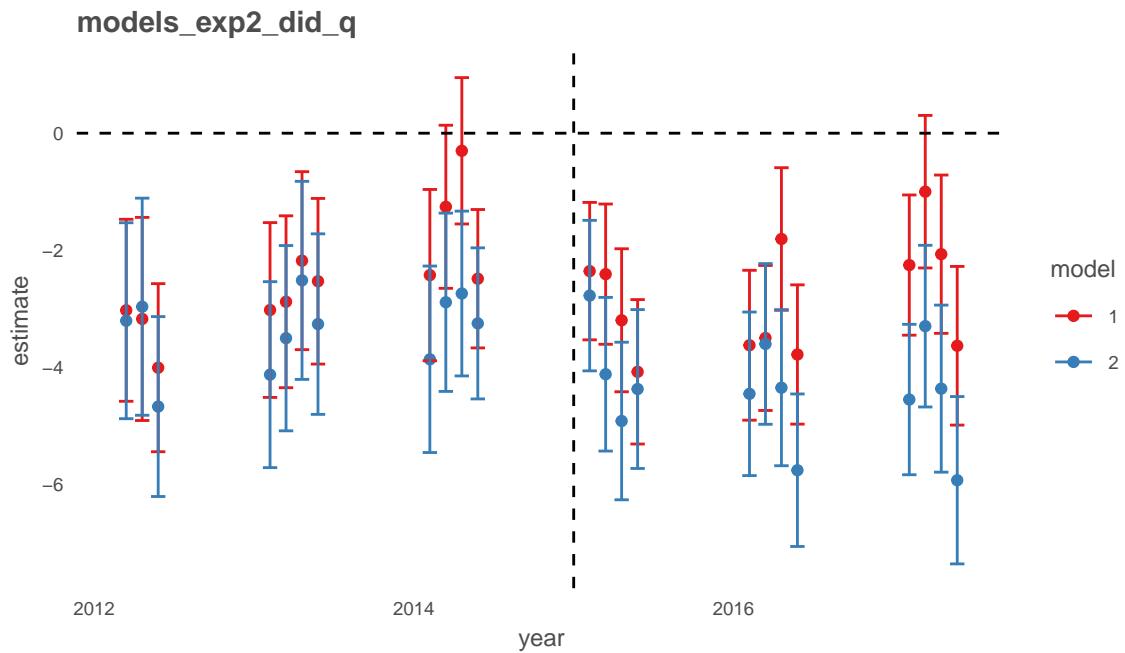


Figure S4: Interaction of quarters and treatment. Control group excludes Chinese vessels.

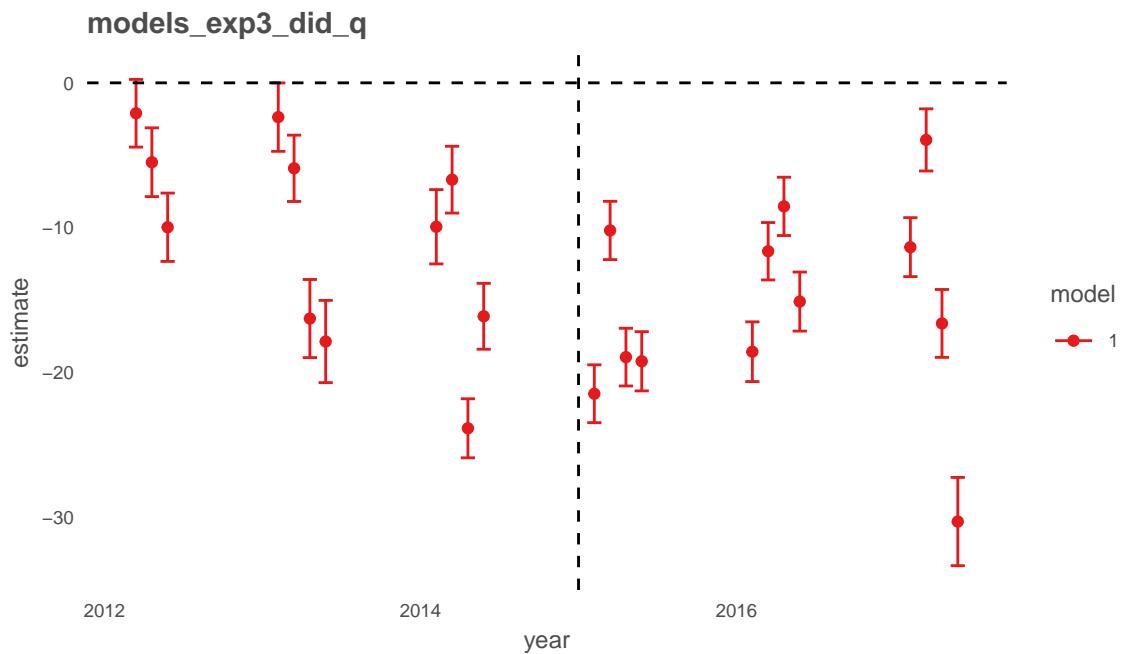


Figure S5: Interaction of quarters and treatment. Control group is Japanese vessels.

<sup>464</sup> 7.2.2 Year-month DID interactions

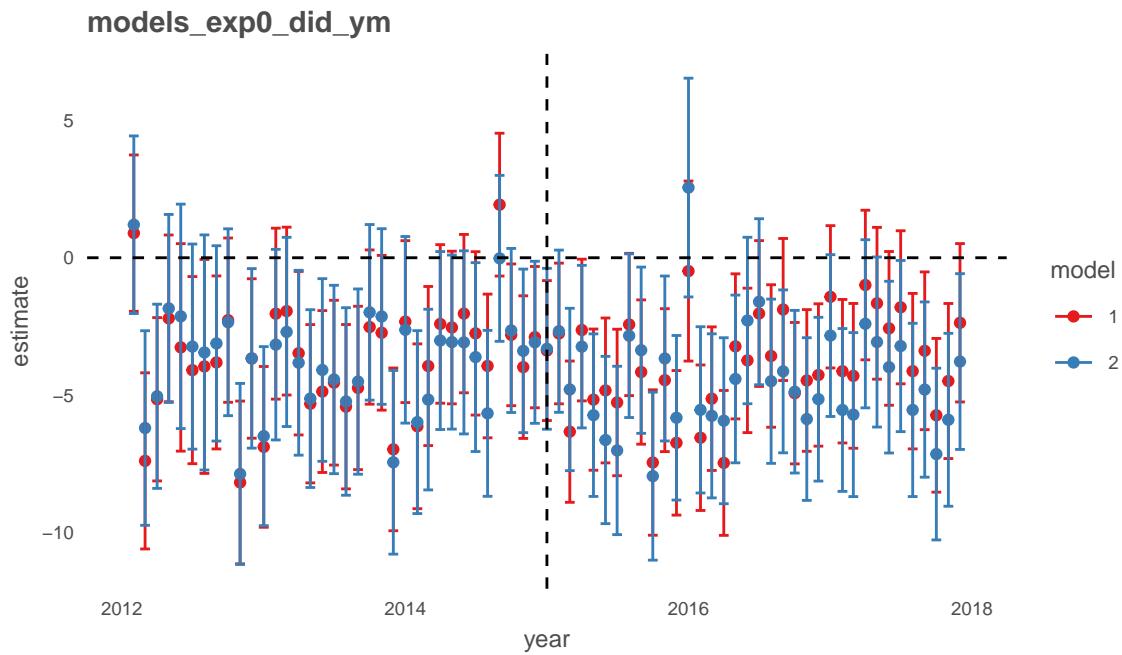


Figure S6: Interaction of year-month and treatment. Control group is all vessels.

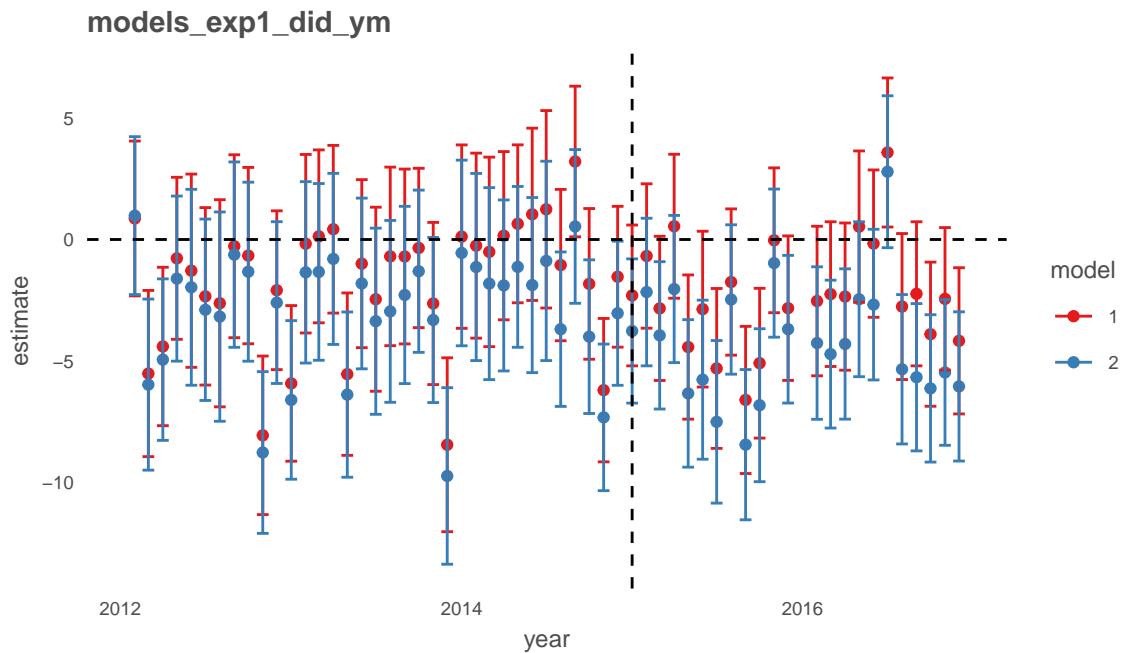


Figure S7: Interaction of year-month and treatment. Control group is vessels from PNA.

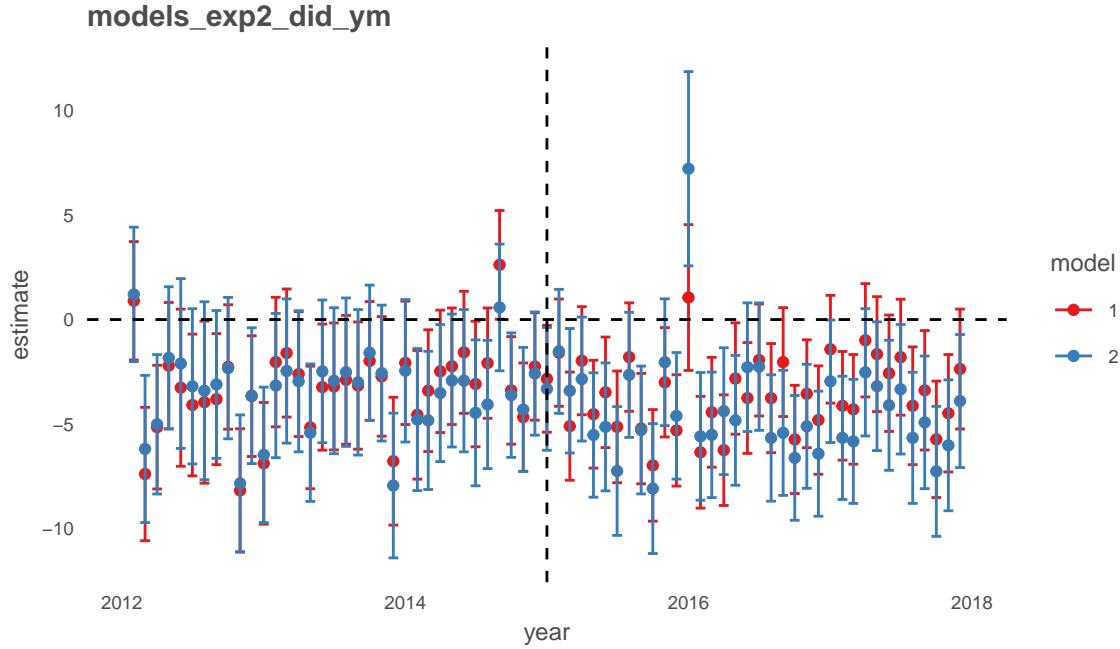


Figure S8: Interaction of year-month and treatment. Control group excludes Chinese vessels.

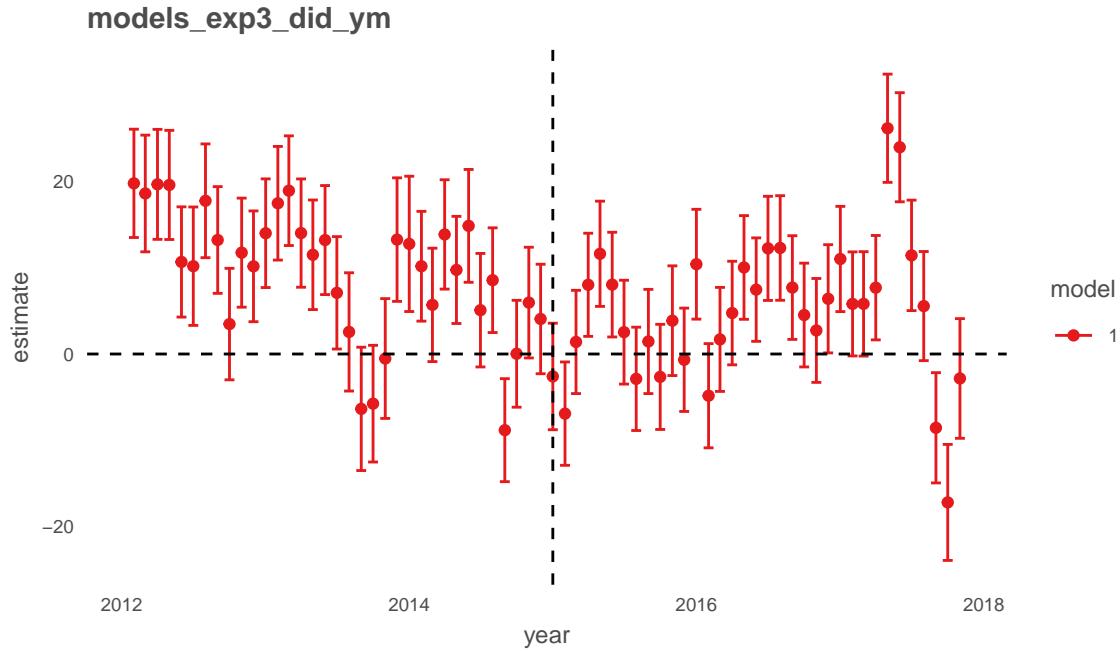


Figure S9: Interaction of year-month and treatment. Control group is Japanese vessels.

### 465 7.3 Other measures of change in behavior

466 Global Fishing Watch data includes two variables of interest that are readily available: distance  
 467 from shore and distance from port. We use these as variables of interest and perform the following

<sup>468</sup> regression:

$$y = \beta_1 Year + \beta_2 Treated + \beta_3 Year \cdot Treated + \epsilon$$

<sup>469</sup> Where  $y$  is our variable of interest,  $Year$  represent year dummies, with 2012 as the reference level,  
<sup>470</sup> and  $Treated$  indicates whether a vessel belongs to the treated or control group.

<sup>471</sup> **7.3.1 Distance from shore**

Table S2: Regression results for distance from shore. Numbers in parentheses are heteroskedastic-robust standard errors.

	<i>Dependent variable:</i>
	distance_from_shore
Constant	233,057.900*** (1,558.294)
year_c2013	−818.044 (2,623.263)
year_c2014	14,220.260*** (1,701.637)
year_c2015	140,980.200*** (1,668.140)
year_c2016	32,557.750*** (1,584.182)
year_c2017	168,283.100*** (1,653.912)
treated	−11,371.280*** (1,688.879)
year_c2013:treated	62,899.900*** (3,274.205)
year_c2014:treated	−17,499.020*** (1,834.090)
year_c2015:treated	−34,356.840*** (1,821.587)
year_c2016:treated	72,512.980*** (1,739.976)
year_c2017:treated	−62,350.120*** (1,805.322)
Observations	4,937,666
R <sup>2</sup>	0.032
Adjusted R <sup>2</sup>	0.032
Residual Std. Error	297,128.600 (df = 4937654)
F Statistic	14,649.360*** (df = 11; 4937654)

*Note:*

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

Table S3: Regression results for distance from shore. Numbers in parentheses are heteroskedastic-robust standard errors.

TRUE
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Table S4: Regression results for distance from shore. Numbers in parentheses are heteroskedastic-robust standard errors.

TRUE
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<sup>472</sup> **7.3.2 Distance from ports**

<sup>473</sup> **7.4 Effort redistribution**

<sup>474</sup> **7.4.1 Rasterized regions**

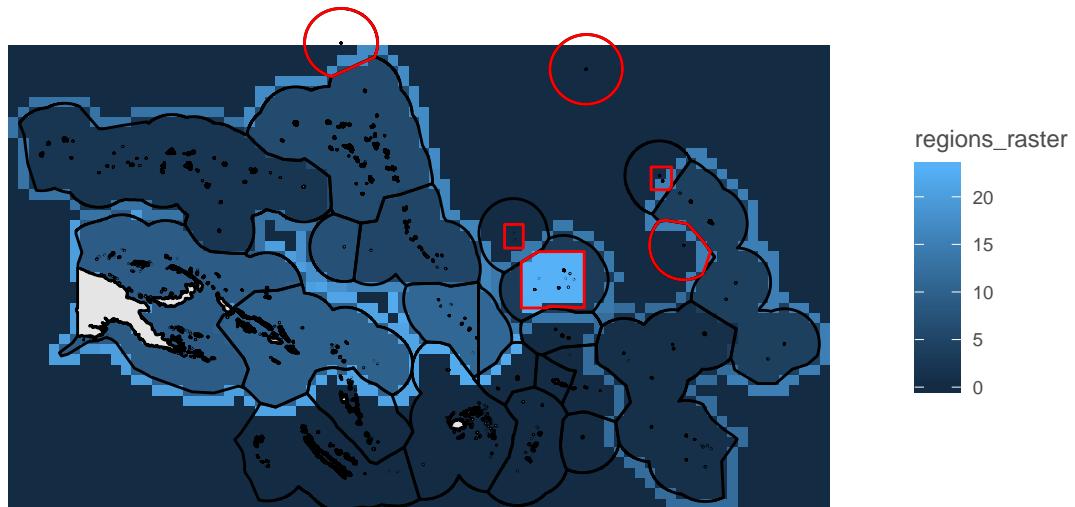


Figure S10: Rasterized regions. Each color (number) indicates a distinct region.

Table S5: Regression results for distance from shore

<i>Dependent variable:</i>	
	distance_from_port
Constant	362.707*** (1.971)
year_c2013	9.082*** (3.198)
year_c2014	105.414*** (2.148)
year_c2015	357.746*** (2.113)
year_c2016	112.441*** (2.009)
year_c2017	356.506*** (2.099)
treated	149.653*** (2.249)
year_c2013:treated	26.366*** (4.125)
year_c2014:treated	50.808*** (2.453)
year_c2015:treated	-151.268*** (2.422)
year_c2016:treated	-49.445*** (2.311)
year_c2017:treated	-252.334*** (2.390)
Observations	4,937,666
R <sup>2</sup>	0.047
Adjusted R <sup>2</sup>	0.047
Residual Std. Error	391.757 (df = 4937654)
F Statistic	22,351.480*** (df = 11; 4937654)

Note:

\*p&lt;0.1; \*\*p&lt;0.05; \*\*\*p&lt;0.01

Table S6: Regression results for distance from shore

<u>TRUE</u>
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Table S7: Regression results for distance from shore

<u>TRUE</u>
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475 7.4.2 Fishing raster

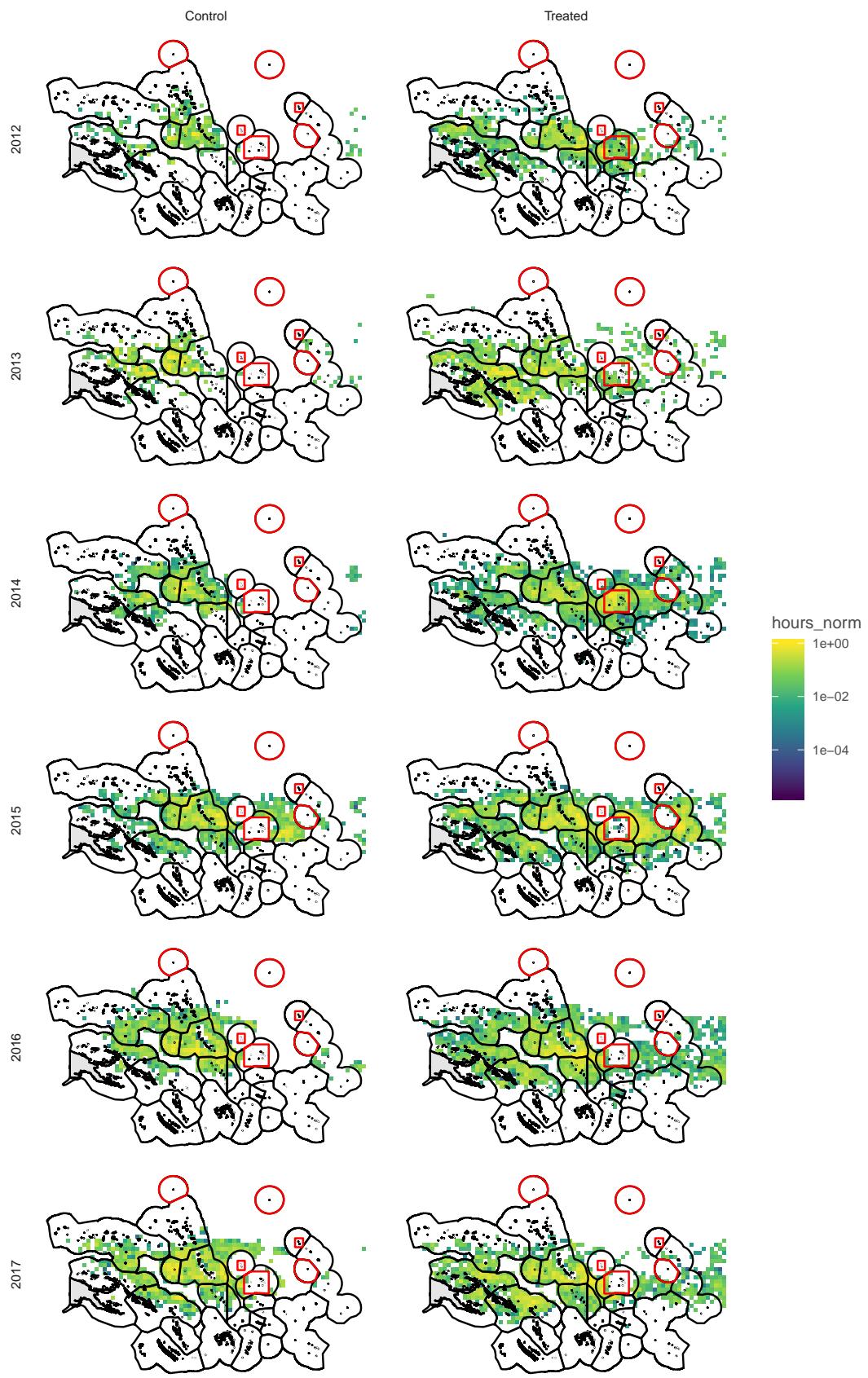


Figure S11: Yearly rasters of fishing hours for each group.