

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.

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\*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).

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

43 Here, we ask, how do fishers respond to the implementation of LSMPA? After a closure, and if  
44 they continue to fish, where do they reallocate fishing effort? We use novel satellite technologies  
45 and causal inference techniques to identify the behavioral changes and spatial redistribution of the  
46 industrial tuna purse seine fleet due to the implementation of a Large Scale Marine Protected Areas  
47 in the Western and Central Pacific Ocean (WCPO).

48 The cutoff at which an MPA is considered to be a LSMPA ranges from areas larger than 30,000  
49 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.,  
50 2013). Figure 1 shows LSMPAs that meet the later, and that are fully no take. LSMPAs are often  
51 implemented in the pelagic environment, where the dominant human activity is industrial fishing  
52 (Gray et al., 2017; Kroodsma et al., 2018). The early literature on LSMPAs focused on the inherent  
53 challenges and difficulties that come with a pelagic environment. Kaplan et al. (2010) claimed that  
54 very large MPAs would result in excessive opportunity costs and that these would be difficult to  
55 enforce. Game et al. (2009) suggested that most of the challenges could be overcome with the  
56 incorporation of technology, in what then became known as Dynamic Ocean Management (Maxwell  
57 et al., 2015). The effectiveness and difficulties of implementing LSMPAs are not the focus of this  
58 paper <sup>1</sup>. Instead, we focus on the effect and implications of the ones that *have been* implemented.

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<sup>1</sup>But see Singleton and Roberts (2014), who provide an objective discussion of pros and cons of LSMPAs.

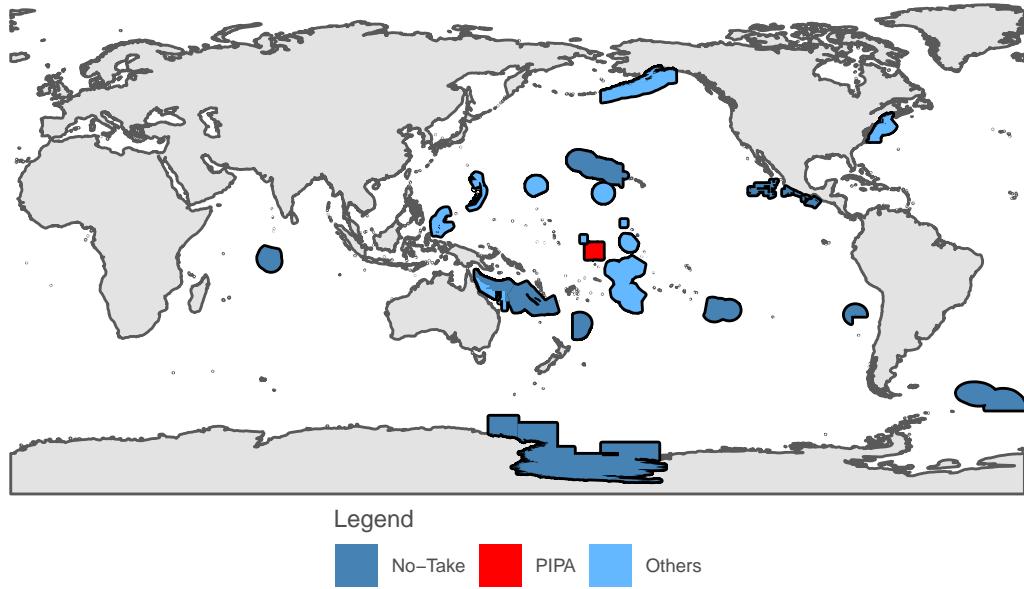


Figure 1: Large Scale Marine Protected Areas. The map shows all areas larger than 250,000 Km<sup>2</sup>. Areas in dark blue meet at least one of these conditions: reported no take area is greater than 0, are categorized as IUCN Ia or Ib, their designated english name is ‘Protected Area’.

- 59 LSMPAs were erroneously assumed to have little social implications due to their remoteness.  
 60 However, there have been calls to incorporate the human dimensions into LSMPAs management and  
 61 evaluation (Agardy et al., 2011; Gray et al., 2017). Most research incorporating these dimensions has  
 62 focused on governance and enforcement of LSMPAs (*i.e.* Alger and Dauvergne (2017); Christie et al.  
 63 (2017)), but they are yet to be the focus of economic analyses (Gray et al., 2017). Overall, there has  
 64 been little empirical work regarding LSMPAs. Recent technological advances in vessel-detection  
 65 systems allows for the discovery and advancement of many important facets of LSMPAs. For  
 66 example, (McDermott et al., 2018) show that the anticipation of a LSMPA can lead to preemptive  
 67 overfishing, which can erode or delay the expected benefits of the intervention. White et al. (2017)  
 68 combine shark tags and vessel-tracking data to demonstrate that the fairly large Palmyra Atoll  
 69 National Wildlife Refuge (54,000 Km<sup>2</sup>) protectes two thrids of the tagged grey reef sharks by  
 70 effectively excluding fishing effort. More recently, (Bradley et al., 2018) use similar data to highlight  
 71 cases of illegal shark fishing *inside* a 2 million km<sup>2</sup> shark sanctuary. To date, no studies have  
 72 evaluated the displacement of fishing effort due to LSMPA implementation.
- 73 The exclusion of these LSMPAs is likely to change fisher’s behavior. Theoretical models of fishing  
 74 effort redistribution range from the simplistic assumption that effort inside the bounded region  
 75 disappears, to spatially explicit models that reallocate fishing effort based on habitat characteristics,  
 76 presence of other vessels, and expected returns (Smith and Wilen, 2003; Hilborn et al., 2006).  
 77 However, these focus on the long term optimal equilibrium and redistribution of fishing effort may  
 78 not be optimal, especially over the first years (Stevenson et al., 2013). The empirical research

79 that has been done in customary sized MPAs suggest that resource users may show idiosyncratic  
80 responses. For example, Stevenson et al. (2013) show that a network of MPAs displaced fishing  
81 effort farther away from ports, resulting in higher *perceived* costs, and increases in catch per unit  
82 effort. Cabral et al. (2017) analyse the redistribution of fishing and non-fishing vessels following the  
83 implementation of a network of MPAs in California, and find that commercial dive boats follow a  
84 fishing-the-line pattern, while some fishing boats follow an ideal free distribution. The way in which  
85 fishers react to a spatial closure can have major implications in its outcome (Smith and Wilen, 2003;  
86 Hilborn et al., 2006) highlighting the need to understand how fishers react to the implementation of  
87 LSMPAs, and fishing effort changes and is spatially redistributed.

88 Our work is novel in the sense that it provides empirical evidence of the effect of large-acale Marine  
89 Protected Areas in fishing behavior and distribution and can help guide future interventions as  
90 countries march towards meetings the targeted 10% of protection. Furthermore, a growing body  
91 of literature suggests that closing the high seas to all fishing could increase fishery yields and  
92 profitability of fisheries, with negligible costs to food security (White and Costello, 2014; Sumaila  
93 et al., 2015; Sala et al., 2018; Schiller et al., 2018). Understanding how effort is displaced from  
94 LSMPAs might provide insights into how the industrial fleet would react to a high seas closure.

95 The paper is outlined as follows: Section 2 provides an overview of the Nauru Agreement and  
96 associated countries, a description of the fleet that operates in the region, and a brief history of  
97 PIPA. Section 3 describes our data and identification strategy. Section 4 presents our results, section  
98 5 provides an extension of our results to other LSMPAs<sup>2</sup> and discusses our results<sup>3</sup>.

## 99 2 Background

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

106 The cooperation that emerged thanks to the PNA allowed for subsequent agreements that strength-  
107 ened fisheries management, like the Palau Agreement, which limited the number of purse seiners at  
108 205 vessels from 1995-2007<sup>4</sup>. However, the most notable regulation is their approach to manage  
109 fishing effort: a Vessel Day Scheme (VDS) implemented in 2007 (Havice, 2013). This effectively  
110 modified how fishing effort was managed, from number of vessels under the Palau Agreement to  
111 fishing hours. The VDS works as follows: Each year, scientific advisors recommend a total number  
112 of fishing vessel-days per year. Hours are allocated to each PNA country based on catch history,  
113 and they then use or sell fishing rights to other non-PNA countries (Aqorau et al., 2018). While  
114 the effectiveness of this scheme has been debated in terms of meeting their fishery management  
115 and conservation objectives, the licensing significantly contributes to the economy of these island  
116 nations (Havice, 2010).

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<sup>2</sup>Not yet. but I think this would be interesting

<sup>3</sup>I might also include a section, after the background, where I explain the different theoretical models of effort redistribution and behavioral responses

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

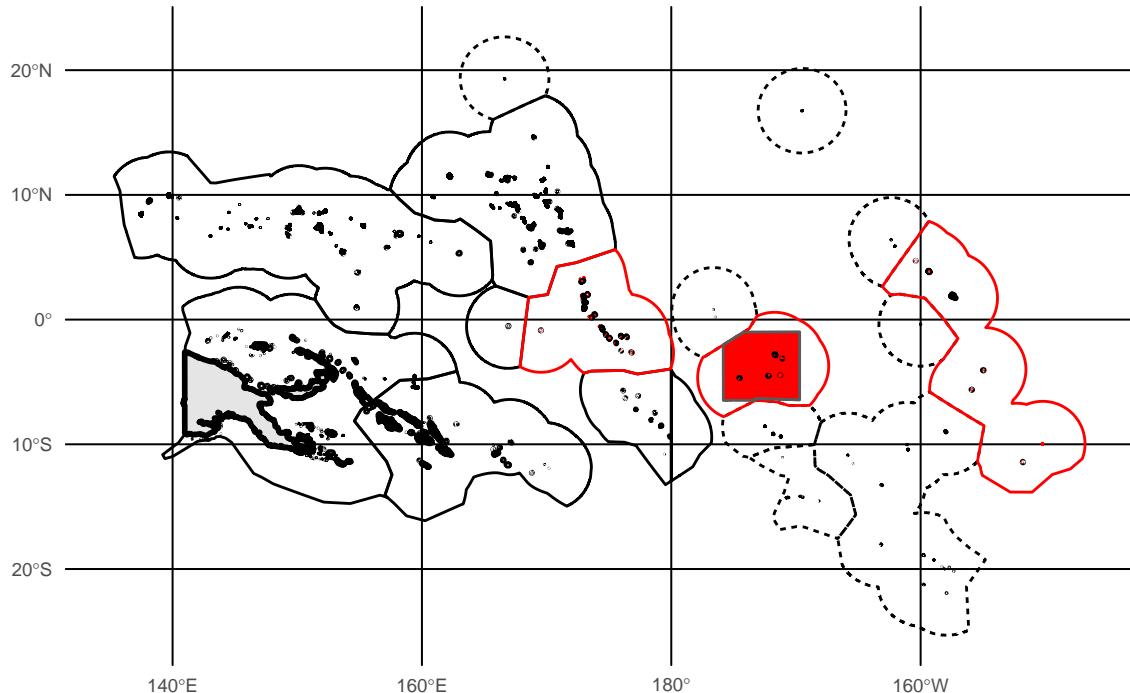


Figure 2: Map of the Exclusive Economic Zones (EEZs) of the region of interest. A solid line indicates countries that belong to the PNA, while a dashed line indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

- 117 The main tuna species caught in the region are skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus*  
 118 *albacares*), albacore (*Thunnus alalunga*) and bigeye (*Thunnus obesus*). From these, the first two are  
 119 amongst the top-10 species represented in global fisheries production statistics, with 2016 catches  
 120 increasing relative to the 2005-2014 average (FAO, 2018). Theis region of the Pacific has historically  
 121 accounted for a large portion of tuna catches (Aqorau and Bergin, 1997). Today, the PNA controls  
 122 close to 50% of the global skipjack tuna production (PNA, 2018). A large portion of these catches  
 123 derive from purse seine vessels licensed under the VDS. Fishing vessels from Australia, New Zeland,  
 124 China, France, Korea, Japan, the Philippines, Taiwan, and the United States participate in the  
 125 purse-seining VDS.
- 126 One of the most notable and recent management interventions in the region is the implementation of  
 127 the Phoenix Island Protected Area (PIPA) by the government of Kiribati. PIPA was first declared  
 128 in 2006, and established in 2008 with only 4% of it was declared as no-take. In January 1<sup>st</sup>, 2015,  
 129 the no-take area within PIPA was expanded to a total area of 397,447 km<sup>2</sup>, roughly 1.5 times the  
 130 size of Ecuador. Figure 2 shows a map of the PNA countries and the Phoenix Island Protected  
 131 Area.
- 132 The implementation of such a large conservation area in one of the most important fishing regions  
 133 in the world provides a great opportunity to evaluate the behavioral responses and redistribution of  
 134 fishing effort by vessels that used to fish there. McDermott et al. (2018) showed that fishing effort  
 135 within the Phoenix Islands Marine Protected Area (PIPA) increased between the anouncement  
 136 (September 1<sup>st</sup>, 2014) and its implementation in Janyary 1<sup>st</sup>, 2015. Likewise, they demonstrate that

<sup>137</sup> fishing effort is effectively reduced after implementation. To this, we pose two questions: How do  
<sup>138</sup> individual vessels respond to the sudden exclusion of such a big area? And where did all the vessels  
<sup>139</sup> go? In the next sections we describe the data and methods used to answer this questions.

## <sup>140</sup> 3 Methods

<sup>141</sup> This section is divided into two main parts. First, we provide a general description of AIS data and  
<sup>142</sup> the process of identification of vessel-level fishing events done by Global Fishing Watch<sup>5</sup>. Alongside,  
<sup>143</sup> we describe the subset of data that we use for these analyses. When relevant, we also point out  
<sup>144</sup> possible shortcomings in the data, or factors that must be considered in the later analyses. We  
<sup>145</sup> then move on to explain our empirical strategy for the identification of the behavioral changes and  
<sup>146</sup> redistribution of fishing effort.

### <sup>147</sup> 3.1 Data

<sup>148</sup> Automatic Identification Systems are on-board devices intended to provide at-sea safety and prevent  
<sup>149</sup> ship collisions by broadcasting vessel position, course, and activities to surrounding vessels. These  
<sup>150</sup> broadcasted messages can be received by satellites and land-based antennas. GFW uses convolutional  
<sup>151</sup> neural networks to infer vessel characteristics and whether each broadcasted position represents  
<sup>152</sup> a fishing event, thus allowing us to estimate near real-time fishing events globally since 2012  
<sup>153</sup> (Kroodsma et al., 2018). Our data contain information for 2012 - 2017. The amount of data gathered  
<sup>154</sup> is dependent on the number of antennas and satellites that can pick up the signals. In June 1<sup>st</sup> 2014  
<sup>155</sup> satellite count increased from 3 to 6, and then to 10 in January 1<sup>st</sup> 2016. This causes an apparent  
<sup>156</sup> increase in the number of broadcasted AIS messages (*i.e.* points), and therefore number of vessels  
<sup>157</sup> and fishing hours. The variability in AIS data and ocean conditions require that temporal trends  
<sup>158</sup> be taken into account. We do that by including specific controls in our identification strategy and  
<sup>159</sup> using a subset of data that meet a BACI design -which gives us the full tracks for vessels affected  
<sup>160</sup> and unaffected by the implementation of PIPA.

<sup>161</sup> Our data contain over 45 million individual AIS messages (*i.e.* positions) for 371 fishing vessels that  
<sup>162</sup> at some point fished in PNA waters. A total of 233 vessels have fished within PIPA waters; 217  
<sup>163</sup> did so at least once before 2015. However, not all vessels continued to fish elsewhere after PIPA  
<sup>164</sup> implementation: 34 vessels have no recorded AIS messages after 2015, leaving us with 176 vessels  
<sup>165</sup> that fished inside PIPA before its implementation, and continued to fish elsewhere afterward<sup>6</sup>. From  
<sup>166</sup> these, we focus on purse seiners -the most important for PNA countries- and are left with 61 vessels<sup>7</sup>.  
<sup>167</sup> New vessels might have also entered the fishery after PIPA closure, and were likely not exposed to  
<sup>168</sup> the policy intervention in the pre-treatment period. To account for this, we identify a subset of  
<sup>169</sup> vessels which we track since before the implementation of PIPA, and categorize them as treated or  
<sup>170</sup> control vessels. Our treatment and control groups are defined as follows.

<sup>171</sup> The treatment group contains all purse seiners ( $n = 61$ ) that fished within PIPA at least once  
<sup>172</sup> before the announcement (09/01/2014), and that continued to fish elsewhere after the January 2015  
<sup>173</sup> implementation. Vessels in the control group meet the following two conditions: i) vessels never

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

<sup>6</sup>The 34 missing vessels might have exited the fishery, been decommissioned or sold (therefore changing their AIS and mmsi), or turned off their AIS transmitters. In either case, we are not able to observe these.

<sup>7</sup>We perform some of the same analyses for longliners and include them in the Appendix

174 fished within PIPA waters, and ii) vessels have fished in surrounding areas (*i.e.* PNA-countries' EEZ)  
 175 before and after PIPA closure. This definition of control vessels provides us with 26 purse seiners  
 176 that never fished inside PIPA but fished in other PNA waters before and after PIPA implementation.  
 177 During our causal identification, we also use two more strict definitions of control groups: one with  
 178 only vessels that belong to PNA countries ( $n = 7$ ), and one that excludes Chinese vessels ( $n = 21$ ).  
 179 Our definition of treatment and control groups leaves us with 61 and 21 treated and control vessels,  
 180 which have just over 22 million observations where about 22% are identified as fishing events. For  
 181 each of the remainig vessels, we calculate their total daily fishing hours and obtain pannel data with  
 182 37,800 observations. Table 1 shows the number of vessels following a BACI design, as well as the  
 183 fishing hours, before and after PIPA. Fig. 4 shows that mean fishing hours for purse seiners have an  
 184 abrupt increase, just before January 1st, 2015. This trend is observed for both treated and control  
 185 groups. Across all measures, the treatment and control vessels follow similar patterns, confirming  
 186 our claim that the control group provides a plausible counterfactual. Figure S1 provides a visual  
 187 representation of the vessel-level fishing events that make up each group through time.

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

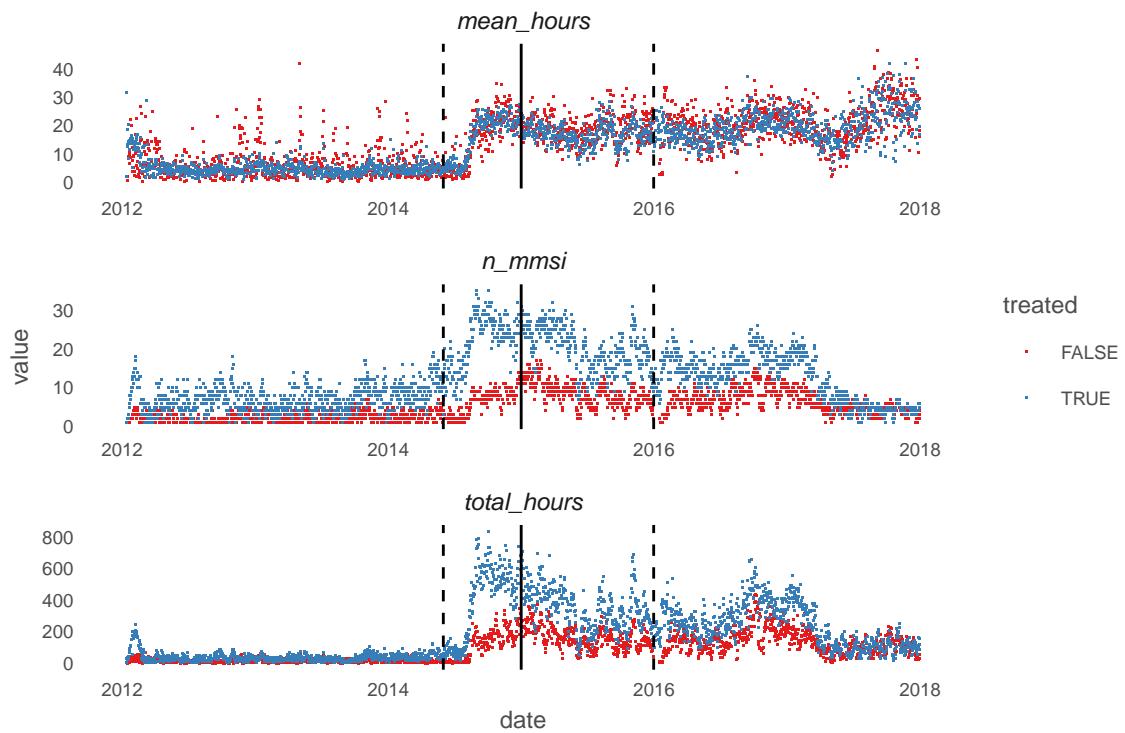


Figure 3: Fishing hours and number of vessels by month for all vessels. Vertical dashed lines indicates dates when satellites were added, solid line indicates PIPA closure.

188 **3.2 Analyses**

189 The first analysis focuses on identifying the response of fishing vessels to PIPA closure. Our variables  
 190 of interests are daily fishing hours, and daily distance traveled (Km). We compare our variable of  
 191 interest before and after the implementation of PIPA using a Difference-in-Differences approach,  
 192 where we track the variable of interest for vessels that used to fish inside PIPA and vessels that  
 193 never fished inside PIPA, before and after PIPA implementation. Our specification is the following:

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

194 Where  $y_{i,t}$  is the variable of interest for vessel  $i$  in time period  $t$ . A dummy variable  $Post_t$  takes the  
 195 value of 0 for all dates prior to PIPA implementation and a value of 1 for all dates including and  
 196 following PIPA implementation.  $Treat_i$  is a dummy variable indicating whether a vessel belongs to  
 197 the control ( $Treat_i = 0$ ) or treatment ( $Treat_i = 1$ ) group.  $\alpha$  is the standard intercept,  $\beta_1$  captures  
 198 the temporal trend change,  $\beta_2$  captures the difference between treated and control groups, and  $\beta_3$   
 199 is our parameter of interest: de DiD estimate capturing the treatment effect. Finally,  $\phi_t$  and  $\gamma_i$   
 200 represent month-, and flag-level dummies that account for seasonality or country-level management  
 201 interventions, and  $\theta_i$  are a set of dummies that account for the addition of more satellites<sup>8</sup>.

202 Our second part of the analyses focuses on the redistribution of fishing effort. In other words,  
 203 identifying where do vessels that used to fish inside PIPA go after its establishment. We discretize  
 204 spatial units by using a polygon for PIPA<sup>9</sup> and distinct spatial units for each EEZ of each country.  
 205 Some vessels might shift from EEZs into the high seas, but we are interested in knowing *where*  
 206 in the high seas, so we incorporate additional regions by using a 1 degree buffer of the high seas  
 207 around each of the EEZ regions. The rest of the high seas are merged into a single spatial unit. For  
 208 example, if we were to do this only for Kiribati, we would have 8 spatial units: PIPA, three EEZs,  
 209 three 1-degree buffers of high seas around each EEZs, and the rest of the high seas. Whenever the  
 210 buffers overlapped between themselves, we randomly clipped one on to the other. EEZs that had  
 211 sporadic fishing events were pooled into a group of “others”.

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

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

215 Our variable of interest,  $y_{i,t}$  represents the proportion of fishing hours that country  $i$  receives at time  
 216  $t$ .  $Post$  also represents a policy dummy that takes the value of 0 for all dates before implementation  
 217 of PIPA, and 1 otherwise.  $Country$  is a dummy variable for countries for the spatial units defined  
 218 above. Our parameter of interest is  $\beta_{1,i}$ , which captures the country-level change in proportional  
 219 fishing effort.  $\theta_i$  accounts for the addition of satellites.

220 All regression coefficients were estimated via ordinary least squares, and heteroskedastic-robust  
 221 standard errors were calculated. All analyses were performed in R version 3.5.1 (R Core Team,  
 222 2018). Raw data and code used in this work are available on github.

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<sup>8</sup>We test for other more complex specifications that interact a quarterly or year-month variable with the treatment group and find qualitatively the same results.

<sup>9</sup>we 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

223 4 Results

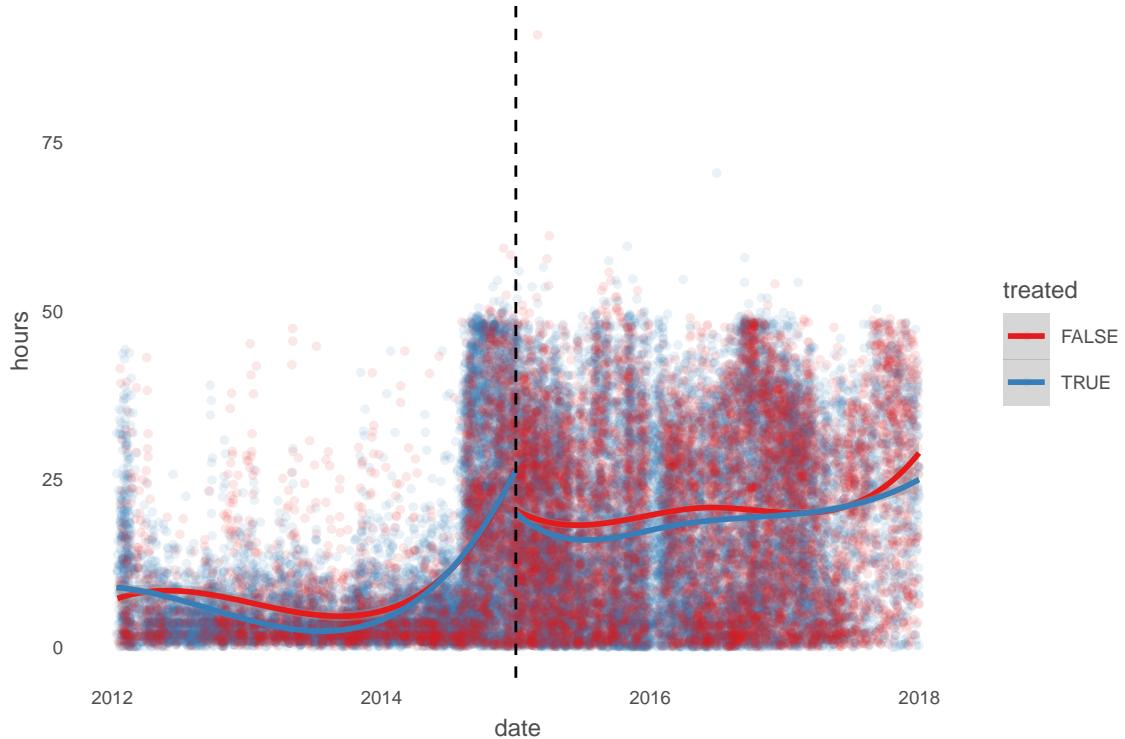


Figure 4: Fishing hours and number of vessels by month for all vessels. Vertical dashed line indicates PIPA closure.

- 224 Our DiD analysis shows that treated purse seiners reduce their fishing effort after PIPA implement-  
 225 ation in the order of 16 hours per month. This result is robust and significant ( $p < 0.05$ ) for  
 226 all model specifications, with the effect varying between  $\beta_3 = -16.457$  and  $\beta_3 = -18.709$ . Model  
 227 specifications that include the year polynomial show lower values for the  $\beta_1$  coefficient associated  
 228 to the  $Post_t$  policy dummy, and show positive and negative values for  $\mu_1$  and  $\mu_2$ , the linear and  
 229 quadratic terms for  $Y_t$ , respectively. These effectively represent the patterns observed in Figure 4.  
 230 Regressions coefficients for each gear type are shown in Tables ?? and S1. Column (1) presents the  
 231 DiD regression with no fixed effects, column (2) includes month fixed effects, column (3) includes  
 232 month and the second degree polynomial for years, and column (4) includes all of the above and  
 233 country-level fixed effects.

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 Taiwanese vessels as controls, and columns 7 - 9 exclude Chinese vessels. Numbers in parentheses are heteroskedastic-robust standard errors.

	Dependent variable: hours								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
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)
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)
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)
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)
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)
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)
Control	All	All	All	PNA	PNA	PNA	-CHN	-CHN	-CHN
Month FE	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Flag FE	No	No	Yes	No	No	Yes	No	No	Yes
Observations	37,840	37,840	30,359	30,583	30,583	25,034	36,415	36,415	28,934
R <sup>2</sup>	0.171	0.200	0.208	0.178	0.208	0.215	0.173	0.203	0.211

Note:

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

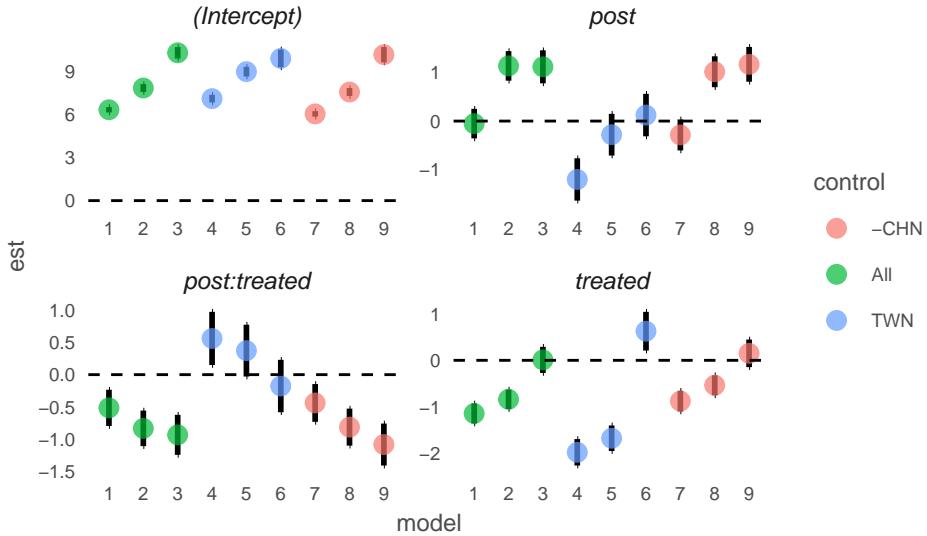


Figure 5: Coefficient estimates for each model. Top pannel indicates variable, x-axis represents model specification, and y-axis coefficient estimate.

234 Recall that to evaluate the redistribution of fishing effort we only track fishing vessels that belong to  
 235 the treated group. In this case, we calculate the proportion of fishing effort allocated every month to  
 236 each spatially explicit region outlined by EEZs and the high seas. For purse seiners, these represent  
 237 9 main EEZs, PIPA, the high seas, and a group of other EEZs. Figure 6 shows the monthly relative  
 238 fishing hours that each region received by all 176 treated vessels. The top-left panel shows the  
 239 change in fishing effort inside PIPA, including the preemptive fishing and immediate reduction  
 240 previously reported (McDermott et al., 2018).

241 The change in the relative allocation of fishing effort by purse seiners increases in eight of the 12  
 242 regions after PIPA implementation (Table ??). The largest increase is observed for the I-Kiribati  
 243 EEZ, with an average increase of 0.11 ( $p < 0.001$ ). In other words, the redistribution of treated  
 244 vessels caused a 10% increase in the *relative* allocation of fishing effort within I-Kiribati waters.  
 245 The only decrease is observed for Papua New Guinea, but the coefficient is not significant. Figure 7  
 246 provides a spatial representation of these changes. It is evident that the increase in relative fishing  
 247 effort is greater for regions closer to PIPA.

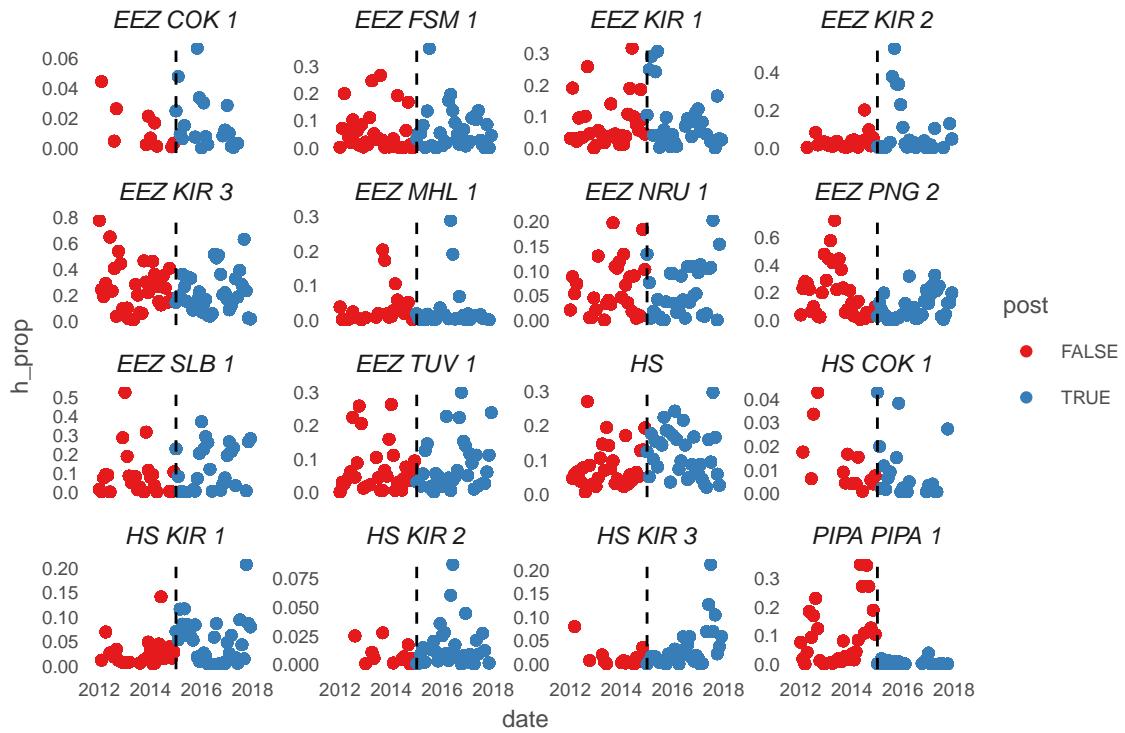


Figure 6: Monthly relative allocation of fishing effort by PIPA-fishing vessels before and after PIPA for 9 EEZs, PIPA, the high seas and ‘other EEZs’.

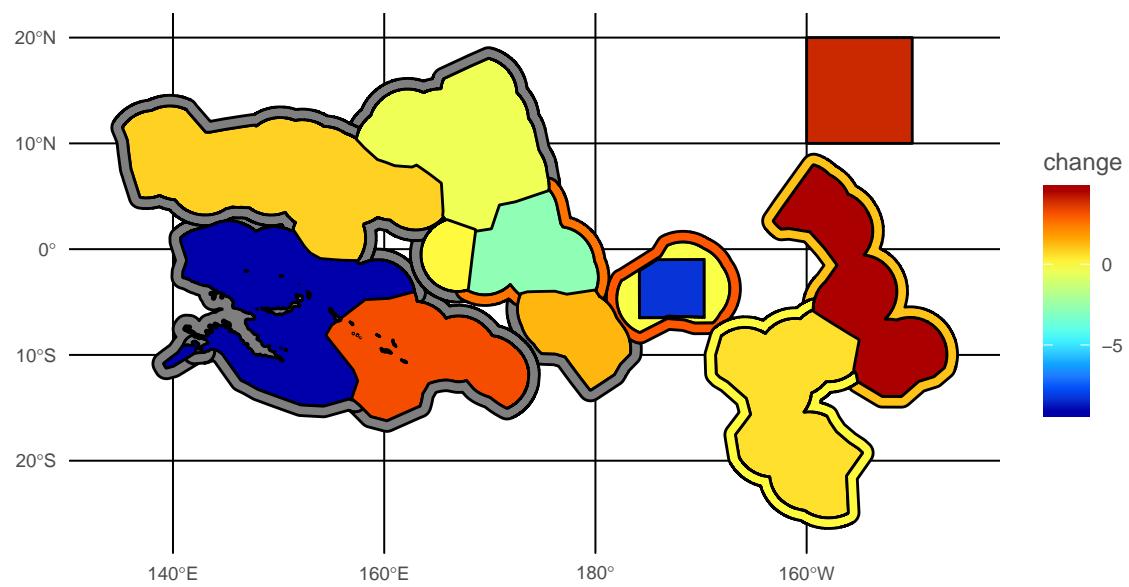


Figure 7: Spatial representation of the mean change in the monthly allocation of fishing effort for purse seiners.

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)***

248 5 Discussion

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

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

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

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

<sup>293</sup> longline fleet, and suggest that the fleet may be under-utilizing the ocean, meaning that they can  
<sup>294</sup> easily redistribute elsewhere.

<sup>295</sup> Our work suggests that the implementation of LSMPAs can have important implications for purse  
<sup>296</sup> seiners, and less so for longliners. We also show that fishing effort is redistributed to areas close  
<sup>297</sup> by. Future management interventions that aim to close large portion of the oceans should consider  
<sup>298</sup> how fishing effort will change in space and through time, and the ecological implications of this  
<sup>299</sup> redistribution to ensure that fishing effort is not just displaced elsewhere, leading to overfishing in  
<sup>300</sup> adjacent waters.

301 6 Appendix

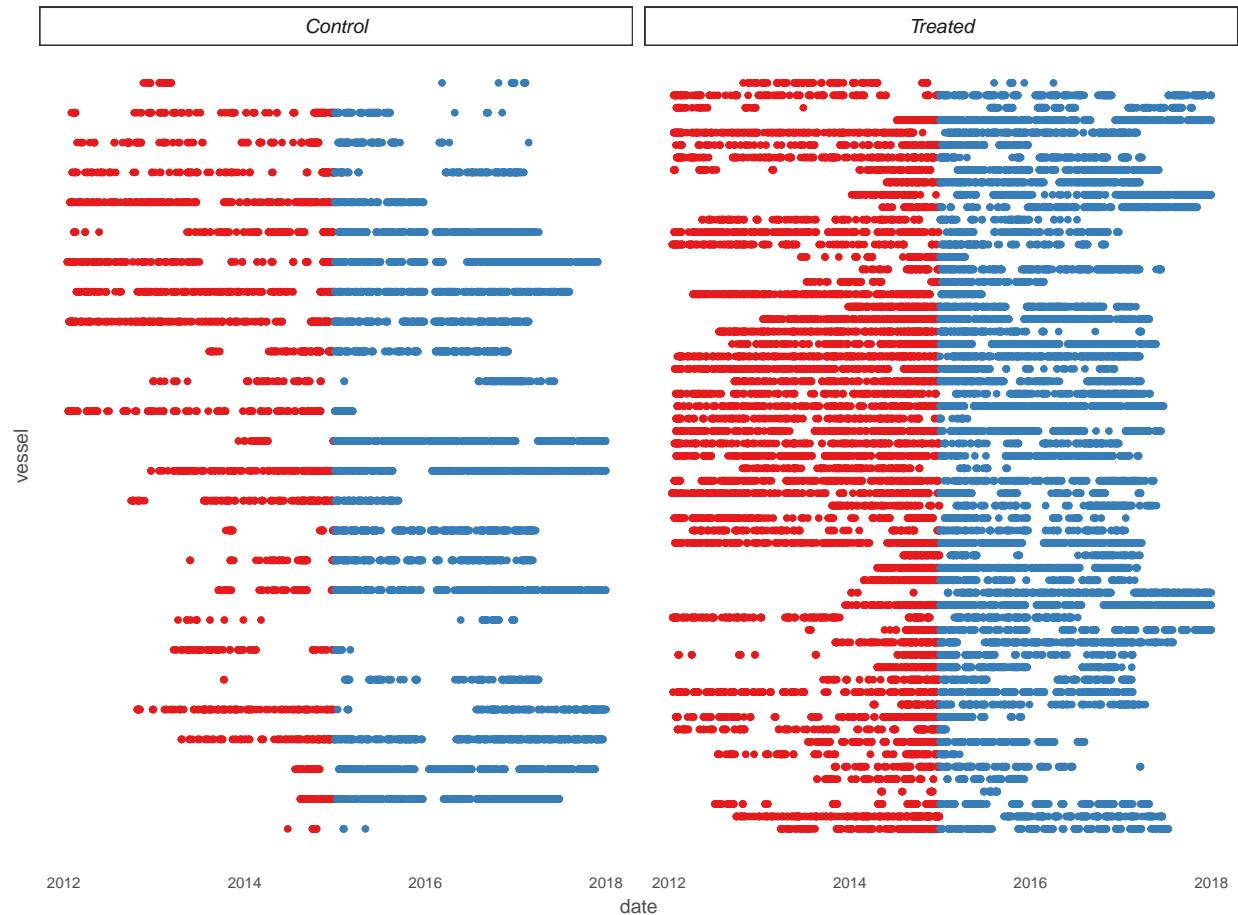


Figure S1: Stream of fishing events by vessels through time. Each line represents a vessel, with dots indicating months with fishing activity and colors indicating the pre and post periods.

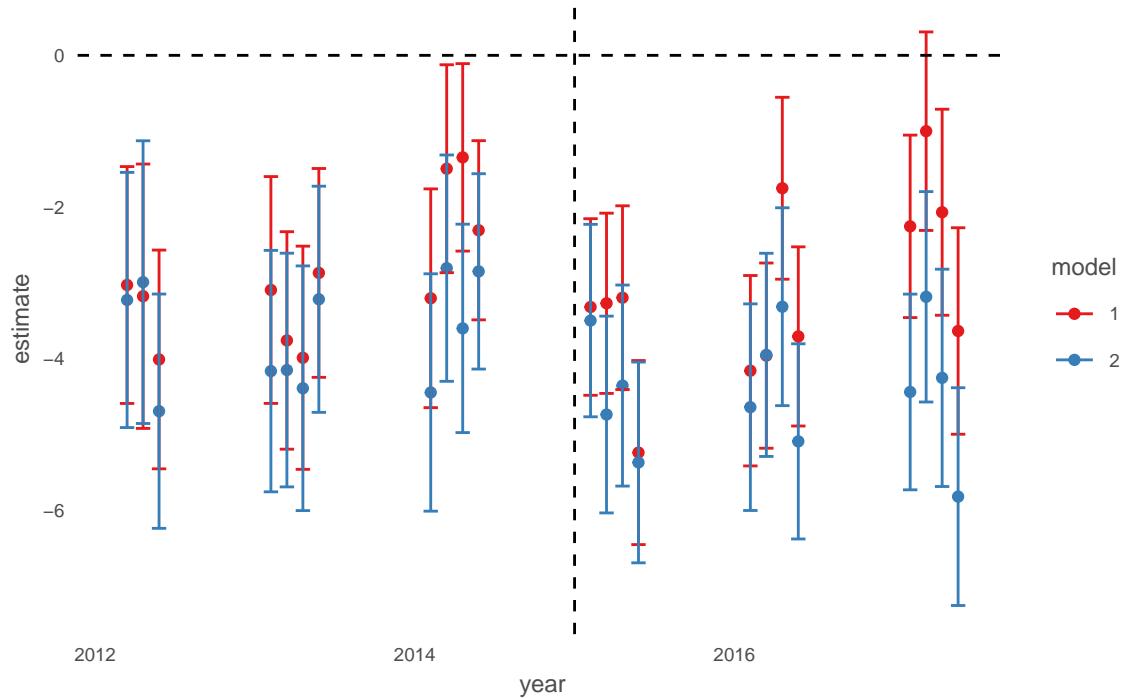
Table S1: Fishing hours from GFW for longliners ( $n = 203$ ; 88 control, 115 treatment). Asterisks indicate significance levels. Numbers in parenthesis represent heteroskedastic-robust standard errors.

	<i>Dependent variable:</i>			
	hours			
	(1)	(2)	(3)	(4)
post	-1.241*** (0.116)	-1.026*** (0.116)	-0.944*** (0.157)	13.292*** (0.330)
treated	2.595*** (0.101)	2.708*** (0.101)	2.639*** (0.102)	1.493*** (0.116)
post:treated	0.053 (0.133)	-0.069 (0.133)	-0.029 (0.134)	-0.060 (0.135)
Constant	39.032*** (0.089)	38.105*** (0.131)	38.388*** (0.150)	36.993*** (0.178)
Month FE	No	Yes	Yes	Yes
Year FE	No	No	Yes	Yes
Flag FE	No	No	No	Yes
Observations	227,873	227,873	227,873	227,873
R <sup>2</sup>	0.010	0.015	0.016	0.030

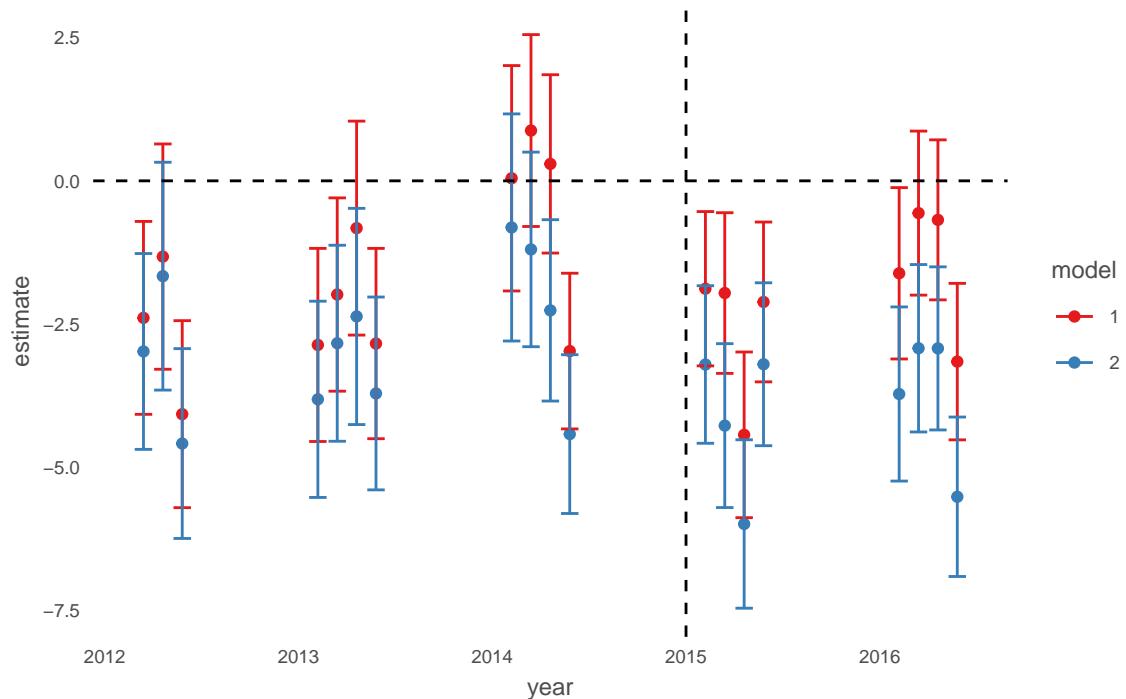
*Note:*

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

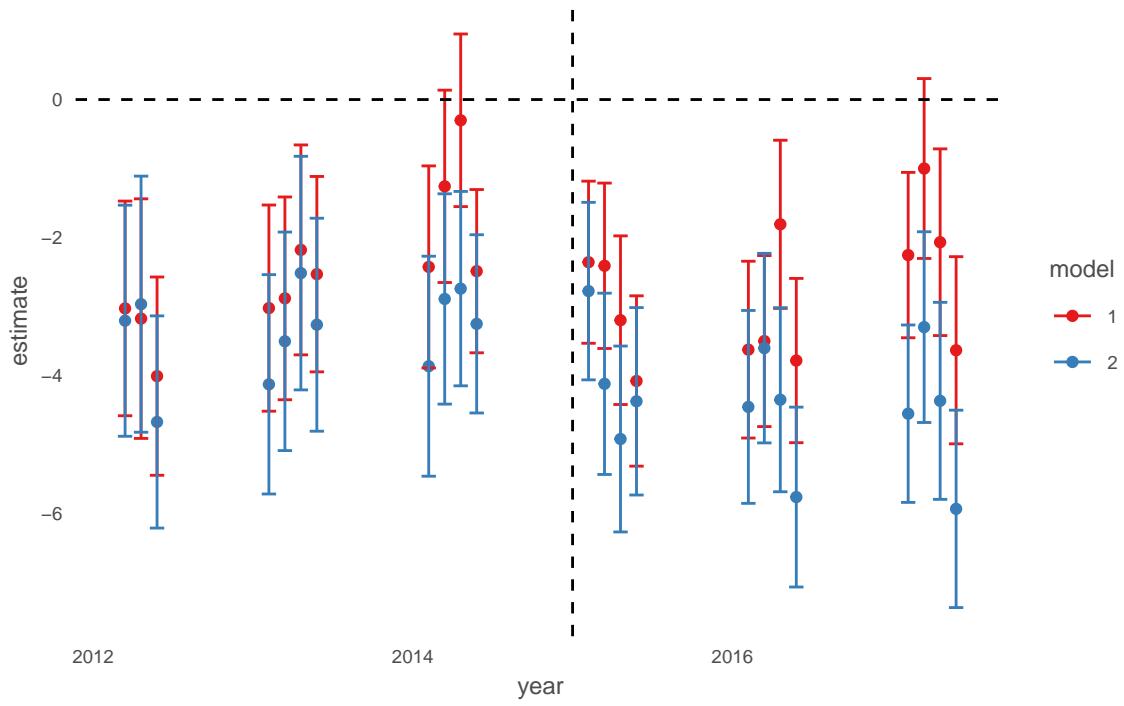
302 6.1 Other model specifications



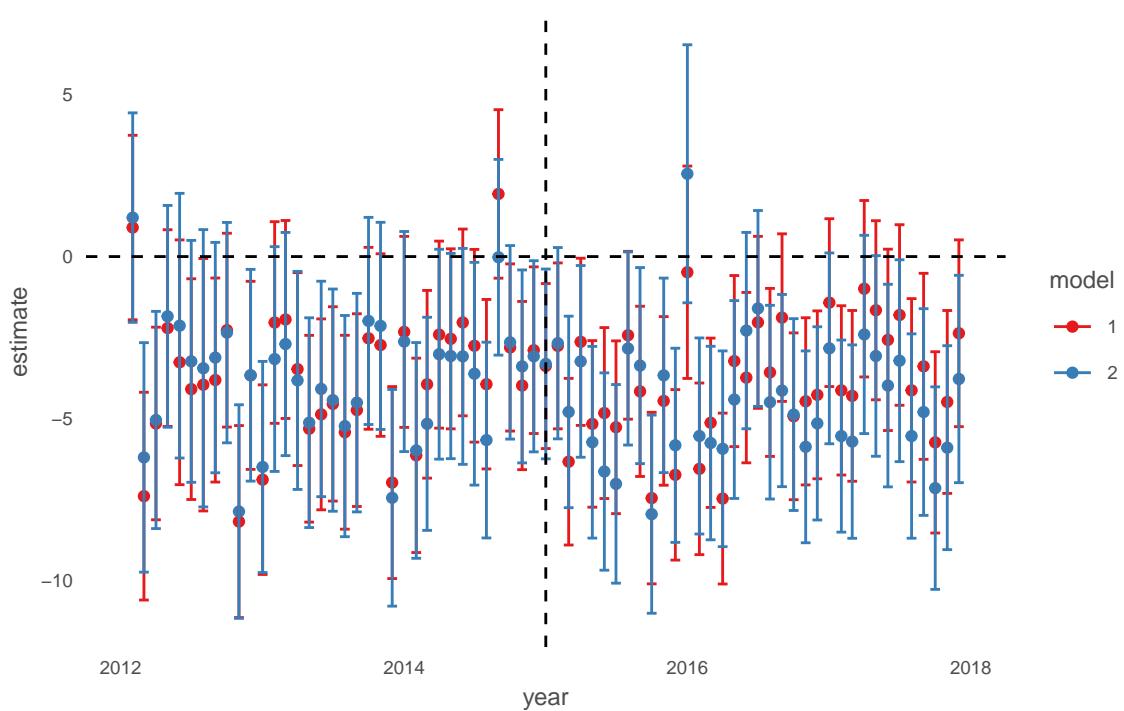
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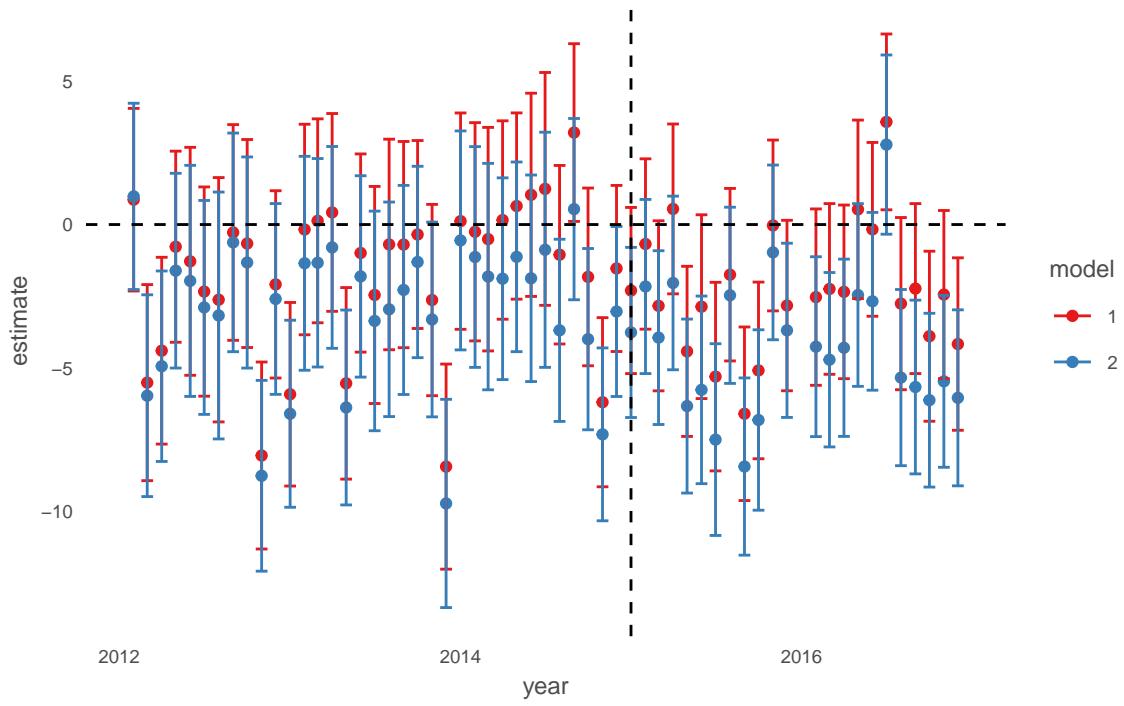
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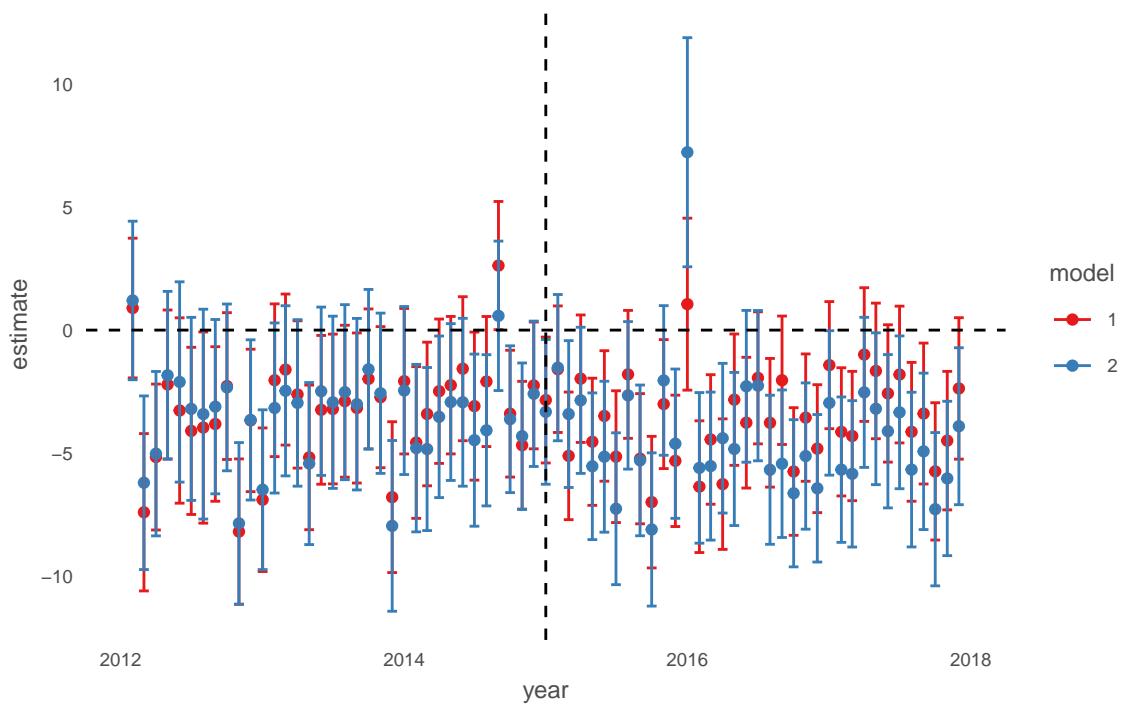
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