Large Scale Marine Protected Areas

Juan CarlosVillaseñor-Derbez* John Lynham†
juancarlos@ucsb.edu lynham@hawaii.edu

Updated on: January 20, 2019

Abstract

Large-scale Marine Protected Areas (LSMPAs) have seen a significant increase over the last years. Fishing effort is effectively eliminated within these protected areas upon implementation. The benefits of reducing effort have been largely studied, but little empirical works evaluate how vessels react and redistribute after an MPA is created. The economic and ecological implications of displacing fishing effort are not yet fully understood. We use identification of fishing activity via Automatic Identification Systems (AIS) and causal inference techniques to provide the first analysis of behavioral changes and spatial redistribution of tuna purse seiners due to the implementation of a Large Scale Marine Protected Area in the Pacific Ocean. Our work provides three main findings: 1) aggregate fishing effort remains relatively unaffected; 2) vessels that fished inside the protected area redistribute to adjacent waters; and 3) we observe a crowding effect for the first months after implementation. Our results not only provide an impact evaluation of the effect of LSMPAs on fishing activity, but provide insights into vessel redistribution dynamics, which may have ecological and economic implications for marine conservation and fisheries management. As countries continue to implement LSMPAs as a way to reach the stated 10% target of ocean protection, managers should consider how fishing effort will change in space and through time to ensure that fishing effort is not just displaced elsewhere, leading to overfishing in adjacent waters. While LSMPAs can provide a wide range of benefits, their implementation must be accompained with traditional fisheries management to maximize their effectiveness.

We do not observe an increase in daily fishing hours for vessels that used to fish within PIPA, compared to a control group of vessels. Thus, for vessels that have chosen to continue to operate following the closure, we do not observe evidence that they are being forced to exert more effort as a result of the closure. Unfortunately, without detailed data on vessel catch, we cannot conclude whether vessels are better or worse off financially following the closure.

Our results suggest that PIPA has displaced some vessels to the high seas just outside the EEZ of Kiribati. This might imply a drop in demand for Kiribati fishing rights and a decline in revenue. We also uncover evidence that there is more congestion immediately following the closure, but this is declining over time.

*Bren School of Environmental Science & Management, University of California at Santa Barbara, Santa Barbara, CA

†Department of Economics, University of Hawaii at Manoa, Honolulu, HI

Next steps: I think we need to make the buffers around the EEZs 5 degrees instead of 1 degree (redistribution of effort section) Might change the specification of the redistribution regression

1 Introduction

Marine Protected Areas (MPAs) are intended to safeguard parts of the ocean from fishing and other extractive activities. Current international goals aim to protect 10% of the ocean environment by 2020. In an effort to meet this target, there has been a rapid increase recently in MPA coverage (Wood et al., 2008; Sala et al., 2018), largely driven by a small number of Large Scale Marine Protected Areas (LSMPAs).[1]). Today, a small number of LSMPAs make up at least 80% of the managed areas in the ocean (Toonen et al., 2013).

Given the relatively recent establishment of most LSMPAs, very little is known about their human dimensions and implication for fisheries (Gray et al., 2017). As with smaller MPAs, it is important that we understand the socioeconomic implications of management interventions. One issue of particular importance is that of the displacement or redistribution of fishing effort, which may influence the outcomes of an MPA (Smith and Wilen, 2003). Theoretical models make different assumptions about the ways in which fishers will reallocate fishing effort after an area closure, which often determine whether or not MPAs produce negative or positive impacts on fisheries. The existing empirical literature focuses on small MPAs and has been criticized for confounding correlation with causation (**?**).

Recent advances in satellite tracking technologies and near real-time identification of fishing activity provide us with an opportunity to ask, how do fishers respond to the implementation of an LSMPA? Does effort increase or decrease and where does it go? We use identification of fishing activity via Automatic Identification Systems (AIS) and causal inference techniques to describe the behavioral changes and spatial redistribution of the industrial tuna purse seine fleet due to the implementation of the Phoenix Islands Protected Area. We use the same data to hypothesize what might be the impacts of the proposed Palau National Marine Sanctuary.

Our work is novel in the sense that it provides empirical evidence of the effect of Large Scale Marine Protected Areas on fishing behavior and distribution and can help guide future interventions. Understanding how effort is displaced from LSMPAs might provide insights into how distant water fishing fleets would react to a high seas closure.

The paper is organized as follows: Section 2 provides more information on Large Scale Marine Protected Areas and some background on empirical studies of effort redistribution. An overview of the Nauru Agreement and associated countries, a description of the fleet that operates in the region, and a brief history of PIPA and PNMS is also included. Section 3 describes our data and identification strategy. Section 4 presents our results, and Section 7 discusses our results.

[1] See, for example, Game et al. (2009), Singleton and Roberts (2014),Boonzaier and Pauly (2016), McCauley et al. (2016), and Alger and Dauvergne (2017).

2 Background

2.1 Large Scale Marine Protected Areas

The cutoff at which an MPA is considered to be a LSMPA ranges from areas larger than 30,000 km^2 as defined by De Santo (2013) or areas larger than 250,000 km^2, as defined by (Toonen et al., 2013). Figure 1 shows LSMPAs that meet the latter condition, and are also fully no-take. LSMPAs are often implemented in the pelagic environment, where the dominant human activity is industrial fishing (Gray et al., 2017; Kroodsma et al., 2018). The early literature on LSMPAs focused on the inherent challenges and difficulties that come with a pelagic environment. Kaplan et al. (2010) claimed that very large MPAs would result in excessive opportunity costs and that these would be difficult to enforce. Game et al. (2009) suggested that most of the challenges could be overcome with the incorporation of technology, in what then became known as Dynamic Ocean Management (Maxwell et al., 2015).[2]

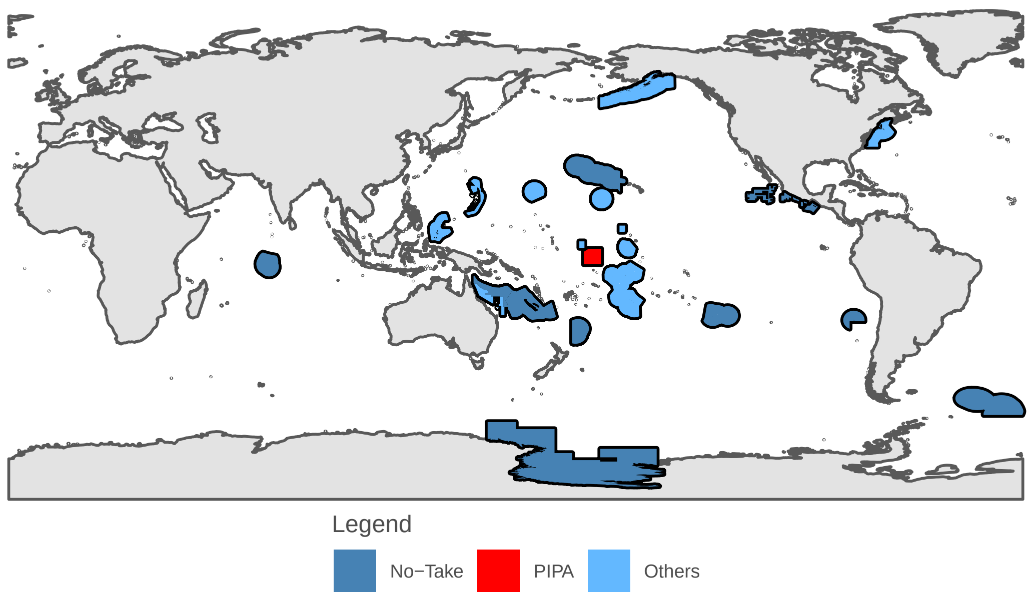

Figure 1: Large Scale Marine Protected Areas. The map shows all areas larger than 250,000 Km^2. Areas in dark blue meet at least one of these conditions: reported no take area is greater than 0, are categorized as IUCN Ia or Ib, their designated English name is 'Protected Area'.

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

[2]See Singleton and Roberts (2014), who provide an objective discussion of the pros and cons 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 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 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 few years (Stevenson et al., 2013).

The empirical research that has been done in smaller sized MPAs suggests 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) analyze 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 for its outcome (Smith and Wilen, 2003; Hilborn et al., 2006), highlighting the need to understand how fishers react to the implementation of LSMPAs, how fishing effort changes, and how it is spatially redistributed. 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 option of moving to the high seas or other countries' EEZs.

2.2 Nauru agreement and the Phoenix Islands Protected Area

The Nauru Agreement was established in 1982 by a select group of Pacific island nations to manage their important tuna resources more effectively. Parties to the Nauru Agreement (PNA) Members include the Federated States of Micronesia, Kiribati, the Marshall Islands, Nauru, Palau, Papua New Guinea, the 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 greater bargaining power when providing fishing access to foreign fleets (Havice, 2010).

The cooperation that emerged under the Nauru Agreement 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[3]. 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 fishing hours. The VDS works as follows: Each year, scientific advisers recommend

[3] See Havice (2010) for a detailed description of the Nauru, Palau, and Federal States of Micronesia agreements.

a total number of fishing vessel-days per year. Hours are allocated to each PNA country based on catch history, and they then use or sell fishing rights to other non-PNA countries (Aqorau et al., 2018). While the effectiveness of this scheme has been debated in terms of meeting their fishery management and conservation objectives, the licensing significantly contributes to the economy of these island nations (Havice, 2010).

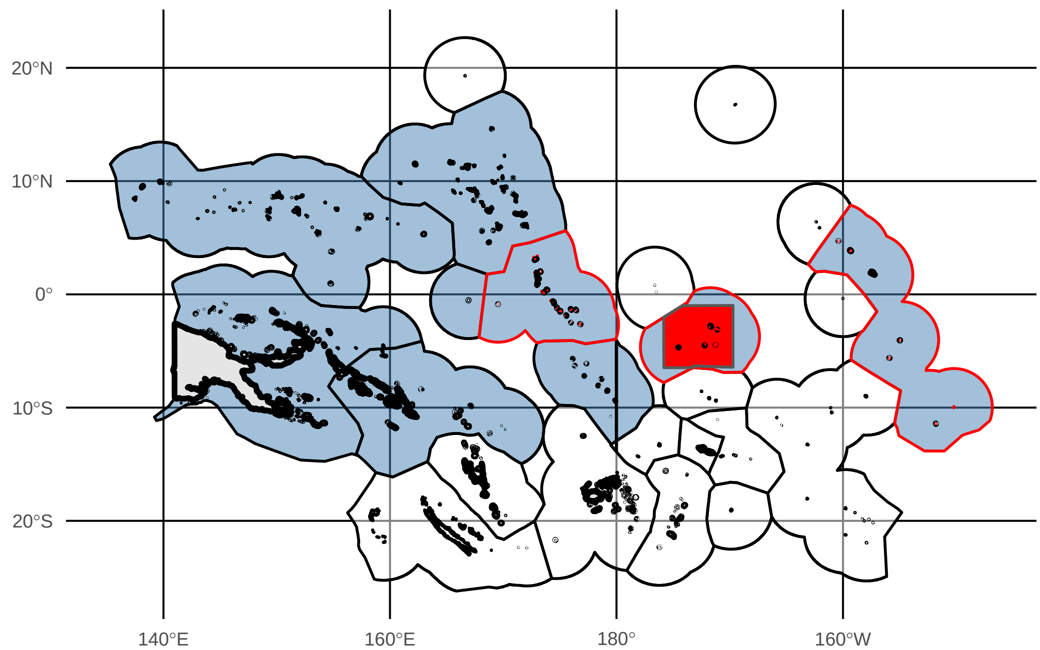

Figure 2: Map of the Exclusive Economic Zones (EEZs) of the region of interest. Countries that belong to the PNA are shown in blue, while empty polygons indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

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

One of the most notable and recent management interventions in the region is the implementation of the Phoenix Islands Protected Area (PIPA) by the government of Kiribati. PIPA was first declared in 2006, and established in 2008 with only 4% of the area declared as no-take. On January 1st, 2015, the no-take area within PIPA was expanded to a total area of 397,447 km^2, roughly 1.5 times the size of Ecuador. Figure 2 shows a map of the PNA countries and the Phoenix Islands Protected Area.

The closure of such a large area in one of the most important fishing regions in the world provides a unique opportunity to evaluate the behavioral responses and redistribution of fishing effort by vessels that used to fish there. PIPA has been the focus of previous research showing that fishing effort is effectively reduced after implementation (McCauley et al., 2016; McDermott et al., 2018). To this, we pose two questions: How did individual vessels respond to the sudden exclusion of such a big area? Where did all the vessels go? And what does this imply for revenues from selling VDS for both Kiribati and the PNA as a whole?

A spatial closure might cause fishers to modify their behavior as they adapt to a new state of the world. For example, some may have to travel further distances to find new fishing grounds, increasing their fuel costs. If fishers had developed experience for fishing in particular sites, being excluded might impose a learning cost on them, as they identify new fishing grounds. This might result in increased search times. However, if the area of knowledge of a vessel is significantly larger than that of the spatial closure, they might already know other places to fish. In the next sections we describe the data and methods used to answer these questions.

3 Methods

This section is divided into two main parts. First, we provide a general description of AIS data and the process of identification of vessel-level fishing events performed by Global Fishing Watch.[4] Alongside, we describe the subset of data used in our analysis. We also point out possible shortcomings in the data, or factors that must be considered in the analysis. We then move on to explain our empirical strategy for the identification of behavioral changes and the redistribution of fishing effort.

3.1 Data

Automatic Identification Systems (AIS) are on-board devices that provide at-sea safety and prevent ship collisions by broadcasting vessel position, course, and activity to surrounding vessels. These broadcast messages can be received by satellites and land-based antennas. GFW then uses machine learning techniques (convolutional neural networks) on the broadcast messages to infer what type of fishing is taking place and where it is taking place, thus allowing the estimation of near real-time fishing events globally (Kroodsma et al., 2018).

The amount of data gathered by GFW is dependent on the number of antennas and satellites that can receive signals. The total satellite count increased from 3 to 6 on June 1st 2014 , and then from 6 to 10 on January 1st 2016. This causes an increase in the number of *received* AIS messages (*i.e.* points), and therefore an apparent increase in the number of vessels and fishing hours. However, the addition of new satellites affects all vessels in the same way.

Our analysis focuses on purse seine vessels, the most important fishery for PNA countries.[5] We identify a total of 103 purse seiners that fished in PNA waters at least once before 2015[6]. These vessels represent over 26 million individual observations for the 2012 - 2017 period. We identify 65 vessels that have fished inside PIPA at least once since 2012. From these, 62 did so before the announcement (*i.e.* 09/01/2014 *sensu* (McDermott et al., 2018)) but we are only able to track

[4]Global Fishing Watch: globalfishingwatch.org

[5]We perform some of the same analyses for longliners and include them in the Appendix

[6]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.

61 for the complete period of study before and after its implementation.[7] On the other hand, 38 vessels never fished inside PIPA but we only have data for 26 of these vessels both before and after MPA implementation.

Therefore, our treatment group contains all purse seiners (n = 61) that fished within PIPA at least once before the announcement, and that continued to fish elsewhere after the January 2015 implementation. Vessels in the control group meet the following two conditions: i) never fished within PIPA waters from 2012-2015, and ii) vessels have fished in surrounding areas (*i.e.* PNA-countries' EEZ) before and after PIPA closure (n = 26).

We include three additional control groups as a robustness check. The first group contains only vessels that belong to PNA countries (n = 7). The second group excludes Chinese vessels (n = 21). Our third control is made up of Japanese purse seiners that fish in the Pacific but have never fished inside PIPA (n = 27).[8] Our main definition of treatment and control groups leaves us with 61 treated and 26 control vessels, which have just over 22 million observations with about 22% of these observations identified as fishing events by the neural network classification.

For each vessel, we calculate total daily fishing hours and build a daily panel with 37,800 observations. Table 1 shows the number of vessels following a Before-After-Control-Impact (BACI) design, as well as the fishing hours, before and after PIPA. Fig. S2 shows that mean fishing hours for purse seiners have an abrupt increase, just before January 1st, 2015. This trend is observed for both treated and control groups. Across all measures, the treatment and control vessels follow similar patterns, confirming our claim that the control group provides a plausible counterfactual. Figure S1 in the Appendix provides a visual representation of the vessel-level fishing events that make up each group through time. We use this panel data to answer our key research questions: Are the 61 purse seiners that used to fish within PIPA affected by the closure? If so, how? What are they doing differently and where are they going that they didn't go to before? The following section describes our empirical identification strategy.

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	1.71
Treatment	61	10.67	18.36	1.72

3.2 Analyses

Our first analysis focuses on identifying the response of vessels to the PIPA closure. We use daily fishing hours, daily proportion of fishing vs. non-fishing hours, daily distance traveled (km), distance from shore (km) and distance from home port(km) as our main outcomes of interest. We compare these outcomes before and after the implementation of PIPA using a Difference-in-Differences approach. Our main specification is the following:

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

[7] 1 vessel never fished again after August 18, 2013.

[8] We also considered a control group of Taiwanese flagged vessels but there are only 4 vessels with pre-2015 data.

where $y_{i,t}$ is the outcome of interest for vessel i on day t. A dummy variable $Post_t$ takes the value of 0 for all dates prior to PIPA implementation and a value of 1 for all dates following PIPA implementation. $Treat_i$ is a dummy variable indicating whether a vessel belongs to the treatment ($Treat_i = 1$) or control ($Treat_i = 0$) group. α is the standard intercept term, β_1 captures the temporal trend, β_2 captures the initial difference between treated and control groups, and β_3 is our parameter of interest: the Difference-in-Differences estimate capturing the treatment effect. Finally, ϕ_t and γ_i represent month and flag dummies that account for seasonality or country-level management interventions. θ_t are time dummies to account for the addition of more satellites over time.[9]

Our second part of the analysis focuses on the redistribution of fishing effort. The role of institutions may play an important role. As stated before, LSMPAs often span the entirety of an EEZ. In the case of purse seining in the PNA, vessels purchase access to the fishery at the beginning of the season (QUESTION FOR JC: WHEN IS THIS? And wasn't the closure expected?). If a vessel decides to fish within the PNA, they've already made the decision to pay for access, expecting higher returns from fishing there than in the high seas. In the particular case of PIPA, one would expect that a vessel previously holding a permit to fish in Kiribati waters would most likely continue to purchase access to PNA waters (either in Kiribati's remaining open areas or a nearby EEZ). Alternatively, if a vessel fishes illegally in Kiribati waters before the implementation, one would expect them to reallocate to other regions with equal or less enforcement. In this case, they might then choose to move to other Kiribati waters, waters of countries that have similar enforcement levels, or to the high seas.

We discretize spatial units by creating a polygon for PIPA and distinct spatial units for each geographically separate EEZ of each country. Some vessels might shift from EEZs into the high seas, but we are interested in knowing *where* in the high seas, so we incorporate additional regions by using a 1 degree buffer of the high seas around each of the EEZ regions. The rest of the high seas are merged into a single spatial unit. For example, if we were to do this only for Kiribati, we would have 8 spatial units: PIPA, three EEZ units, three 1-degree buffers of high seas around each EEZ, and the rest of the high seas. Whenever the buffer units overlap, we randomly clip one on to the other (QUESTION FOR JC: WHAT DOES THIS MEAN?).

We then take these spatial polygons and rasterize them to a 1-degree grid (see Figure S11 in the Appendix), which we then use to rasterize points of fishing activity. For each cell, we calculate the total monthly fishing hours by treated and control vessels (see Figure 5). Since we are interested in the redistribution of fishing effort, we use this gridded data to calculate the proportion of fishing hours that each region receives each month relative to the total fishing hours observed across all regions and all cells in that month.

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

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

Our variable of interest, $y_{i,t}$ represents the proportion of fishing hours that region i receives at time t. Years are modeled as factors ($Year_t$), using 2012 as the reference level. *Region* is a dummy variable for regions defined above. Our parameter (QUESTION FOR JC: VECTOR?) of interest is

[9] 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.

$\beta_{3,i}$, which captures the yearly by-country change in proportional allocation of fishing effort relative to 2012.

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

4 Results

Regression coefficients for our DiD analysis are shown in Table 2. Columns 1 -3 use our primary control group. 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 don't include flag fixed-effects to avoid perfect collinearity between the Japanese flag and control group status. Our DiD analysis shows an overall increase in purse seine fishing hours, even after accounting for the introduction of new satellites (Table 2).[10] This *post* coefficient estimate is consistent across different model specifications and across controls, and effectively represents the patterns observed in Figure S2.

The β_3 coefficient indicating our treatment effect suggests that, relative to the control, treated vessels fish less: to the order of 0.5-3.7 hours per day. In 6 out of 11 specifications, there is a statistically significant decrease in daily fishing hours. Another way to interpret this is that the increase in fishing effort by treated vessels has occurred at a lower rate than control vessels. These values are equivalent to a reduction of 15 - 111 fishing hours per month. However, this result is only robust and significant ($p < 0.01$) in the simplest specification of the Diff-in-Diff. When reducing the linear structure of the $Pre \times Post$ design and instead interacting the treatment dummy with quarterly or year-month combinations, we are not able to reject the null hypothesis of no change, suggesting that the total fishing hours remains similar for the displaced vessels (Figs. S3-S10). Since vessels don't seem to be fishing a lot less, an obvious question arises: where are they fishing now?

Figure 5 provides a spatial representation of these changes. Note that the 2013 effort distribution is roughly similar across vessels. Then, in 2014, there is a sharp increase in fishing hours by treated vessels inside PIPA (the so-called Blue Paradox). In 2015, treated vessels then allocate more effort to the easternmost Kiribati EEZ and the high seas. In 2016, the spatial distribution of fishing effort is again similar across groups. It is evident that the increase in relative fishing effort is greater for regions closer to PIPA.

Along a similar line, Figure 6 shows a detailed temporal evolution of the relative allocation of fishing effort.[11] It shows the change in fishing effort inside PIPA, including the preemptive fishing and immediate reduction previously reported (McDermott et al., 2018). Kiribati waters in KIR 1 and KIR 2 show an increase in fishing effort for 2015; the same pattern is observed for their respective High Seas buffers, and the general High Seas. Other regions farther away from PIPA don't show a clear pattern under visual inspection. This suggests fishing effort inside PIPA has moved to the high seas around Kiribati instead of paying to fish within alternative Kiribati EEZ waters.

We then move on to our regression results, presented as a figure showing the year-region interaction coefficient estimates for each region as a stream of changes through time (Figure 7 and Table 3). As noted before, the marginal change in the relative allocation of fishing effort relative to 2012 increases in 2014 for PIPA. Most coefficients are not statistically significant, but follow the same trends previously discussed, with a tendency for regions closer to PIPA to show an increase in the relative allocation of fishing effort in the post-implementation period. The largest increase is observed for the Kiribati EEZ 2, where the redistribution of treated vessels caused a 15% increase in the *relative* allocation of fishing effort within Kiribati waters. This displacement is likely causing

[10]Results of the same analysis is shown for longliners in Table S1

[11]Recall that to evaluate the redistribution of fishing effort we only track fishing vessels that belong to the treated group.

a crowding effect after PIPA-fishing vessels redistribute to other areas.

We use the rasterized effort to evaluate if the PIPA closure increased crowding outside the LSMPA. We count the number of raster cells that had both treated and control vessels each year (Fig. 8A). The pattern observed here could just be an artifact of satellite detections increasing though time. Therefore we also calculate a spatial correlation of presence/absence and observe similar patterns (Fig. 8B). While this is at the year level and cannot assure that vessels were in effect at the same time in the same place, it provides a of what we would expect to find if our claims of displacement are true. Spatial overlap increases in 2015 as vessels from PIPA are excluded, but then starts to decline. [QUESTIONS FOR JC: Is this significant? Can we do a daily measure? What about mean or shortest distance between vessels. Treated/Control/Combined]

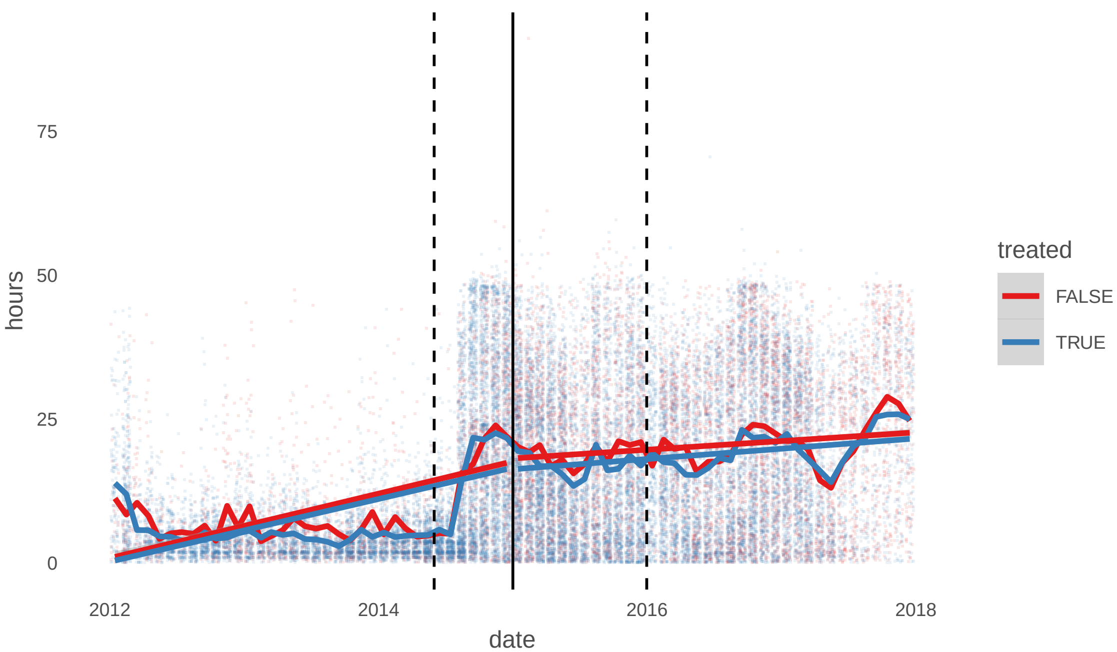

Figure 3: Daily fishing hours for all vessels in our main treatment-control groups. Solid straight lines show a linear trend by period (pre-post) and treatment. The other red and blue lines show monthly avarages. Vertical dashed lines indicate dates when satellites were added, solid line indicates PIPA closure.

Table 2: Difference-in-differences estimates for 3 different controls and 3 different specifications. The first three columns use our primary control group. 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 heteroskedasticity-robust standard errors.

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

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

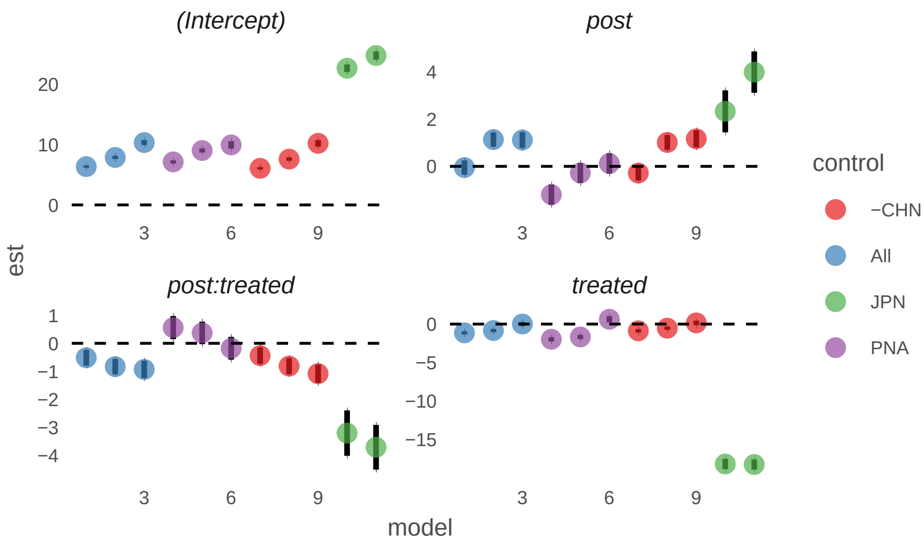

Figure 4: Coefficient estimates for each model. Top panel indicates variable, x-axis represents model specification, and y-axis coefficient estimate. [QUESTION FOR JC: delete the intercept panel.]

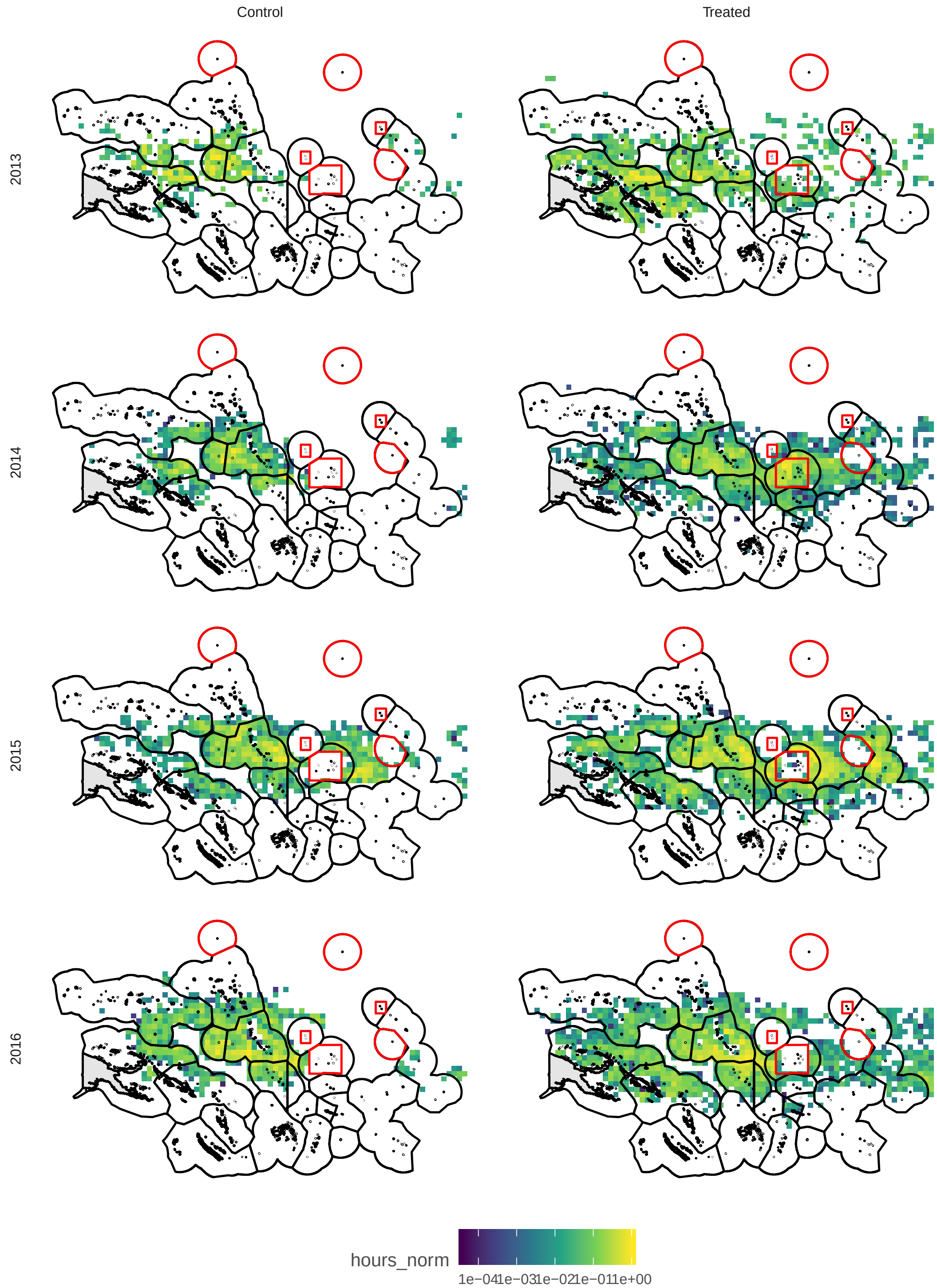

Figure 5: Yearly spatial distribution of fishing effort by treated and control vessels. Colors have been adjusted relative to the maximum observed by group and year. Red polygons show LGMPAs in the region. For visualization purposes only some years are presented, the full 2012 - 2017 period is shown in Figure S12. [QUESTION FOR JC: we should include all years in the main text. Is there a way to normalize this, e,g. color corresponds to % of total fishing effort, so it's easier to compare?]

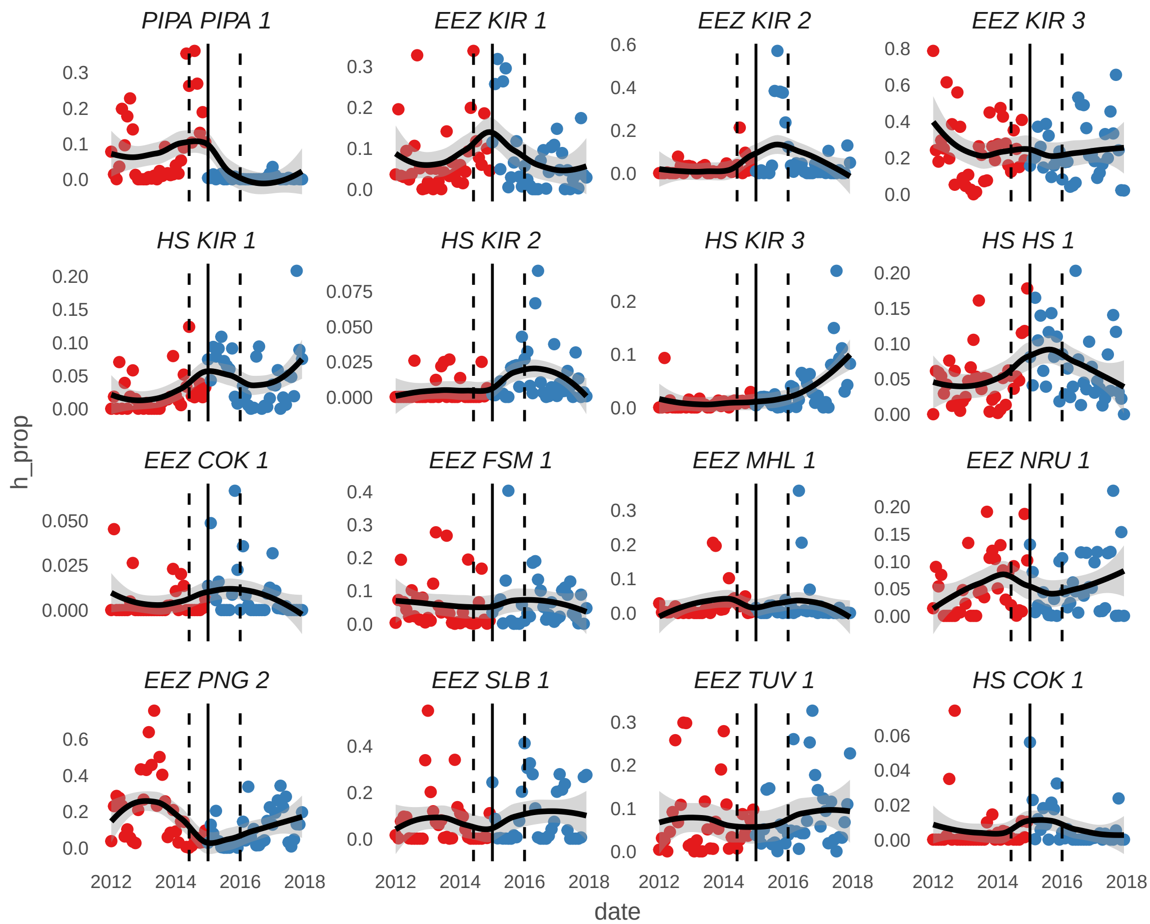

Figure 6: Monthly relative allocation of fishing effort by PIPA-fishing vessels before and after PIPA by region. Colors indicate the pre- and post- periods. Solid line across points shows local mean with a region-specific loess smoother. Vertical dashed lines indicates dates when satellites were added, solid vertical line indicates PIPA closure. Note that inflection points of the loess smoother are not affected by the addition of satellites. [QUESTION FOR JC: this figure needs a lot of work. subplot titles need to be more intuitive. I would combine all EEZ KIR into one group and all HS KIR into one group.]

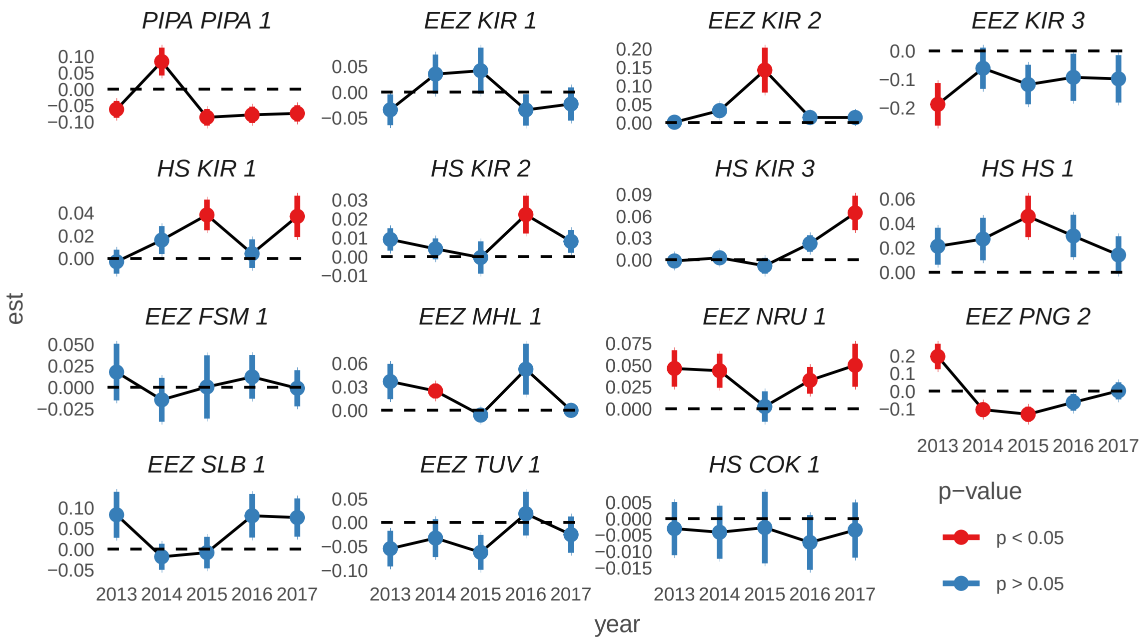

Figure 7: Coefficient estimates for the redistribution regression. Each panel shows the region-specific coefficients, with heteroskedasticity-robust standard errors as error bars. The horizontal dashed line represents 0 change relative to the 2012 region-specific levels. [QUESTION FOR JC: just do 95% confidence intervals.]

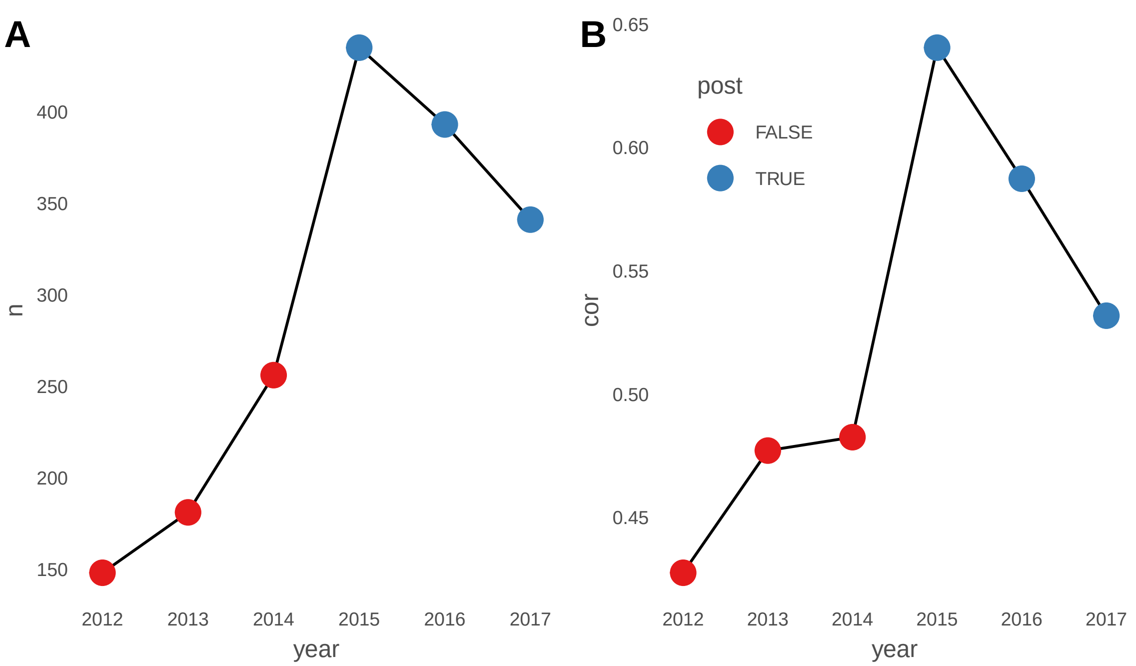

Figure 8: Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B).

Table 3: Coefficient estimates for the interaction of year and region. Each row represents a region, each column a year. Numbers in parentheses are heteroskedaticity-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)

5 Palau National Marine Sanctuary

On October 28, 2015 the President of Palau, H.E. Tommy E. Remengesau Jr., signed into law the Palau National Marine Sanctuary Act. Starting in December 2020, this will close 193,000 square miles to commercial fishing activities, creating the 14th largest protected area in the world.

5.1 Background on Commercial Fishing in Palau

Foreign tuna fishing in Palau's EEZ began before WWI. Pole and line was the initial gear used to target skipjack tuna by the Japanese. Foreign fishing activities stopped during WWII and started again in the 1960s when the Japanese returned and the locally based Van Camp Seafood Company carried out fishing with boats crewed by Okinawans. The Japanese also began purse seine fishing in the 1960s and 1970s and limited longline fishing for yellowfin tuna during the same time. During the 1980s, longline fishing began to set their lines deeper, shifting their targets to bigeye tuna. During the 1980s Korean and Taiwanese vessels also began longline fishing in Palauan waters for export to Japan (**?**). There are currently three transshipment companies operating in Palau.

5.1.1 Purse seine fishing

Purse seine vessels target schools of skipjack tuna that are used for canning. Compared to other EEZs in the Pacific, Palau's EEZ is not known to be preferred for purse seining (Sisior, pers. comm.). Currently all purse seine boats fishing in Palau's EEZ are Japanese and do not land their catches in Palau Table **??**.

5.1.2 Longline fishing

All longline vessels fishing in Palau's EEZ are foreign owned (Table 2). Japanese longline vessels do not land their catches in Palau. Locally based, foreign owned longline boats are mostly Taiwanese vessels that are contracted by one of the two main fishing companies (Palau International Traders Incorporated (PITI), Kuniyoshi Fishing Company (KFC)) (Table 2). Ninety-five percent of the catch from PITI and KFC contracted boats is exported to Japan, upon landing in Koror. Most of the discards, or portion of the catch that is of too low quality to export, is either sold or donated in Palau. A very small portion of the discards is frozen and transported to Taiwan when the vessels return to their home ports.

5.1.3 Access fees

An agreement between Palau and four Japanese fishing associations[12] covers three methods of fishing (longline, purse seine, pole and line) and has allowed Japan to have up to 290 vessels in Palau waters with no limits on catch. Japan pays 4-5% of catch returns, but there was no way to validate their catch (**?**). Between 2010 and 2014, Japan has paid Palau between \$196,100- \$867,120

[12]This is a single agreement between Palau and four associations—1)Federation of Japan Tuna Fisheries Co-operative Associations, 2) National Offshore Tuna Fisheries Association of Japan, 3) Japan Far Seas Purse Seine Fishing Association, 4) Federation of North Pacific District Purse Seine Fisheries Cooperative Association of Japan (Performance Audit Report on Managing Sustainable Fisheries (Tuna) 2013).

annually in access fees (?). Currently, these access fees have been replaced by the vessel day schemes (described in section 3).

5.1.4 Uniform Longline Agreement for locally based vessels (ULA)

Agreements between the Republic of Palau and foreign owned, local based companies (PITI and KFC) (?). Vessels under these agreements are internationally owned, locally based vessels that have payed for annual licenses per vessel based on the size of the vessel. These are the vessels in Table ?? (excluding the Japanese vessels). So, for example, 38 vessels in 2016. Between 2010 and 2014, total licensing fee revenue was between $219,000-$284,600 per year (?). Currently, these access fees have been replaced by the vessel day scheme (described in section 3).

5.1.5 US Multilateral Tuna Treaty and Federated States of Micronesia Arrangement

These two multilateral treaties grant preferential access to the US and FSM flagged purse seine boats, respectively. The US Treaty was renegotiated in 2016 with stipulations on minimum vessel day fees (more in section 3). Very little purse seine fishing is conducted by FSM and US vessels in Palau's EEZ, but Palau still receives a portion of these treaty funds. Some Pacific Island countries treat this money as foreign aid, not for fishing access (?).

5.1.6 Other sources of revenue from pelagic fisheries

The export tax for all commercial tuna and billfish, either fresh or frozen is $0.35/kg. Average revenues from export taxes was approximately $500,000 annually from 2011-2014 (?). Otherwise there is little additional revenue from pelagic fisheries, especially considering that very few jobs are created by the fishery. Between 80-90 people are employed by offshore fisheries, of these only 20% are Palauans and average wages are 50% average wages in the country (?).

5.1.7 Parties to the Nauru Agreement and the Vessel Day Scheme

The Parties to the Nauru Agreement (PNA) is an agreement between Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu to manage the largest tuna fishery in the world. The Purse Seine Vessel Day Scheme (PS VDS), established in 2006 with the Palau Agreement, is the current method used by the PNA to manage effort in the fishery. Although not a PNA member, Tokelau joined the PS VDS in 2014, with 1,000 transferrable days (?).

In the PS VDS, a total number of annual vessel days for the entire fishery is agreed upon by the parties. Each party's allowable effort (PAE) is then calculated based on historic effort and biomass within each party's EEZ. Sixty percent of the PAE is calculated based on the party's effort over the last seven years and 40% of the PAE is calculated based on the 10 year average of the party's share of estimated skipjack and yellowfin biomass within its EEZ (as explained in Article 12.5 of the 2012 Amendment to the Palau Agreement and in Hagrannsoknir sf 2014). A minimum benchmark fee is set for purse seine vessel days (PS VD) which each party can transfer (i.e., sell to another PNA member) or sell to the highest bidder (i.e., sell to fishing company). Vessel days can be transferred to fish in any PNA party's EEZ, without penalty to the transferred parties

VD allocation (?). The process of transferring days between parties is described in Article 7 of the Management Scheme (?). The mean value of a vessel day has steadily increased since 2007 (Havice, 2013). A minimum benchmark fee of $8,000/day was set from 2015 (?). Detailed records on sales or transfers of vessel days are not publicly available (Havice, 2013; ?). ? summarize the PNA 'implementing arrangements' as follows: "foreign vessels [are required] to be registered and licensed, report catches, maintain log books, allow observers on board and maintain transparency over their fishing activities." Further, vessels registered with the Vessel Day Scheme are required to have Automatic Location Communicators (ALC) or Mobile Transceiver Units (MTU) that transmit their locations at least once per hour while they are within the VDS Management Area (?). Every entire day that a vessel is within the VDS Management Area is counted as a vessel day used, unless the vessel reports a "no fishing day" (e.g., travel, maintenance, etc.) and periods of less than 24 hours are counted as partial days (?). As described in the Palau Arrangement (?), fishing days by vessels shorter than 50m or longer than 80m count as 0.5 and 1.5 vessel days, respectively. Parties are responsible for ensuring registered vessels comply with the implementing arrangements and that they stay within the PAE. Parties that exceed their PAE should reportedly be penalized by reductions to the following year's PAE (?). However, there are criticisms of the PNA PS VDS claiming that there is a lack of monitoring, compliance, and transparency that could hinder the future success of the SP VDS (??). In the case of Palau, the VDS is run by the Bureau of Marine Resources, within the Ministry of Natural Resources, Environment and Tourism. Palau's currently PS VD allotment is reportedly 700 vessel days annually (Sisior, pers. comm., ?), though historically, this number has been lower (average of 580 days between 2008-2011 (?). Palau sells most of its vessel days to the US for $12,500 each (as negotiated in the US treaty), regardless of whether US vessels actually fish in Palau's EEZ. The remainder of Palau's PS vessel days are sold for between $9-10,000 each. When vessel days are purchased to transfer to another EEZ, Palau charges a transfer fee (approximately $500), for administration costs and future opportunity costs (since vessel day allotments are based partly on historical effort within the EEZ). Though records are confidential, it has been publicly reported that one PNA member party that Palau has transferred PS VD to is Papua New Guinea (?) and this year, PS VD have been sold to a fishing company in the Philippines for the first time (?). This year, Palau has brought in approximately $9 million USD in PS VDS revenue (Sisior pers. comm.).

The longline VDS (LL VDS) is in its infancy and has not yet been fully implemented at the PNA-scale, although several countries are now implementing at the country-scale. Palau was the first party to implement the VDS for the longline fishery in 2017. In 2014, longline boats fishing in Palau's EEZ fished 10,500 days (Sisior, pers. comm.). Since 2016, the number of allowed longline VDs has been a fraction of the 2014 days, reducing each year as stipulated in the PNMS Act. Palau sells its LL VD for $150-$250 (Sisior pers. comm.). Because the LL VDS is still new and has yet to be fully implemented by all parties, LL VD are not currently transferable between PNA member EEZs.

5.1.8 The Palau National Marine Sanctuary Act

In 2015, Palau enacted a policy to protect 500 thousand square kilometers of its ocean, representing 80% of its exclusive economic zone (EEZ), by 2020. The policy's goal is to preserve and manage the stocks, health, and beauty of Palau's waters and natural resources by limiting fishing in its deep ocean waters. State waters hugging the coasts of the archipelago are not affected by the policy. Commercial fishing will still be allowed within the open 20% that surrounds the main islands of

Koror and Babeldaob, but all catch must be landed in Palau and exports of pelagic fish will be prohibited. Alongside these protections, the Palau National Marine Sanctuary (PNMS) Act will support a domestic pelagic fishery.

5.1.9 Future of pelagic fisheries under the PNMS

To prepare for full enactment of the PNMS, the act stipulates a "winding down" period, in which baseline vessel days (i.e., the number of vessel days used in 2014) were reduced by 20% in 2016; and an additional 10% from baseline in each subsequent year until full enactment in 2020. This appears to be occurring for the LL VDS, but it is uncertain whether this is being followed for the PS VDS, because PS VD can be transferred for use in other EEZs. There has been no official statement on what will happen to Palau's vessel days upon full implementation of PNMS. However, there is a sense that Palau will be able to keep its allotment come 2020 (Hanich, pers. comm.). In the 2015 Micronesian Presidents Summit, a letter was drafted by heads of state, calling on PNA members to be supportive of Palau as they moved forward with the PNMS Act (**?**). Further, other PNA members have not been penalized for other protected area closures (e.g., Phoenix Islands Protected Area in Kiribati) (Hanich, pers. comm.). Table 3 estimates the potential losses of revenue under full enactment of the PNMS under four scenarios. In Scenario 1, Palau is able to keep its current allotment of purse seine vessel days (700) to transfer to other parties at the current benchmark price ($8,000/day). Scenario 1 is likely if Palau retains its PAE, but the US no longer purchases its days (note, US is currently purchasing days at $12,500). Scenario 2 is the same as the first scenario, except instead of being able to transfer its days at the current benchmark price, it is able to transfer its days for $12,000 (to account for current price to US of $12,500, which will increase in accordance with the US Treaty, and also the general increasing trend in the value of PS vessel days). It should be noted that if PAE continues to be calculated based on effort and biomass, and if Palau continues to be allocated vessel days, its PAE will decrease as effort in its EEZ reaches zero. In Scenario 3 and 4, Palau loses all of its PS vessel days, at $8,000/day and $12,000/day, respectively. In all scenarios, all longline vessel day and export tax revenue are lost. Longline vessel day loss is calculated using an average value of $200 for 10,500 days. Export tax loss is calculated given the average tax revenue from 2012-2014 ($482,236 from **?**).

5.1.10 Plans for a domestic pelagic fishery

In the recent past, a single domestic pole and line vessel supplied Palau with an estimated 100mt of catch Plans for domestic fishery (**?**). The vessel ceased operations in recent years when the captain became ill and passed away, but there is talk that it is gearing up to start operations again under new leadership (Sisior, pers. comm.). Otherwise, there are no domestic vessels dedicated to full-time offshore fishing. A number of fishers occasionally troll offshore for tuna and other pelagics, but there are no official estimates of volumes (although Phil James with SPC has results that should come out soon). Local NGOs have sponsored short trainings on small-scale canning and proper techniques for processing high grade tuna to encourage existing fishers to devote more time to offshore fishing. There are several possible scenarios for domestic fishery (including those featured in a feasibility report by FFA (**?**)), but there has yet to be any official action towards a particular scenario.

We will use aggregated GFW data at the 1km * 1km level to estimate what % of fishing effort under the PNA is currently taking place in the proposed sanctuary? This will estimate the impact on foreign-flagged fleets that used to fish in Palau waters. We are currently in possession of this data. In terms of the impact on PNA payments, it is our understanding that the allocation will not be reduced (in the near future) but perhaps the price received per VDS will be lower. But we do not have good information on prices paid for VDS. We also don't yet have good data on local fishers in Palau that are likely to be positively impacted since they will be allowed to fish in the sanctuary.

6 Conclusion

Figure 9: Fishing Effort in Palau Relative to the Total PNA Area

Figure 10: Fishing Effort in Palau Relative to the Total PNA Area By Distant Water Fishing Fleet

7 Discussion

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

Previous studies on protected areas around Pacific islands suggest that vessels move to distant places, which might be translated as increased costs (Stevenson et al., 2013). Others have used similar satellite-tracking systems to show that fishing effort accumulates near the edges of spatial closures, yielding greater catches over time (Murawski et al., 2005). But these vessel tracks do not cover the pre-reserve period, making it difficult to identify the contribution of spatial closures to the observed spatial distribution of fishing vessels. Recent work by Elahi et al. (2018) identified that total fishing effort in a focal region where a short-term MPA was implemented showed little change, likely indicating that fishers redistributed fishing effort to compensate for the reduction in available space. Our data, which is assembled in a similar way, allows us to make similar inferences about the unobserved change in aggregate fishing effort and its spatial redistribution.

The role of the institutions at play is evident. Vessels that fished inside PIPA before the implementation were likely fishing in Kiribati waters under a VDS license. Upon implementation, some vessels redistribute to other areas of the Kiribati EEZ and the adjacent high seas for the year immediately after the closure. As stated before, it is reasonable for a vessel holding a license to fish in Kiribati waters to simply reallocate their effort to other parts of that EEZ. However, the shift to the high seas may not follow the same logic. Instead, it is possible that vessels that redistribute to the high seas were operating in Kiribati illegally, and decide to reallocate in the high seas to continue fishing without a license. Or they are now not willing to pay Kiribati to fish in the remaining open areas.

A major shortcoming of our analysis is that we do not observe catches or revenues, which ultimately are the factors that guide the decision making process of profit-maximizing agents. Therefore, it is difficult to know whether the small change in fishing hours represents a positive or negative impact. An additional factor that we are yet to test is the change in non-fishing hours spent at sea. It is plausible that fishing hours remain constant, but vessels have to increase search time. Upon being relocated, fishers may not identify the best fishing grounds as easily as before, and therefore invest a greater proportion of their time searching for their catch. Further analysis of temporal trends in non-fishing hours, as well as distance traveled should provide us with insights as to why fishers reduced fishing hours. However, the widespread footprint of the treated fleet may suggest that they are well acquainted with the region (see Figure 5), and it's unlikely that they would need to invest much time to identify new fishing grounds.

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

8 Further work

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

References

Agardy, T., G. N. di Sciara, and P. Christie (2011, mar). Mind the gap: Addressing the shortcomings of marine protected areas through large scale marine spatial planning. *Marine Policy 35*(2), 226–232.

Alger, J. and P. Dauvergne (2017, jul). The global norm of large marine protected areas: Explaining variable adoption and implementation. *Env. Pol. Gov. 27*(4), 298–310.

Aqorau, T., J. Bell, and J. N. Kittinger (2018, sep). Good governance for migratory species. *Science 361*(6408), 1208.2–1209.

Aqorau, T. and A. Bergin (1997, mar). Ocean governance in the western pacific purse seine fishery - palau arrangement. *Marine Policy 21*(2), 173–186.

Boonzaier, L. and D. Pauly (2016, jan). Marine protection targets: an updated assessment of global progress. *Oryx 50*(01), 27–35.

Bradley, D., J. Mayorga, D. J. McCauley, R. B. Cabral, P. Douglas, and S. D. Gaines (2018, oct). Leveraging satellite technology to create true shark sanctuaries. *Conserv Lett*, e12610.

Cabral, R. B., S. D. Gaines, B. A. Johnson, T. W. Bell, and C. White (2017, mar). Drivers of redistribution of fishing and non-fishing effort after the implementation of a marine protected area network. *Ecol Appl 27*(2), 416–428.

Christie, P., N. J. Bennett, N. J. Gray, T. 'Aulani Wilhelm, N. Lewis, J. Parks, N. C. Ban, R. L. Gruby, L. Gordon, J. Day, S. Taei, and A. M. Friedlander (2017, oct). Why people matter in ocean governance: Incorporating human dimensions into large-scale marine protected areas. *Marine Policy 84*, 273–284.

De Santo, E. M. (2013, jul). Missing marine protected area (MPA) targets: How the push for quantity over quality undermines sustainability and social justice. *J Environ Manage 124*, 137–146.

Elahi, R., F. Ferretti, A. Bastari, C. Cerrano, F. Colloca, J. Kowalik, M. Ruckelshaus, A. Struck, and F. Micheli (2018, aug). Leveraging vessel traffic data and a temporary fishing closure to inform marine management. *Front Ecol Environ*.

FAO (2018, jul). *The state of world fisheries and aquaculture 2018: meeting the sustainable development goals*. The state of world fisheries and aquaculture. UN.

Game, E. T., H. S. Grantham, A. J. Hobday, R. L. Pressey, A. T. Lombard, L. E. Beckley, K. Gjerde, R. Bustamante, H. P. Possingham, and A. J. Richardson (2009, jul). Pelagic protected areas: the missing dimension in ocean conservation. *Trends Ecol Evol (Amst) 24*(7), 360–369.

Gray, N. J., N. J. Bennett, J. C. Day, R. L. Gruby, T. A. Wilhelm, and P. Christie (2017, oct). Human dimensions of large-scale marine protected areas: Advancing research and practice. *Coastal Management*, 1–9.

Havice, E. (2010, sep). The structure of tuna access agreements in the western and central pacific ocean: Lessons for vessel day scheme planning. *Marine Policy 34*(5), 979–987.

Havice, E. (2013, nov). Rights-based management in the western and central pacific ocean tuna fishery: Economic and environmental change under the vessel day scheme. *Marine Policy 42*, 259–267.

Hilborn, R., F. Micheli, and G. A. De Leo (2006, mar). Integrating marine protected areas with catch regulation. *Can. J. Fish. Aquat. Sci. 63*(3), 642–649.

Kaplan, D. M., E. Chassot, A. Gruss, and A. Fonteneau (2010, feb). Pelagic MPAs: the devil is in the details. *Trends Ecol Evol (Amst) 25*(2), 62–3; author reply 63.

Kroodsma, D. A., J. Mayorga, T. Hochberg, N. A. Miller, K. Boerder, F. Ferretti, A. Wilson, B. Bergman, T. D. White, B. A. Block, P. Woods, B. Sullivan, C. Costello, and B. Worm (2018, feb). Tracking the global footprint of fisheries. *Science 359*(6378), 904–908.

Maxwell, S. M., E. L. Hazen, R. L. Lewison, D. C. Dunn, H. Bailey, S. J. Bograd, D. K. Briscoe, S. Fossette, A. J. Hobday, M. Bennett, S. Benson, M. R. Caldwell, D. P. Costa, H. Dewar, T. Eguchi, L. Hazen, S. Kohin, T. Sippel, and L. B. Crowder (2015, aug). Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy 58*, 42–50.

McCauley, D. J., P. Woods, B. Sullivan, B. Bergman, C. Jablonicky, A. Roan, M. Hirshfield, K. Boerder, and B. Worm (2016, mar). Ending hide and seek at sea. *Science 351*(6278), 1148–1150.

McDermott, G. R., K. C. Meng, G. G. McDonald, and C. J. Costello (2018, aug). The blue paradox: Preemptive overfishing in marine reserves. *Proc Natl Acad Sci USA*.

Murawski, S., S. Wigley, M. Fogarty, P. Rago, and D. Mountain (2005, jul). Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science*.

PNA (2018). Parties to the nauru agreement.

R Core Team (2018). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Sala, E., J. Lubchenco, K. Grorud-Colvert, C. Novelli, C. Roberts, and U. R. Sumaila (2018, may). Assessing real progress towards effective ocean protection. *Marine Policy 91*(2), 11–13.

Sala, E., J. Mayorga, C. Costello, D. Kroodsma, M. L. D. Palomares, D. Pauly, U. R. Sumaila, and D. Zeller (2018, jun). The economics of fishing the high seas. *Sci Adv 4*(6), eaat2504.

Schiller, L., M. Bailey, J. Jacquet, and E. Sala (2018, aug). High seas fisheries play a negligible role in addressing global food security. *Sci Adv 4*(8), eaat8351.

Singleton, R. L. and C. M. Roberts (2014, oct). The contribution of very large marine protected areas to marine conservation: giant leaps or smoke and mirrors? *Mar Pollut Bull 87*(1-2), 7–10.

Smith, M. D. and J. E. Wilen (2003, sep). Economic impacts of marine reserves: the importance of spatial behavior. *Journal of Environmental Economics and Management 46*(2), 183–206.

Stevenson, T. C., B. N. Tissot, and W. J. Walsh (2013, apr). Socioeconomic consequences of fishing displacement from marine protected areas in hawaii. *Biological Conservation 160*, 50–58.

Sumaila, U. R., V. W. Y. Lam, D. D. Miller, L. Teh, R. A. Watson, D. Zeller, W. W. L. Cheung, I. M. Côté, A. D. Rogers, C. Roberts, E. Sala, and D. Pauly (2015, jul). Winners and losers in a world where the high seas is closed to fishing. *Sci Rep 5*(1), 8481.

Toonen, R. J., T. A. Wilhelm, S. M. Maxwell, D. Wagner, B. W. Bowen, C. R. C. Sheppard, S. M. Taei, T. Teroroko, R. Moffitt, C. F. Gaymer, L. Morgan, N. Lewis, A. L. S. Sheppard, J. Parks, A. M. Friedlander, and B. O. T. Tank (2013, dec). One size does not fit all: the emerging frontier in large-scale marine conservation. *Mar Pollut Bull 77*(1-2), 7–10.

White, C. and C. Costello (2014, mar). Close the high seas to fishing? *PLoS Biol 12*(3), e1001826.

White, T. D., A. B. Carlisle, D. A. Kroodsma, B. A. Block, R. Casagrandi, G. A. De Leo, M. Gatto, F. Micheli, and D. J. McCauley (2017, mar). Assessing the effectiveness of a large marine protected area for reef shark conservation. *Biological Conservation 207*, 64–71.

Wood, L. J., L. Fish, J. Laughren, and D. Pauly (2008, jul). Assessing progress towards global marine protection targets: shortfalls in information and action. *Oryx 42*(03).

624 # 9 Appendix

625 ## 9.1 Stream of data by vessel, group, and period

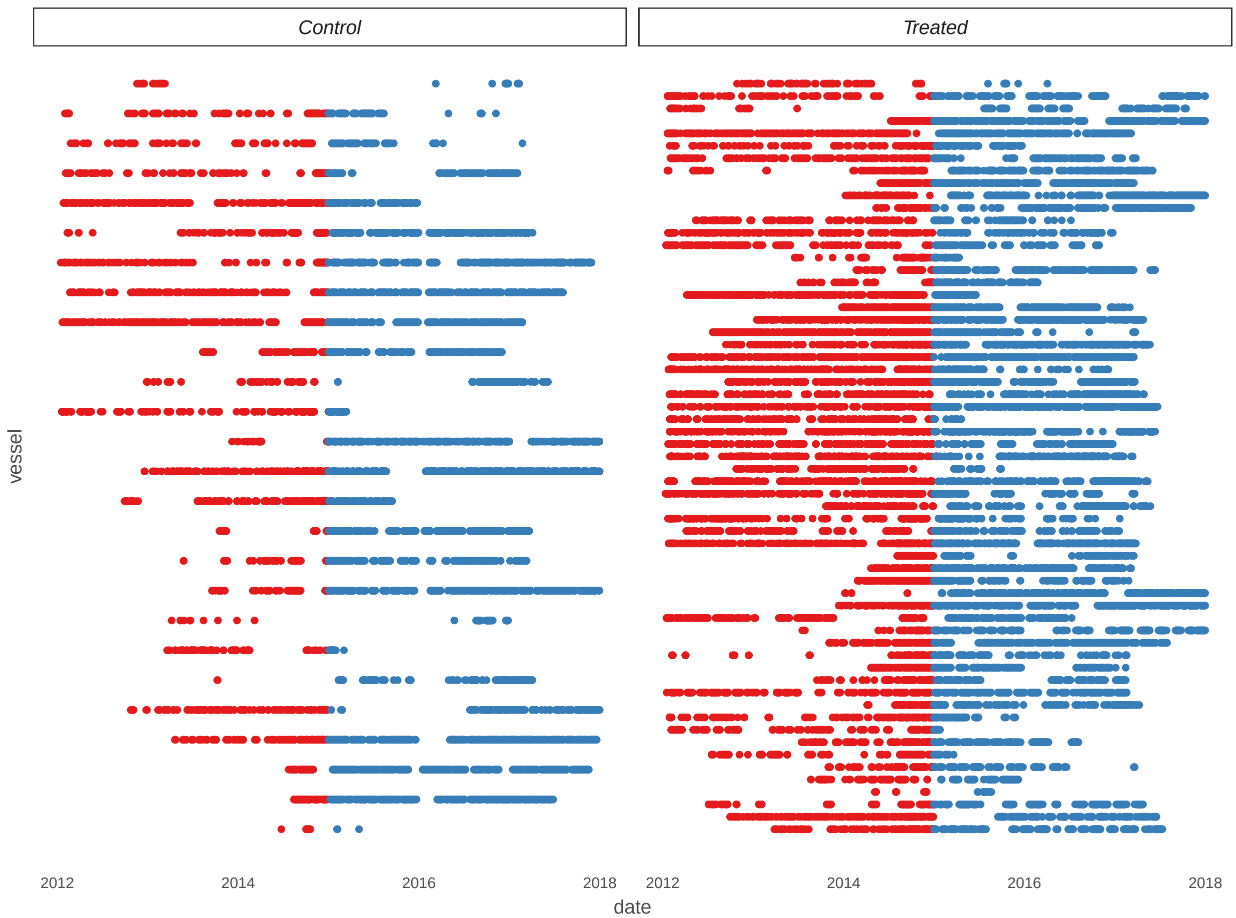

Figure S1: Stream of fishing events by vessels through time. Each line represents a vessel, with dots indicating months with fishing activity and colors indicating the pre and post periods.

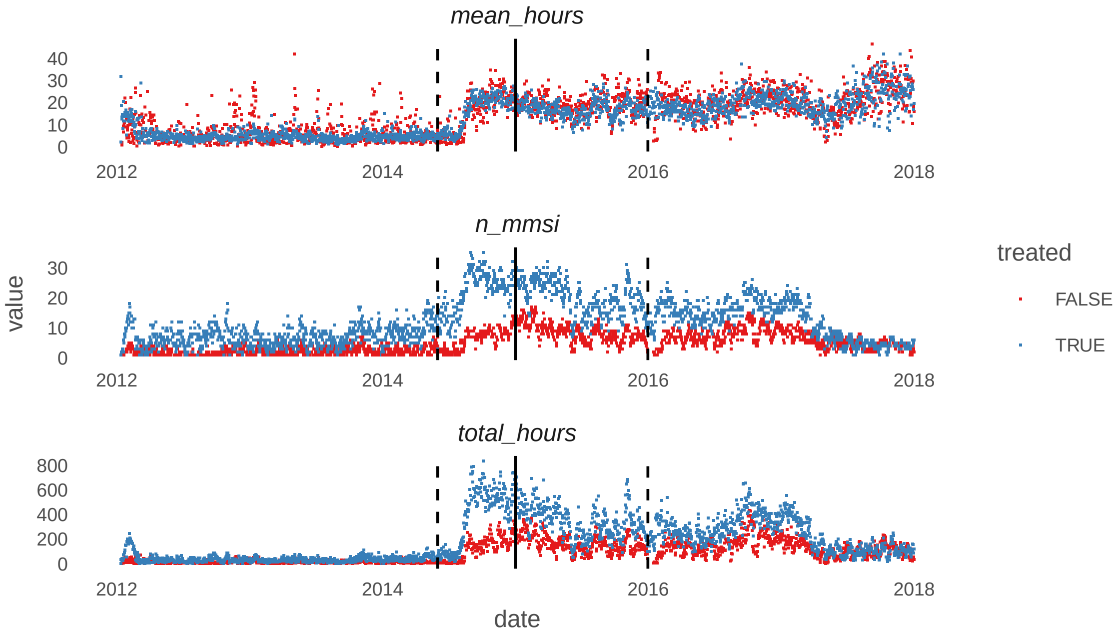

Figure S2: Fishing hours and number of vessels by month for all vessels. Vertical dashed lines indicates dates when satellites were added, solid line indicates PIPA closurePIPA closure.

9.2 Longliners

Longliners show a similar pattern of effort reduction. However, the magnitude of the β_3 coefficient is smaller and not significant unless including month and flag FEs for the general treatment-control groups, or when excluding Chinese vessels. This, along with higher standard error values suggest that longliners have a smaller and more variable 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.

	Dependent variable:					
	hours					
	(1)	(2)	(3)	(4)	(5)	(6)
Constant	39.192***	38.411***	36.520***	39.402***	38.636***	34.402***
	(0.095)	(0.132)	(0.169)	(0.102)	(0.140)	(0.236)
post	−1.014***	−0.189	0.710***	−1.400***	−0.574***	0.896***
	(0.143)	(0.145)	(0.158)	(0.163)	(0.165)	(0.186)
treated	2.544***	2.570***	2.724***	2.349***	2.391***	3.299***
	(0.101)	(0.101)	(0.121)	(0.110)	(0.110)	(0.135)
sate2	−0.495***	−1.488***	−0.898***	−0.561***	−1.497***	−1.015***
	(0.099)	(0.105)	(0.110)	(0.104)	(0.110)	(0.114)
sate3	−0.313**	−1.150***	0.050	−0.375***	−1.129***	0.001
	(0.129)	(0.132)	(0.143)	(0.134)	(0.138)	(0.149)
post:treated	0.098	0.056	−1.125***	0.532***	0.427***	−1.280***
	(0.134)	(0.134)	(0.148)	(0.149)	(0.149)	(0.171)
Control	All	All	All	-CHN	-CHN	-CHN
Month FE	No	Yes	Yes	No	Yes	Yes
Flag FE	No	No	Yes	No	No	Yes
Observations	227,873	227,873	217,467	209,135	209,135	198,729
R^2	0.010	0.016	0.022	0.010	0.016	0.023
Note:						*p<0.1; **p<0.05; ***p<0.01

631 ### 9.2.1 Quarterly DID interactions

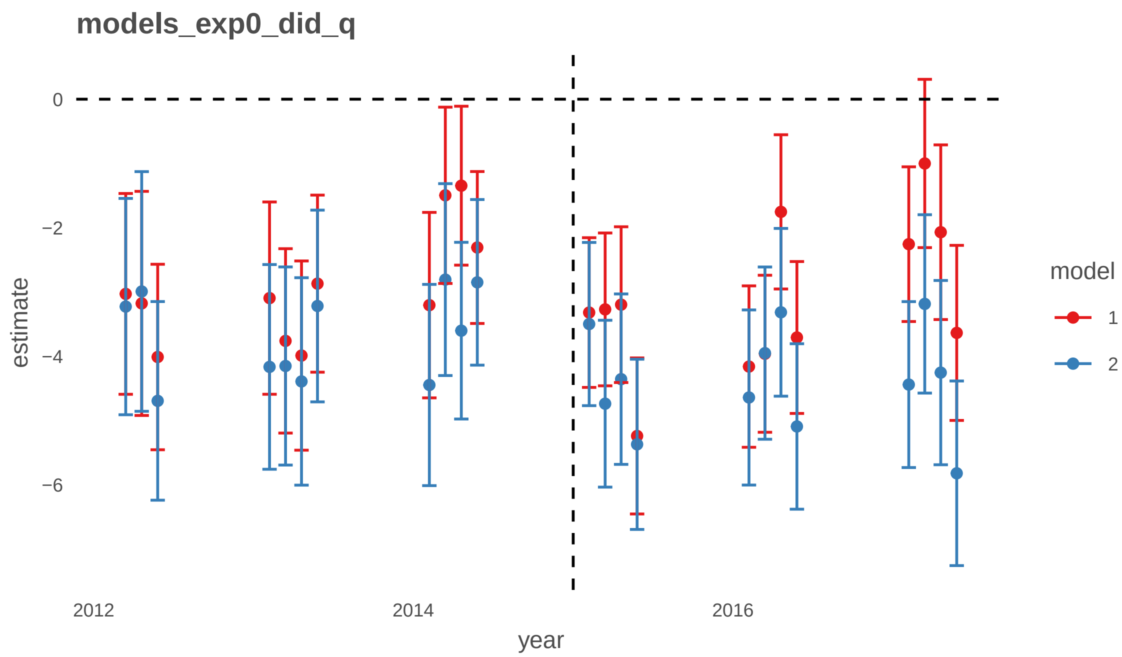

Figure S3: Interaction of quarters and treatment. Control group is all vessels.

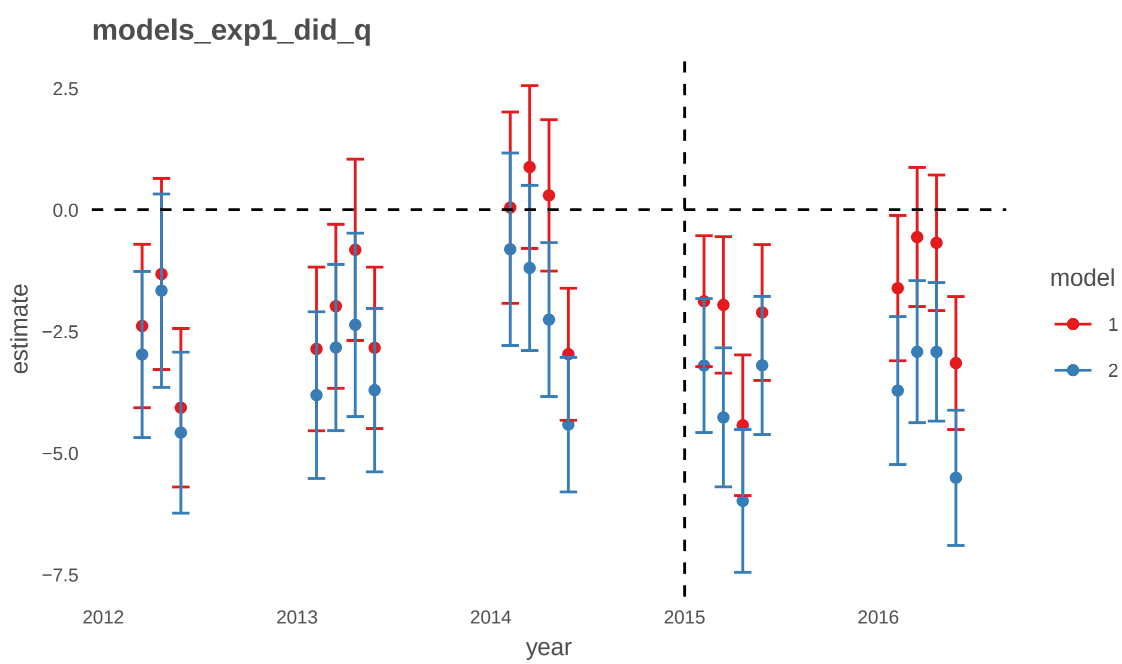

Figure S4: Interaction of quarters and treatment. Control group is vessels from PNA.

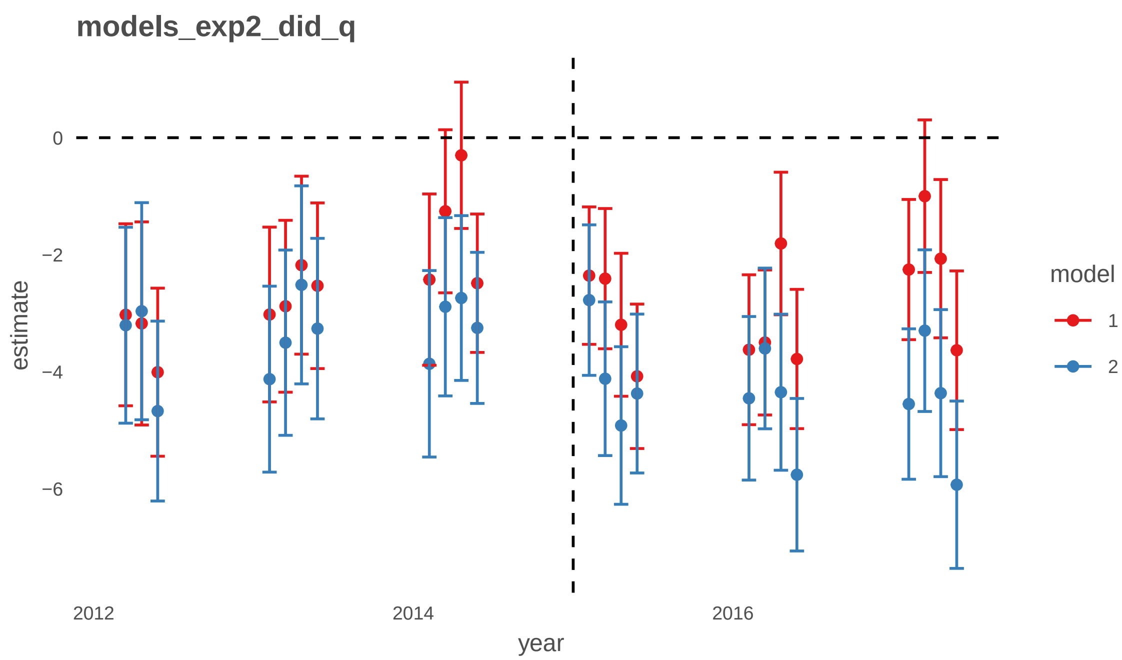

Figure S5: Interaction of quarters and treatment. Control group excludes Chinese vessels.

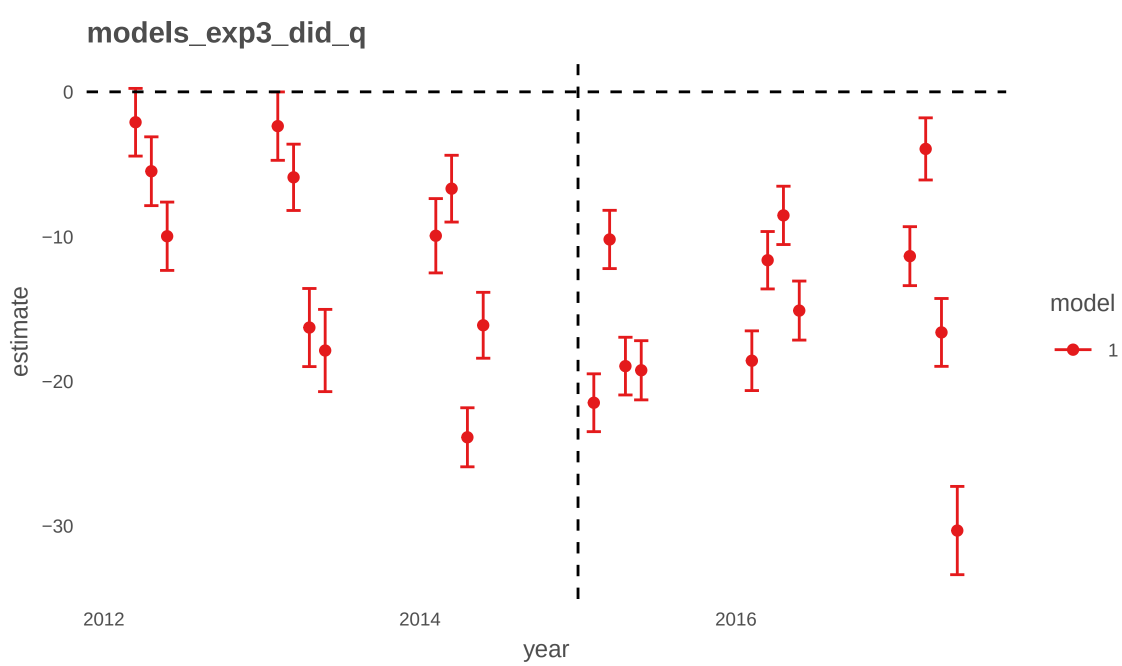

Figure S6: Interaction of quarters and treatment. Control group is japanese vessels.

9.2.2 Year-month DID interactions

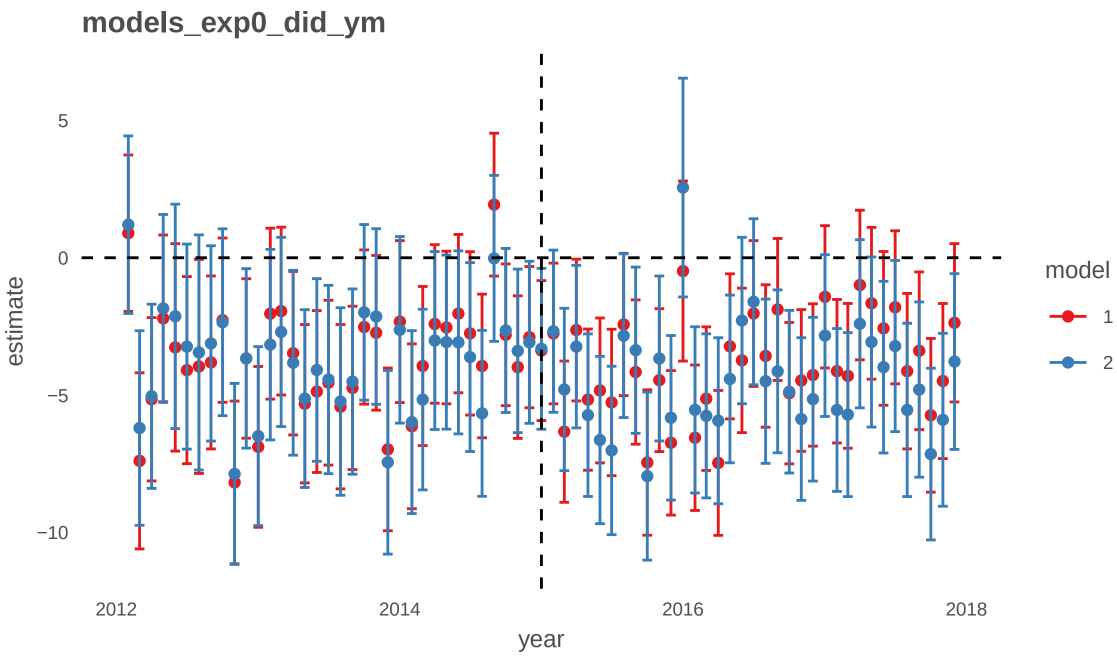

Figure S7: Interaction of year-month and treatment. Control group is all vessels.

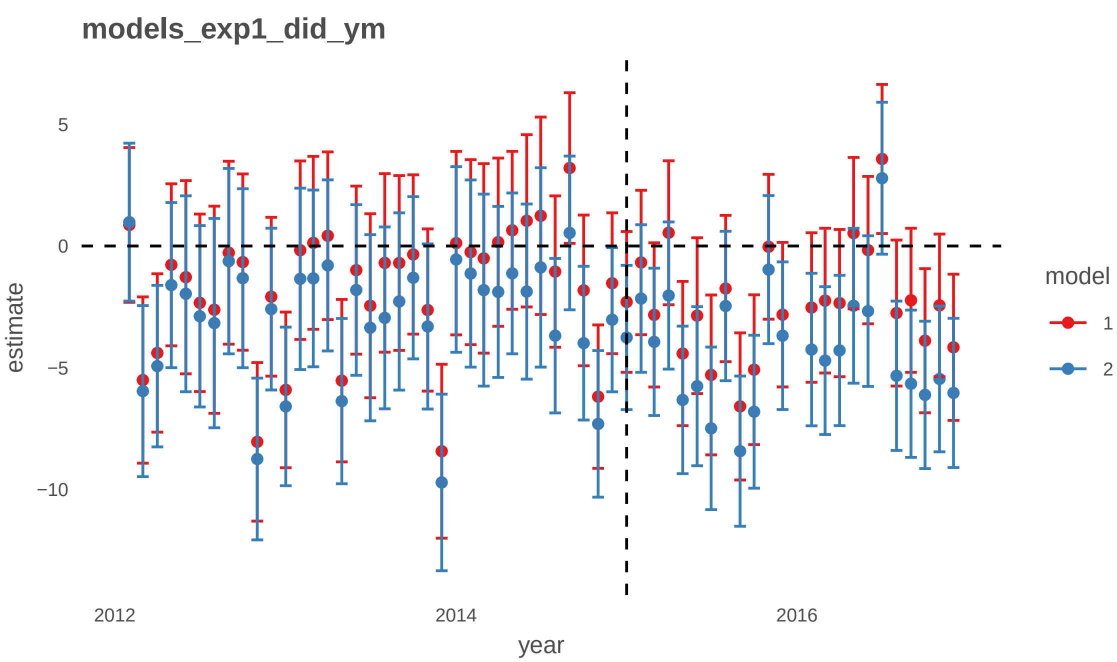

Figure S8: Interaction of year-month and treatment. Control group is vessels from PNA.

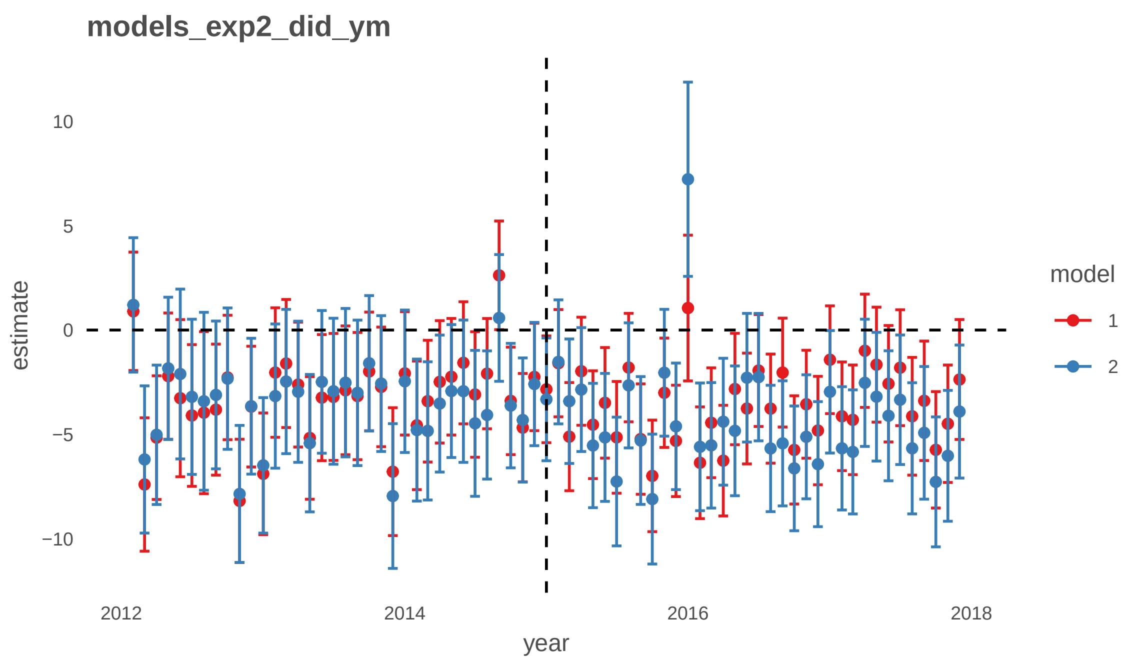

Figure S9: Interaction of year-month and treatment. Control group excludes Chinese vessels.

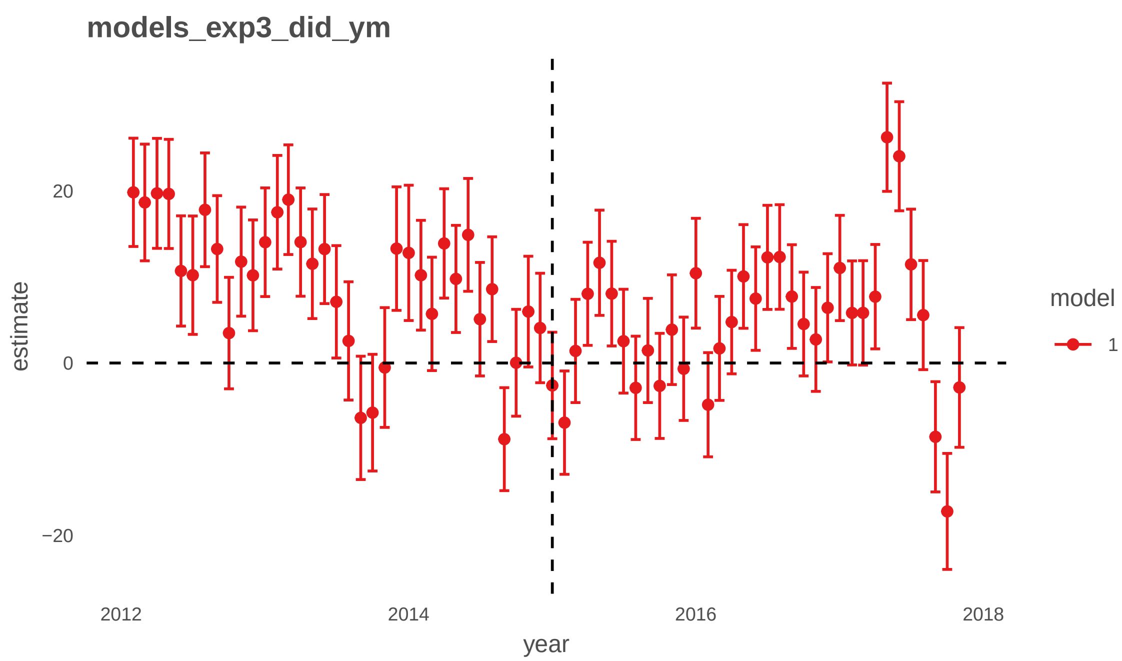

Figure S10: Interaction of year-month and treatment. Control group is japanese vessels.

9.3 Other measures of change in behavior

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

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

Where y is our variable of interest, $Year$ represent year dummies, with 2012 as the reference level, and $Treated$ indicates wether a vessel belongs to the treated or control group.

9.3.1 Distance from shore

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

	Dependent variable:
	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^2	0.032
Adjusted R^2	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

9.3.2 Distance from ports

9.4 Effort redistribution

9.4.1 Rasterized regions

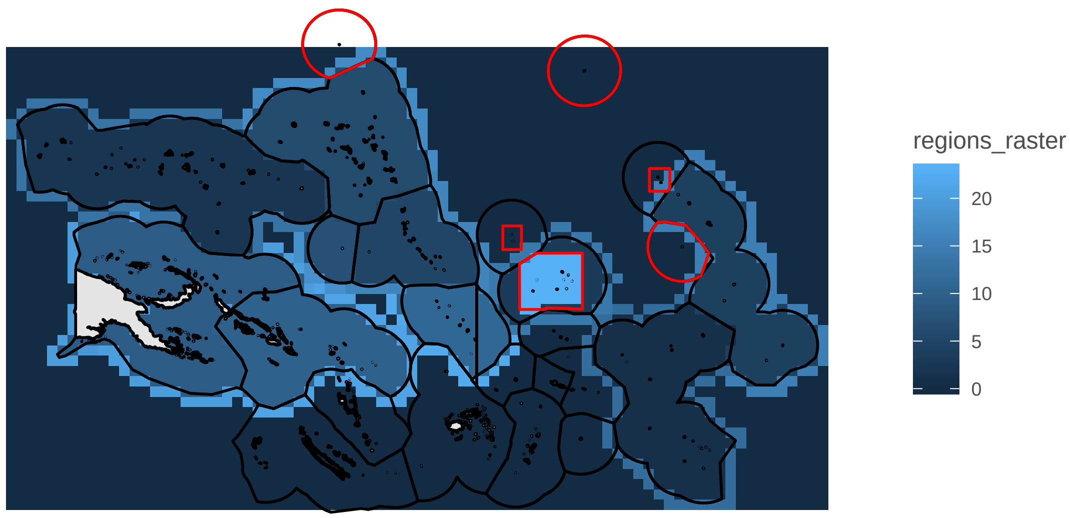

Figure S11: Rasterized regions. Each color (number) indicates a distinct region.

Table S3: Regression results for distance from shore

	Dependent variable:
	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^2	0.047
Adjusted R^2	0.047
Residual Std. Error	391.757 (df = 4937654)
F Statistic	22,351.480*** (df = 11; 4937654)
Note:	*p<0.1; **p<0.05; ***p<0.01

643 ### 9.4.2 Fishing raster

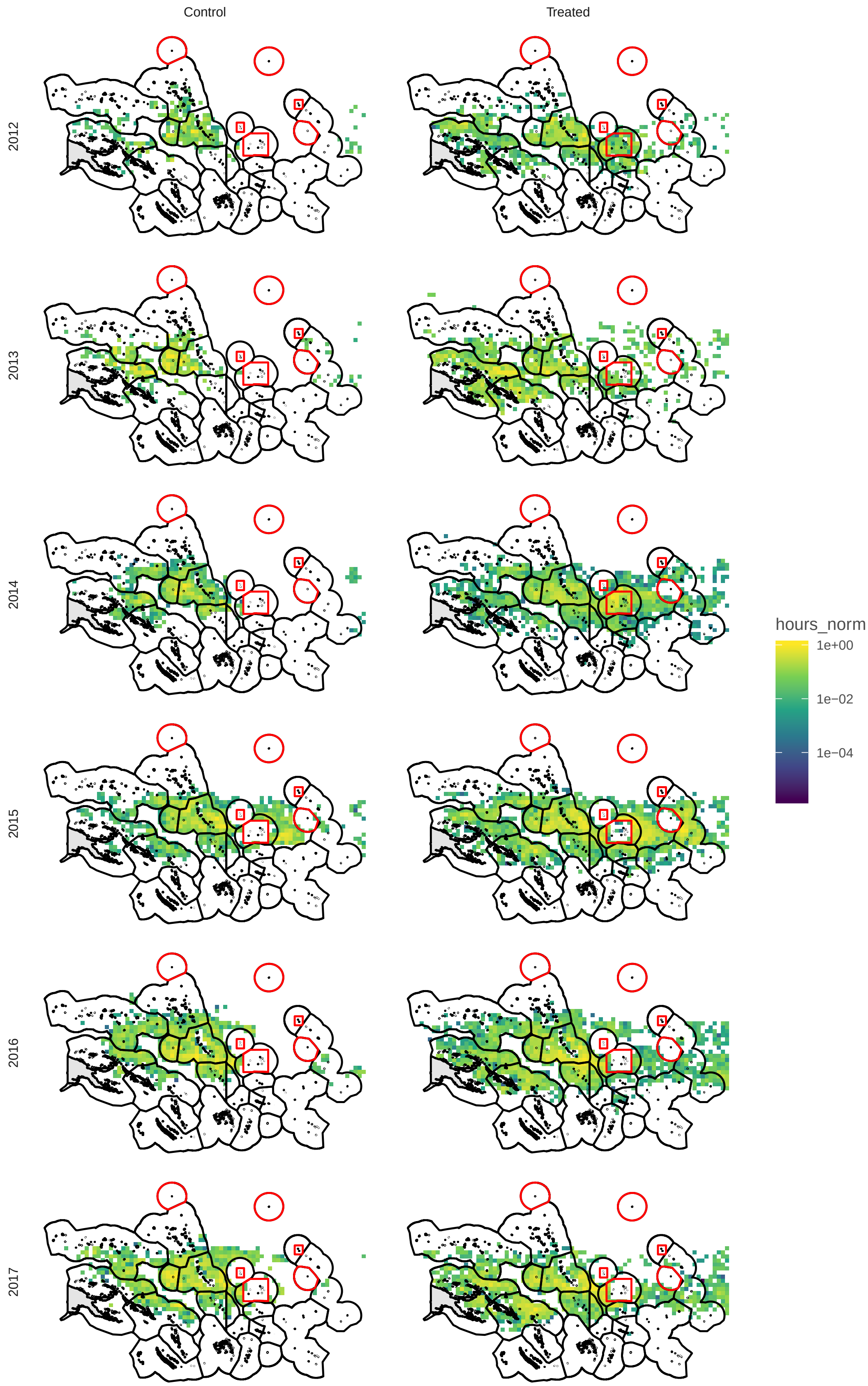

Figure S12: Yearly rasters of fishing hours for each group.