Large-Scale Marine Protected Areas in the World's Largest Tuna Fishery

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The Parties to the Nauru Agreement (PNA) is a system for managing the world's largest skipjack tuna fishery, covering an area of 14.6 million km^2 in the Pacific Ocean. In 2015, PNA member Kiribati implemented one of the world's largest conservation areas: The Phoenix Island Protected Area (397,447 km^2). It is still unclear what the effects of such a big MPA have been and what effects are likely to occur in the future. We use identification of fishing activity via Automatic Identification Systems (AIS) and causal inference techniques evaluate the behavioral changes and spatial redistribution of tuna purse seiners due to the implementation of a Large-Scale Marine Protected Area. Our work provides three main findings: 1) we observe a crowding effect for the first months after implementation, 2) aggregate fishing effort remains relatively constant; and 3) vessels that fished inside the protected area redistribute to adjacent waters, including the high seas. This suggests that rights to fish in PNA waters might now be less valuable. We do not observe an increase in daily fishing hours for vessels that used to fish within the LSMPA, 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. We use our results to inform predictions of the impacts of a proposed LSMPA in Palau (a PNA member). Our estimates of the potential losses range from $2.5 to $11 million annually. This wide range hinges on what Palau's future PNA allocation will be and the extent to which US aid will continue through non-fishing channels. 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 ocean protection targets, managers should consider how fishing effort will change in space and time to ensure that fishing effort is not just displaced elsewhere.

Marine Protected Areas | Fisheries | Purse Seining | Marine Conservation

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 (1, 2), largely driven by a small number of Large-Scale Marine Protected Areas (LSMPAs).* Today, a small number of LSMPAs make up at least 80% of the managed areas in the ocean (8).

Given the relatively recent establishment of most LSMPAs, very little is known about their human dimensions and implication for fisheries (9). 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 (10). 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 (11).

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. These are two of the largest protected areas on the planet and both are within the Parties to the Nauru Agreement (PNA) region, which is a group of (originally eight and now) nine Pacific Islands countries that collectively manage their valuable tuna stocks.

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 5 discusses our results.

*See, for example, (3–7).

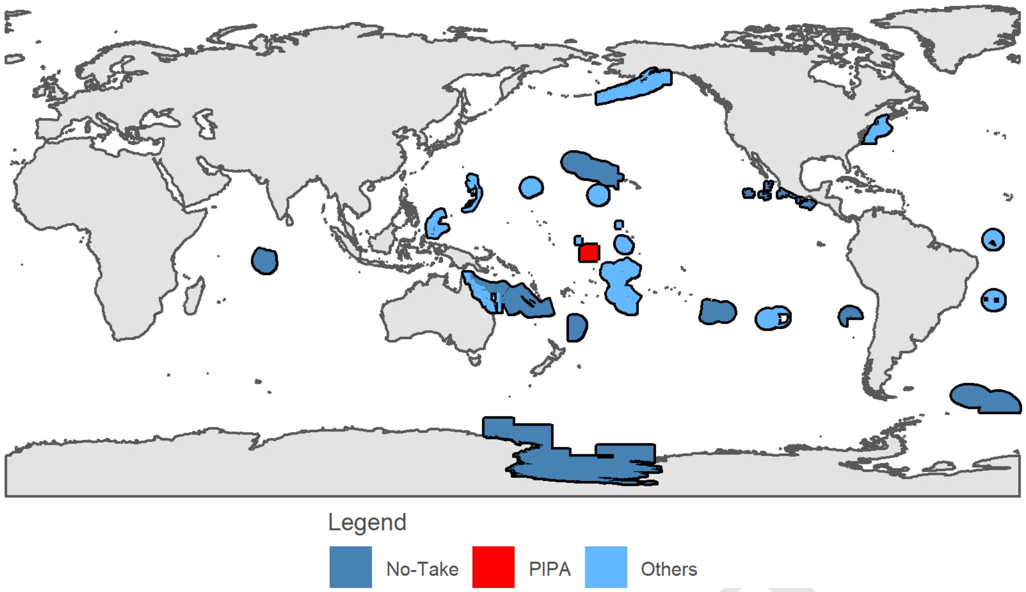

Fig. 1. Large Scale Marine Protected Areas. The map shows all areas larger than 250,000 Km^2. Areas in dark blue meet at least one of these conditions: reported no take area is greater than 0, are categorized as IUCN Ia or Ib, their designated English name is 'Protected Area'.

2. Background

A. 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 (12) or areas larger than 250,000 km^2, as defined by (8). 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 (9, 13). The early literature on LSMPAs focused on the inherent challenges and difficulties that come with a pelagic environment. (14) claimed that very large MPAs would result in excessive opportunity costs and that these would be difficult to enforce. (3) suggested that most of the challenges could be overcome with the incorporation of technology, in what then became known as Dynamic Ocean Management (15).[†]

LSMPAs were initially assumed to have little social implications due to their general remoteness. However, there have been calls to incorporate the human dimensions into LSMPA management and evaluation (9, 16). Most research incorporating these dimensions has focused on governance and enforcement of LSMPAs (7, 17), but they are yet to be the focus of economic analyses (9). 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. For example, (18) show that the anticipation of a LSMPA can lead to preemptive overfishing, which can erode or delay the expected benefits of the intervention. (19) 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 tagged gray reef sharks by effectively excluding fishing effort. More recently, (20) 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 (10, 21).

[†] See (4), who provide an objective discussion of the pros and cons of LSMPAs.

Significance Statement

Authors must submit a 120-word maximum statement about the significance of their research paper written at a level understandable to an undergraduate educated scientist outside their field of speciality. The primary goal of the Significance Statement is to explain the relevance of the work in broad context to a broad readership. The Significance Statement appears in the paper itself and is required for all research papers.

All authors contributed equally to this work

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However, these focus on the long term optimal equilibrium, and redistribution of fishing effort may not always be optimally distributed, especially over the first few years (22).

The empirical research that has been done in smaller sized MPAs suggests that resource users may show idiosyncratic responses. For example, (22) 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. (23) analyze the redistribution of fishing and non-fishing vessels following the implementation of a network of MPAs in California, and find that dive boats follow a fishing-the-line pattern, while some fishing boats follow an ideal free distribution. More recently (24) 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 (10, 21), 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 studies evaluate relatively small closures 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, with potentially very different fishing regulations.

B. 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. Tokelau joined the PNA group in 2012 and started selling access rights in 2013. The Nauru Agreement regulates access of foreign vessels (*i.e.* those from non-PNA countries). Holding ~80% of historical skipjack tuna purse seine grounds within their Exclusive Economic Zones, PNA countries have achieved greater bargaining power when providing fishing access to foreign fleets (25).

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.[‡] However, the most notable regulation is the approach to manage fishing effort: a Vessel Day Scheme (VDS) implemented in 2007 (26). This effectively modified how fishing effort was managed, from total number of vessels (under the Palau Agreement) to total vessel-days. Under the purse seine VDS, a total number of annual vessel days for the entire fishery is agreed upon by the PNA 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 EEZ effort over the last seven years and 40% of the PAE is calculated based on the 10-year average of each country's share of estimated skipjack and yellowfin biomass within its EEZ.[§]. A minimum benchmark fee is set for purse seine vessel days which each party can transfer (*i.e.* sell to another PNA member) or sell to the highest bidder (*i.e.* sell to a fishing company). Vessel days can be transferred to fish in any PNA party's EEZ, without penalty to the transferred parties' allocations (28).[¶] The mean value of a vessel day has steadily increased since 2007 (26). Although detailed records on sales or transfers of vessel days are not publicly available (26, 29), a minimum benchmark fee of $8,000/day was set from 2015 (30).

(29) 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 (28). 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 (28). As described in the Palau Arrangement, fishing days by vessels shorter than 50m (longer than 80m) count as 0.5 (1.5) vessel days. Countries are responsible for ensuring registered vessels comply with the implementing arrangements and that they stay within their PAE. Parties that exceed their PAE should reportedly be penalized by reductions to the following year's PAE (28). There are some 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 program (29, 31). While the effectiveness of this scheme has been debated in terms of meeting fishery management and conservation objectives, the licensing significantly contributes to the economy of these island nations (25).

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 (32). This region of the Pacific has historically accounted for a large portion of tuna catches (33). Today, the PNA controls close to 50% of global skipjack tuna production (34) and the combined area of all EEZs involved is 14.6 million km^2, larger than the land mass of the United States of America. A large portion of global skipjack catch derives 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

‡ See (25) for a detailed description of the Nauru, Palau, and Federal States of Micronesia agreements.

§ This is explained in more detail in Article 12.5 of the 2012 Amendment to the Palau Agreement and in (27)

¶ The process of transferring days between parties is described in Article 7 of the Management Scheme (28).

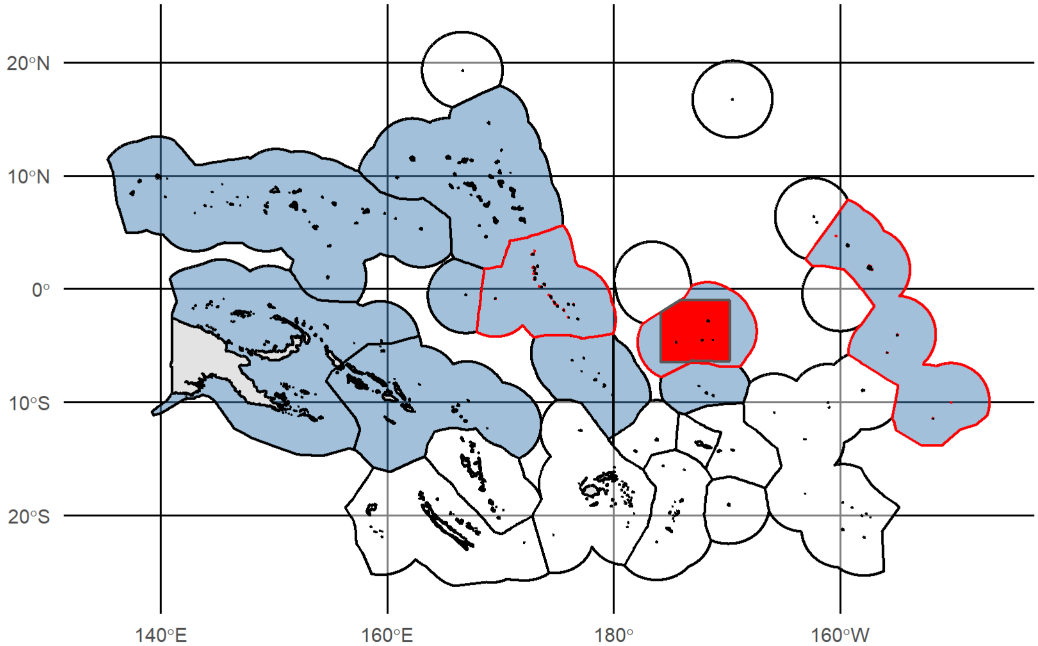

Fig. 2. Map of the Exclusive Economic Zones (EEZs) of the region of interest. Countries that belong to the PNA are shown in blue, while empty polygons indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

km^2, roughly 1.5 times the size of Ecuador. Figure 2 shows a map of the PNA countries (excluding Palau) 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 (6, 18). 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.[‖] 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.

A. 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 (13).

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. The addition of new satellites affects all vessels in the same way.

Our analysis focuses on tune purse seine vessels, the most important fishery for PNA countries.[**] We identify a total of 186 purse seiners that fished in PNA waters at least once before 2015. 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, leaving us with 125 vessels. We identify 90 vessels that have fished inside PIPA at least once since 2012; 72 did so before the announcement of the closure (*i.e.* 09/01/2014 *sensu* (18)). From these, we only observe before and after data for 64 tuna purse seiners. On the other hand, 45 vessels never fished inside PIPA during the 2012 - 2015 period, but we only observe befora and after data for 28 of these.

Therefore, our treatment group contains all purse seiners (n = 64) 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 = 28). Together, these vessels represent more than 20 million georeferenced positions for which we know activity (fishing or not fishing).

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 all Chinese vessels (n = 12). Our third control is made up of Japanese purse seiners that fish in the Pacific but have never fished inside PIPA (n = 27). Our main definition of treatment and control groups leaves us with 64 treated and 28 control vessels, which have just over 22 million observations with about 22% of these observations identified as fishing events by the neural network classification.

The behavioral responses that vessels can have to a spatial closure may occurr in different ways. For example, displacement to new fishing grounds may represent a cost, as fishers search the ocean to identify the most suitable fishing places. This may result in increased fuel and labor costs. Therefore, we are interested in three key measures that could capture a captain's response to a spatial closure: daily fishing hours, daily non-fishing at-sea hours, and the proportion of fishing to non-fishing hours at sea. We calculate these measures for each vessel, and build a daily panel with 152,802 observations. Table 1 shows the number of vessels following a Before-After-Control-Impact (BACI) design, as well as the mean fishing hours, before and after PIPA was implemented.

Following the idea behind increased search time, we also use each vessel's track to compute the total daily distance traveled (km) by calculating the distance between every observation. Additionally, we include the daily mean distance to the nearest port and mean distance to shore for all positions and for fishing events only. Finally, we calculate the monthly proportion of each vessel's fishing time that was allocated to Kiribati waters and PNA waters

Fig. 3 shows that monthly mean values of the 10 variables that we use, for treated and control vessels. Across all measures, the treatment and control vessels follow similar patterns, confirming our claim that the control group provides a plausible counterfactual.

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	28	7.15	10.68	1.49
Treatment	64	6.21	9.89	1.59

[‖] Global Fishing Watch: globalfishingwatch.org

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

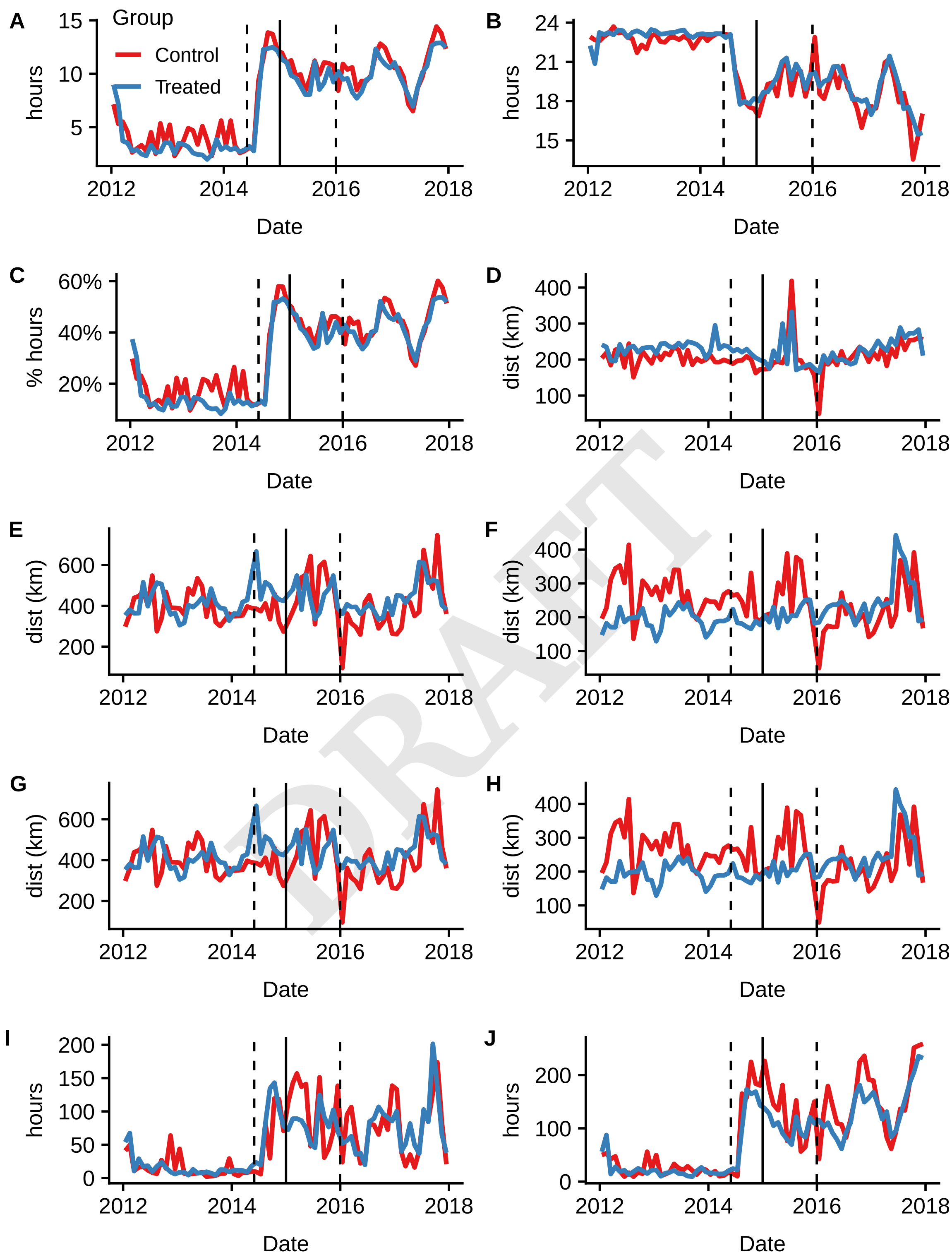

Fig. 3. Time series showing mean monthly values es for our 10 variables of interest: A) Fishing hours, B)Non-fishing hours at-sea, C) Proportion of fishing hours to total hours at-sea, D) Distance traveled, E) Mean distance from port, F) Mean distance from shore, G) Mean distance from port for fishing events, H) Mean distance from shore for fishing events, I) Proportion of hours spent in Kiribati waters, J) Proportion of fishing hours spent in PNA waters.

B. Analyses. Our first analysis focuses on identifying the response of vessels to the PIPA closure. We use daily fishing and non-fishing hours, daily proportion of fishing vs. non-fishing hours, daily distance traveled (km), distance from shore (km) and distance from home port(km) for fishing and non-fishing events, and proportion of total fishing hours allocated to Kiribati waters and PNA waters 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:

$$log(y)_{i,t} = \alpha + \beta_1 Post_t + \beta_2 Treat_i + \beta_3 Post_t \times Treat_i + \phi_t + \gamma_i + \epsilon_{i,t}$$

where $log(y_{i,t})$ is the log-transformed 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, $beta_1$ captures the temporal trend, $beta_2$ captures the initial difference between treated and control groups, and $beta_3$ is our parameter of interest: the Difference-in-Differences estimate capturing the treatment effect. Finally, phi_t and γ_i represent month and flag dummies that account for seasonality or country-level management interventions. 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[††].

Our second part of the analysis focuses on the redistribution of fishing effort, where 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. 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[‡‡] 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 of the EEZ regions. around each EEZ, and the rest of the high seas. We clipped any overlapping high seas buffers to avoid duplication.

We then take these spatial polygons and rasterize them to a 1-degree grid (see Figure S2 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 (Fig. 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 vector of parameters of of interest is $\beta_{3,i}$, which captures the yearly by-country change in proportional allocation of fishing effort relative to 2012.

Finally, we inspect the crowding effects that may arise due to the net reduction in fishing area. We use the rasterized fishing effort and calculate two potential indices of crowding. For the first one, we count the number of cells that had fishing activity from treated and control vessels over a given month. For the second one, we calculate the correlation of presence/absence of fishing events between both groups over one month. If the implementation of the reserve induces a crowding effect, we would expect to observe no trend before the implementation of the reserve. The implementation would lead to an increase in these measures, which, if vessels avoid crowding, should then come back down. We therefore expect to have three inflection points: 1) in the transition between no trend and initial crowding due to MPA implementation, 2) When the crowding has reached its maximum and starts to decrease, and 3) when the decrease levels off, pressumably to pre-MPA levels. For this reason, we fit a 4th degree polynomial to our monthly indices. We do so by centering our time series of crowding indices on the day of implementation. Our explanatory variable is therefore the number of months before or after the implementation. For example,

[††] I actually need more time to run these, but I don't think they'll change

[‡‡] Currently running the 5-degree version too

since PIPA was implemented in January 1st of 2015, December of 2014 has a value of -1, and Feb of 2015 would receive a value of 1.

$$y_t = \alpha + \beta_1 month_t + \beta_2 month_t^2 + \beta_3 month_t^3 + \beta_4 month_t^4 + \epsilon_t$$

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 (35). Raw data and code used in this work are available on github.

4. Results

Regression coefficients for our DiD analysis are shown in Table 4. Our DiD analysis shows that PIPA closure had no effect on the number of fishing hours, but that it caused non-fishing at-sea hours to increase by 1%, This coefficient is only marginally significant. The proportion of fishing to non-fishing hours shows a positive change, but it is not significant. However, treated vessels travel on average 19% less than control vessels, and opperate closer to shore and port. Furthermore, PIPA implementation caused fishing events of treated vessel to occur 23% and 4% closer to port and to shore, respectively. Other specificationf that exclude fixed effects produce similar estimates (Fig. 4) 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. 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. It shows the change in fishing effort inside PIPA, including the preemptive fishing and immediate reduction previously reported (18). Recall that to evaluate the redistribution of fishing effort we only track fishing vessels that belong to the treated group. Kiribati waters show an increase in fishing effort for 2015; the same pattern is observed for their respective High Seas buffers, and the general High Seas. 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 (Fig. 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, followed by an abrupt reduction in 2015 and afterwards. This reduction confirms that effort within PIPA has been virtually eliminated. 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 (Kiribati's easternmost EEZ), where the redistribution of treated vessels caused a 10% increase in the *relative* allocation of fishing effort within Kiribati waters. The high seas around Kiribati's EEZ exhibit similar increases the year of implementation or the year after. Overall, the high seas receive an incresse in the order of 5% for 2015.This displacement is likely causing 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 month (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). Spatial overlap increases in 2015 as vessels from PIPA are excluded, but then starts to decline. Our 4th degree polynomial shows the expected patterh of a relative constant trend before implementation which is followed by rapid increased and subsequent decrease.

Table 2. Difference-in-differences estimates for our 10 variables of interest: 1) Daily fishing hours, 2) Daily non-fishing at-sea hours, 3) Daily proportion of fishing hours to total at-sea hours, 4) Daily distance traveled, 5) Daily mean distance from port, 6) Daily mean distance from shore, 7) Daily mean distance from port for fishing events, 8) Daily mean distance from shore for fishing events, 9) Monthly hours spent in Kiribati waters, 10) Monthly fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	2.343***	3.624***	0.327***	4.599***	4.860***	11.030***	6.176***	12.513***	3.246***	4.062***
	(0.035)	(0.010)	(0.009)	(0.045)	(0.052)	(0.071)	(0.025)	(0.023)	(0.208)	(0.160)
Post	0.599***	−0.211***	0.139***	−0.167***	−0.364***	−0.532***	0.338***	0.261***	1.477***	1.457***
	(0.027)	(0.008)	(0.007)	(0.034)	(0.042)	(0.059)	(0.017)	(0.018)	(0.148)	(0.122)
Treated	−0.065**	0.007	−0.025***	0.326***	0.040	0.099*	0.158***	−0.010	0.375**	0.116
	(0.029)	(0.006)	(0.007)	(0.031)	(0.037)	(0.054)	(0.019)	(0.019)	(0.150)	(0.126)
Post × Treated	0.017	0.003	0.015**	−0.187***	0.070	0.077	−0.274***	−0.072***	−0.562***	−0.353**
	(0.031)	(0.009)	(0.008)	(0.039)	(0.048)	(0.068)	(0.020)	(0.020)	(0.170)	(0.139)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	24,152	73,259	24,152	73,001	73,668	73,668	24,152	24,152	1,420	1,998
R^2	0.143	0.075	0.154	0.014	0.021	0.015	0.157	0.291	0.174	0.246

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

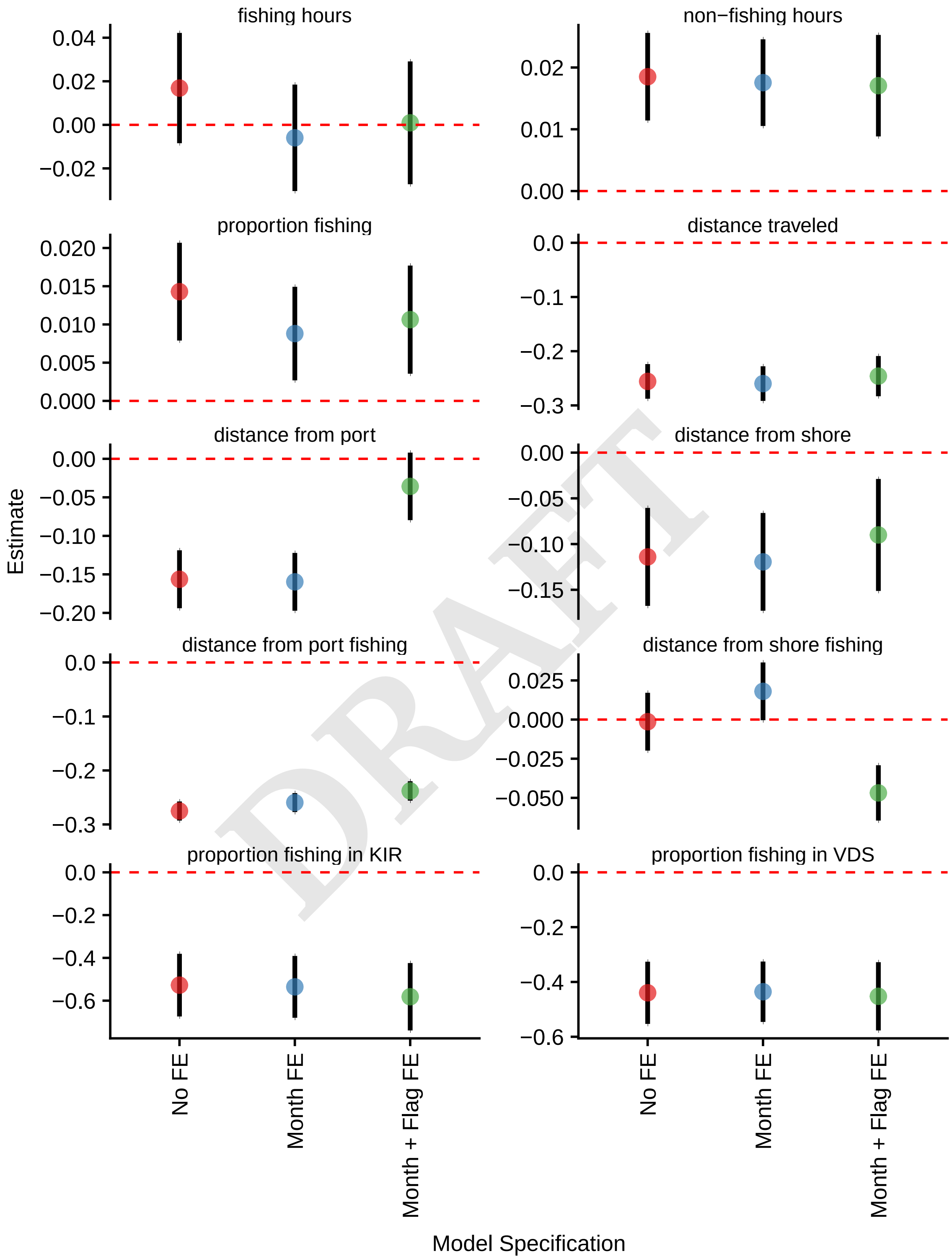

Fig. 4. Alternative difference-in-differences estimates for our variables of interest using different model specifications. Table 4 reports estimates for models with month and flag fixed effects (*i.e.* green dots).

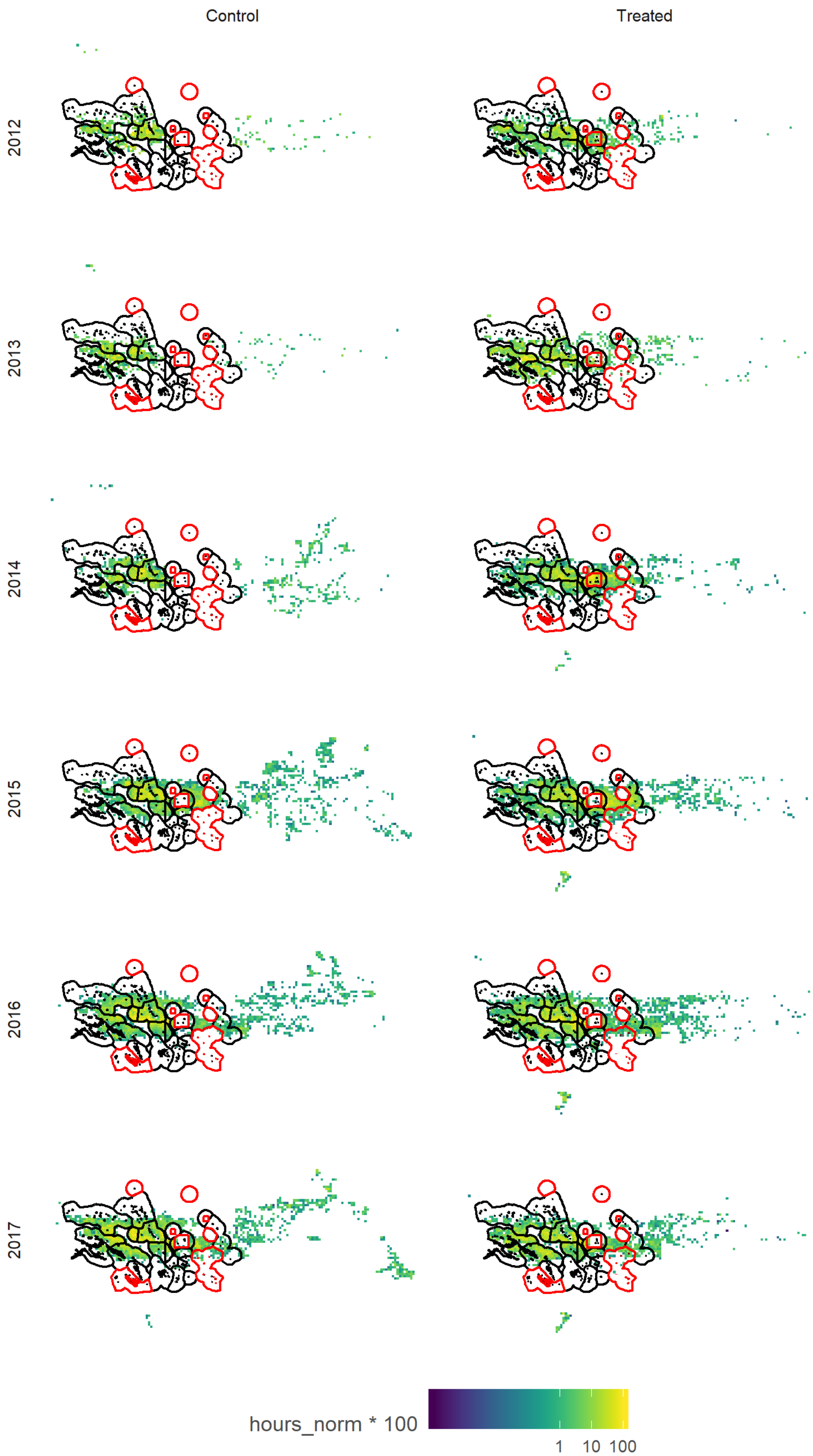

Fig. 5. Yearly spatial distribution of fishing effort by treated and control vessels. Color corresponds to % of total fishing effort in each panel. Red polygons show LSMPAs in the region.

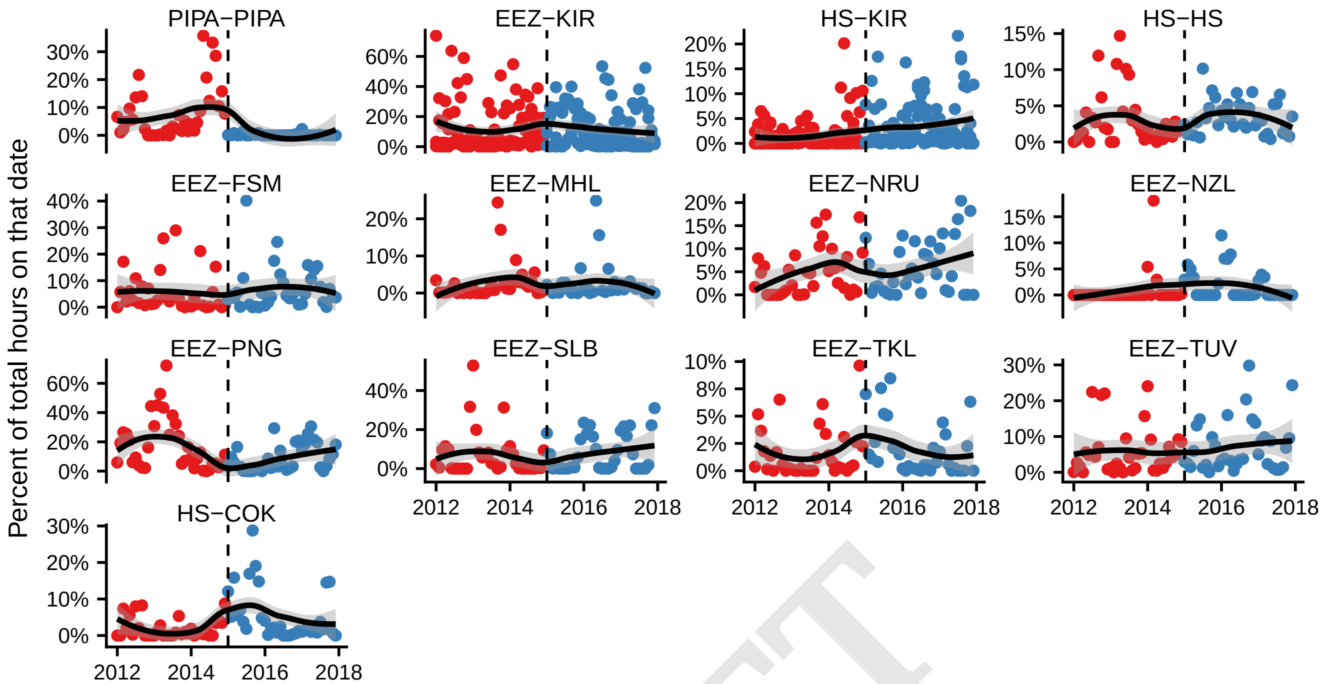

Fig. 6. Monthly relative allocation of fishing effort by PIPA-fishing vessels before and after PIPA by region. Colors indicate the pre- and post- periods. Solid line across points shows local mean with a region-specific loess smoother. Vertical dashed lines indicates dates when satellites were added, solid vertical line indicates PIPA closure. Note that inflection points of the loess smoother are not affected by the addition of satellites.

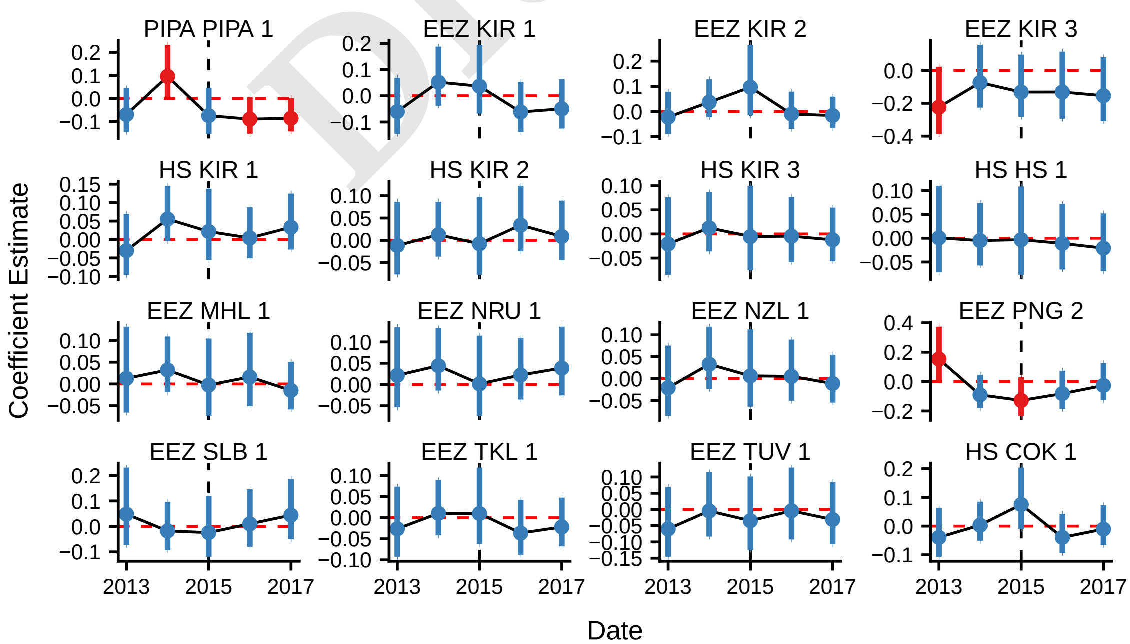

Fig. 7. Coefficient estimates for the redistribution regression. Each panel shows the region-specific coefficients, with 95% condifence intervals as error bars. The horizontal dashed line represents 0 change relative to the 2012 region-specific levels.

Table 3. Coefficient estimates for the interaction of year and region. Each row represents a region, each color a year. Numbers in parentheses are heteroskedatic-robust standard errors.

Coefficient	2013	2014	2015	2016	2017
PIPA PIPA 1	-0.070 (0.039)*	0.096 (0.046)**	-0.074 (0.040)*	-0.090 (0.032)***	-0.085 (0.029)***
EEZ KIR 1	-0.060 (0.044)	0.052 (0.046)	0.037 (0.053)	-0.062 (0.039)	-0.050 (0.038)
EEZ KIR 2	-0.022 (0.034)	0.037 (0.031)	0.096 (0.057)*	-0.010 (0.030)	-0.016 (0.025)
EEZ KIR 3	-0.224 (0.083)***	-0.074 (0.078)	-0.132 (0.077)*	-0.132 (0.083)	-0.154 (0.079)*
HS KIR 1	-0.030 (0.034)	0.055 (0.030)*	0.022 (0.039)	0.004 (0.028)	0.033 (0.031)
HS KIR 2	-0.012 (0.033)	0.012 (0.025)	-0.008 (0.036)	0.034 (0.030)	0.009 (0.027)
HS KIR 3	-0.021 (0.033)	0.013 (0.025)	-0.005 (0.036)	-0.005 (0.028)	-0.012 (0.023)
HS HS 1	0.001 (0.037)	-0.005 (0.027)	-0.003 (0.038)	-0.011 (0.028)	-0.021 (0.025)
EEZ MHL 1	0.013 (0.040)	0.032 (0.026)	-0.002 (0.036)	0.016 (0.034)	-0.015 (0.022)
EEZ NRU 1	0.022 (0.038)	0.044 (0.030)	0.002 (0.038)	0.022 (0.029)	0.039 (0.033)
EEZ NZL 1	-0.021 (0.033)	0.033 (0.029)	0.006 (0.036)	0.005 (0.028)	-0.011 (0.022)
EEZ PNG 2	0.153 (0.074)**	-0.090 (0.046)*	-0.128 (0.053)**	-0.082 (0.053)	-0.026 (0.051)
EEZ SLB 1	0.048 (0.062)	-0.018 (0.039)	-0.024 (0.048)	0.010 (0.046)	0.044 (0.048)
EEZ TKL 1	-0.026 (0.034)	0.010 (0.027)	0.010 (0.037)	-0.036 (0.026)	-0.022 (0.023)
EEZ TUV 1	-0.060 (0.044)	-0.005 (0.040)	-0.035 (0.046)	-0.004 (0.045)	-0.031 (0.039)
HS COK 1	-0.039 (0.034)	0.003 (0.028)	0.075 (0.043)*	-0.039 (0.028)	-0.010 (0.028)

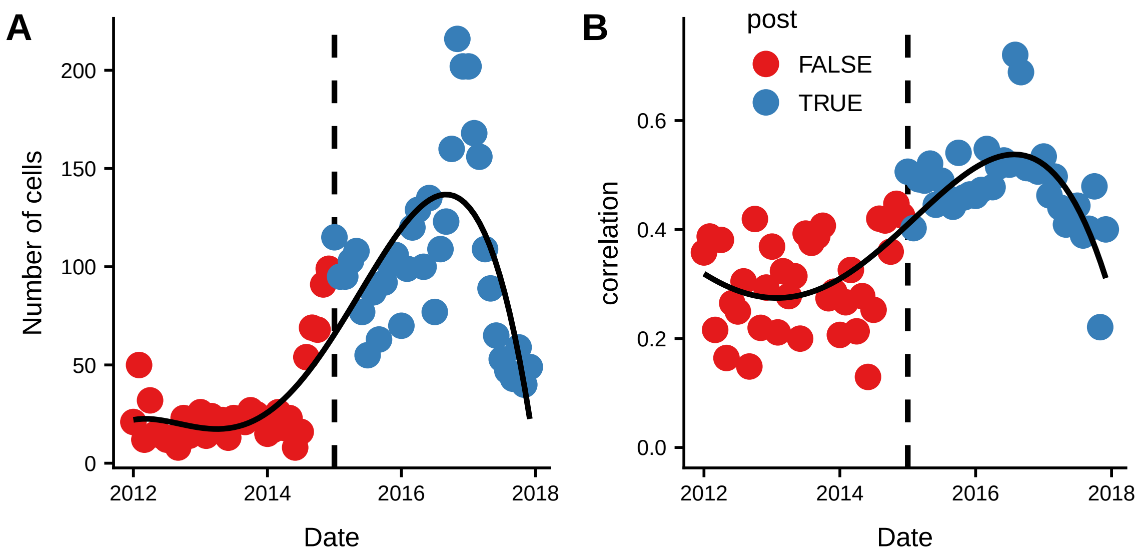

Fig. 8. Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B).

Table 4. Coefficient estimates for a third-polinomial fit to the measures of crowding. The first column shows coefficients for the number of cells with treated and control vessels during the same month. The second column shows coefficients for the spatial correlation for presence / absence of treated and control vessels. The explanatory variable is the number of months before implementation of PIPA. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)
Constant	65.538^{***} (5.878)	0.409^{***} (0.016)
Months	4.429^{***} (0.402)	0.010^{***} (0.001)
Months ^{2}	0.060^{*} (0.033)	0.00003 (0.0001)
Months ^{3}	-0.004^{***} (0.0004)	-0.00001^{***} (0.00000)
Months ^{4}	-0.0001^{***} (0.00003)	-0.00000 (0.00000)
Month FE	Yes	Yes
Flag FE	Yes	Yes
Observations	72	72
R^2	0.741	0.631

Note: *p<0.1; **p<0.05; ***p<0.01

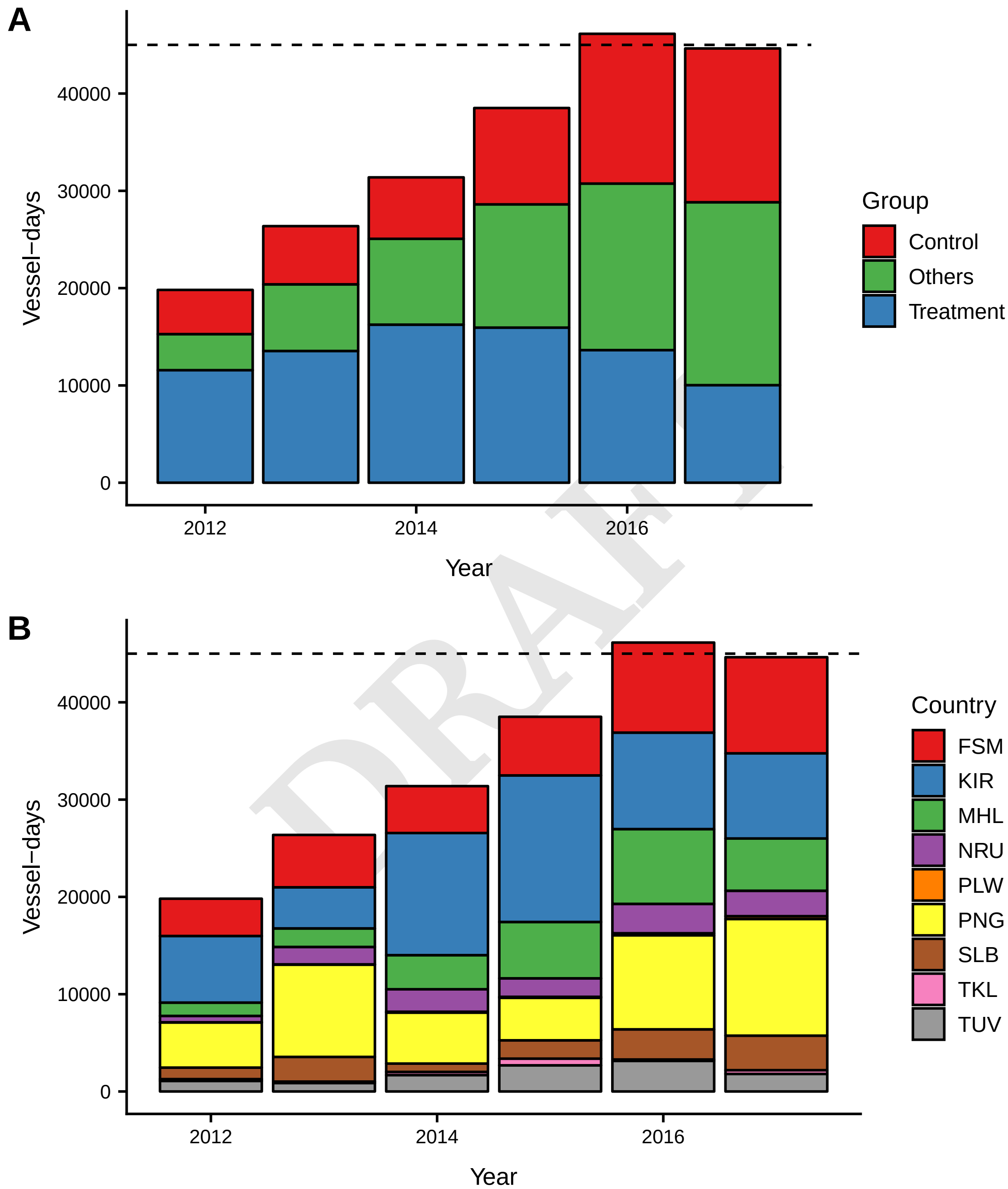

Fig. 9. A)Observed vessel-days for all VDS countries by fishing and non-fishing days. B) Observed vessel-days for all VDS countries by country.

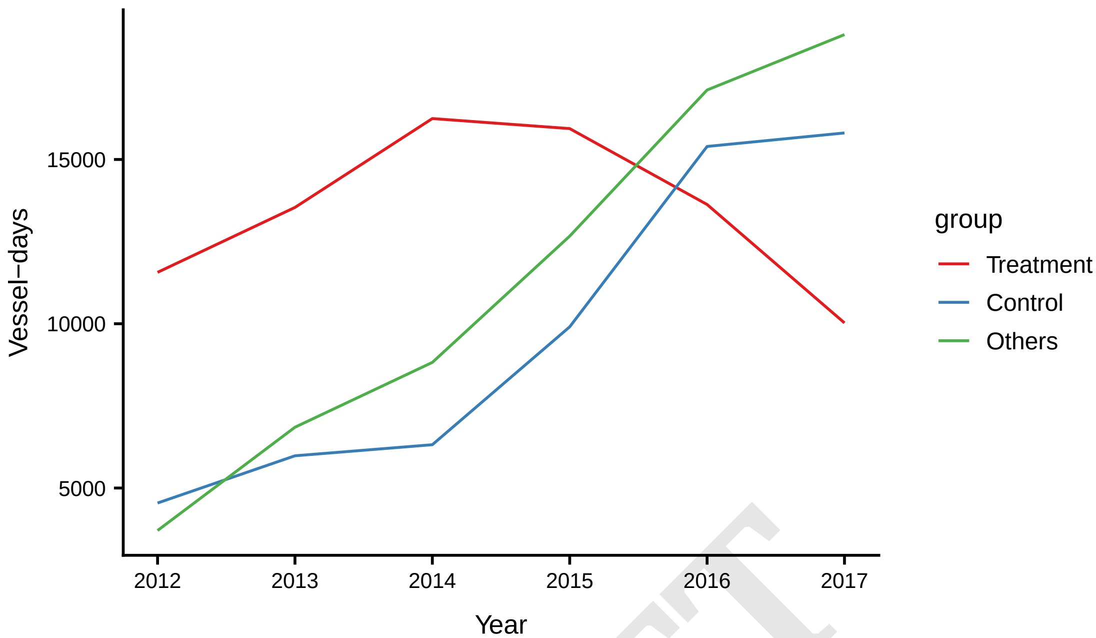

Fig. 10. Vessel days spent inside VDS waters by group of vessels.

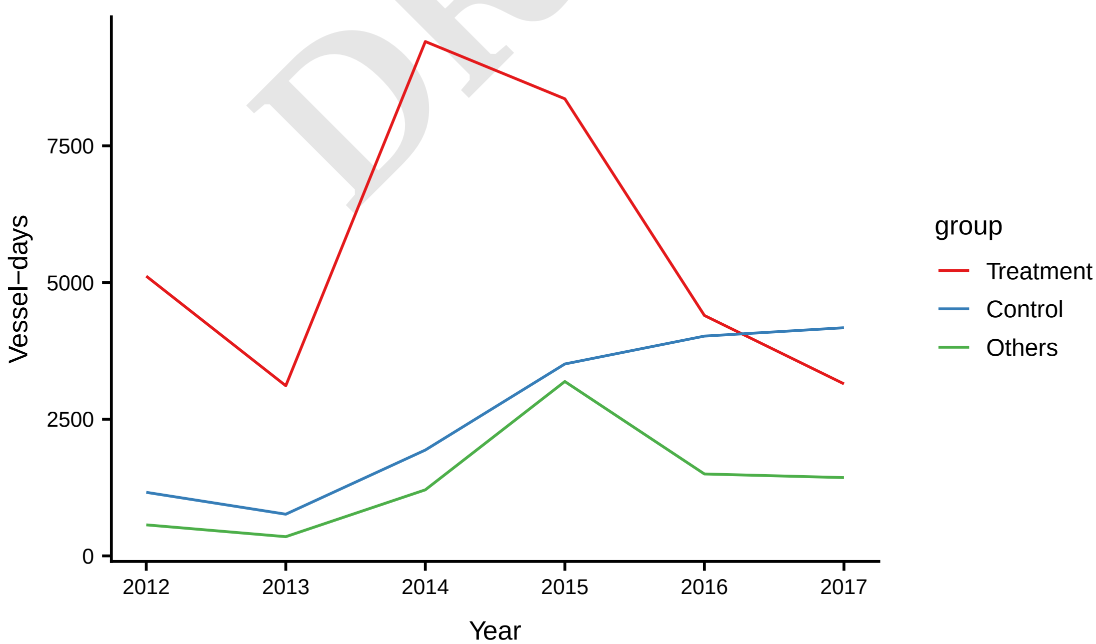

Fig. 11. Vessel days spent inside Kiribati waters by group of vessels.

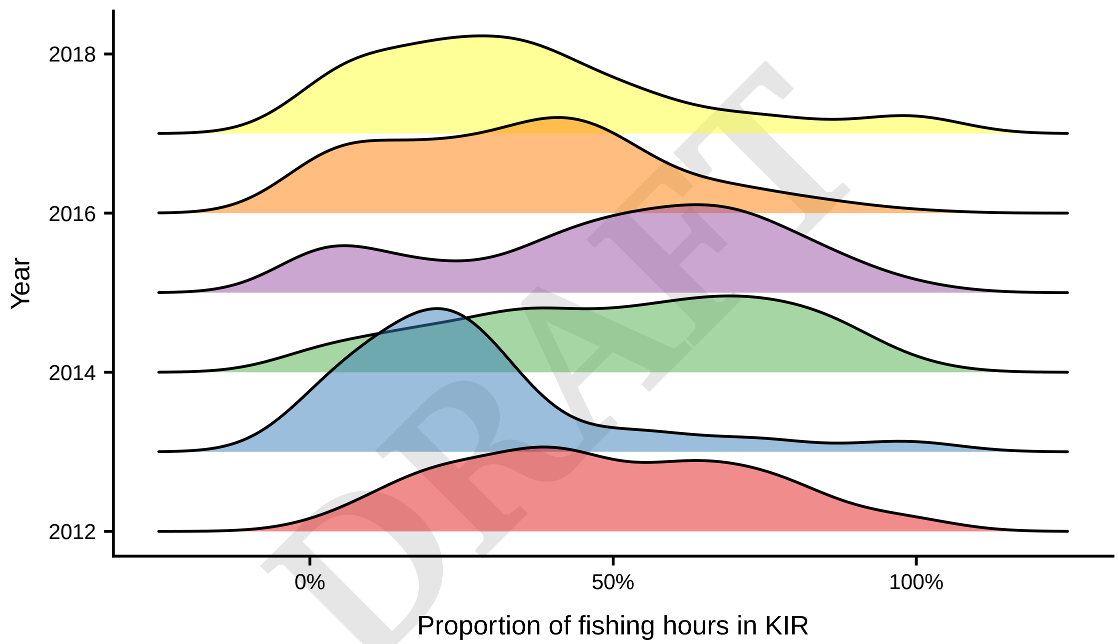

Fig. 12. Ridgeplot for the density of the % of total fishing hours that take place within Kiribati EEZ waters by year for treated vessels where the unit of observation is an individual vessel.

5. 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 (22). Others have used similar satellite-tracking systems to show that fishing effort accumulates near the edges of spatial closures, yielding greater catches over time (36). 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 (24) 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 (37–40). 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.

6. Conclusion

7. References

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8. Appendix

9. Palau National Marine Sanctuary

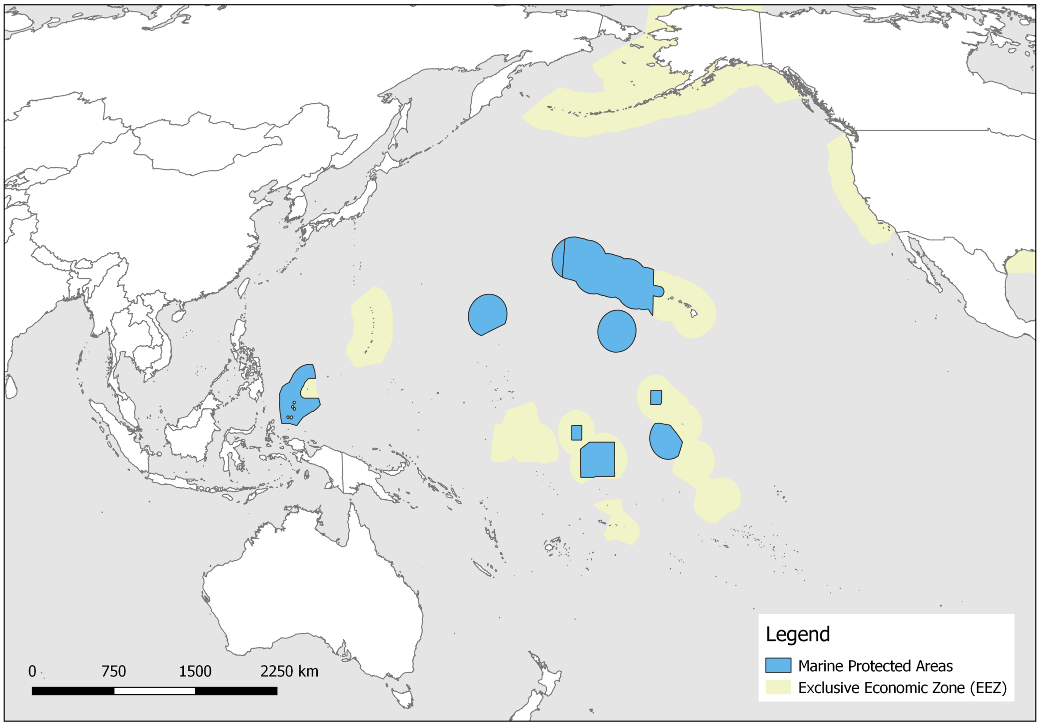

Fig. S1. Map of the Four Protected Areas

On October 28, 2015, the President of Palau, H.E. Tommy E. Remengesau Jr., signed into law the Palau National Marine Sanctuary (PNMS) Act. Starting in December 2020, this Act will close 500,000 km^2 to commercial fishing activities, creating the 14th largest protected area in the world. The sanctuary will fully protect about 80 percent of the nation's EEZ. The remaining 20% of Palau's EEZ (close to the most heavily populated islands: Koror and Babeldaob) will become a Domestic Fishing Zone in which traditional and domestic fishing activities will be allowed to provide fish solely for the domestic market (*i.e.* exports of pelagic fish will be prohibited). Alongside these protections, the Palau National Marine Sanctuary (PNMS) Act will support a domestic pelagic fishery. In this section, we use our preceding analysis on the ex-post impacts of PIPA to attempt to make some *ex ante* predictions about the potential impacts of PNMS. We start by giving some background on the fishing that is currently taking place inside the future PNMS.

A. 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 Japanese vessels. Foreign fishing activities stopped during WWII and started again in the 1960s when Japanese fishers 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 developed during the same time. During the 1980s, longline fishers 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 (41). There are currently three transshipment companies operating in Palau.

Purse seine vessels target schools of skipjack tuna that are then canned. Compared to other EEZs in the Pacific, especially the PNA EEZs, Palau's EEZ is not known to be a preferred fishing ground for purse seining (Sisior, pers. comm.). This can be seen in Figure 9. Currently all purse seine boats fishing in Palau's EEZ are Japanese and they do not land their catch in Palau (Table S1).

All longline vessels fishing in Palau's EEZ are foreign owned (Table S2). Japanese longline vessels do not land their catch 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) and Kuniyoshi Fishing Company (KFC)). Ninety-five percent of the catch from PITI and KFC contracted boats is exported to Japan upon landing in Koror (the largest town in and former capital of Palau). Most of the discards are either sold or donated in Palau. A very small portion of the discards is frozen and transported to Taiwan when vessels return to their home ports.

Table S1. Japanese Purse Seine Fleet Statistics

Year	No. Vessels	Catch in metric tonnes (mt)
2012	36	not reported
2013	5	246
2014	21	453
2015	30	169
2016	30	130

Source: Annual Report to the Western and Central Pacific Fisheries Commussion. Palau. 2017

Table S2. Longline Fleet Statistics

Year	Total Vessels	Flag	No. Vessels	Total catches (mt)
2012	77	Belize	2	not reported
		Taiwan	50	2080
		Japan	25	1148
2013	83	Belize	1	6
		Taiwan	54	1871
		Japan	28	1159
2014	71	Belize	1	not reported
		Taiwan	41	1356
		Japan	28	721
		Vanuatu	1	17
2015	51	Taiwan	30	970
		Japan	19	314
		Vanuatu	2	33
2016	57	China	3	40
		Taiwan	33	1828
		Japan	19	550
		Vanuatu	2	27

Source: Annual Report to the Western and Central Pacific Fisheries Commussion. Palau. 2017

A.1. Access fees and taxes. An agreement between Palau and four Japanese fishing associations[§§] covered three methods of fishing (longline, purse seine, and pole and line) and allowed Japan to have up to 290 vessels in Palau waters with no limits on catch. Japan paid 4-5% of catch returns for this access, but there was no way to validate their catch (42). Between 2010 and 2014, Japan paid Palau between $196,100- $867,120 annually in access fees (43). Currently, these access fees have been replaced by the PNA vessel day scheme (described earlier).

There used to be a number of agreements between the Republic of Palau and foreign owned, local based companies, in particular PITI and KFC, to allow longline fishing (42). Vessels under these agreements were internationally-owned, locally-based vessels that paid for annual licenses based on the size of each vessel. These are the vessels shown in Table S2 (excluding the Japanese vessels). So, for example, there were 38 vessels as part of these agreements in 2016. Between 2010 and 2014, licensing fee revenue from these agreements was between $219,000-$284,600 per year (43). These access fees have also been replaced by a new longline-specific version of the VDS (described in more detail below).

There are two multilateral treaties that grant preferential access to Palau waters to US and Federated States of Micronesia (FSM) flagged purse seine boats: the US Multilateral Tuna Treaty and the Federated States of Micronesia Arrangement. The US Treaty was renegotiated in 2016 with stipulations on minimum vessel day fees. 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. These agreements have been described by some commentators as foreign aid, with little connection to underlying fish stocks (43).

The export tax for all commercial tuna and billfish, either fresh or frozen, is $0.35/kg. Average annual revenue from export taxes was around $500,000 from 2011-2014 (43). Other than the access fees and tax revenue, Palau receives little additional economic benefits from pelagic fisheries, especially considering that very few jobs are created by the fishery. Between 80 to 90 people are employed by offshore fisheries, and of these only around 20% are Palauans, earning wages that are only 50% of average wages in Palau (43).

A.2. Parties to the Nauru Agreement and the Vessel Day Scheme. 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 current purse seine VDS allotment is reportedly around 700 vessel days annually (Sisior, pers. comm., (44)), although historically this number has been lower (average of 580 days between 2008-2011 (42)). Palau sells most of its vessel days to the US for $12,500 per day (as negotiated in the US treaty), regardless of whether US vessels actually fish in Palau's EEZ. The remainder of Palau's purse seine vessel days are sold for between $9-10,000 each. When vessel days are purchased to transfer to another EEZ, Palau charges a transfer

[§§] This is a single agreement between Palau and four associations—1)Federation of Japan Tuna Fisheries Cooperative 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).

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 vessel days to is Papua New Guinea (42) and in 2018, vessel days were sold to a fishing company in the Philippines for the first time (44). In 2018, Palau brought in approximately $9 million USD in 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 it at the country-scale. Palau was the first party to implement the VDS for longline fishing 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.

A.3. Potential Revenue Loss 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 longline VDS, but it is uncertain whether this is being followed for the purse seine VDS, because purse seine VDS can be transferred for use in other EEZs. There has been no official statement on what will happen to Palau's VDS upon full implementation of the 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 (45). Further, other PNA members have not been penalized for other protected area closures (e.g., PIPA) (Hanich, pers. comm.).

Table S3 presents estimates of the potential revenue losses following full enactment of the PNMS under four different scenarios. In Scenario 1, Palau is able to keep its current allotment of purse seine vessel days (700) and is able to sell them for a similar price to what it is currently selling them to the US for ($12,500/day). In Scenario 2, 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 2 is likely if Palau retains its current PAE, but the US no longer purchases 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 $12,500/day, respectively. In all scenarios, all longline vessel day and export tax revenues 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 (43)).

Table S3. Estimated revenue losses under different scenarios of PNMS (in USD)

Scenario	PS VDS	LL VDS	Export tax	Total revenue loss
1	0	-2,100,000	-482,236	-2,582,236
2	-3,150,000	-2,100,000	-482,236	-5,732,236
3	-5,600,000	-2,100,000	-482,236	-8,182,236
4	-8,750,000	-2,100,000	-482,236	-11,332,236

A.4. 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 (43). 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. 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 a domestic fishery (including those featured in a feasibility report by FFA (46)), but there has yet to be any official action towards a particular scenario.

10. Alternative Controls

Table S4. Difference-in-differences estimates for our 10 variables of interest: 1) Daily fishing hours, 2) Daily non-fishing at-sea hours, 3) Daily proportion of fishing hours to total at-sea hours, 4) Daily distance traveled, 5) Daily mean distance from port, 6) Daily mean distance from shore, 7) Daily mean distance from port for fishing events, 8) Daily mean distance from shore for fishing events, 9) Monthly proportion of hours spent in Kiribati waters, 10) Monthly proportion of fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	1.875***	3.860***	0.198***	4.878***	5.513***	10.647***	7.199***	13.886***	2.497***	2.624***
	(0.038)	(0.007)	(0.009)	(0.045)	(0.054)	(0.088)	(0.026)	(0.028)	(0.281)	(0.255)
Post	0.654***	−0.243***	0.157***	−0.099***	−0.077*	−0.201***	0.336***	0.248***	1.537***	1.556***
	(0.026)	(0.008)	(0.007)	(0.036)	(0.042)	(0.061)	(0.016)	(0.017)	(0.154)	(0.119)
Treated	0.008	0.008	−0.007	0.275***	0.059	0.087	0.180***	−0.018	0.393***	0.244**
	(0.028)	(0.006)	(0.007)	(0.032)	(0.037)	(0.055)	(0.017)	(0.018)	(0.151)	(0.119)
Post × Treated	−0.020	0.033***	0.0002	−0.250***	−0.248***	−0.267***	−0.281***	−0.059***	−0.531***	−0.368***
	(0.030)	(0.009)	(0.007)	(0.040)	(0.048)	(0.069)	(0.019)	(0.019)	(0.175)	(0.135)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	25,073	74,600	25,073	73,265	74,995	74,995	25,073	25,073	1,460	2,056
R^2	0.141	0.075	0.151	0.011	0.019	0.013	0.163	0.293	0.198	0.282

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

A. Excluding all Chinese vessels.

Table S5. Difference-in-differences estimates for our 10 variables of interest: 1) Daily fishing hours, 2) Daily non-fishing at-sea hours, 3) Daily proportion of fishing hours to total at-sea hours, 4) Daily distance traveled, 5) Daily mean distance from port, 6) Daily mean distance from shore, 7) Daily mean distance from port for fishing events, 8) Daily mean distance from shore for fishing events, 9) Monthly proportion of hours spent in Kiribati waters, 10) Monthly proportion of fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	2.438***	3.602***	0.362***	4.575***	5.007***	11.149***	6.400***	12.771***	2.842***	3.659***
	(0.042)	(0.012)	(0.011)	(0.051)	(0.056)	(0.080)	(0.030)	(0.028)	(0.238)	(0.187)
Post	0.466***	−0.173***	0.095***	−0.174***	−0.636***	−0.771***	0.096***	0.006	1.794***	1.778***
	(0.037)	(0.010)	(0.010)	(0.048)	(0.051)	(0.076)	(0.025)	(0.024)	(0.197)	(0.164)
Treated	−0.142***	0.023***	−0.059***	0.450***	0.048	0.158**	0.077***	−0.164***	0.570***	0.443***
	(0.037)	(0.007)	(0.009)	(0.040)	(0.043)	(0.067)	(0.025)	(0.025)	(0.197)	(0.164)
Post × Treated	0.152***	−0.031***	0.061***	−0.236***	0.275***	0.253***	−0.072***	0.139***	−0.910***	−0.728***
	(0.040)	(0.011)	(0.010)	(0.052)	(0.056)	(0.082)	(0.027)	(0.026)	(0.216)	(0.177)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	21,523	63,902	21,523	61,827	64,224	64,224	21,523	21,523	1,280	1,759
R^2	0.137	0.073	0.148	0.015	0.020	0.015	0.165	0.316	0.187	0.271

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

B. Excluding all PNA vessels.

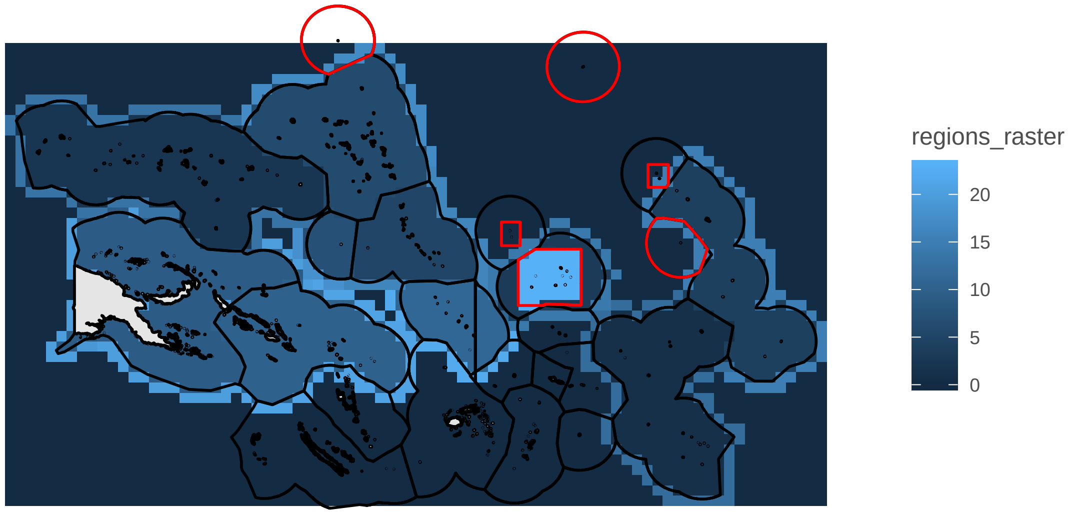

Fig. S2. Rasterized regions. Each color (number) indicates a distinct region.

Table S6. Difference-in-differences estimates for our 10 variables of interest: 1) Daily fishing hours, 2) Daily non-fishing at-sea hours, 3) Daily proportion of fishing hours to total at-sea hours, 4) Daily distance traveled, 5) Daily mean distance from port, 6) Daily mean distance from shore, 7) Daily mean distance from port for fishing events, 8) Daily mean distance from shore for fishing events, 9) Monthly proportion of hours spent in Kiribati waters, 10) Monthly proportion of fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	2.343***	3.624***	0.327***	4.599***	4.860***	11.030***	6.176***	12.513***	3.246***	4.062***
	(0.035)	(0.010)	(0.009)	(0.045)	(0.052)	(0.071)	(0.025)	(0.023)	(0.208)	(0.160)
Post	0.599***	−0.211***	0.139***	−0.167***	−0.364***	−0.532***	0.338***	0.261***	1.477***	1.457***
	(0.027)	(0.008)	(0.007)	(0.034)	(0.042)	(0.059)	(0.017)	(0.018)	(0.148)	(0.122)
Treated	−0.065**	0.007	−0.025***	0.326***	0.040	0.099*	0.158***	−0.010	0.375**	0.116
	(0.029)	(0.006)	(0.007)	(0.031)	(0.037)	(0.054)	(0.019)	(0.019)	(0.150)	(0.126)
Post × Treated	0.017	0.003	0.015**	−0.187***	0.070	0.077	−0.274***	−0.072***	−0.562***	−0.353**
	(0.031)	(0.009)	(0.008)	(0.039)	(0.048)	(0.068)	(0.020)	(0.020)	(0.170)	(0.139)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	24,152	73,259	24,152	73,001	73,668	73,668	24,152	24,152	1,420	1,998
R^2	0.143	0.075	0.154	0.014	0.021	0.015	0.157	0.291	0.174	0.246

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

C. Excluding all USA and TWN vessels.

D. Effort redistribution.

D.1. Rasterized regions.