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

Juan CarlosVillaseñor-Derbez[a,1] **and John Lynham**[b]

[a]Bren School of Environmental Science & Management, University of California at Santa Barbara, Santa Barbara, CA; [b]Department of Economics, University of Hawaii at Manoa, Honolulu, HI

This manuscript was compiled on February 27, 2019

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. The fishery in the region operates under a vessel-day scheme (VDS), which sells access rights that allow vessels to fish in PNA waters. In 2015, PNA member Kiribati implemented one of the world's largest conservation areas: The Phoenix Island Protected Area (PIPA, 397,447 km^2), effectively excluding all tuna purse seining activities. Such an intervention is likely to have effects on vessel spatial distribution and behavior, as well as induce costs (due to the reduction in fishable area) to Kiribati. We use identification of fishing activity via Automatic Identification Systems and causal inference techniques to evaluate the effect of PIPA on vessel distribution, behavior, and costs to Kiribati and the PNA. We find a short-term crowding effect within PNA waters after the implementation of the protected area. Vessels continue to fish with similar intensity after the implementation. The eventual decrease in crowding within PNA waters but constant fishing intensity suggests that vessels redistribute to adjacent waters, including the high seas. This redistribution results in a reduction of 2,310 vessel-days in Kiribati, which represents a loss of \$27.7 million USD; similar estimates are obtained when looking at country-level license fees revenues directly (\$30.5 million USD). We use our results to inform predictions of the impacts of a proposed LSMPA in Palau (a PNA member) and estimate potential losses to range from \$2.5 to \$11 million annually. PNA members who decide to implement MPAs should consider mechanisms that reward such conservation actions.

Marine Spatial Planning | Fisheries | Marine Conservation

1. Introduction

Humans are increasingly utilizing the oceans. Multiple ocean uses such as off-shore aquaculture, conservation, energy harvesting, deep-sea mining, and fisheries are likely to compete for space. As we move forward with blue growth, we must understand the potential effects of activities displacing each other and etablish causal links between past management interventions and their outcomes (1). One of the most notable spatial spatial interventions are no-take Marine Protected Areas, which seek to conserve the environment by eliminating fishing effort within their waters.

Global 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 in MPA coverage (2, 3), largely driven by a small number of Large-Scale Marine Protected Areas (LSMPAs), some of which ocurr in the world's largest fishing grounds for tuna. While today a small number of LSMPAs make up at least 80% of the managed areas in the ocean (4), very little is known about their human dimensions and implication for fisheries (5). Furthermore, most of the research on LSMPAs has focused on their potential ecological benefits, but have left aside the economic implications. One issue of particular importance is that of the displacement or redistribution of fishing effort, which may influence the outcomes of a spatial closure and represent large opportunity costs (6, 7).

The Phoenix Island Protected Area (PIPA) in Kiribati is one of the most notable Large-Scale Marine Protected Areas. Implemented in January 1st of 2015, PIPA has an extension of 397,447 km^2 and was implemented within an area that produces 50% of the World's tuna. Tuna purse seine fisheries in the region are collectively managed under a Vessel-day scheme (VDS) by nine countries commonly refered to as the 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% (14.6 million km^2) of historical skipjack

Significance Statement

The oceans are becoming increasingly crowded, with different activities competing for space, but little research has been done to understand how activities displace each other. Marine Protected Areas are inherently spatial and have the sole objective of conserving bounded waters through the displacement of fishing effort. Our work shows that displacement of fishing effort occurs, but that it comes at a large cost to countries that would have otherwise been able to charge a price for vessels to fish in the now-protected areas. With global conservation targets seeking to protect 10% of the world's ocean by 2020 and the expansion of offshore aquaculture, it is important that the spatial displacement of economic activities is fully considered.

All authors contributed equally to this work

The authors declare that they have no conflicts of interest

[1]To whom correspondence should be addressed. E-mail: juancarlos@ucsb.edu

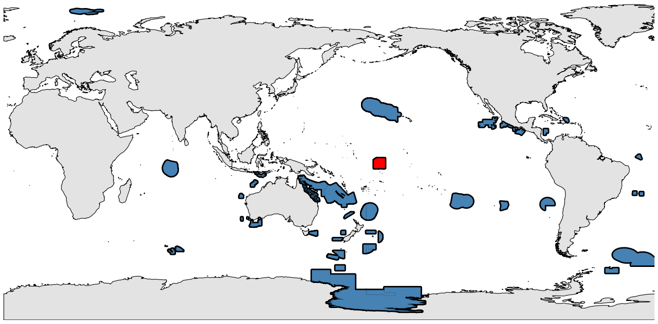

Fig. 1. Large Scale Marine Protected Areas. The map shows all areas larger than 30,000 Km^2. The Phoenix Island Protected Area is shown in red.

tuna purse seine grounds within their Exclusive Economic Zones (EEZ), PNA countries have achieved greater bargaining power when providing fishing access to foreign fleets (8). The revenue from access fees may represent up to 50% of government revenue for some of the members.

A spatial closure of such dimensions is likely to cause changes in spatial distribution and behavior of fishing vessels. For example, the anticipation of LSMPAs may lead to preemptive overfishing, which will likely erodes or delay the expected benefits of an intervention (9). After a spatial closure, users can exhibit idiosyncratic responses driven by different incentives (10). Moreover, this reduction in total fishing area within one country's EEZ is likely to result in selling less fishing licenses. While no studies have assessed the immplications of PIPA, other PNA members have pledged the implementation of LSMPAs by 2020. We evaluate the behavioral responses and spatial redistribution of the industrial tuna purse seine fleet resulting from the implementation of the Phoenix Islands Protected Area, and quantify its economic ramifications and impacts to Kiribati. 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 controled by PNA countries, where the largest tuna fisheries ocurr.

We use identification of fishing activity via Automatic Identification Systems (AIS) to track 313 tuna purse seine vessels that fished in PNA waters between 2012 and 2018. We continuously observe 92 vessels for the 2012 - 2018 period. Of these, 64 vessels fished within PIPA at least once prior to its implementation. The remaining 28 vessels never fished in PIPA these waters. We refer to these groups as treated and control groups. The group with the remaining 221 vessels contains vessels that were not observed before and after the implementation of PIPA, and we refer to these as "other vessels".

2. Results

A. Crowding effect. We first inspect the crowding effects that may arise due to the net reduction in fishing area. We produced 1-degree rasters of monthly fishing effort for our treatment and control groups, and calculated two indices of spatial overlap between thm: 1) the number of cells that had fishing activity from treated and control vessels for each month and 2) the correlation of presence/absence of fishing events between both groups over one month. We find that the two fleets significantly interact more with each other after the implementation of PIPA (Table S2 Fig. 2). The number of vessels with presence from both fleets and spatial correlations increase by a factor of four and three, respectively. This increase in crowding is likely to increase the encounter rates within vessels, and reduce the efficiency of fishing opperations, resulting in a nusicance to vessels. This would cause vessels to leave curent fishing grounds, leading to the subsequent decrease as the crowding measures return to pre-implementation levels.

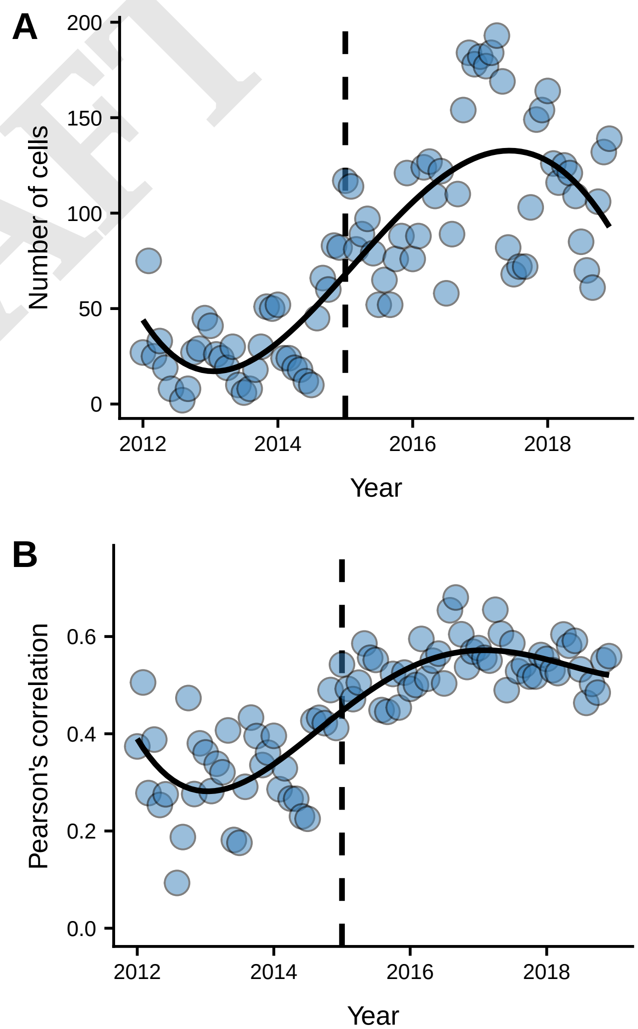

Fig. 2. Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B). The solid lines represent the 4[th] degree polynomial fit reported in S2

B. Behavioral changes. 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. For every vessel in each group, we calculate in eight key measures that could capture responses to spatial closures: daily fishing hours, daily non-fishing at-sea hours, the proportion of fishing to non-fishing hours at sea, daily distance traveled, daily mean distance from shore of fishing events (km), daily mean distance from port of fishing events (km), as well as monthly hours spent in PNA waters and Kiribati waters (Fig. S2). We leverage our BACI design and implement a log-linear difference-in-differences analyses to evaluate how these measures change for treated vessels after implementation of PIPA, relative to the trends observed for control vessels (See Methods section for our empirical specification).

We find no evidence of treated vessels fishing for more hours after PIPA implementation, and a slight increase of 1% more time at sea ($p < 0.05$; Table S5). Treated vessels traveled 20% less, with fishing events ocurring 23.8% closer to shore and 5% closer to port. These changes in distance from shore and port are likely caused by redistribution, as we observe that treated vessels fish 58% and 45% less in PNA and Kiribati waters, compared to the trend observed for control vessels ($p < 0.01$). The fact that the amount of time that vessels spent at sea (fishing and non-fishing) did not decrease, and that their time spent in PNA and Kiribati waters decreases suggests that these vessels have re-distributed elsewhere. This is consistent with the eventual decrease in crowding meassures.

C. Economic impacts. The crowding effect combined with the reduction of hours spent in Kiribati and PNA waters overall suggests that treated vessels have redistributed elsewhere, meaning that they no longer buy access fees from PNA countries. To quantify the potential impacts of this leakage, we estimate the total annual vessel-days received by all PNA countries by each group of vessels (Fig. 3). In this case we look at all 313 vessels, but continue to group them as treated (n = 64) and control (n = 28) vessels, as well as other vessels (n = 221). We find that the treated vessels spent 2,310 less days in PNA waters when comparing their values for 2015 and 2016, while control and other vessels increased their activities in PNA waters by 5,489 and 4,447 days for the same period, respectively (Fig. 4). The 2,310 vessel-day reduction by treated vessels corresponds to $27.7 million USD at an average price of $12,000 USD per vessel-day. Looking at the total anual vessel-days allocated by all vessels to all countries, we see that the largest reductions ocurr for Kiribati, while Papua New Guinea exhibits a proportional increase (Fig. S3). Furthermore, in 2017 treated vessels exhibit the lowest vessel-day allcoation to PNA waters at just 10,026 vessel-days. This is 2,526 vessel-days lower (~$30.3 million USD) than pre-implementation levels of 2012 - 2013 (mean ± sd of 12,552.46 ± 1,396.46; we exclude 2014 due to the blue paradox effect (9)).

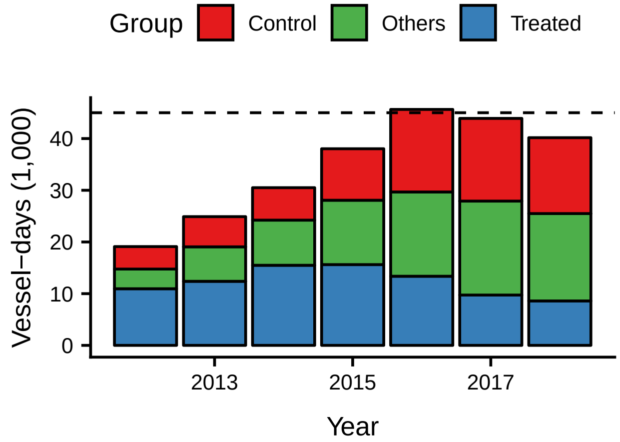

Fig. 3. Observed vessel-days for all countries by treated, control, and excluded vessels.

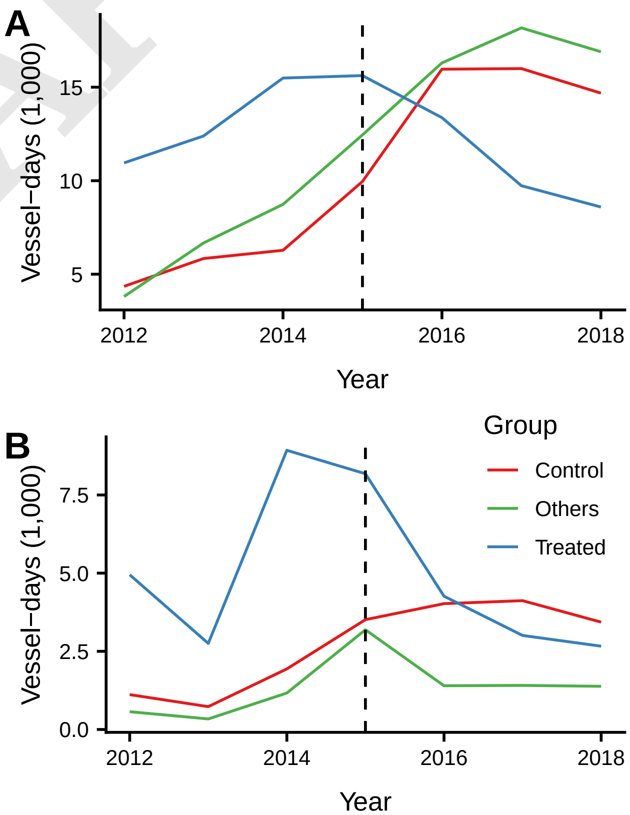

Fig. 4. Vessel days spent inside A) PNA waters and B) Kiribati waters by group of vessels.

We compliment our analysis of change in observed vessel-days by looking at country-level data. Specifically,

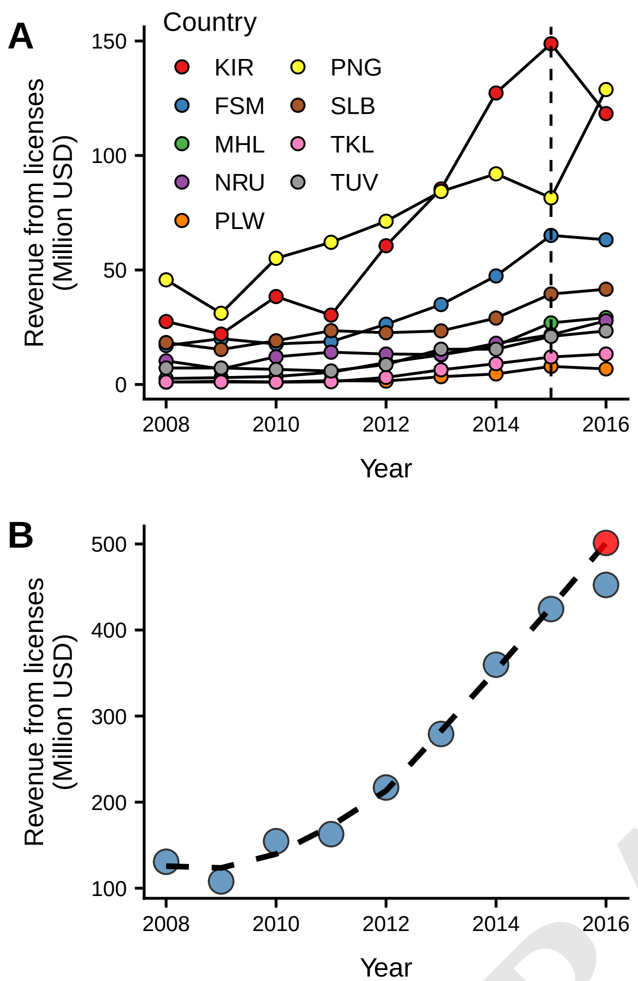

Fig. 5. Financial indicators for PNA countries. A) Revenue from fishing licenses fees, B) Total annual revenues for all 9 PNA countries with dashed line showing the local polynomial regression fit to the 2008 - 2015 data and the red dot representing the prediction from this regression. Vertical dashed line in both plots denotes implementation of PIPA.

we use data compiled by the Pacific Islands Forum Fisheries Agency (FFA*) where annual revenues from license fees are reported for each country (2008 - 2016; Fig. 5A). We find that by 2016, Kiribati's revenue went from $148.8 million USD in 2015 to $118.3 million USD in 2016, representing a decrease of $30.5 million USD. We then calculate total annual revenues to all PNA members (Fig. 5B). To estimate what would have been the total revenue to PNA members, we use a local polynomial regression fit to obtain a trend line for the total revenues between 2008 and 2015, and extrapolate the trend to obtain an expected value for 2016. Our model suggests that total revenues to all PNA members in 2016 should be in the order of $463.5 million USD, but the FFA data show only $423.5 million, suggesting that potential losses to the entire PNA are in the order of $40 million USD.

Catches for each country's EEZ for the 1997 - 2016 period were also obtained from the FFA (Fig. S5). Catches in Kiribati waters decreased from 24,051 to 12,894 tonnes between 2015 and 2016 (46.3% decrease). Similar decreases were observed for The Federal States of Micronesia (60.9%), Papua New Guinea (43.4%) and the Solomon Islands (58.5%). In contrast, Tokelau (due south of Kiribati) showed a 22.3% increase in catches over the same period.

* https://www.ffa.int/node/2050

D. Potential Revenue Loss for Palau. 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. 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 (11). Further, other PNA members have not been penalized for other protected area closures (e.g., PIPA) (Hanich, pers. comm.).

Table 1 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 (12)).

Table 1. 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

3. Discussion

Our findings provide insights into the effect that LSMPAs can have on vessel behavior and the redistribution of fishing effort. We find a short-term crowding effect after the implementation of the protected area. Behavioral analysis shows that the implementation of PIPA had little effect on the total fishing effort exerted by purse seiners. This, combined with our analysis of crowding effects that eventually return to pre-implementation levels, suggests that vessels redistribute elsewhere. Our analysis suggests that vessels that fish elsewhere represent a loss in profits of around $27.7 million USD to Kiribati. A thought experiment for Palau's Marine Sanctuary suggests losses in profits of up to $11 million USD. Here, we discuss the implications of our findings and possible shortcommings in our analyses.

Previous studies on protected areas around Pacific islands suggest that vessels move to distant places, which might be translated as increased costs (13). Others have used similar satellite-tracking systems to show that fishing effort accumulates near the edges of spatial closures, yielding greater catches over time (14). 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 (15) 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.

A major shortcoming of our analysis is that we do not observe catches or revenues at he vessel level, 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 and redistribution 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 S7), and it's unlikely that they would need to invest much time to identify new fishing grounds.

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 (16–19). Our work suggests that the implementation of LSMPAs has little impact on total fishing effort, but that it may result in large losses to countries. We also show that spatial closures lead to short-term crowding effects, which causes vessels to redistribute to areas close by. 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. While LSMPAs can provide a wide range of benefits, their implementation must be accompained with traditional fisheries management to maximize effectiveness, consider the opportunity costs of such closure, and identify sustainable mechanisms that would compensate losses and incentivize marine conservation.

4. Methods

A. Data. Automatic Identification Systems (AIS) are onboard 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 algorithms (convolutional neural networks) on the broadcast messages to infer what type and location of fishing events (20).

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 excludes all Chinese vessels, the second group excludes all PNA vessels, and the third group excludes US and Taiwanese vessels. Our main definition of treatment and control groups leaves us with 64 treated and 28 control vessels, which have just over 36 million observations.

B. Analyses.

B.1. Crowding effect. If the implementation of the reserve induces a crowding effect, we would expect to observe no

$$y_t = \alpha + \beta_1 M_t + \beta_2 M_t^2 + \beta_3 M_t^3 + \beta_4 M_t^4 + \epsilon_t \quad [1]$$

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 (M) before or after the implementation. For example, 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.

B.2. Behavioral changes. We then focus 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:

$$log(y)_{i,t} = \alpha + \beta_1 P_t + \beta_2 T_i + \beta_3 P_t \times T_i + \phi_t + \gamma_i + \epsilon_{i,t} \quad [2]$$

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[†].

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

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

B.3. Revenues. Information about FFA reports here

5. References

1. Burgess MG, Clemence M, McDermott GR, Costello C, Gaines SD (2018) Five rules for pragmatic blue growth. *Marine Policy* 87:331–339.
2. Wood LJ, Fish L, Laughren J, Pauly D (2008) Assessing progress towards global marine protection targets: shortfalls in information and action. *Oryx* 42(03).
3. Sala E, et al. (2018) Assessing real progress towards effective ocean protection. *Marine Policy* 91(2):11–13.
4. Toonen RJ, et al. (2013) One size does not fit all: the emerging frontier in large-scale marine conservation. *Mar Pollut Bull* 77(1-2):7–10.
5. Gray NJ, et al. (2017) Human dimensions of large-scale marine protected areas: Advancing research and practice. *Coastal Management* pp. 1–9.
6. Smith MD, Wilen JE (2003) Economic impacts of marine reserves: the importance of spatial behavior. *Journal of Environmental Economics and Management* 46(2):183–206.
7. Smith MD, Lynham J, Sanchirico JN, Wilson JA (2010) Political economy of marine reserves: understanding the role of opportunity costs. *Proc Natl Acad Sci USA* 107(43):18300–18305.
8. Havice E (2010) 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.
9. McDermott GR, Meng KC, McDonald GG, Costello CJ (2018) The blue paradox: Preemptive overfishing in marine reserves. *Proc Natl Acad Sci USA*.
10. Cabral RB, Gaines SD, Johnson BA, Bell TW, White C (2017) Drivers of redistribution of fishing and non-fishing effort after the implementation of a marine protected area network. *Ecol Appl* 27(2):416–428.
11. Senase JRT (2015) Micronesian presidents call on pna to support palau sanctuary. *Island Times*. Palau.
12. Gillett R (2016) *Fisheries in the economies of the Pacific island countries and territories*. (Pacific Community), 2nd edition.
13. Stevenson TC, Tissot BN, Walsh WJ (2013) Socioeconomic consequences of fishing displacement from marine protected areas in hawaii. *Biological Conservation* 160:50–58.
14. Murawski S, Wigley S, Fogarty M, Rago P, Mountain D (2005) Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science*.
15. Elahi R, et al. (2018) Leveraging vessel traffic data and a temporary fishing closure to inform marine management. *Front Ecol Environ*.
16. White C, Costello C (2014) Close the high seas to fishing? *PLoS Biol* 12(3):e1001826.
17. Sumaila UR, et al. (2015) Winners and losers in a world where the high seas is closed to fishing. *Sci Rep* 5(1):8481.
18. Sala E, et al. (2018) The economics of fishing the high seas. *Sci Adv* 4(6):eaat2504.
19. Schiller L, Bailey M, Jacquet J, Sala E (2018) High seas fisheries play a negligible role in addressing global food security. *Sci Adv* 4(8):eaat8351.
20. Kroodsma DA, et al. (2018) Tracking the global footprint of fisheries. *Science* 359(6378):904–908.
21. R Core Team (2018) *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria).

6. Appendix

424

7. Supplementary tables and figures

425

Table S1. 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 for fishing events, 6) Daily mean distance from shore for fishing events, 7) Monthly fishing hours spent in Kiribati waters, 8) Monthly fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.497***	3.607***	0.075***	5.203***	12.997***	12.461***	3.678***	4.445***
	(0.022)	(0.012)	(0.004)	(0.029)	(0.021)	(0.019)	(0.192)	(0.151)
Post	0.839***	−0.228***	0.137***	0.304***	0.326***	0.296***	1.059***	1.180***
	(0.016)	(0.008)	(0.003)	(0.019)	(0.014)	(0.014)	(0.140)	(0.109)
Treated	0.136***	0.014**	0.015***	0.400***	0.223***	0.116***	0.534***	0.149
	(0.013)	(0.007)	(0.002)	(0.020)	(0.016)	(0.016)	(0.148)	(0.118)
Post × Treated	−0.244***	0.013	−0.034***	−0.483***	−0.281***	−0.155***	−0.565***	−0.399***
	(0.019)	(0.009)	(0.003)	(0.022)	(0.017)	(0.017)	(0.161)	(0.127)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	83,052	83,052	83,051	64,387	32,055	32,055	1,814	2,588
R^2	0.102	0.072	0.107	0.028	0.062	0.080	0.113	0.198

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

Table S2. 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	67.894*** (5.363)	0.448*** (0.014)
Months	3.301*** (0.317)	0.009*** (0.001)
Months ^{2}	0.007 (0.023)	−0.0001** (0.00005)
Months ^{3}	−0.002*** (0.0003)	−0.00001*** (0.00000)
Months ^{4}	0.00001 (0.00002)	0.00000** (0.00000)
Month FE	Yes	Yes
Flag FE	Yes	Yes
Observations	83	84
R^2	0.681	0.683
Note:		*p<0.1; **p<0.05; ***p<0.01

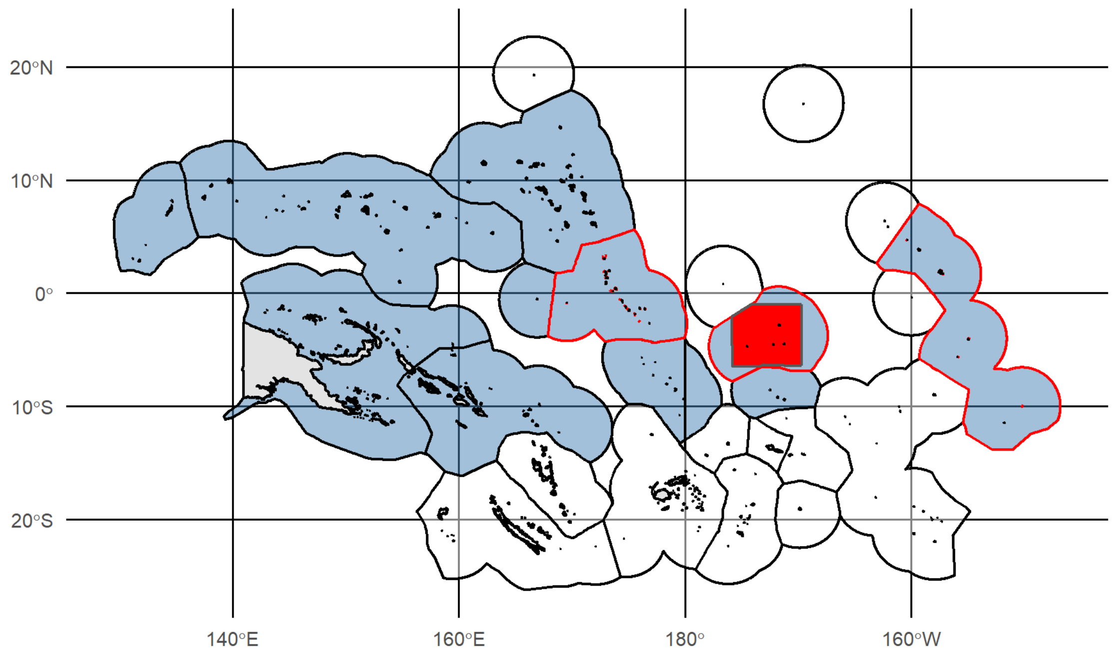

Fig. S1. Map of the Exclusive Economic Zones (EEZs) of the region of interest. Countries that belong to the PNA are shown in blue, while empty polygons indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA.

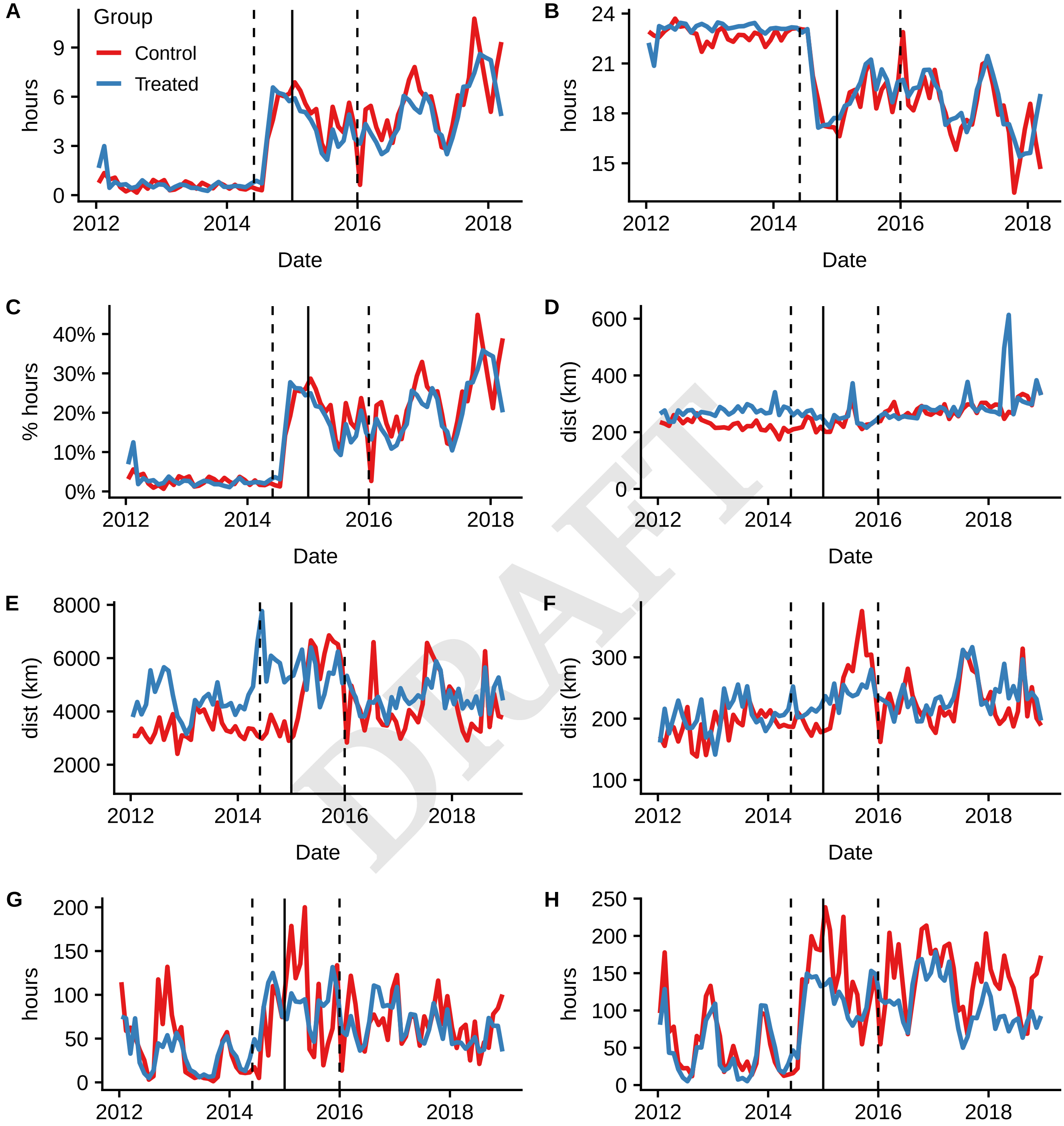

Fig. S2. Time series showing monthly averages for eight variables of interest: A) Fishing hours, B) Non-fishing hours at-sea, C) Proportion of fishing hours to total hours at-sea, D) Distance traveled, E) Mean distance from port for fishing evetns, F) Mean distance from shore for fishing events, I) Monthly hours spent in Kiribati waters, J) Proportion of fishing hours spent in PNA waters.

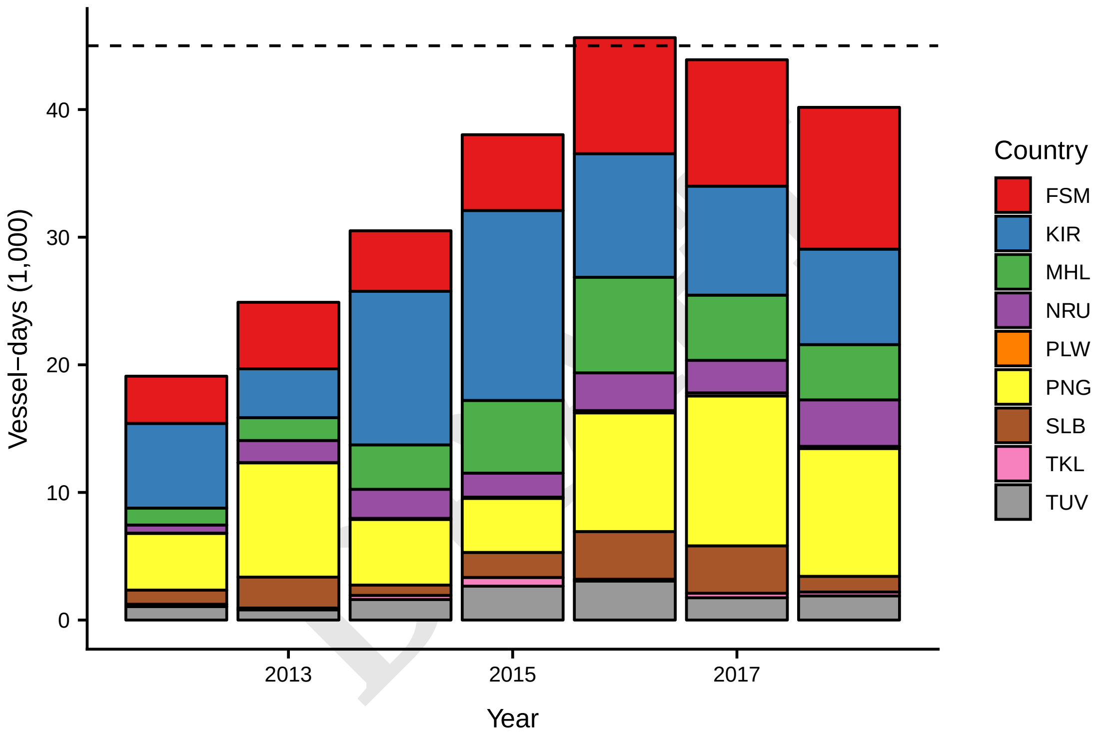

Fig. S3. Observed vessel days by country and year

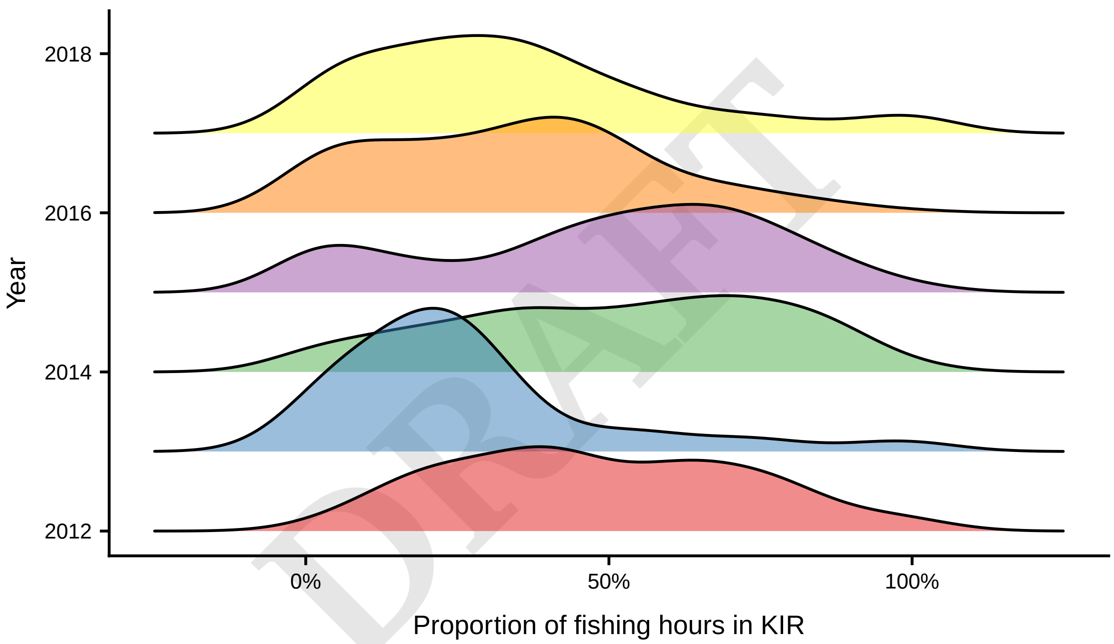

Fig. S4. Ridgeplot for the density of the % of total fishing hours that take place within Kiribati EEZ waters by year for treated vessels where the unit of observation is an individual vessel.

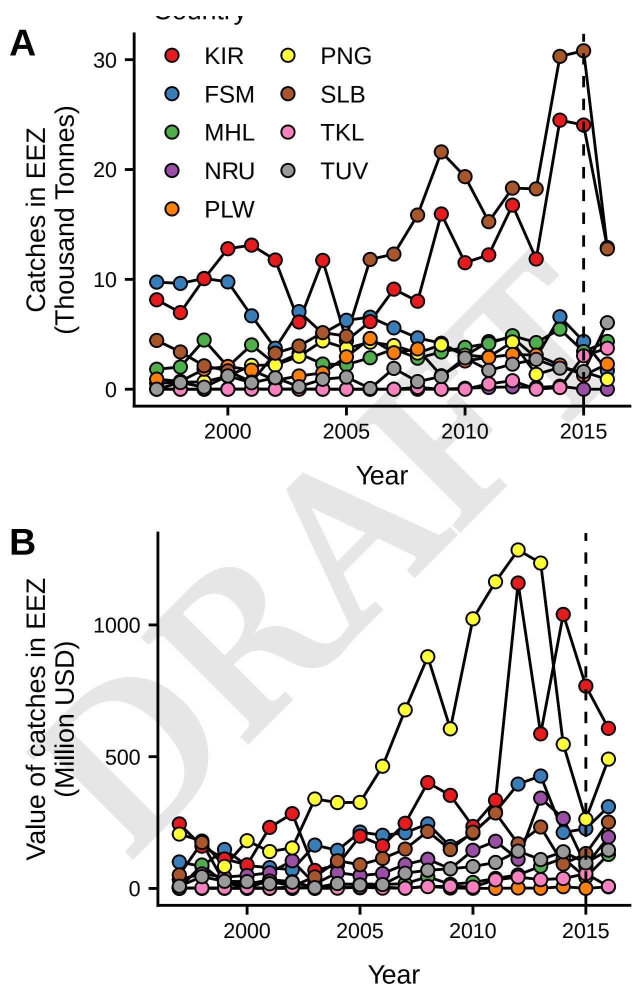

Fig. S5. Financial indicators for PNA countries. A) Annual catches by EEZ and, B) Annual value of catches by EEZ. Vertical dashed line in both plots denotes implementation of PIPA.

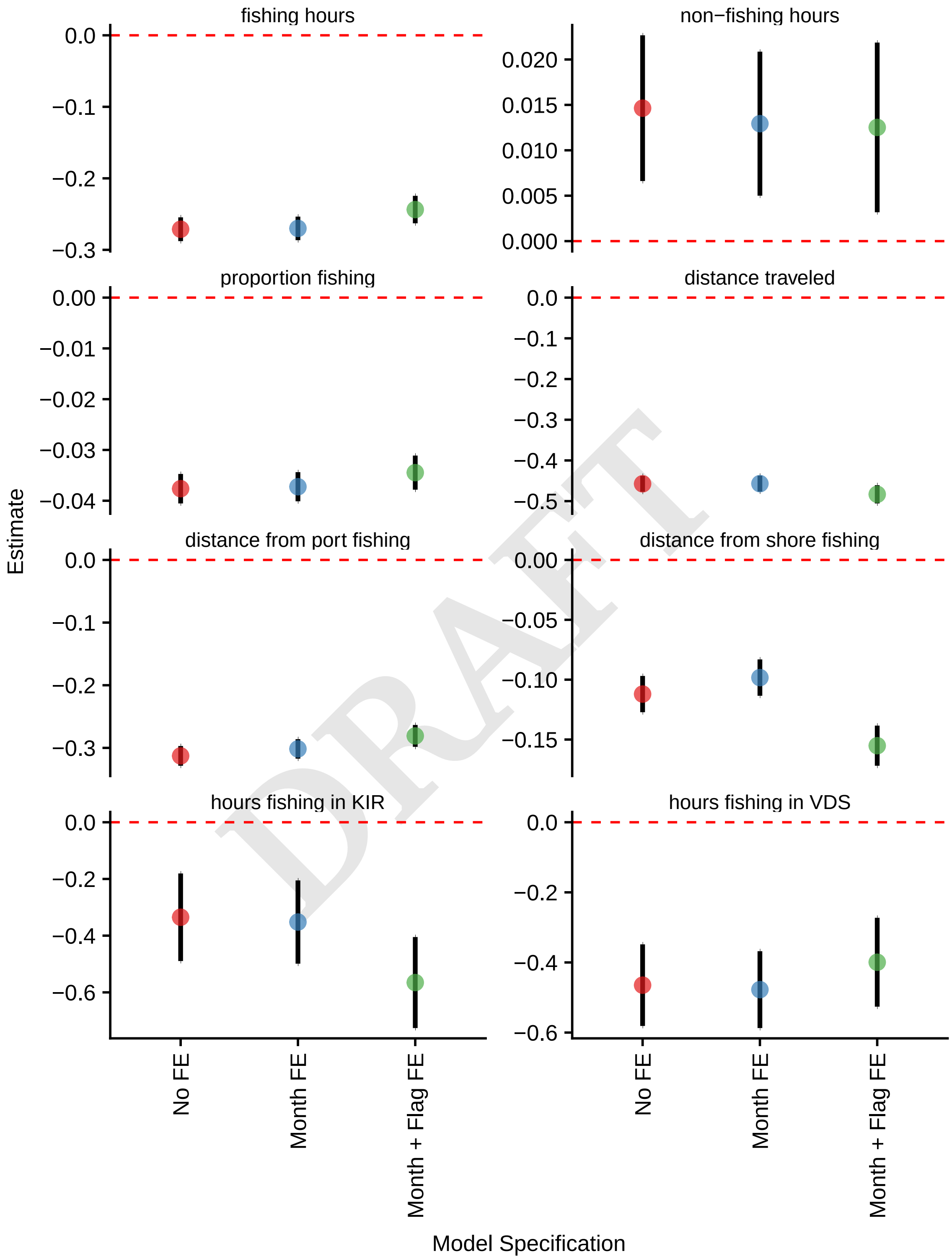

Fig. S6. Alternative difference-in-differences estimates for our variables of interest using different model specifications. Table S5 reports estimates for models with month and flag fixed effects (*i.e.* green dots).

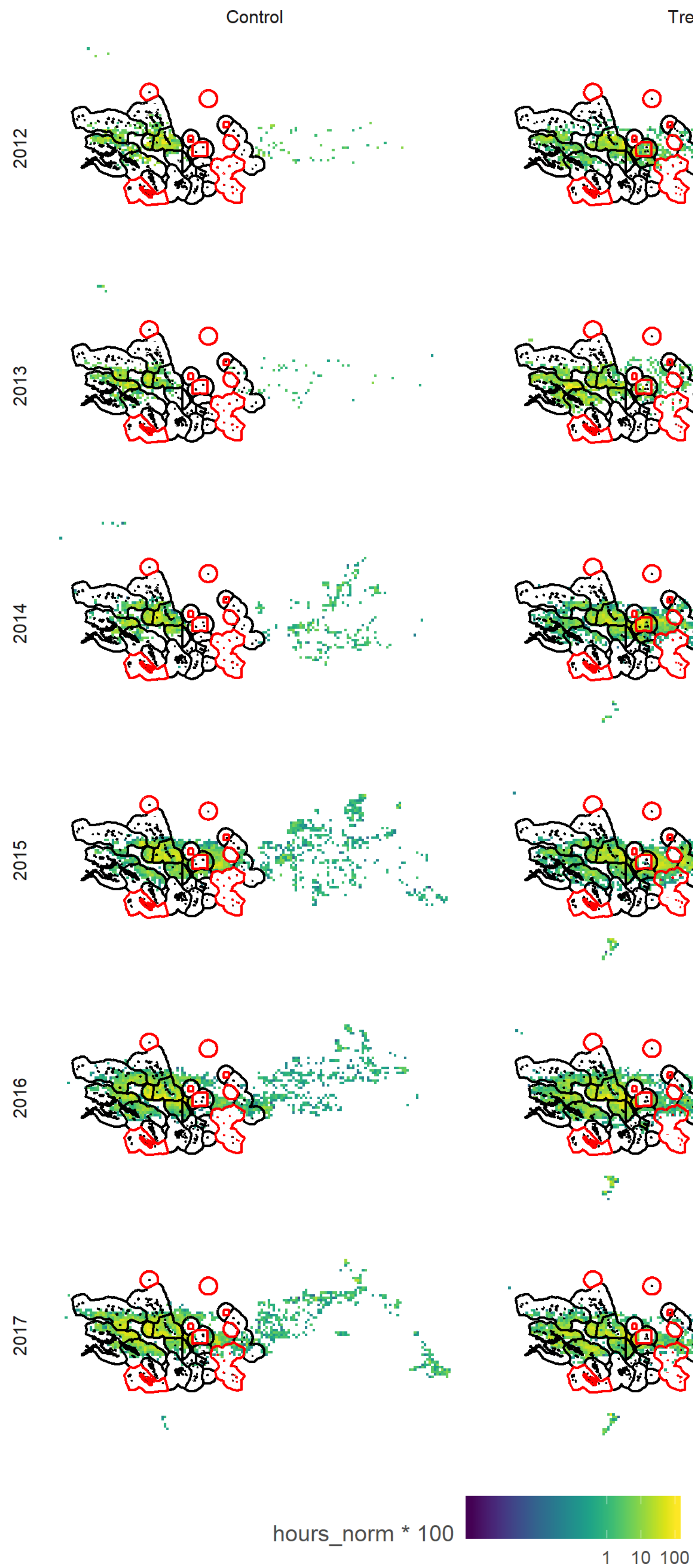

Fig. S7. Yearly spatial distribution of fishing effort by treated and control vessels. Color corresponds to % of total fishing effort in each panel. Red polygons show LSMPAs in the region.

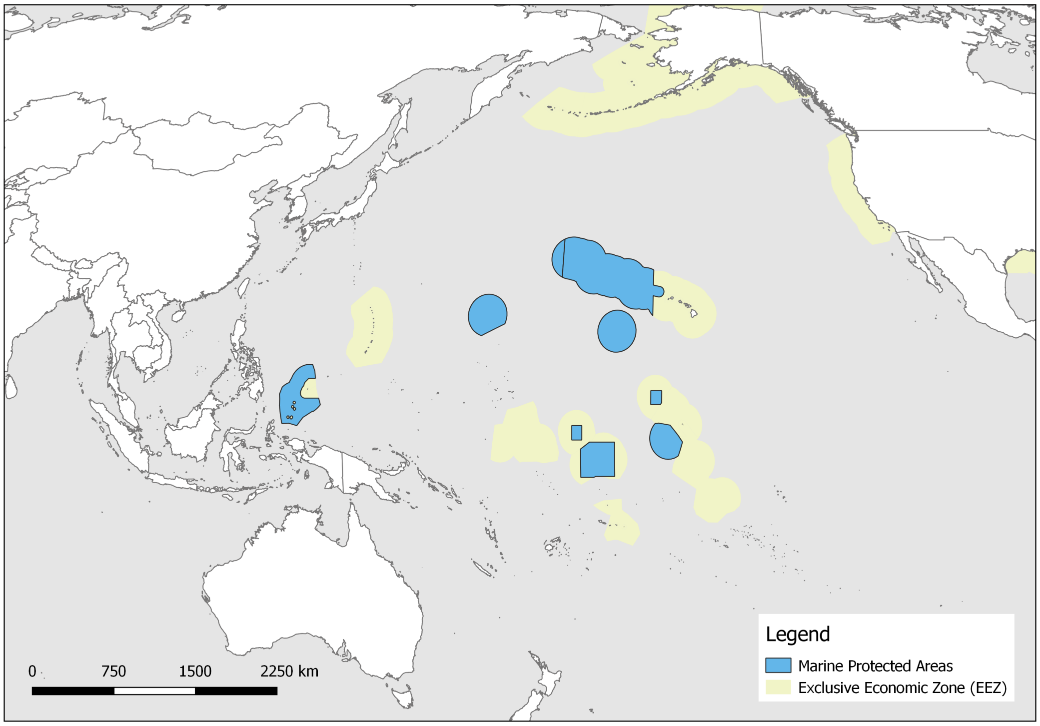

Fig. S8. Map of the Four Protected Areas

8. Palau National Marine Sanctuary

9. Alternative Controls

Table S3. 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 for fishing events, 6) Daily mean distance from shore for fishing events, 7) Monthly fishing hours spent in Kiribati waters, 8) Monthly fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.060***	3.864***	−0.003	6.149***	13.775***	13.146***	3.896***	4.484***
	(0.019)	(0.008)	(0.003)	(0.043)	(0.044)	(0.058)	(0.341)	(0.303)
Post	0.817***	−0.258***	0.136***	0.125***	0.365***	0.344***	1.056***	1.205***
	(0.018)	(0.009)	(0.003)	(0.019)	(0.015)	(0.016)	(0.154)	(0.120)
Treated	0.108***	0.009	0.012***	0.294***	0.268***	0.157***	0.489***	0.148
	(0.013)	(0.007)	(0.002)	(0.020)	(0.017)	(0.017)	(0.162)	(0.132)
Post × Treated	−0.212***	0.039***	−0.031***	−0.318***	−0.335***	−0.203***	−0.547***	−0.409***
	(0.021)	(0.010)	(0.004)	(0.023)	(0.019)	(0.018)	(0.174)	(0.137)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	75,327	75,327	75,326	58,129	28,449	28,449	1,570	2,279
R^2	0.102	0.073	0.108	0.011	0.063	0.089	0.114	0.207

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

A. Excluding all Chinese vessels.

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 for fishing events, 6) Daily mean distance from shore for fishing events, 7) Monthly fishing hours spent in Kiribati waters, 8) Monthly fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.513***	3.559***	0.083***	5.002***	13.189***	12.672***	3.307***	4.068***
	(0.024)	(0.013)	(0.004)	(0.044)	(0.027)	(0.025)	(0.264)	(0.202)
Post	0.772***	−0.159***	0.121***	0.630***	0.136***	0.074***	1.237***	1.546***
	(0.021)	(0.011)	(0.004)	(0.043)	(0.023)	(0.022)	(0.230)	(0.181)
Treated	0.203***	0.040***	0.019***	0.676***	0.147***	−0.018	0.747***	0.514***
	(0.015)	(0.009)	(0.003)	(0.041)	(0.024)	(0.022)	(0.232)	(0.183)
Post × Treated	−0.220***	−0.055***	−0.023***	−0.893***	−0.148***	0.015	−0.753***	−0.792***
	(0.024)	(0.012)	(0.004)	(0.045)	(0.026)	(0.024)	(0.246)	(0.195)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	64,560	64,560	64,559	47,375	22,654	22,654	1,366	1,928
R^2	0.093	0.069	0.099	0.030	0.055	0.066	0.109	0.198

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

B. Excluding all PNA 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 for fishing events, 6) Daily mean distance from shore for fishing events, 7) Monthly fishing hours spent in Kiribati waters, 8) Monthly fishing hours spent in PNA waters. Numbers in parentheses are heteroskedastic-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	2.661***	3.154***	0.393***	5.256***	12.977***	12.434***	3.776***	4.722***
	(0.031)	(0.019)	(0.008)	(0.032)	(0.023)	(0.021)	(0.216)	(0.165)
Post	0.313***	−0.371***	0.075***	0.244***	0.394***	0.332***	1.096***	0.978***
	(0.024)	(0.014)	(0.006)	(0.022)	(0.016)	(0.016)	(0.158)	(0.127)
Treated	−0.154***	0.040***	−0.049***	0.455***	0.223***	0.137***	0.422**	−0.062
	(0.027)	(0.014)	(0.007)	(0.022)	(0.018)	(0.018)	(0.166)	(0.129)
Post × Treated	0.067**	−0.047***	0.031***	−0.482***	−0.335***	−0.179***	−0.475***	−0.117
	(0.028)	(0.017)	(0.007)	(0.025)	(0.020)	(0.019)	(0.179)	(0.145)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	24,005	50,737	24,005	52,825	24,005	24,005	1,375	1,981
R^2	0.065	0.095	0.067	0.029	0.072	0.096	0.129	0.194

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

C. Excluding all USA and TWN vessels.

10. Additional 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. 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 1^{st} 2014 , and then from 6 to 10 on January 1^{st} 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.

Table S6. 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

Table S7. 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 S8. 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

[‡] Global Fishing Watch: globalfishingwatch.org