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

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This manuscript was compiled on March 5, 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 Islands 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 crowding effect within PNA waters after the implementation of the protected area. Vessels continue to fish with similar intensity after the implementation. In the first year of the closure, there is no drop in total fishing effort within Kiribati's EEZ and a reported increase in revenue from access rights sold. However, from 2016 onward there is a noticeable drop in fishing effort within Kiribati and a reported drop in VDS revenue. At the same time, fishing effort increases in other parts of the PNA. This redistribution of fishing effort eventually results in a reduction of 5,195 vessel-days in Kiribati, which represents a loss of $46.7 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 Large-Scale Marine Protected Area (LSMPA) in Palau (another PNA member) and estimate potential losses to range from $2.5 to $11 million annually. PNA members who indirectly benefit from 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 establish causal links between past management interventions and their outcomes (1). One of the most notable spatial interventions is the creation of no-take Marine Protected Areas (MPAs), 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; areas larger than 30,000 km^2 *sensu* (4)). Today, a small number of LSMPAs represent at least 80% of the managed areas in the ocean (Fig. 1; (5)). However, very little is known about their human dimensions and implications for fisheries (6). Furthermore, most 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 (7, 8).

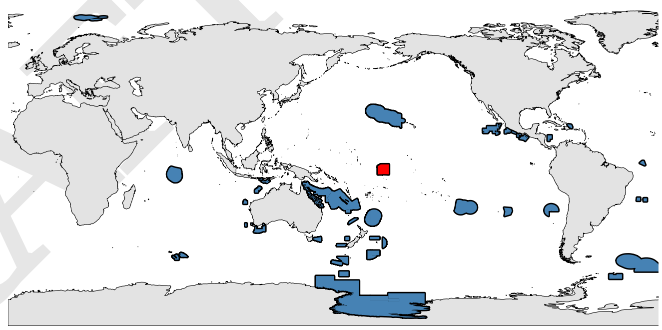

Fig. 1. Large Scale Marine Protected Areas. The map shows all areas larger than 30,000 Km^2. The Phoenix Islands Protected Area is shown in red.

Significance Statement

The oceans are becoming increasingly crowded, with different activities competing for space. Marine Protected Areas are inherently spatial, and have the sole objective of conserving bounded waters by displacing or limiting fishing effort. Our work shows that when a fishery is managed by limiting effort (*e.g.* with a Vessel-Day Scheme), spatial closures displace fishing effort at a high cost to the implementing country, and that the benefits are perceived by other countries. 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.

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The authors declare that they have no conflicts of interest

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The Phoenix Islands Protected Area (PIPA) in Kiribati is one of the most notable Large-Scale Marine Protected Areas. Implemented on January 1st of 2015, PIPA closed an area of 397,447 km^2 to fishing and was implemented within an area where approximately 50% of the world's tuna is caught. Tuna purse seine fisheries in the region are collectively managed under a Vessel-Day Scheme (VDS) by nine countries commonly referred 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 (Figure S1). 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 tuna purse seine grounds within their Exclusive Economic Zones (EEZ), PNA countries have achieved greater bargaining power when providing fishing access to foreign fleets (9). The vessel-day price rose from \$5,000 USD in 2012 to at least \$9,000 USD in 2016. The revenue from access fees may represent up to 50% of government revenue for some of the members.

A spatial closure the size of PIPA 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 likely erodes or delays the expected benefits of an intervention (10, 11). Under a VDS, a reduction in total fishing area within one country's EEZ will result in a reduction in license revenues to said country. However, the benefits of the spatial closure are dispersed amongst all other PNA members (through fish movement), who in turn benefit from the conservation efforts of the initial country. While no studies have assessed the implications of PIPA, other PNA members have pledged the implementation of LSMPAs by 2020 (*i.e.* Palau).

We simulate the PNA fishery with the addition of spatial closures to characterize possible outcomes of such interventions. We then empirically 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 controlled by PNA countries, where the largest tuna fisheries occur.

Our empirical portion uses 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, and refer to them as the "displaced vessels". The remaining 28 vessels never fished in PIPA waters, and we refer to them as "non-displaced vessels". The group with the remaining 221 vessels contains vessels that were not continuously observed before and after the implementation of PIPA, and we refer to these as "other vessels".

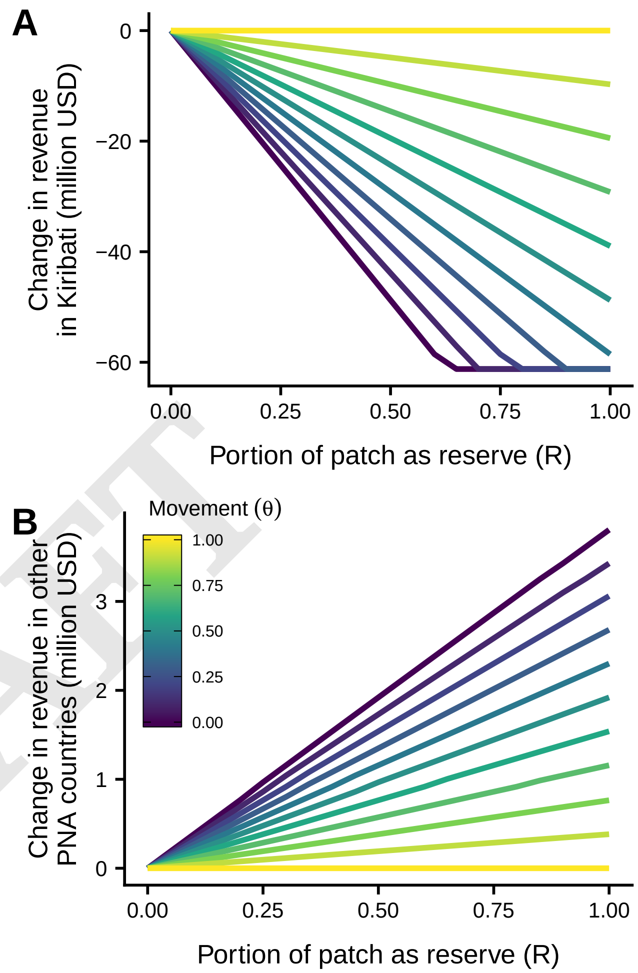

Fig. 2. Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B). The solid lines represent the 4th degree polynomial fit reported in S1

2. Results

A. PNA model with conservation. We simulate the PNA as a ten-patch meta-population system with discrete time, where Patch 1 considers the implementation of a spatial closure. Patches 2-9 are the other PNA countries, and Patch 10 represents the high seas and non-PNA countries. The stock remains within a Patch during the season, but escapement (*i.e.* stock minus catches) is distributed between all countries at the end of each year. A detailed explanation of the model is presented in the Methods section. We find that a spatial closure in Patch 1 always results in a loss or no-change in revenue from vessel-days, even when the stock to moves freely between the protected and non-protected portion of the Patch. The loss in revenue increases with reserve size, but decreases as within-patch movement increases (Fig. 2A). For all other PNA countries, however, a spatial closure in Patch 1 results beneficial, especially as within-patch movement decreases and reserve size increase (Fig. 2B). The inverse effects of the spatial closure on Kiribati and the other PNA countries are driven by the redistribution of escapement. The stock not fished in the protected portion of Patch 1 eventually redistribute to the other patches, which increases stock size and causes vessel-day prices to increase. This model shows that the costs of conservation are incurred by Patch 1, but the benefits are perceived by the other eight patches. Moreover, the gains in revenue for other PNA countries does not compensate for the total losses to Kiribati, as a great portion of effort is redistributed to the High Seas.

B. 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 displaced and non-displaced vessels, and calculated two indices of spatial overlap between them: 1) the number of cells that had fishing activity from both groups for each month and 2) the correlation of presence/absence of fishing activity between both groups over one month. We find that the two fleets significantly interact more with each other after the implementation of PIPA (Table S1 Fig. 3). The number of cells with presence from both fleets and spatial correlation increase by a factor of four and three, respectively. This increase in crowding is likely to increase the encounter rates with other vessels, and reduce the efficiency of fishing operations. This might cause vessels to leave their current fishing grounds and re-optimize their spatial effort, leading to a subsequent decrease as the crowding measures return towards pre-implementation levels.

C. Behavioral changes. The behavioral responses that vessels can have to a spatial closure may occur 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 spots. This may result in increased fuel and labor costs. For every vessel in each group, we calculate 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 Before-After-Control-Impact (BACI) design and implement a log-linear difference-in-differences analysis to evaluate how these measures change for treated vessels after implementation of PIPA, relative to the trends observed for control vessels (see the Methods section for our empirical specification).

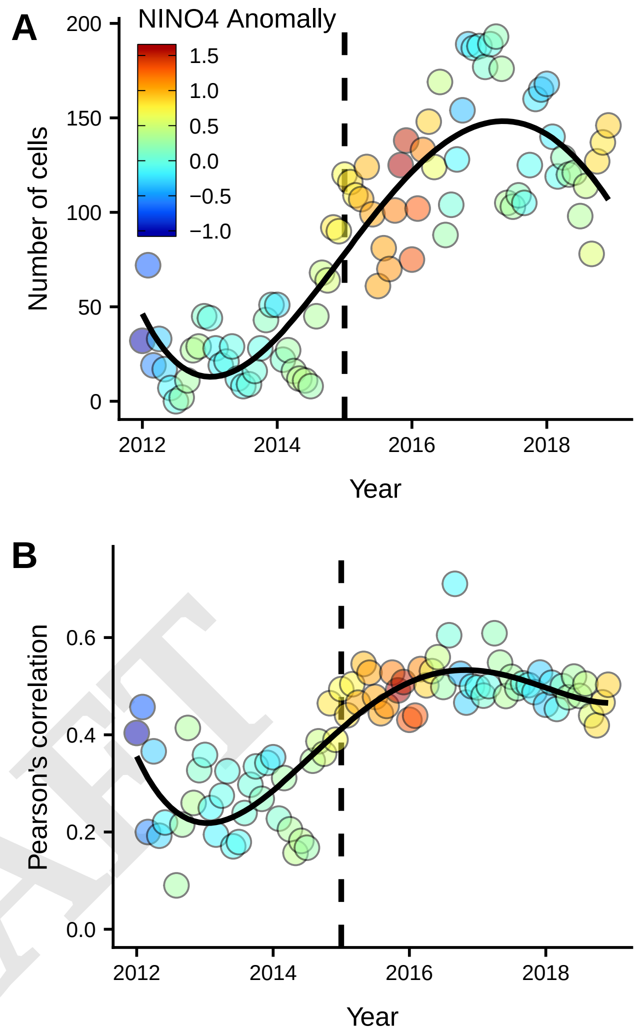

Fig. 3. Number of cells that had treated and control vessels (A) and spatial correlation in the presence-absence of treated and control vessels per cell (B). The solid lines represent the 4th degree polynomial fit reported in S1

We find no evidence of treated vessels fishing for more hours after PIPA implementation, and in fact observe a negative effect (24.4% decrease; $p < 0.01$; Table S2) relative to the non-displaced vessels. Likewise, we observe a slight decrease of fishing hours relative to total at-sea hours ($p < 0.01$; Table S2). Treated vessels traveled less distance, with fishing events occurring closer to shore and closer to port following PIPA implementation. These changes in distance from shore and port are likely caused by redistribution, as we observe that treated vessels fish 56.5% and 39.9% less in Kiribati and PNA waters, compared to the trend observed for control vessels ($p < 0.01$). We do not observe a statistically significant increase in fishing hours on the high seas. This suggests that treated vessels are fishing less overall and this decrease is driven by a decline in fishing within PNA waters. In summary, vessels that used to fish in PIPA are now fishing less in both Kiribati and the PNA region. Vessels that did not use to fish in PIPA are fishing more in Kiribati and PNA waters.

D. Economic impacts. The crowding effect combined with the reduction in hours spent in Kiribati and PNA waters overall suggests that treated vessels have redistributed elsewhere, meaning that they buy less vessel-days from PNA countries. To quantify the potential impacts of this leakage, we estimate the total annual vessel-days received by Kiribati and all PNA countries by each group of vessels (Fig. 4), and convert these to license revenues using a conservative vessel-day price of $9,000 USD*. We look at all 313 vessels to obtain a more accurate representation of total revenues, but continue to group vessels as displaced (n = 64), non-displaced (n = 28), and other vessels (n = 221). We find that between 2015 and 2016, displaced vessels spent 3,916 and 2,249 less vessel-days in Kiribati and PNA waters, respectively (Figs. 4-5). Over the same period, non-displaced and other vessels spent 1,278 less days in Kiribati, but spent 9,853 more days in PNA waters overall. These changes result in a net loss of 5,195 vessel-days for Kiribati, and a net gain of 7,600 vessel-days at the PNA-level (*i.e.* to the other 8 countries). The net reduction of vessel-days in Kiribati represents a loss of $46.7 million USD, while the net gain at the PNA-level results in $68 million USD in increased revenues. Moreover, annual vessel-days in Kiribati continued to decrease to just 7,479 in 2018 (Fig. S3). This trend is mainly caused displaced vessels allocating less time to Kiribati (S6). Looking at the total annual vessel-days allocated by all vessels to all countries, we see that the largest reductions occur for Kiribati, while Papua New Guinea exhibits a proportional increase (Fig. S4).

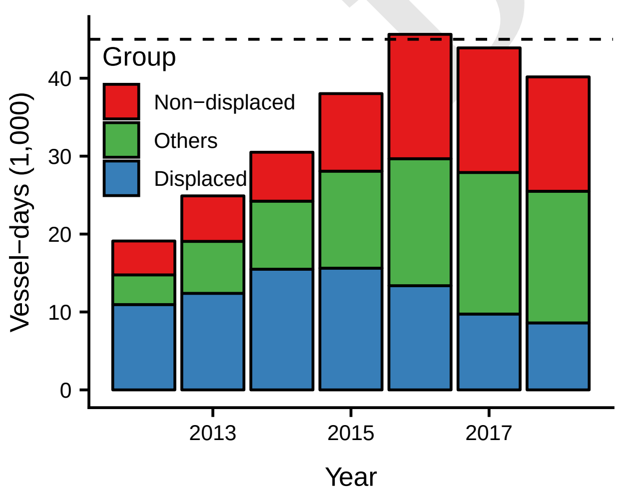

Fig. 4. Observed vessel-days for all PNA countries by treated, control, and excluded vessels.

*The Pacific Islands Forum Fisheries Agency *Tuna Development Indicators 2016* report states that "Days are currently [2016] selling in a range between $9,000 and $13,000 USD."

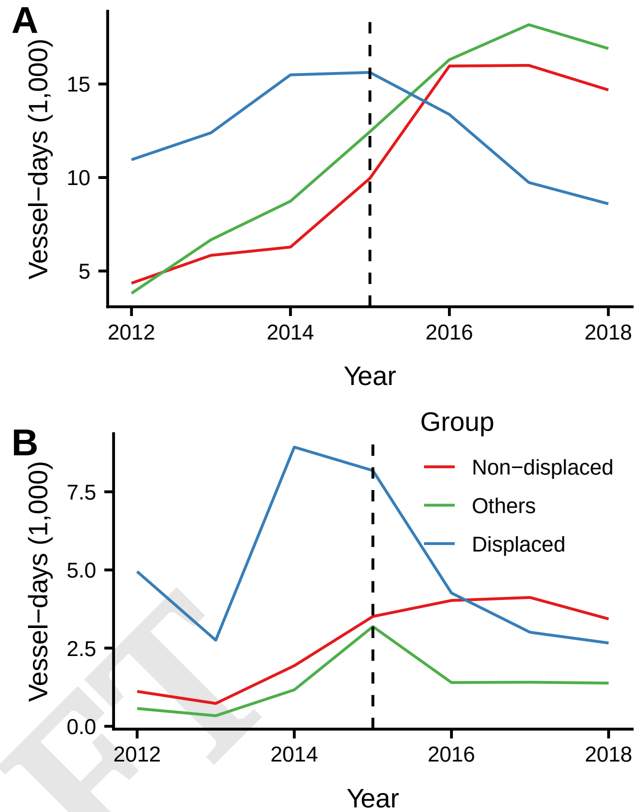

Fig. 5. Vessel days spent inside A) PNA waters and B) Kiribati waters by vessel group. The large increase for Kiribati in 2014 is likely explained by the blue paradox (10)

We complement our analysis of change in observed vessel-days by looking at country-level data. Specifically, 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. 6A). We find that 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. However, total PNA revenues showed a net increase of $28 million USD (Fig. S9). The largest decrease was observed for Kiribati, while the largest increase was observed for Papua New Guinea.

Catch for each country's EEZ for the 1997 - 2016 period were also obtained from the FFA (Fig. S10). 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 Federated States of Micronesia (60.9%), Papua New Guinea (43.4%) and the Solomon Islands (58.5%). In contrast, Tokelau (due south of PIPA) showed a 22.3% increase in catch over the same period.

E. Potential Revenue Loss for Palau. On October 28, 2015, the President of Palau signed into law the Palau National Marine Sanctuary (PNMS) Act. Starting in December 2020, this Act will close 500,000 km^2 to commer-

†https://www.ffa.int/node/2050

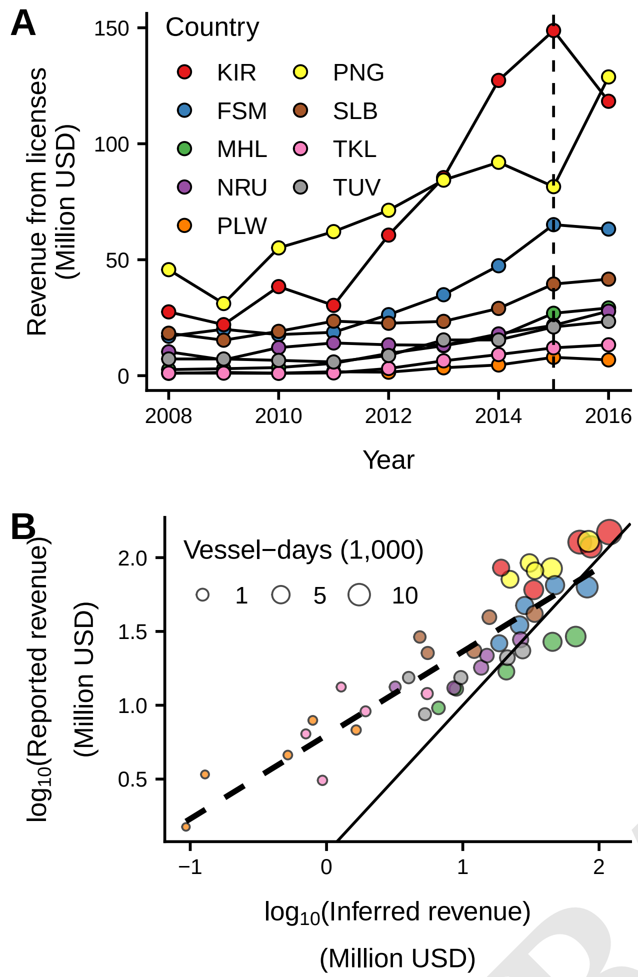

Fig. 6. License revenue for PNA countries. A) Annual revenue from fishing license fees by country and year (2008 - 2016) B) log_{10}-transformed FFA-reported revenues vs. the revenues inferred from vessel activity observations (2012 - 2016). The dashed line represents line of best fit, solid line represents 1:1 line. The same graph using absolute values is shown in S5.

cial fishing activities, creating the 14th largest protected area in the world. The sanctuary will fully protect about 80 percent of Palau's EEZ. 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 United States for under the South Pacific Tuna Treaty a.k.a. Multilateral Treaty on Fisheries ($12,500/day). In Scenario 2, Palau is able to keep its current allotment of purse seine vessel days (700) to transfer to other PNA countries at the current benchmark price ($8,000/day). Scenario 2 is likely if Palau retains its current allocation, but the US no longer purchases days. It should be noted that if allocation continues to be calculated based on effort and biomass, and if Palau continues to be allocated vessel days, its allocation will decrease as effort in its EEZ reaches zero. In Scenarios 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, since longline vessel days are currently not tradable and Palau is planning on banning the export of fish. The longline vessel day loss is calculated using an average value of $200 for 10,500 days. The 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 redistribution of fishing effort and change in behavior. Our simulation predicts losses in revenue to countries that implement a spatial closure, increases in revenue to other countries, and an increased fishing of the high seas. Using vessel track data, we observe a crowding effect after the implementation of the protected area, as displaced vessels redistribute spatially. Our analysis shows that the implementation of PIPA had little effect on the *total* fishing effort exerted by purse seiners. But there is considerable redistribution of effort across space and within the fleet of purse seiners. Surprisingly, there is no drop off in fishing effort in Kiribati in 2015 but a noticeable drop from 2016 onwards. Our analysis suggests that the displacement of vessels results in losses 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 shortcomings in our analysis.

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.

Our analysis of vessel-days from vessel tracks and loss of profits to Kiribati suggests losses of \$46.7 million USD, while revenue data show a decrease in only \$30 million USD. Here, we provide some plausible explanations for these discrepancies. First, it is possible that as waters in Kiribati became more crowded, the price of vessel-days decreased significantly bellow the \$9,000 USD estimate that we use. This woudl imply that vessel-day prices fell to \$5,800 in Kiribati. This is a number similar to what our simulation estimates provide for a closure similar to PIPA (*i.e.* $R = 0.11$), which range from \$5,250 to \$6,134, depending on the movement of fish. Another possible explanation is that the dataset used incorrectly labeled vessels as purse seiners. However, the scoring algorithm has a high accuracy, and accuracy increases with the number of observations for a vessel. Moreover, on any given year, 90% of total fishing activity can be explained by at least 68% of the vessels. Therefore, if there are any mislabeled vessels in our data, these would contribute little to the large trends that we observe. Finally, vessels fishing within PNA waters can report their activity as transiting to port or solving mechanical issues; this time does not count towards a vessel's usage of days (forgot the reference). These explanations are not mutually exclusive, and a combination of them could certainly explain the discrepancy. While the magnitude is not the same, the trends and patterns through time are certainly similar.

A major shortcoming of our analysis is that we do not observe catch or revenue at the 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. Likewise, the available data from the FFA does not cover the 2017 and 2018 period, and we do not observe vessel-day transactions or prices. Furthernore, our estimates of revenue loss for PIPA do not account for the allocation calculated each year. Each party's allowable effort is 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% is calculated based on the 10-year average of each country's share of estimated skipjack and yellowfin biomass within its EEZ.[‡].

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 (17–20). Our work suggests that the implementation of LSMPAs has little impact on total fishing effort, but that it may result in losses to countries that have been receiving revenue from granting fishing access. We also show that spatial closures lead to crowding effects, which causes some vessels to redistribute to areas close by. While LSMPAs can provide a wide range of benefits, their implementation must be accompanied with traditional fisheries management to maximize effectiveness, consider the opportunity costs of such closure, and identify sustainable financing mechanisms that would compensate losses and incentivize marine conservation.

[‡] This is explained in more detail in Article 12.5 of the 2012 Amendment to the Palau Agreement and in (16)

4. Methods

A. PNA Model with Conservation. We model the PNA as a ten-patch discrete-time meta-population system, where Patch 1 is considering a spatial closure. Patches 2-9 are the other PNA countries, and Patch 10 represents the high seas and non-PNA countries. The stock of fish in each country is relatively stationary within a single fishing season, but redistributes across all patches annually. The price of fish is p, and catchability is given by q.

In the absence of a reserve, the revenue for vessels in patch i is given by pqE_iX_i, where E_i and X_i are effort (vessel-days) and stock size in patch i at the beginning of a period. The cost of fishing in patch i is given by cE_i^β, where $\beta = 1.3$ matches commonly-used cost functions. Patch 1 considers a spatial closure by implementing a reserve as a fraction R of the total patch ($R \in [0,1]$). Fish move within a patch based on θ, where $\theta = 0$ implies to movement within the patch, and $\theta = 1$ implies that fish within the patch are well mixed over during the fishing season. In this patch, revenues are given by $pqE_1X1(\theta + (1 - \theta)(1 - R))$. The parameterization of movement and reserve size imply that profit from fishing Patch 1 is given by:

$$\Pi_1(E_1, X_1, R) = pqE_1X_1(\theta + (1-\theta)(1-R)) - cE_1^\beta \quad [1]$$

And profits from fishing in Patch $j = \{2, 3, ..., 10\}$ are:

$$\Pi_j(E_j, X_j) = pqE_jX_j - cE_1^\beta \quad [2]$$

The above equations imply that the marginal profit from the last unit of effort in a patch are given by:

$$\pi_1(E_1) = pqX_1(\theta + (1-\theta)(1-R)) - \beta cE_1^{\beta-1} \quad [3]$$

$$\pi_j(E_j) = pqX_j - \beta cE_j^{\beta-1} \quad [4]$$

However, Patch 10 represents the high seas under open access dynamics. Therefore, we assume that effort continues to enter Patch 10 until the profit from the last unit of effort is exactly zero, indicating that E_{10} is the value for which $\pi E_{10} = 0$. Setting Equation 4 equal to zero and solving for E_j gives:

$$E_{10} = \left(\frac{pqX_{10}}{\beta c}\right)^{\frac{1}{(\beta-1)}} \quad [5]$$

The patch-level harvest is then determined by effort and stock size:

$$H_1 = qE_1X_1(\theta + (1-\theta)(1-R)) \quad [6]$$

$$H_j = qE_jX_j \quad [7]$$

Therefore, escapement in patch i is the difference between initial stock size and harvests as $e_{it} = Xit - H_{it}$. At the entire stock then grows according to:

$$X_{t+1} = e_t + \frac{(\phi+1)}{\phi} g e_t \left(1 - \left(\frac{e_t}{K}\right)^{\phi}\right) \quad [8]$$

After the stock grows, a constant and patch-specific fraction f_i of the total stock redistributes to patch i, so:

$$X_{it+1} = f_i X_{t+1} \quad [9]$$

The vessel-day price that a country charges is given by π_i from Equations 3 and 4. Therefore, patch-level license revenues are given by:

$$\omega = \pi_i E_i \quad [10]$$

Equations 6 shows that low values of θ and $R > 0$ would increase escapement, which would lead to an increase in stock size (Equation 8). This would cause for the stock in the high seas (X_{10}) to increase through the redistribution (Equation 9), leading to an increased effort being allocated to the high seas (Equation 5).

B. 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 algorithms (convolutional neural networks) on the broadcast messages to infer type and location of fishing events (21).

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 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.

C. Analysis.

$$y_t = \alpha + \beta_1 M_t + \beta_2 M_t^2 + \beta_3 M_t^3 + \beta_4 M_t^4 + \sigma_s + \epsilon_t \quad [11]$$

C.1. Crowding effect. We test for a crowding effect using the specification in Equation [11]. We have two different outcome variables: 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 allow for the possibility of three inflection points: 1) initial crowding due to MPA implementation, 2) When the crowding has reached its peak and star ts to decrease, and 3) when this decrease potentially levels off. 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. Note that we restrict the sample to our treated and control vessels (vessels that show up in the dataset before PIPA implementation) to try to minimize bias from more and more vessels using AIS over time. We also include controls (σ_s) that captures the effect of additional satellites receiving AIS signals, which incorporated in April 1st, 2014 and December 31st, 2015.

C.2. Behavioral changes. We attempt to identify 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:

$$log(y)_{i,t} = \alpha + \beta_1 P_t + \beta_2 T_i + \beta_3 P_t \times T_i + \phi_t + \gamma_i + \epsilon_{i,t} \quad [12]$$

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, β_1 captures the temporal trend, β_2 captures the initial difference between treated and control groups, and β_3 is our parameter of interest: the Difference-in-Differences estimate capturing the treatment effect. Finally, ϕ_t and γ_i represent month and flag dummies that account for seasonality or country-level management interventions.

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

C.3. Revenues. We obtained information on license fee revenues from the Pacific Islands Forum Fisheries Agency *Tuna Development Indicators 2016* report. For countries in the PNA, we assume that all license fee revenue is coming from the sale of VDS.

5. References

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6. Appendix

7. Supplementary tables and figures

Table S1. 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)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	78.040***	84.639***	60.962***	66.725***	0.412***	0.417***	0.370***	0.377***
	(5.438)	(8.990)	(15.598)	(15.988)	(0.014)	(0.032)	(0.062)	(0.066)
M	3.943***	4.065***	3.066***	3.139***	0.010***	0.010***	0.009**	0.009**
	(0.302)	(0.348)	(0.966)	(1.040)	(0.001)	(0.001)	(0.003)	(0.004)
M^2	−0.005	−0.021	0.008	−0.008	−0.0001***	−0.0001	−0.0001	−0.0001
	(0.019)	(0.026)	(0.027)	(0.030)	(0.00004)	(0.0001)	(0.0001)	(0.0001)
M^3	−0.002***	−0.002***	−0.002***	−0.002***	−0.00001***	−0.00001***	−0.00001***	−0.00001***
	(0.0003)	(0.0003)	(0.001)	(0.001)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
M^4	0.00001	0.00002	0.00000	0.00001	0.00000***	0.00000**	0.00000	0.00000
	(0.00001)	(0.00002)	(0.00002)	(0.00002)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
NINO4		−8.095		−10.395		−0.006		−0.014
		(8.287)		(9.481)		(0.029)		(0.031)
σ_1			21.318	25.102			0.057	0.062
			(19.493)	(22.486)			(0.076)	(0.080)
σ_2			5.299	3.194			−0.015	−0.018
			(18.874)	(18.670)			(0.035)	(0.035)
NINO4	No	Yes	No	Yes	No	Yes	No	Yes
Satellites	No	No	Yes	Yes				
Observations	84	84	84	84	84	84	84	84
R^2	0.791	0.793	0.795	0.798	0.703	0.704	0.709	0.710

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

8. Alternative Controls

A. Excluding all Chinese vessels.

B. Excluding all PNA vessels.

C. Excluding all USA and TWN vessels.

Table S2. Difference-in-differences estimates for our nine 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, and 9) Monthly fishing hours in the high seas. Numbers in parentheses are heteroskedasticity-robust standard errors.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Constant	0.497***	3.607***	0.075***	5.206***	12.997***	12.461***	3.678***	4.445***	2.420***
	(0.022)	(0.012)	(0.004)	(0.028)	(0.021)	(0.019)	(0.192)	(0.151)	(0.421)
Post	0.839***	−0.228***	0.137***	0.298***	0.326***	0.296***	1.059***	1.180***	0.920***
	(0.016)	(0.008)	(0.003)	(0.018)	(0.014)	(0.014)	(0.140)	(0.109)	(0.273)
Treated	0.136***	0.014**	0.015***	0.413***	0.223***	0.116***	0.534***	0.149	−0.244
	(0.013)	(0.007)	(0.002)	(0.019)	(0.016)	(0.016)	(0.148)	(0.118)	(0.236)
Post × Treated	−0.244***	0.013	−0.034***	−0.513***	−0.281***	−0.155***	−0.565***	−0.399***	0.338
	(0.019)	(0.009)	(0.003)	(0.022)	(0.017)	(0.017)	(0.161)	(0.127)	(0.288)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	83,052	83,052	83,051	66,981	32,055	32,055	1,814	2,588	684
R^2	0.102	0.072	0.107	0.027	0.062	0.080	0.113	0.198	0.233

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

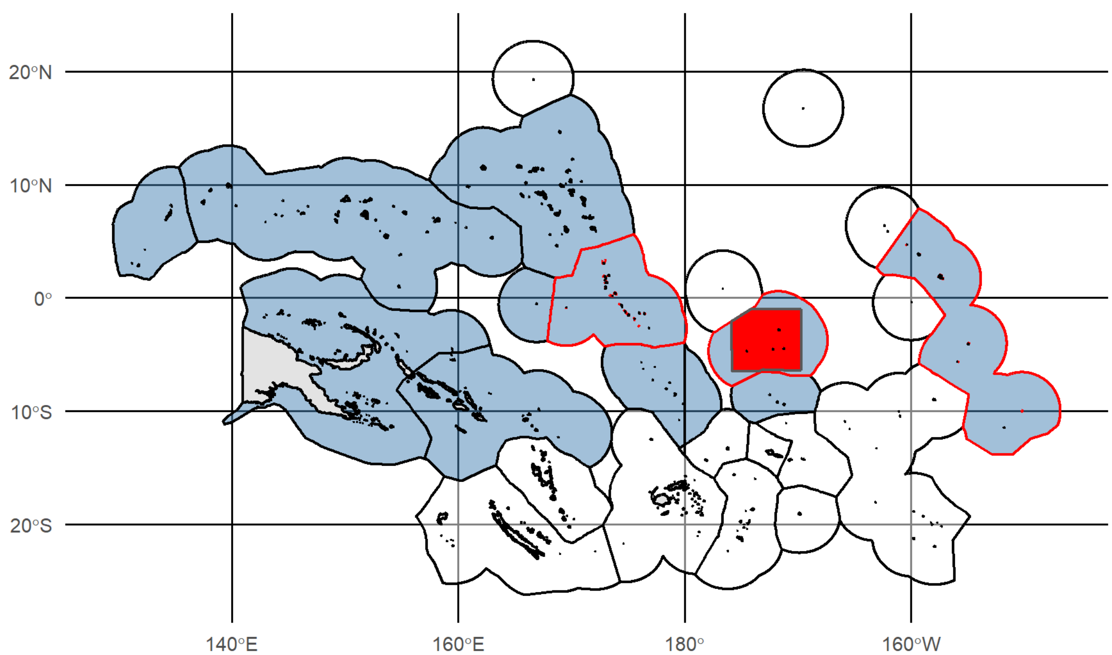

Fig. S1. Map of the Exclusive Economic Zones (EEZs) of the region of interest. Countries that belong to the PNA are shown in blue, while empty polygons indicates all others. A red line indicates the Kiribati EEZ, and a solid red polygon delineates PIPA. Land masses are shown in gray.

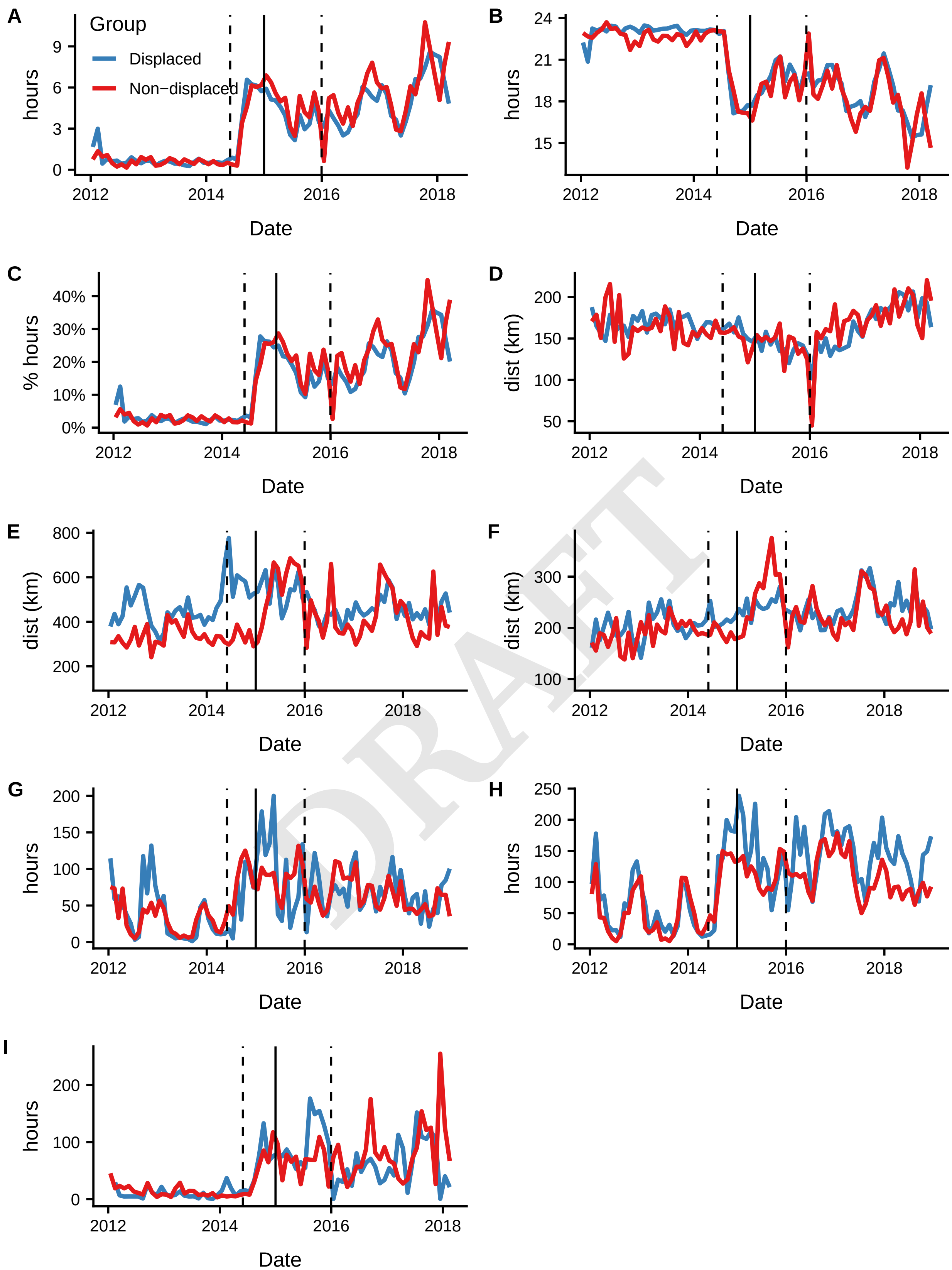

Fig. S2. Time series showing monthly averages for our nine variables of interest: A) Fishing hours, B) Non-fishing hours at-sea, C) Proportion of fishing hours to total hours at-sea, D) Distance traveled, E) Mean distance from port for fishing evetns, F) Mean distance from shore for fishing events, G) Monthly hours spent in Kiribati waters, H) Monthly hours spent in PNA waters, I) Monthly hours spent on the high seas. Dashed vertical lines indicate the addition of new AIS satellites. Solid vertical line indicates the closure of PIPA.

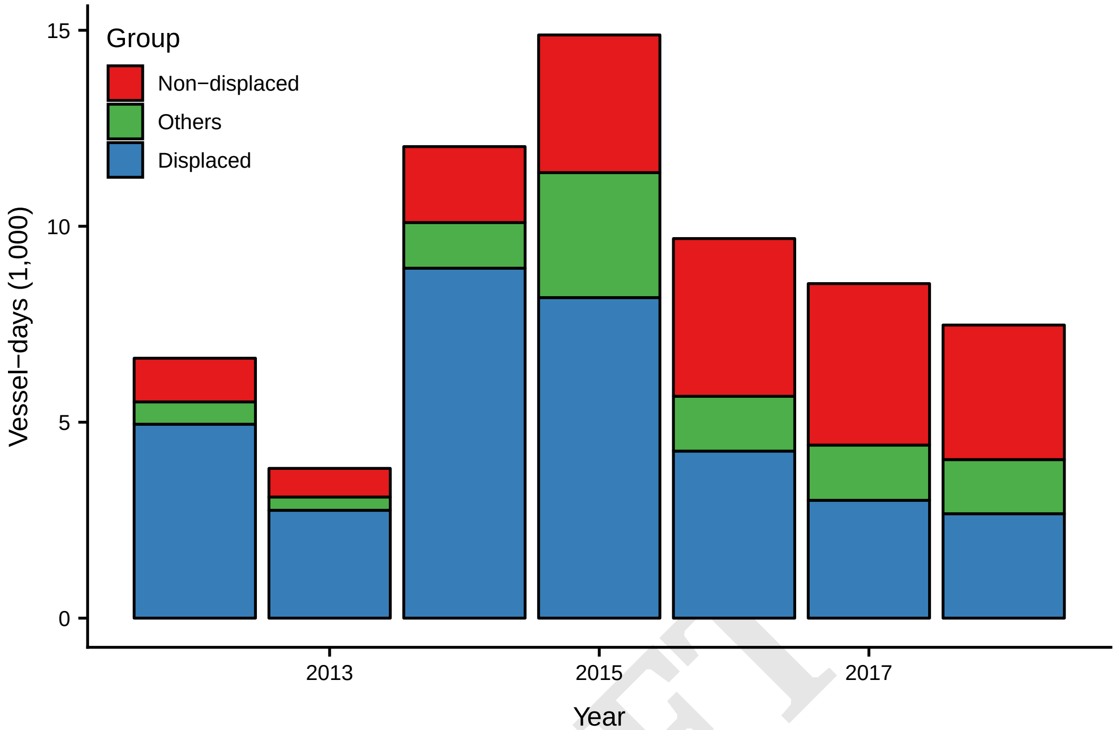

Fig. S3. Annual vessel-days in Kiribati by group of vessels.

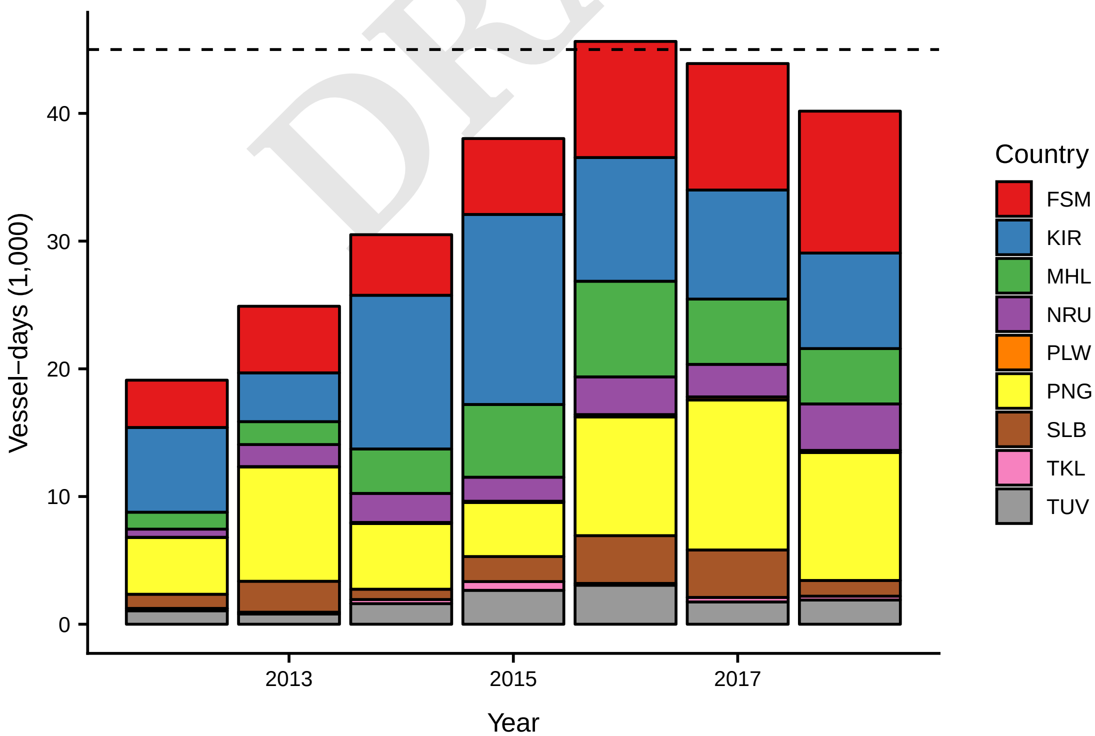

Fig. S4. Annual vessel-days for all PNA countries, by country.

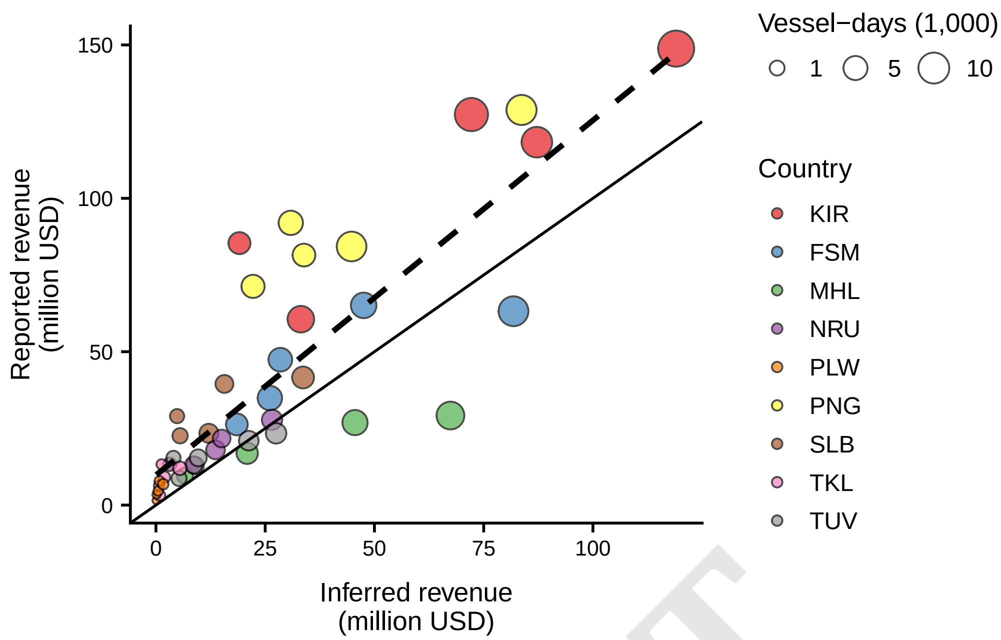

Fig. S5. Inferred revenues vs. reported revenues. The dashed line represents line of best fit, and the solid line represents a 1:1 line.

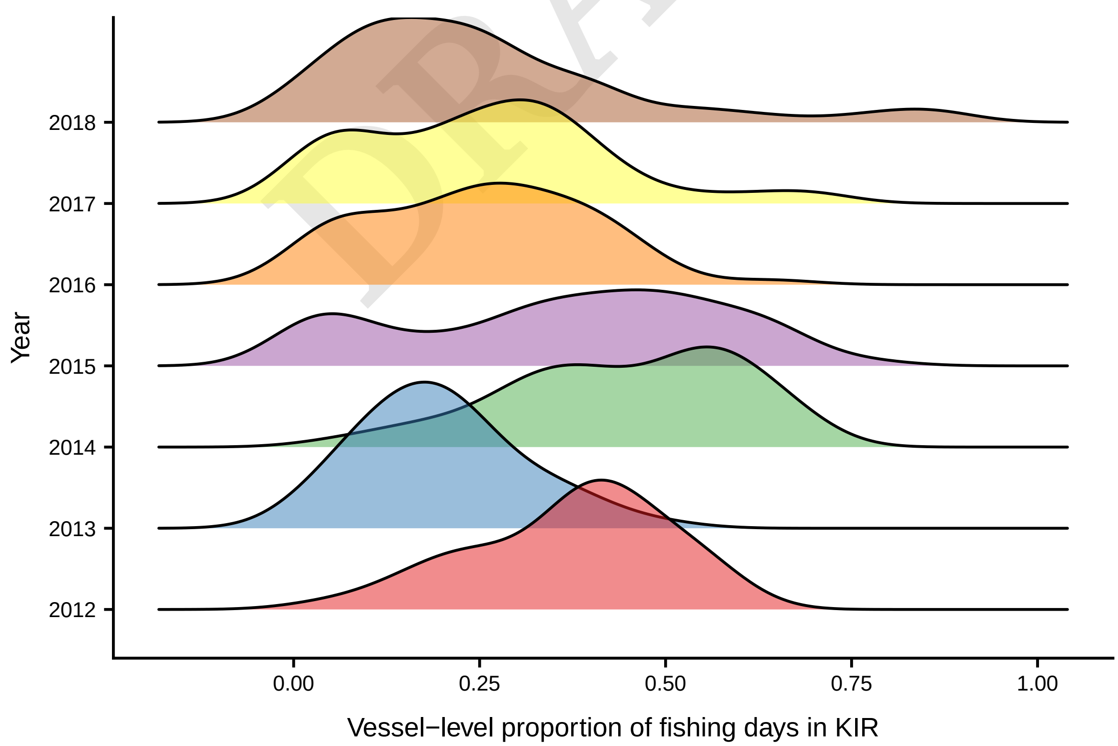

Fig. S6. Ridgeplot for the density of the % of total fishing hours that take place within Kiribati EEZ waters by year for treated vessels where the unit of observation is an individual vessel.

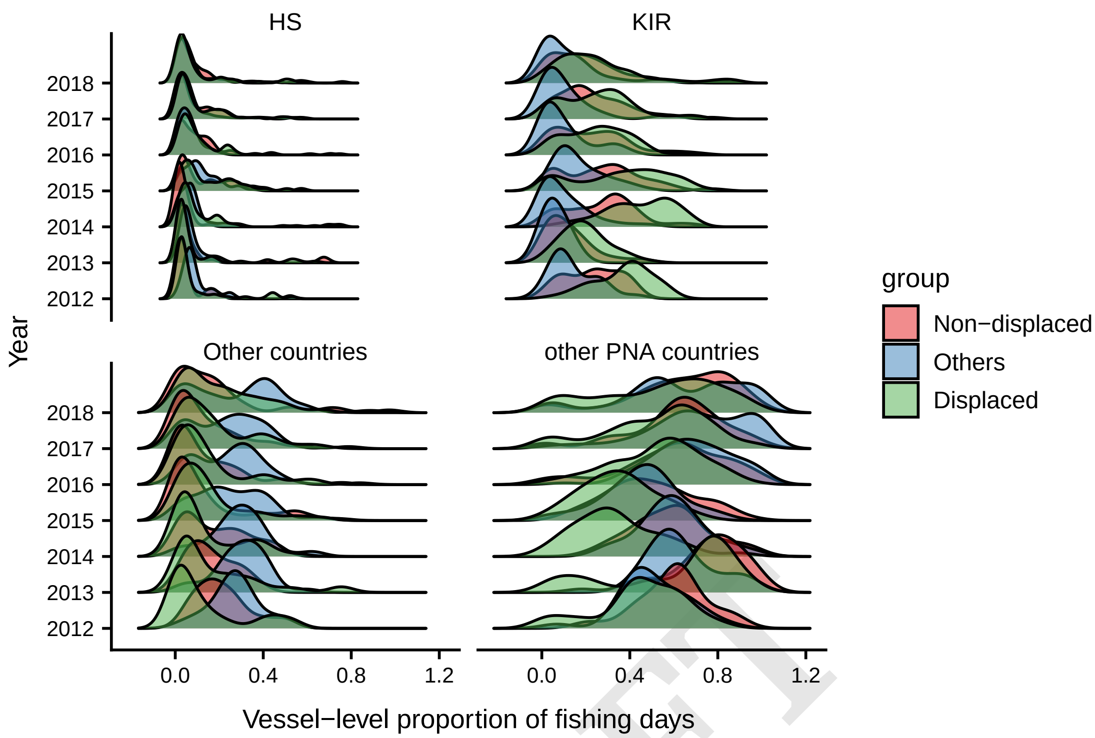

Fig. S7. Ridgeplot for the density of the % of total fishing hours that take place in each region for all vessels

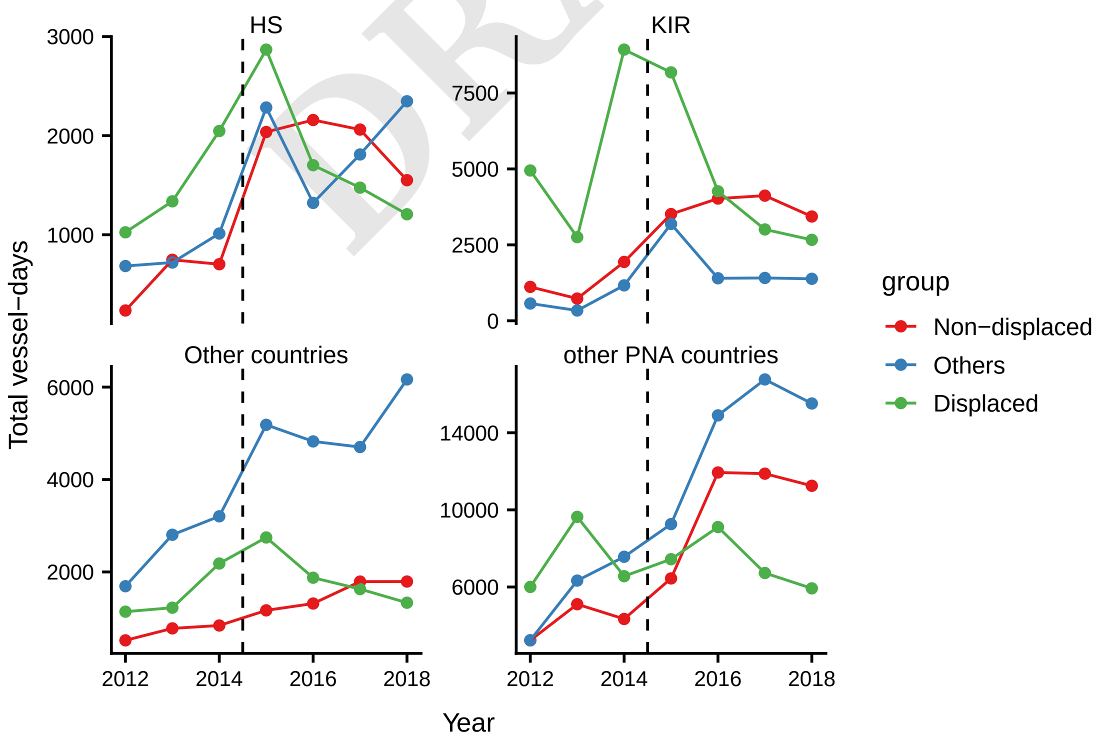

Fig. S8. Total fishing by region.

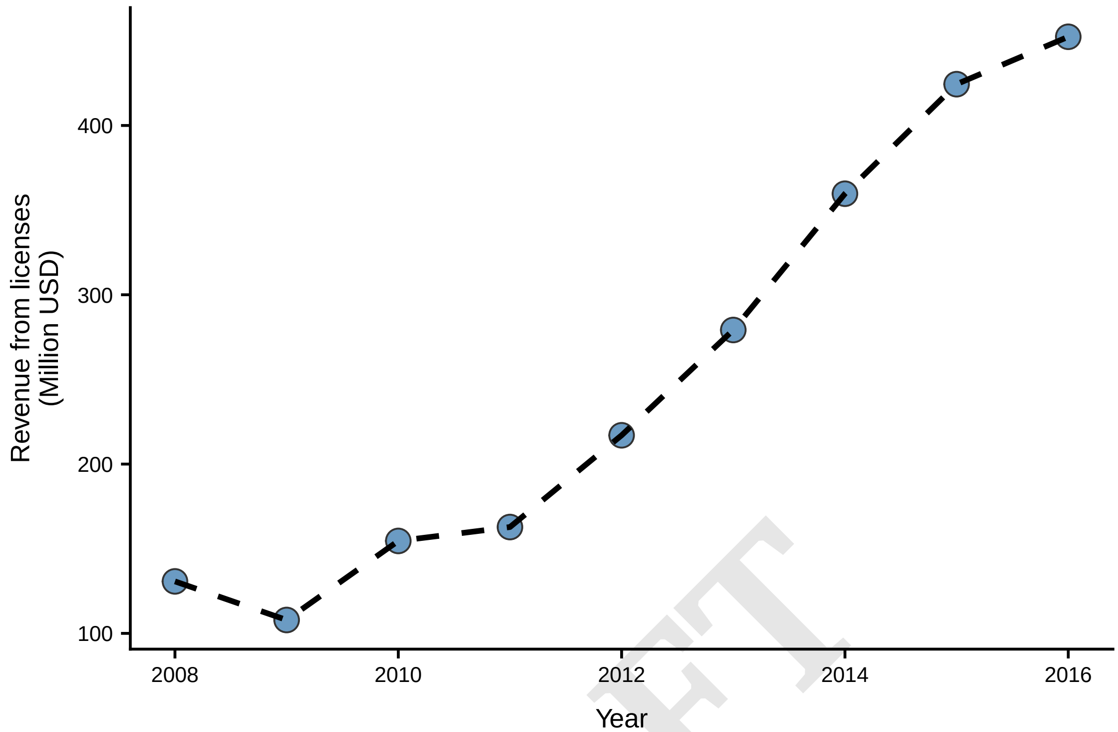

Fig. S9. Total revenues for all PNA countries combined.

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

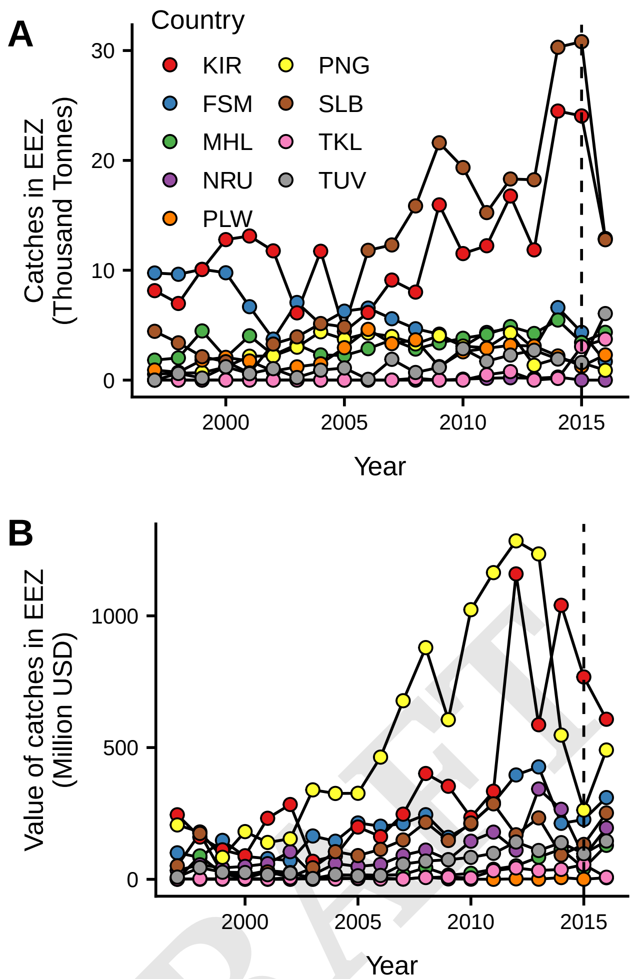

Fig. S10. Financial indicators for PNA countries. A) Annual catches by EEZ and, B) Annual value of catches by EEZ. Vertical dashed line in both plots denotes implementation of PIPA.

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

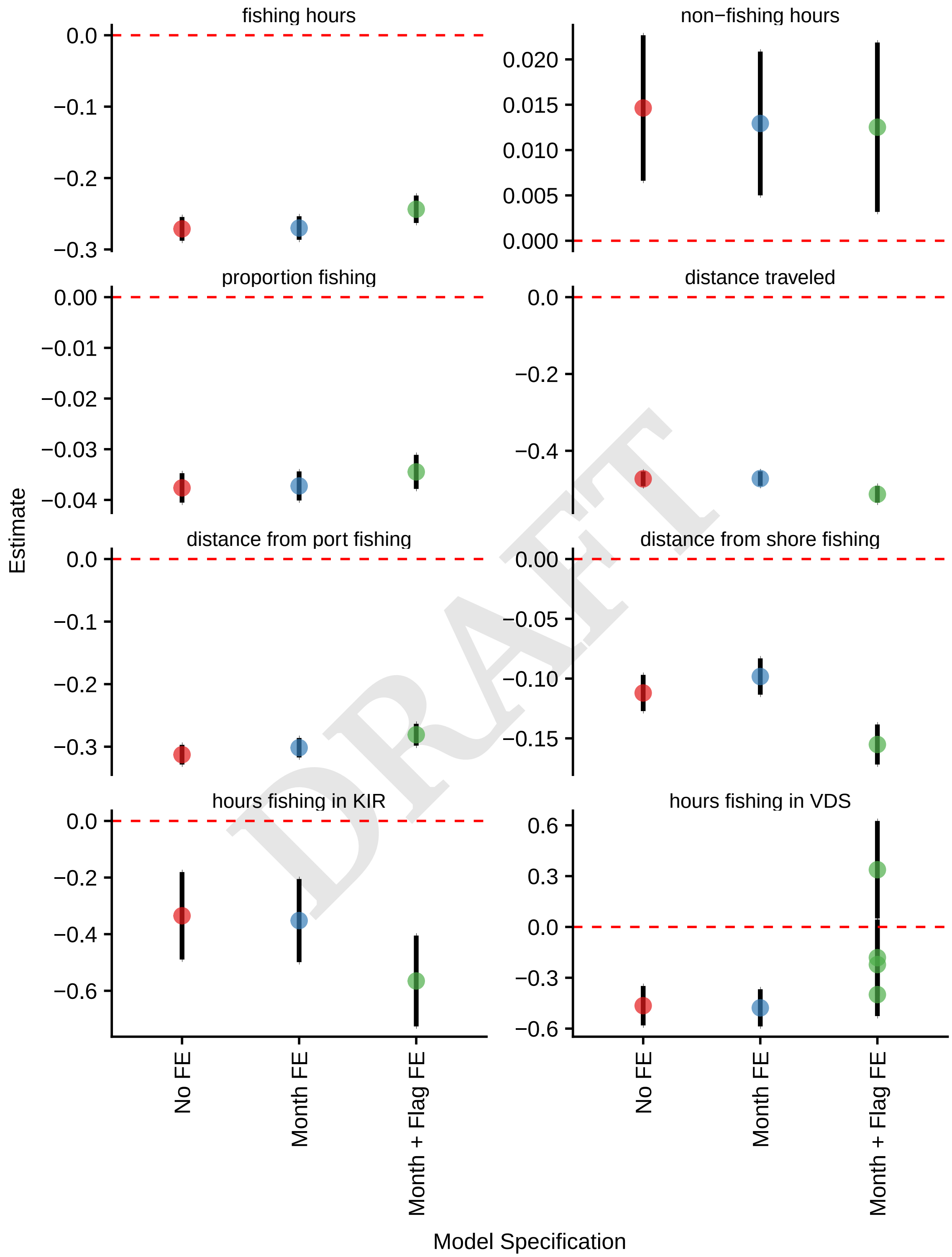

Fig. S11. Alternative difference-in-differences estimates for our variables of interest using different model specifications. Table S2 reports estimates for models with month and flag fixed effects (*i.e.* green dots).

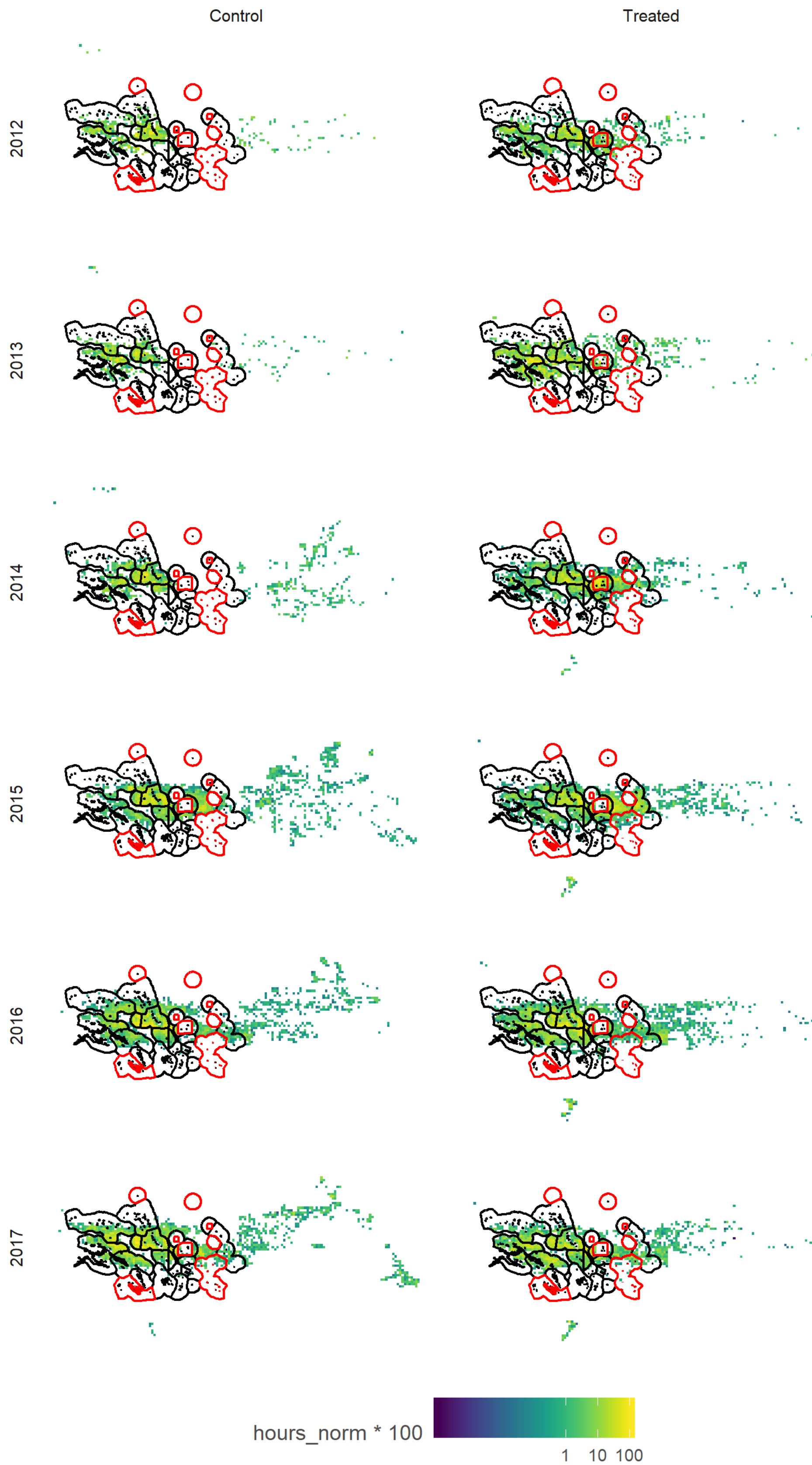

Fig. S12. Yearly spatial distribution of fishing effort by treated and control vessels. Color corresponds to % of total fishing effort in each panel. Red polygons show LSMPAs in the region.

Fig. S13. figure that shows treated minus control effort and maybe just compare 2013 with 2017 (or 2012-2014 average with 2015-2018 average).

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	0.536***	3.600***	0.082***	5.237***	12.995***	12.435***	3.808***	4.703***
	(0.023)	(0.012)	(0.004)	(0.031)	(0.022)	(0.020)	(0.206)	(0.157)
Post	0.795***	−0.218***	0.130***	0.278***	0.360***	0.321***	0.985***	0.961***
	(0.018)	(0.009)	(0.003)	(0.021)	(0.015)	(0.016)	(0.153)	(0.119)
Treated	0.142***	0.016**	0.015***	0.461***	0.231***	0.128***	0.481***	−0.021
	(0.013)	(0.007)	(0.002)	(0.022)	(0.018)	(0.017)	(0.163)	(0.127)
Post $\times$ Treated	−0.212***	−0.002	−0.029***	−0.526***	−0.328***	−0.184***	−0.525***	−0.222
	(0.021)	(0.010)	(0.004)	(0.024)	(0.019)	(0.018)	(0.175)	(0.138)
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flag FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	73,717	73,717	73,716	57,806	26,920	26,920	1,546	2,236
R^2	0.095	0.072	0.102	0.029	0.061	0.090	0.100	0.166

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