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# Supplementary Materials for

## Spillover benefits from the world's largest fully protected MPA

Sarah Medoff, John Lynham, Jennifer Raynor

Corresponding author: John Lynham, lynham@hawaii.edu

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# Materials and Methods

The aim of this study is to identify whether spillover benefits have materialized from the world's largest fully protected MPA, the Papahānaumokuākea Marine National Monument (PMNM) surrounding the northwest Hawaiian islands.

## Data

Our empirical analysis focuses on the Hawaii-based, limited-entry, longline fishery. This fishery has a maximum of 164 permits and is split into two fleets for regulatory purposes (50 CFR Part 665). The "deep-set" fishery primarily targets tunas, especially bigeye tuna (*Thunnus obesus*), and sets hooks at a depth of about 250m; the "shallow-set" fishery primarily targets swordfish (*Xiphias gladius*) and sets hooks at a depth of about 60m. According to the federal regulations cited above, a deep-set will have float lines at least 20 m in length, at least 15 branch lines between any two floats, and no light sticks; a shallow-set will deploy longline gear in a way that does not meet the definition of a deep-set. This cutoff for hooks per float will be important for classifying deep- versus shallow-sets. Historically, the shallow-set fishery was the most important. However, in recent years, most fishing activity has occurred in the deep-set fishery, which accounted for 97-99% of Hawaii-based longline trips, sets, hooks, and catch in 2020. For this reason, we focus only on the deep-set fleet.

Longline permit owners are required to comply with the rules and regulations of the National Marine Fisheries Service (NMFS) Pacific Islands Regional Observer Program (PIROP). PIROP is responsible for deploying observers on U.S. fishing vessels to collect data on fishing operations and catch by species. Observers remain present for the full duration of a trip and must observe the complete haul-back of every fishing set. The observers record data ("observer data") on trip departure and return dates, port of landing, gear configuration, the time and location of the beginning and end of each set and haul, and the species of each fish caught, among other variables.

PIROP began in 1994, and observer coverage was about 3% to 5% of trips during the first 6 years of the program. Since 2000, observers have been placed on 100% of shallow-set trips and at least 20% of deep-set trips. To facilitate observer deployment and vessel sampling, the permit holder or a designated representative must notify NMFS at least 72 hours prior to their intended departure date and declare the intended trip type. Once declared, the trip may only make sets of that type. Also, there are limits on the number of swordfish that may be possessed or landed on deep-set trips. Assignment of observers to deep-set trips is random, with very rare exceptions under unexpected events (e.g., a vessel malfunction that causes a trip to be delayed or unfulfilled).

At the time of our analysis, raw observer data was available between March 3, 1994 to January 15, 2020 and captured 94,298 fishing sets. We selected observations using the following criteria. First, we removed 10 sets with missing data for the begin set latitude or longitude. Next, we removed 44,783 sets that occurred before January 1, 2010 and 60 sets that occurred after December 31, 2019. We limited observations to those sets that had at least 15 hooks per float to capture deep-set trips only, resulting in a final data set that consists of 38,832 fishing sets. Because the observer data is measured at the fish level, we calculated the total number of fish caught for each species and set; we included catch equal to zero when a species was not caught on a set. We used the begin set location to classify sets spatially. We used this metric rather than haul locations because captains cannot control haul locations due to drift while the set is soaking.

## Identification Strategy

Estimating a causal spillover from an MPA is difficult due to two main endogeneity concerns. The first concern is the natural time trend of the fishery ("time trend bias"). Fishery characteristics such as fleet size, advancements in fishing technology, and species populations change over time. Simply comparing fishing conditions before and after MPA establishment fails to control for these time trends, potentially leading to biased estimates. The second concern is heterogeneity in captain efficiency ("selection bias"). It is plausible that more efficient captains might fish closer to an MPA after it is created so a purely spatial comparison of catch without controlling for heterogeneities across captains would lead to biased results. For example, a researcher might think they are estimating a spatial change in fish abundance but, in reality, they are estimating a spatial change in fishing effort.

The fisheries economics literature typically tackles these concerns by using a difference-in-differences regression model with fixed effects. This modeling framework controls for endogeneity that would otherwise arise due to selection bias or time trend bias by comparing fishing productivity between a predefined "treatment" and "control" group, before and after the MPA was established, holding vessel efficiency fixed. More specifically, our analysis closely follows (11), which measures the biological spillover from two MPAs in a Gulf of Mexico reef-fish fishery. They (11) define their treatment group as the statistical reporting areas that contain the MPAs and the control group as those that do not; they also control for gear type, differences in captain skill, spatial distribution of fish stocks, seasonal fluctuations, and the effects of co-occurring policies.

## Modeling Framework

To quantify the effects of the monument expansion on fishery catch, we used species-specific difference-in-differences models. As we describe in detail below, we estimated three models with different sets of covariates, for four distance specifications, using both observer and logbook data. We also estimated a placebo test for each model. For each specification, we estimated the model separately for bigeye tuna, yellowfin tuna, all species combined ("All"), and all species other than bigeye tuna and yellowfin tuna combined ("Other"). To facilitate comparisons across species, the outcome variable is $standardizedCPUE_{f,i,s,t}$, defined as catch per 1,000 hooks for each fish species $f$ caught by vessel $i$ on set $s$ on day $t$, standardized based on its pre-expansion moments (subtract the pre-expansion mean and divide by the pre-expansion standard deviation of CPUE) (Equation 1). Estimated regression coefficients, therefore, represent the number of standard deviations away from the pre-expansion mean.

$$standardizedCPUE_{f,i,s,t} = \frac{CPUE_{f,i,s,t} - mean(CPUE_{f,t \leq ExpansionDate})}{sd(CPUE_{f,t \leq ExpansionDate})} \tag{1}$$

**Discrete Regions**

Following (11), we tested for spillover benefits based off of distance from the Papahānaumokuākea Marine National Monument border. We defined a "near" treatment area that extends (0, *x*] nautical miles (nmi; equivalent to 1.852 km) from the border and a "far" control area that extends (*x*, 2*x*] nmi from the border. We set *x* to be 100, 200, and 300 because these radii have a convenient interpretation. The MPA extends exactly 200 nmi from land, so these buffers translate to 0.5, 1, and 1.5 times the "radius" of the monument or, alternatively, 0.25, 0.5, and 0.75 times the "diameter" of the monument.

Table S2 presents summary statistics for participation, effort, gear, and bait type for the expansion area, each region radius, and the full fishery footprint over the preferred study period (2010-2019), using observer data; recall that observed trips constitute about 20% of total annual effort by the deep-set fleet. To provide context for whether fishing strategies have changed in response to the monument expansion, Figure S1 presents time trends of annual effort (total sets, total hooks, average soak time, and average hooks per float) in each of the near and far regions.

We also present the share of fishing effort in each near area that is US-flagged over time, based on Automatic Identification System (AIS) data provided to us by Global Fishing Watch in Table S1. These shares provide context for how much spillover benefits, if any, might be captured by the studied fleet versus other non-US-flagged fleets. However, note that many US vessels did not use AIS until after March 1, 2016, when it was required by a regulatory change (33 CFR Part 164).

### Continuous Distance

To examine potential sampling bias that could arise from the arbitrarily chosen region-radius specifications, we also use a continuous distance treatment variable. Fishing activity in our sample occurs up to 2,329 nmi away from the Papahānaumokuākea Marine National Monument border. As sets move farther away from the monument, it is more likely that fishing activity will be influenced by factors other than proximity to the monument, such as changing environmental conditions. To limit the effects of confounding factors, we restrict our sample to fishing grounds within 600 nmi of the Papahānaumokuākea Marine National Monument border (i.e. the maximum radius of the combined near and far areas in the discrete region specifications). We use the negative of distance divided by 1,000 nmi in the regressions described below so that a positive coefficient estimate would imply a spillover benefit from the monument (i.e. the coefficient represents the effect of moving 1,000 nmi closer to the monument), matching our discrete region approach.

### Model Specifications

We used three model specifications, each imposing additional layers of control variables.

**Baseline**. The first model includes no additional control variables beyond the basic dummy variables required for a basic difference-in-differences estimation (Equation 2); this serves as our baseline model. The time treatment $ExpansionDummy_t$ takes a value of 1 if day $t$ takes place after the monument expansion and 0 otherwise. For the region-radius specifications, the group treatment or distance indicator $Distance_{i,s,t}$ takes a value of 1 if vessel $i$ placed set $s$ in the "near" fishing region on day $t$, and 0 otherwise. For the continuous specifications, $Distance_{i,s,t}$

is the distance to the nearest monument border, multiplied by -1 so that the coefficient can be interpreted as the effect of moving closer to the monument. To avoid having extremely small regression coefficients relative to the region-radius specifications, we re-scaled distance to be in units of 1,000 nmi. $\epsilon_{f,s,i,t}$ is the error term. The difference-in-differences coefficient $\beta_3$ ("Diff in diff") measures the effect of fishing closer to the monument after the monument borders were expanded; thus, a positive estimate for $\beta_3$ indicates evidence of a spillover benefit. Results are presented in Table S3.

$$\begin{aligned} CPUE_{f,i,s,t} = \beta_1 ExpansionDummy_t + \beta_2 Distance_{i,s,t} \\ + \beta_3 (ExpansionDummy_t * Distance_{i,s,t}) + \epsilon_{f,i,s,t} \end{aligned} \tag{2}$$

**Time-vessel fixed effects (preferred)**. The second model adds vectors of vessel fixed effects $\mathbf{V}_i$ and month-year fixed effects $\mathbf{MY}_t$ as a means to control for heterogeneity in captain and crew efficiency and intra- and inter- annual variation in CPUE (Equation 3).[1] Other variables are defined as previously. Results are presented in Table S4.

$$\begin{aligned} CPUE_{f,i,s,t} = \beta_1 ExpansionDummy_t + \beta_2 Distance_{i,s,t} \\ + \beta_3 (ExpansionDummy_t * Distance_{i,s,t}) + \mathbf{V}_i + \mathbf{MY}_t + \epsilon_{f,i,s,t} \end{aligned} \tag{3}$$

This model is the preferred specification because it includes the most theoretically relevant variables, while avoiding dropping observations with missing data required for the Gear controls model (see next subsection). In addition, the results are essentially unchanged when moving to the Gear controls specification.

**Gear controls**. The final and most restrictive model adds controls related to gear configurations, which can affect fishing success (Equation 4). The vessel effects in the Time-vessel fixed effects model will capture gear effects if gear type is time-invariant for a vessel; however, gear

[1] Sometimes captains change vessels, but the data does not reliably track captains directly.

setup can and does change. $\mathbf{Gear}_{i,s,t}$ is a matrix of four variables: bait type, hooks per float, float line diameter, and soak time.[2] Number of hooks per float and bait type is correlated with higher catch rates; number of hooks per float and float line diameter affect hook depth, and thus affect the type of species caught. In addition, longer soak times would tend to increase catch of all species, which have more time to find the hooks in the water. About 650 sets are missing gear information in the observer data. Other variables are defined as previously. Results are presented in Table S5.

$$\begin{aligned} CPUE_{s,i,t} = {} & \beta_1 ExpansionDummy_t + \beta_2 Distance_{i,s,t} \\ & + \beta_3 (ExpansionDummy_t * Distance_{i,s,t}) + \mathbf{V}_i + \mathbf{MY}_t \\ & + \mathbf{Gear}_{i,s,t} + \epsilon_{f,i,s,t} \end{aligned} \tag{4}$$

## Robustness Checks

Next, we test the robustness of our preferred specification (Time-vessel fixed effects) to using alternative data sources and to a series of falsification tests.

### Logbook Data

On both observed and unobserved trips, permit holders are required to submit self-reports ("logbook data") of fishing activity to NMFS at the end of the trip. Logbooks include roughly the same data as those recorded by observers, with the exception that catch is measured at the set level and fish weight is rarely recorded. There is generally high correspondence between logbook and observer catch data on observed trips for commercially valuable species; however, logbooks rarely record catch for species that are not commercially valuable, such as lancetfish (*Alepisaurus spp.*). Catch data for unobserved trips are difficult to validate. Finally, information on gear configuration is much more limited in the logbook data.

[2] Soak time is measured as the number of hours between the end of setting activity to the beginning of hauling activity.

Due to these limitations of the logbook data, we rely on observer data for our main analysis; however, we also estimate the preferred specification using the logbook data as a robustness check. The comparison to logbook data is useful for several reasons. First, captains may adjust their behavior to the presence of observers. This behavior could affect both species composition and location choices. Second, the logbook data is comprehensive, covering all observed and unobserved trips. More observations should increase the precision and power of the estimated models. Finally, these data will provide a true population estimate if the self-reports are trustworthy. Results are presented in Table S7: the estimated spillover benefits for yellowfin and bigeye tuna tend to be stronger and more statistically significant.

**Placebo Tests**

Next, we further test whether changes in spatio-temporal conditions that occurred coincidentally with the monument expansion might be affecting our results. As a reminder, the difference-in-differences framework already controls for the possibility that: 1) areas closer to the monument are more productive on average (we are not comparing cross-sectional success rates; we are comparing how success rates changed *within a region* before versus after the monument expansion) and 2) environmental or technological conditions improved everywhere after the monument expansion (we are comparing whether areas close to the monument had *larger* increases in catch after the monument expansion compared to areas far away). However, the difference-in-differences coefficient estimate would be biased if environmental conditions improved after the monument expansion *and* these conditions differentially affected the area close to the monument.

A common way to examine potential sources of bias is a "placebo test," which applies the same methodology in a setting or subset of the data where the expectation is that no effect will be detected. If statistically significant effects are consistently detected using placebo tests, then it suggests omitted variables may be biasing regression coefficient estimates. We used placebo tests to examine potential sources of bias correlated with the timing and location of the monument expansion, which we describe in detail below.

Our placebo tests explore whether environmental conditions favorable to tuna recruitment differentially affect areas near the monument. Phytoplankton levels in year $y - 4$ are a robust predictor of bigeye tuna catch in year $y$ (26). We examine phytoplankton levels in 2012 to identify environmental conditions that could have led to an increase in CPUE near the monument in 2016, the year of the monument expansion. We then identify a "time placebo" or a year in which we would expect a similar increase in CPUE, based on having similar phytoplankton levels four years prior.

We find that phytoplankton levels were nearly identical in 2006 and 2012, so we use 2010 (2006 + 4 years) as our time placebo. We selected August 26, 2010 specifically because this is the day of the year the monument expanded in 2016. By keeping this date consistent, we reduce the number of potential confounders. We re-run the Time-vessel fixed effects difference-in-differences specification but set the post-expansion dummy variable equal to 1 for sets that occur after the time placebo. We limit the observations to sets that occur between January 1, 2004 and December 31, 2013 to mirror the main specification, which includes data for 6 years pre-expansion and 3 years post-expansion. A statistically insignificant estimate for the difference-in-differences coefficient ("Diff in diff") suggests that environmental conditions occurring coincidentally at the timing of the monument expansion are not driving the spillover effects identified in the main specifications. Trends in standardized CPUE before and after the time placebo are presented in the main text. Regression results are presented in Table S9: we do not detect any statistically significant spillover benefits.

## Results in Context

As noted above, the outcome variable for all regression specifications is $standardizedCPUE$, defined in Eq. 1. Estimated coefficients, therefore, represent the number of standard deviations away from the pre-expansion mean value of CPUE for that species or species group. To put the results in a different context (numbers of fish), it is possible to calculate the effect of the monument expansion on raw CPUE levels by multiplying the difference-in-differences coefficient by the standard deviation of CPUE in the pre-expansion period. We present these calculations for the preferred specification (time-vessel fixed effects) using observer data in Table S6 and logbook data in Table S8. However, rather than calculate these raw effects manually, we directly ran the regressions using raw CPUE as the outcome variable, so that we can estimate the associated standard errors in terms of raw CPUE.

## Replication Using Non-Confidential Data

In order to support rapid replication, refinement, and criticism of our results, we demonstrate that the general pattern of our findings can be replicated using a non-confidential, but heavily aggregated, version of the logbook data described above. As part of its agreements under the Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean, the United States of America is required to submit summaries of all US-flagged longline fishing in the western Pacific Ocean to the Western & Central Pacific Fisheries Commission (WCPFC). This dataset combines deep-set and shallow-set longline fishing logbook data and it is temporally (monthly) and spatially (grid cells of 5 degrees longitude by 5 degrees latitude) aggregated . As a result, we can not observe individual vessel behavior and the precise location of fishing sets. But the dataset is freely available to the general public on the WCPFC's website: https://www.wcpfc.int/wcpfc-public-domain-aggregated-catcheffort-data-download-page.

We downloaded the "Aggregated data, grouped by 5x5 latitude/longitude grids, FLAG, YEAR and MONTH" dataset for the longline fishery and then restricted the sample to only US-flagged vessels. We then repeated all of the analysis explained in the Modeling Framework section of this document. To calculate distance from the monument boundary, we used the centroid of each grid cell. The Baseline regressions are exactly the same as before. The equivalent of the Time-vessel fixed effects regressions include month-year fixed effects but do not include individual vessel fixed effects because we do not observe individual vessel data. The equivalent of the Gear Controls regressions do not include vessel fixed effects or gear controls (both unobserved) but do include grid cell fixed effects. In Figure S2, we replicate Figure 3 from the main manuscript using these three adjusted specifications. It can be seen that we continue to observe statistically significant evidence of a spillover benefit for yellowfin tuna. The results are now too imprecise to reject a zero spillover effect for bigeye tuna. This makes sense given that the results for bigeye tuna using both observer and logbook data are weaker than the results for yellowfin tuna (both in terms of relative magnitude and statistical significance). The results for all species and other species are also imprecise. It is important to remember that not all species caught by captains are recorded in the logbooks, unlike the observer data, and this matches the results for other species obtained with the vessel-level logbook data.

# Supplementary Text

Marine protected areas have been a focal point of the fisheries and marine conservation literature for decades. We find that the world's largest fully protected MPA generates spillover fishery benefits for both bigeye tuna and yellowfin tuna. An unresolved question is the degree to which the size of Papahānaumokuākea is responsible for the stronger spillover effects documented in this paper. If nothing else, 1,500,000 km$^2$ can serve as a reference point for ongoing discussions on creating new MPAs on the high seas. Another key feature of Papahānaumokuākea that may be contributing to the strong spillovers observed is its elongated shape: it extends much further in a longitudinal direction than it does in a latitudinal direction. This is important because most documented movement of both yellowfin and bigeye tuna is longitudinal and not latitudinal. An MPA of similar size that was roughly circular or square-shaped (such as the MPAs in the Galápagos and Chagos islands) or elongated in a latitudinal direction would not provide tuna species with a similar refuge from fishing pressure. Another possible explanation for the stronger spillover effects documented here is the high quality and resolution of the data collected by NOAA. A very similar study to our own documents a divergence in total yellowfin catch between a near and far region starting two years after the strict enforcement of the Galápagos islands marine reserve but does not find a statistically significant divergence in CPUE (27). The data used in that study was aggregated monthly and on a grid scale of roughly 111 km by 111 km. The observer data used in this study reports the exact time (hour and minute) and geographic coordinates (up to four decimal places) of each individual fishing event.

Our results may actually represent a lower bound on the equilibrium effects of the MPA. The MPA expansion occurred fairly recently (mid-2016) and the last fishing observations in our data set are from December 31st 2019. Bigeye tuna and yellowfin tuna have life expectancies of around seven years and reach reproductive maturity at age two or three (therefore, it is possible that not enough time has passed for the full benefits of increased recruitment to appear). It also remains to be seen the degree to which future climate change will affect the distribution of tuna species in and around the MPA. Most models predict that a warming ocean will cause tuna biomass in the Pacific to move eastward and towards higher latitudes, which would imply both a decrease and an increase in tuna abundance within Papahānaumokuākea. Higher sea surface temperatures are also correlated with earlier sexual maturity in yellowfin tuna.

The statistically insignificant effect of the monument expansion on other species is likely due to a range of factors. Predator-prey interactions or inter-specific competition for resources could mean that the abundance of some species declines within the MPA area, especially at lower trophic levels. Further, since bigeye and yellowfin tuna are the target species, the catch of other species is more intermittent and stochastic, resulting in larger standard errors around estimated effects. Future research is needed to understand the full ecosystem impacts of Papahānaumokuākea and other large MPAs, beyond our current focus on commercially valuable top predators.

# Figures

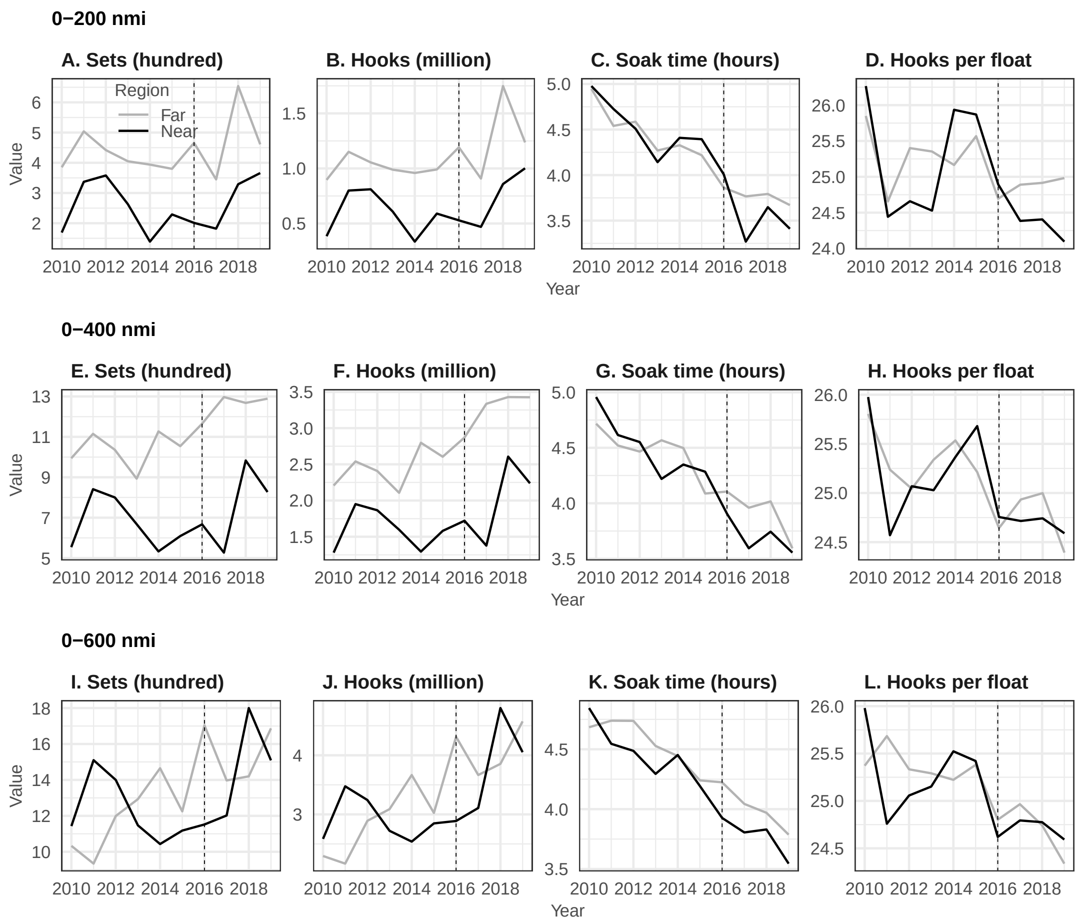


Figure S1: *Observer Data, Descriptive Statistics* for fishing effort and gear configuration for the deep set fishing fleet. Rows 1-3 include fishing sets within 200 nmi, 400 nmi, and 600 nmi of the PMNM expansion area boundary, respectively; the "near" region includes the inner half of each distance range while the "far" region includes in the outer half of each distance range. The vertical dashed line indicates the 2016 expansion year for PMNM. Sets are total counts. Hooks are summed across sets. Soak time and hooks per float are averaged across sets.

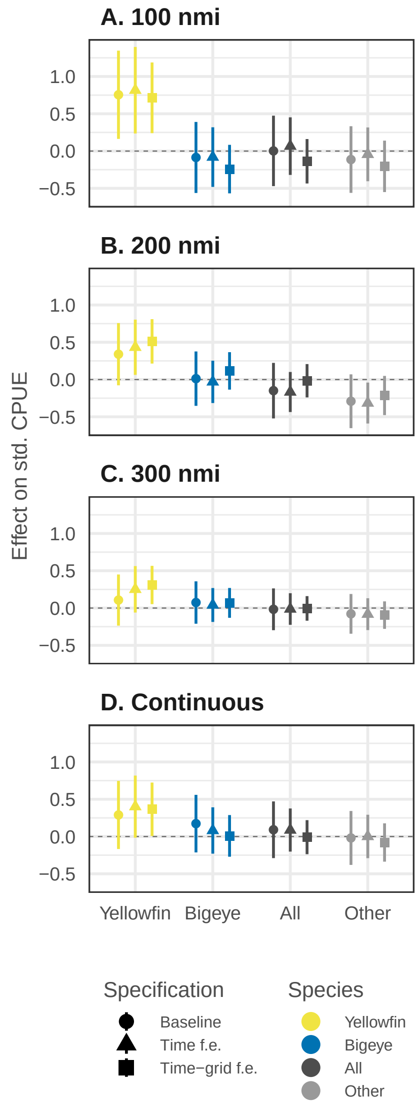


Figure S2: **Coefficient estimates for the effect of the monument expansion on catch-per-unit-effort using non-confidential Western & Central Pacific Fisheries Commission data.** (**A-C**) Results for the 100 nmi, 200 nmi, and 300 nmi specifications, respectively. (**D**) Results for the continuous distance specification. Results are scaled such that the estimated coefficient represents the effect of moving 500 nmi closer to the boundary of the monument. Symbols indicate point estimates and lines indicate 95% confidence intervals.

# Tables

Table S1. *AIS Data, Descriptive Statistics* for fishing hours by US-flagged vessels as a percent of total international fishing hours in the study area. Columns 2-5 include fishing effort within 100 nmi, 200 nmi, 300 nmi, and 600 nmi of the Papahānaumokuākea Marine National Monument expansion area boundary, respectively. Columns 2-4 represent the "near" areas in the three region radii models (i.e. the area where spillover benefits are hypothesized to occur). Column 5 represents the full area over which the continuous distance specification is based. Note that many US vessels did not use AIS until after March 1, 2016, when it was required by a regulatory change (33 CFR Part 164); therefore, data in the early years likely undercounts US-flagged effort.

| Year | 0-100 nmi | 0-200 nmi | 0-300 nmi | 0-600nmi |
|---|---|---|---|---|
| 2016 | 42.9% | 48.8% | 50.9% | 35.4% |
| 2017 | 52.5% | 57.7% | 62.9% | 51.1% |
| 2018 | 73.6% | 75.6% | 75.5% | 55.3% |
| 2019 | 67.5% | 63.7% | 63.2% | 50.9% |
| 2020 | 56.4% | 65.9% | 65.1% | 47.5% |

Table S2.*Observer Data, Descriptive Statistics* for fishing effort and gear configuration for the deep set fishing fleet (annual means with standard deviations in parentheses). Column 2 includes fishing sets that occurred in the Papahānaumokuākea Marine National Monument expansion area, before the monument expansion. Columns 3-5 include fishing sets within 200 nmi, 400 nmi, and 600 nmi of the Papahānaumokuākea Marine National Monument expansion area boundary, respectively; these data represent the combined “near” and “far” areas in the three region radii models. The continuous distance specification is based on data within the largest region radii specification, 0-600 nmi. Column 6 includes all sets available in the source data, including those outside the geographic extent of our analysis. The sample covers fishing sets that occurred between January 1, 2010 and December 31, 2019.

| | Expansion Area | 0-200 nmi | 0-400 nmi | 0-600 nmi | Historical Fishing Grounds |
|---|---|---|---|---|---|
| Participation: | | | | | |
| Number of Vessels | 19 (10.7) | 73.7 (5.9) | 105.2 (6.5) | 115.8 (8) | 125.5 (8.4) |
| Effort: | | | | | |
| Number of Sets | 138.8 (87.1) | 700.9 (154.8) | 1,824.7 (231.8) | 2,638.1 (348.8) | 3,883.2 (344.7) |
| Number of Hooks (1,000) | 332.4 (200.3) | 1,751.1 (427.4) | 4,523.6 (798.4) | 6,580.5 (1,252.4) | 9,820.6 (1,473.8) |
| Soak Time (Hours) | 4.3 (1.5) | 4.2 (1.4) | 4.2 (1.4) | 4.2 (1.4) | 4.3 (1.4) |
| Gear: | | | | | |
| Number of Hooks per Float | 24.4 (2.7) | 25 (2.5) | 25.1 (2.5) | 25 (2.4) | 24.9 (2.4) |
| Float Line Diam | 6.2 (0.4) | 6.2 (0.4) | 6.2 (0.5) | 6.2 (0.5) | 6.2 (0.5) |
| Bait Type (%) | | | | | |
| Saury (sanma) | 97.3 | 96.9 | 96.5 | 96.3 | 95.3 |
| Mixed | 0.9 | 2.1 | 2.1 | 2.3 | 2.9 |
| Mackerel (saba) | 1.6 | 0.7 | 0.7 | 0.8 | 0.7 |
| Sardine | 0.2 | 0.3 | 0.6 | 0.5 | 0.9 |
| Other | 0 | 0 | 0 | 0 | 0.2 |

Table S3. *Observer Data, Baseline* difference-in-differences regression results, using observer data. A-D display results from the 100 nmi, 200 nmi, 300 nmi, and continuous distance specifications, respectively. The outcome variable is standardized catch per 1,000 hooks for each species displayed in columns (1)-(4). The "Diff in Diff" coefficients measure the effect of fishing close to Papahānaumokuākea Marine National Monument after Papahānaumokuākea Marine National Monument was expanded in 2016. The sample covers fishing sets that occurred between January 1, 2010 and December 31, 2019. $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 White heteroskedasticity-robust standard errors presented in parentheses.

**Panel A. 100nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.168$^{***}$ | 0.193$^{***}$ | 0.204$^{***}$ | 0.123$^{***}$ |
| | (0.050) | (0.067) | (0.047) | (0.045) |
| Expansion Dummy | 0.103$^{***}$ | 0.591$^{***}$ | −0.061$^{**}$ | −0.242$^{***}$ |
| | (0.029) | (0.045) | (0.029) | (0.027) |
| Distance Dummy | −0.048 | 0.060$^{*}$ | −0.047 | −0.046 |
| | (0.031) | (0.031) | (0.031) | (0.031) |
| Observations | 7,009 | 7,009 | 7,009 | 7,009 |
| $R^2$ | 0.008 | 0.066 | 0.003 | 0.011 |

**Panel B. 200nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.190$^{***}$ | 0.225$^{***}$ | 0.160$^{***}$ | 0.063$^{**}$ |
| | (0.030) | (0.045) | (0.029) | (0.027) |
| Expansion Dummy | −0.028 | 0.520$^{***}$ | −0.147$^{***}$ | −0.252$^{***}$ |
| | (0.018) | (0.023) | (0.018) | (0.018) |
| Distance Dummy | −0.085$^{***}$ | 0.154$^{***}$ | −0.020 | −0.013 |
| | (0.019) | (0.020) | (0.019) | (0.019) |
| Observations | 18,247 | 18,247 | 18,247 | 18,247 |
| $R^2$ | 0.003 | 0.065 | 0.004 | 0.014 |

**Panel C. 300nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.153$^{***}$ | 0.158$^{***}$ | 0.184$^{***}$ | 0.120$^{***}$ |
| | (0.023) | (0.035) | (0.023) | (0.022) |
| Expansion Dummy | −0.070$^{***}$ | 0.509$^{***}$ | −0.221$^{***}$ | −0.310$^{***}$ |
| | (0.016) | (0.021) | (0.016) | (0.016) |
| Distance Dummy | −0.023 | 0.289$^{***}$ | −0.058$^{***}$ | −0.104$^{***}$ |
| | (0.016) | (0.016) | (0.016) | (0.016) |
| Observations | 26,381 | 26,381 | 26,381 | 26,381 |
| $R^2$ | 0.002 | 0.070 | 0.007 | 0.019 |

**Panel D. Continuous Distance**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.604$^{***}$ | 0.916$^{***}$ | 0.719$^{***}$ | 0.419$^{***}$ |
| | (0.075) | (0.111) | (0.072) | (0.069) |
| Expansion Dummy | 0.196$^{***}$ | 0.884$^{***}$ | 0.096$^{***}$ | −0.120$^{***}$ |
| | (0.026) | (0.043) | (0.025) | (0.024) |
| Distance Dummy | −0.090$^{*}$ | 0.928$^{***}$ | −0.113$^{**}$ | −0.241$^{***}$ |
| | (0.049) | (0.051) | (0.050) | (0.050) |
| Observations | 26,381 | 26,381 | 26,381 | 26,381 |
| $R^2$ | 0.003 | 0.078 | 0.008 | 0.018 |

Table S4. *Observer Data, Time-vessel fixed effects* difference-in-differences regression results, using observer data. A-D display results from the 100 nmi, 200 nmi, 300 nmi, and continuous distance specifications, respectively. The outcome variable is standardized catch per 1,000 hooks for each species displayed in columns (1)-(4). The "Diff in Diff" coefficients measure the effect of fishing close to Papahānaumokuākea Marine National Monument after Papahānaumokuākea Marine National Monument was expanded in 2016. The sample covers fishing sets that occurred between January 1, 2010 and December 31, 2019. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$ White heteroskedasticity-robust standard errors presented in parentheses.

**Panel A. 100nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.120* | 0.291*** | 0.173** | 0.087 |
| | (0.068) | (0.106) | (0.079) | (0.085) |
| Expansion Dummy | −0.248 | −1.482*** | −1.380*** | −1.200*** |
| | (0.151) | (0.365) | (0.165) | (0.244) |
| Distance Dummy | −0.038 | 0.006 | 0.002 | 0.018 |
| | (0.035) | (0.045) | (0.048) | (0.052) |
| Observations | 7,009 | 7,009 | 7,009 | 7,009 |
| $R^2$ | 0.144 | 0.146 | 0.145 | 0.141 |

**Panel B. 200nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.069 | 0.306*** | 0.056 | −0.020 |
| | (0.047) | (0.080) | (0.060) | (0.065) |
| Expansion Dummy | −0.626*** | −1.821*** | −1.020*** | −0.587*** |
| | (0.117) | (0.283) | (0.071) | (0.128) |
| Distance Dummy | −0.065** | 0.116*** | −0.007 | 0.0003 |
| | (0.029) | (0.034) | (0.036) | (0.040) |
| Observations | 18,247 | 18,247 | 18,247 | 18,247 |
| $R^2$ | 0.106 | 0.136 | 0.128 | 0.125 |

**Panel C. 300nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.024 | 0.115* | 0.085* | 0.070 |
| | (0.044) | (0.063) | (0.048) | (0.052) |
| Expansion Dummy | −1.027*** | −1.828*** | −1.392*** | −0.866*** |
| | (0.157) | (0.231) | (0.268) | (0.304) |
| Distance Dummy | −0.027 | 0.191*** | −0.058* | −0.087** |
| | (0.029) | (0.027) | (0.033) | (0.035) |
| Observations | 26,381 | 26,381 | 26,381 | 26,381 |
| $R^2$ | 0.094 | 0.134 | 0.128 | 0.121 |

**Panel D. Continuous Distance**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.101 | 0.823*** | 0.375** | 0.259 |
| | (0.128) | (0.200) | (0.173) | (0.184) |
| Expansion Dummy | −0.964*** | −1.736*** | −1.282*** | −0.781*** |
| | (0.151) | (0.211) | (0.260) | (0.297) |
| Distance Dummy | −0.175* | 0.654*** | −0.155 | −0.208* |
| | (0.092) | (0.079) | (0.114) | (0.122) |
| Observations | 26,381 | 26,381 | 26,381 | 26,381 |
| $R^2$ | 0.094 | 0.139 | 0.129 | 0.121 |

Table S5. *Observer Data, Gear controls* difference-in-differences regression results, using observer data. A-D display results from the 100 nmi, 200 nmi, 300 nmi, and continuous distance specifications, respectively. The outcome variable is standardized catch per 1,000 hooks for each species displayed in columns (1)-(4). The "Diff in Diff" coefficients measure the effect of fishing close to Papahānaumokuākea Marine National Monument after Papahānaumokuākea Marine National Monument was expanded in 2016. The sample covers fishing sets that occurred between January 1, 2010 and December 31, 2019. $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 White heteroskedasticity-robust standard errors presented in parentheses.

**Panel A. 100nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.117$^{*}$ | 0.296$^{***}$ | 0.146$^{*}$ | 0.056 |
| | (0.066) | (0.109) | (0.080) | (0.087) |
| Expansion Dummy | −0.228$^{*}$ | −1.520$^{***}$ | −1.214$^{***}$ | −1.005$^{***}$ |
| | (0.136) | (0.388) | (0.174) | (0.240) |
| Distance Dummy | −0.041 | 0.003 | −0.003 | 0.014 |
| | (0.036) | (0.045) | (0.049) | (0.053) |
| Observations | 6,885 | 6,885 | 6,885 | 6,885 |
| $R^2$ | 0.152 | 0.153 | 0.163 | 0.153 |

**Panel B. 200nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.062 | 0.304$^{***}$ | 0.035 | −0.041 |
| | (0.046) | (0.079) | (0.059) | (0.064) |
| Expansion Dummy | −0.610$^{***}$ | −1.826$^{***}$ | −0.899$^{***}$ | −0.452$^{***}$ |
| | (0.113) | (0.284) | (0.079) | (0.144) |
| Distance Dummy | −0.057$^{**}$ | 0.130$^{***}$ | −0.001 | 0.001 |
| | (0.028) | (0.030) | (0.036) | (0.040) |
| Observations | 17,953 | 17,953 | 17,953 | 17,953 |
| $R^2$ | 0.115 | 0.146 | 0.151 | 0.145 |

**Panel C. 300nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.021 | 0.125$^{**}$ | 0.077 | 0.060 |
| | (0.042) | (0.057) | (0.047) | (0.052) |
| Expansion Dummy | −1.013$^{***}$ | −1.841$^{***}$ | −1.324$^{***}$ | −0.790$^{***}$ |
| | (0.160) | (0.230) | (0.257) | (0.294) |
| Distance Dummy | −0.015 | 0.197$^{***}$ | −0.043 | −0.076$^{**}$ |
| | (0.029) | (0.025) | (0.032) | (0.034) |
| Observations | 25,910 | 25,910 | 25,910 | 25,910 |
| $R^2$ | 0.100 | 0.141 | 0.146 | 0.137 |

**Panel D. Continuous Distance**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.093 | 0.832$^{***}$ | 0.348$^{**}$ | 0.231 |
| | (0.131) | (0.195) | (0.170) | (0.182) |
| Expansion Dummy | −0.955$^{***}$ | −1.738$^{***}$ | −1.226$^{***}$ | −0.719$^{**}$ |
| | (0.154) | (0.211) | (0.250) | (0.288) |
| Distance Dummy | −0.143 | 0.668$^{***}$ | −0.113 | −0.175 |
| | (0.093) | (0.080) | (0.113) | (0.121) |
| Observations | 25,910 | 25,910 | 25,910 | 25,910 |
| $R^2$ | 0.101 | 0.146 | 0.146 | 0.136 |

Table S6. *Pre Expansion Statistics and Regression Coefficients for the Observer Data* Panel A. reports pre-expansion average CPUE with standard deviations given in parentheses. Panels B. and C. present the difference in difference coefficients for standardized CPUE and raw CPUE as the outcome variable, respectively. Coefficients represent the effect of the monument expansion on the outcome variable in the "near" area from the time-vessel fixed effects model, where each column corresponds to the 100 nmi, 200 nmi, and 300 nmi region-radii specifications, respectively.

| | 0-200nmi | 0-400nmi | 0-600nmi |
|---|---|---|---|
| **Pre-Statistics [average (sd)]**: | | | |
| Bigeye Tuna | 4.28 (4.15) | 4.5 (4.22) | 4.47 (4.34) |
| Yellowfin Tuna | 1.03 (1.92) | 0.87 (1.71) | 0.75 (1.54) |
| All | 23.63 (10.77) | 23.77 (11.14) | 23.82 (11.17) |
| Other | 18.32 (9.16) | 18.4 (9.55) | 18.6 (9.54) |
| **Standardized Diff-in-Diff**: | | | |
| Bigeye Tuna | 0.12 (0.07) | 0.07 (0.05) | 0.02 (0.04) |
| Yellowfin Tuna | 0.29 (0.11) | 0.31 (0.08) | 0.11 (0.06) |
| All | 0.17 (0.08) | 0.06 (0.06) | 0.09 (0.05) |
| Other | 0.09 (0.09) | -0.02 (0.06) | 0.07 (0.05) |
| **Raw Diff-in-Diff**: | | | |
| Bigeye Tuna | 0.5 (0.28) | 0.29 (0.2) | 0.11 (0.19) |
| Yellowfin Tuna | 0.56 (0.2) | 0.52 (0.14) | 0.18 (0.1) |
| All | 1.86 (0.85) | 0.62 (0.66) | 0.95 (0.54) |
| Other | 0.8 (0.78) | -0.19 (0.62) | 0.67 (0.5) |

Table S7. *Logbook Data, Time-vessel fixed effects* difference-in-differences regression results, using logbook data. A-D display results from the 100 nmi, 200 nmi, 300 nmi, and continuous distance specifications, respectively. The outcome variable is standardized catch per 1,000 hooks for each species displayed in columns (1)-(4). The "Diff in Diff" coefficients measure the effect of fishing close to Papahānaumokuākea Marine National Monument after Papahānaumokuākea Marine National Monument was expanded in 2016. The sample covers fishing sets that occurred between January 1, 2010 and December 31, 2019. $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 White heteroskedasticity-robust standard errors presented in parentheses.

**Panel A. 100nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.176$^{***}$ | 0.117$^{**}$ | 0.095$^{**}$ | −0.027 |
| | (0.034) | (0.047) | (0.045) | (0.046) |
| Expansion Dummy | −0.214$^{**}$ | −0.864 | −0.626$^{**}$ | −0.436$^{**}$ |
| | (0.095) | (0.569) | (0.300) | (0.208) |
| Distance Dummy | −0.085$^{***}$ | 0.072$^{***}$ | 0.022 | 0.066$^{**}$ |
| | (0.023) | (0.024) | (0.029) | (0.029) |
| Observations | 26,281 | 26,281 | 26,281 | 26,281 |
| $R^2$ | 0.120 | 0.139 | 0.090 | 0.125 |

**Panel B. 200nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.084$^{**}$ | 0.161$^{***}$ | 0.028 | −0.070$^{**}$ |
| | (0.033) | (0.037) | (0.030) | (0.029) |
| Expansion Dummy | −0.122 | −0.669$^{***}$ | −0.426$^{**}$ | −0.314$^{*}$ |
| | (0.168) | (0.255) | (0.196) | (0.181) |
| Distance Dummy | −0.057$^{***}$ | 0.075$^{***}$ | −0.022 | −0.012 |
| | (0.022) | (0.025) | (0.019) | (0.020) |
| Observations | 80,931 | 80,931 | 80,931 | 80,931 |
| $R^2$ | 0.076 | 0.103 | 0.082 | 0.099 |

**Panel C. 300nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.109$^{***}$ | 0.132$^{***}$ | 0.095$^{***}$ | 0.022 |
| | (0.023) | (0.029) | (0.023) | (0.023) |
| Expansion Dummy | −0.169 | −0.416$^{*}$ | −0.583$^{**}$ | −0.571 |
| | (0.127) | (0.230) | (0.291) | (0.367) |
| Distance Dummy | −0.075$^{***}$ | 0.133$^{***}$ | −0.076$^{***}$ | −0.085$^{***}$ |
| | (0.024) | (0.027) | (0.021) | (0.018) |
| Observations | 121,089 | 121,089 | 121,089 | 121,089 |
| $R^2$ | 0.070 | 0.111 | 0.087 | 0.106 |

**Panel D. Continuous Distance**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.346$^{***}$ | 0.630$^{***}$ | 0.388$^{***}$ | 0.136 |
| | (0.073) | (0.102) | (0.085) | (0.088) |
| Expansion Dummy | −0.016 | −0.155 | −0.416 | −0.513 |
| | (0.126) | (0.242) | (0.291) | (0.365) |
| Distance Dummy | −0.220$^{***}$ | 0.615$^{***}$ | −0.209$^{***}$ | −0.288$^{***}$ |
| | (0.046) | (0.043) | (0.060) | (0.067) |
| Observations | 121,089 | 121,089 | 121,089 | 121,089 |
| $R^2$ | 0.070 | 0.116 | 0.087 | 0.106 |

Table S8. *Pre Expansion Statistics and Regression Coefficients for the Logbook Data* Panel A. reports pre-expansion average CPUE with standard deviations given in parentheses. Panels B. and C. present the difference in difference coefficients for standardized CPUE and raw CPUE as the outcome variable, respectively. Coefficients represent the effect of the monument expansion on the outcome variable in the "near" area from the time-vessel fixed effects model, where each column corresponds to the 100 nmi, 200 nmi, and 300 nmi region-radii specifications, respectively.

| | 0-200nmi | 0-400nmi | 0-600nmi |
|---|---|---|---|
| **Pre-Statistics [average (sd)]**: | | | |
| Bigeye Tuna | 3.91 (3.74) | 4.07 (4.04) | 4.05 (3.97) |
| Yellowfin Tuna | 0.86 (1.61) | 0.79 (1.68) | 0.66 (1.48) |
| All | 13.03 (7.31) | 13.28 (7.88) | 13.31 (8) |
| Other | 8.26 (5.47) | 8.43 (5.55) | 8.6 (5.92) |
| **Standardized Diff-in-Diff**: | | | |
| Bigeye Tuna | 0.18 (0.03) | 0.08 (0.03) | 0.11 (0.02) |
| Yellowfin Tuna | 0.12 (0.05) | 0.16 (0.04) | 0.13 (0.03) |
| All | 0.1 (0.04) | 0.03 (0.03) | 0.09 (0.02) |
| Other | -0.03 (0.05) | -0.07 (0.03) | 0.02 (0.02) |
| **Raw Diff-in-Diff**: | | | |
| Bigeye Tuna | 0.66 (0.13) | 0.34 (0.14) | 0.43 (0.09) |
| Yellowfin Tuna | 0.19 (0.08) | 0.27 (0.06) | 0.19 (0.04) |
| All | 0.7 (0.33) | 0.22 (0.24) | 0.76 (0.19) |
| Other | -0.15 (0.25) | -0.39 (0.16) | 0.13 (0.14) |

Table S9. *Time placebo, time-vessel fixed effects* difference-in-differences regression results, using observer data. A-D display results from the 100 nmi, 200 nmi, 300 nmi, and continuous distance specifications, respectively. The outcome variable is standardized catch per 1,000 hooks for each species displayed in columns (1)-(4). The "Diff in Diff" coefficients measure the effect of fishing close to Papahānaumokuākea Marine National Monument after the time placebo expansion date of August 26, 2010. To maintain consistency, a 10-year sample is chosen preserving the 6-year pre-expansion and 4-year post expansion periods. The time placebo sample ranges between January 1, 2004 and December 31, 2013. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$ White heteroskedasticity-robust standard errors presented in parentheses.

**Panel A. 100nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.034 | −0.058 | 0.019 | 0.025 |
| | (0.080) | (0.067) | (0.095) | (0.093) |
| Expansion Dummy | 0.785*** | −0.477*** | −0.161 | −0.437** |
| | (0.139) | (0.139) | (0.165) | (0.206) |
| Distance Dummy | −0.044 | 0.010 | 0.010 | 0.030 |
| | (0.061) | (0.047) | (0.072) | (0.065) |
| Observations | 6,923 | 6,923 | 6,923 | 6,923 |
| $R^2$ | 0.172 | 0.112 | 0.166 | 0.143 |

**Panel B. 200nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | −0.018 | 0.032 | −0.015 | −0.021 |
| | (0.051) | (0.042) | (0.054) | (0.067) |
| Expansion Dummy | −0.036 | −0.215** | 0.595 | 0.831 |
| | (0.239) | (0.090) | (0.816) | (1.015) |
| Distance Dummy | −0.057* | 0.050 | 0.031 | 0.048 |
| | (0.030) | (0.038) | (0.031) | (0.038) |
| Observations | 18,232 | 18,232 | 18,232 | 18,232 |
| $R^2$ | 0.117 | 0.099 | 0.129 | 0.118 |

**Panel C. 300nmi**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.041 | 0.015 | 0.003 | −0.018 |
| | (0.042) | (0.046) | (0.051) | (0.058) |
| Expansion Dummy | −0.170 | −0.331*** | 0.157 | 0.358 |
| | (0.200) | (0.115) | (0.760) | (0.925) |
| Distance Dummy | −0.041* | 0.113** | −0.002 | −0.018 |
| | (0.022) | (0.048) | (0.030) | (0.034) |
| Observations | 26,492 | 26,492 | 26,492 | 26,492 |
| $R^2$ | 0.106 | 0.093 | 0.127 | 0.115 |

**Panel D. Continuous Distance**

| | Bigeye | Yellowfin | All | Other |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Diff in Diff | 0.003 | −0.093 | 0.137 | 0.191 |
| | (0.147) | (0.100) | (0.171) | (0.201) |
| Expansion Dummy | −0.142 | −0.343*** | 0.195 | 0.395 |
| | (0.208) | (0.113) | (0.770) | (0.936) |
| Distance Dummy | −0.186** | 0.516*** | 0.031 | −0.032 |
| | (0.081) | (0.078) | (0.110) | (0.121) |
| Observations | 26,492 | 26,492 | 26,492 | 26,492 |
| $R^2$ | 0.106 | 0.095 | 0.127 | 0.115 |

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