MARINE CONSERVATION

Spillover benefits from the world's largest fully protected MPA

Sarah Medoff[1], John Lynham[2]*, Jennifer Raynor[3]

Previous research has cast doubt on the potential for marine protected areas (MPAs) to provide refuge and fishery spillover benefits for migratory species as most MPAs are small relative to the geographic range of these species. We test for evidence of spillover benefits accruing from the world's largest fully protected MPA, Papahānaumokuākea Marine National Monument. Using species-specific data collected by independent fishery observers, we examine changes in catch rates for individual vessels near to and far from the MPA before and after its expansion in 2016. We find evidence of spillover benefits for yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*).

A number of governments around the world (including the USA) have committed to protecting 30% of their ocean territory by the year 2030 (*1*). Although the definition of protection varies across (and sometimes within) countries, achieving this goal will require the creation of new marine protected areas (MPAs): spatial zones in the ocean where activities such as fishing or mining are strictly controlled or prohibited (*2*). Part of the debate surrounding MPA impacts is the degree to which the cost of lost fishing grounds may be offset by the recovery and subsequent spillover of fish populations beyond the boundaries of an MPA (*3*). We define a spillover benefit as the recovery of a previously fished species within a protected area combined with some movement of the recovered population beyond the boundaries of the protected area, resulting in a higher catch rate of the species near the protected area than what would have been observed if the protected area had not been created.

There are several reasons why spillover benefits have been hard to detect. First, ocean ecosystems are complex and dynamic (*4*, *5*). Many factors that affect the abundance and location of fish species are changing concurrently with the creation of MPAs (*6*). Second, marine protected areas lead to changes in human behavior that may exaggerate or mask spillover effects, as most analyses rely on data derived from human activities (*7*). Third, most marine protected areas are relatively new and more time may be needed for populations to recover to the point that a spillover benefit is generated. For example, over 95% of the area contained in MPAs in the USA received protection only within the last 20 years (*8*). Finally, spillover benefits may not be detected simply because they are not occurring (*9*).

The aim of this study is to identify whether spillover benefits have accrued from the world's largest fully protected MPA, the Papahānaumokuākea Marine National Monument (PMNM) surrounding the northwest Hawaiian islands. We use the term "fully protected" to describe an MPA that prohibits extractive or other destructive activities, in line with *The MPA Guide* (*2*). The northwest Hawaiian islands have long been recognized for their conservation value. In 1909, a small area was designated as a refuge for seabird nesting colonies. In 2006, US President George W. Bush expanded this area, making it the largest MPA in US waters (at 360,000 km^2), and renamed it Papahānaumokuākea Marine National Monument (*10*). On 26 August 2016, President Barack Obama further expanded the reserve's boundaries, thereby establishing the largest, contiguous reserve within a single national jurisdiction in the world (at 1,510,000 km^2; see Fig. 1A). Our analysis focuses on the 2016 expansion.

Our approach follows the "gold standard" proposed by (*11*) for testing for the presence of a spillover benefit from an MPA: "did a particular vessel deploying a particular type and quantity of gear catch more in an area near the reserve after formation of the reserve than it would have caught had the reserve never been established?" (p. 154). This approach specifically accounts for changes in fishing effort across space which may create the false impression that spillover benefits are occurring—an increase in total catch [or even catch per unit effort (CPUE)] near the boundary of an MPA could be caused by greater fishing intensity or more efficient vessels fishing there, and not necessarily by an increase in fish abundance. The gold standard approach holds fishing effort and fishing efficiency as fixed. This approach also controls for time-invariant spatial heterogeneity that may cause differences in catch rates across space (such as the presence of seamounts).

Testing for the presence of a spillover benefit requires spatiotemporal data on catch by species, fishing locations, vessel characteristics, and gear configurations. Our primary data source is the National Marine Fisheries Service Pacific Islands Region Observer Program, which collects detailed information on catch and fishing effort for the Hawaii-based, limited-entry, longline fishery (*12*). We focus on the deep-set segment of the longline fleet, which primarily targets bigeye (*Thunnus obesus*) and yellowfin (*Thunnus albacares*) tuna and accounts for the vast majority (97 to 99%) of US longline fishing activity in this region (*13*). Bigeye and yellowfin tuna have life expectancies of around 7 years and reach reproductive maturity at age 2 or 3 (*14*, *15*) but recent evidence from the Eastern Pacific suggests that yellowfin tuna are maturing earlier and at smaller sizes (*16*). The Hawaii-based longline fishery accounts for most fishing activity within 300 nautical miles (nmi) of the MPA, according to data provided by Global Fishing Watch (*17*) (table S1). Because the PMNM expansion took place in 2016, we restricted our main analysis to observations since 2010.

In accordance with (*11*), we tested for spillover benefits based on distance from the PMNM border. We defined regions that are "near" to versus "far" from the border. We defined a near region as one that extends $(0, x]$ nmi from the monument border and a far region that extends $(x, 2x]$ nmi from the monument 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 0.25, 0.5, and 0.75 times the "diameter" of the monument. The amount of historical fishing effort in each of these zones (and inside the MPA prior to closure) is summarized in table S2 and fig. S1.

We start by examining spatial and then temporal trends in CPUE near to and far from the MPA boundary, with CPUE defined as fish per 1000 hooks. To examine spatial patterns, we first calculated how CPUE changes as a function of distance from the monument boundary; we did this separately for the pre- and post-expansion time periods. We then calculated the difference between pre- and post-expansion CPUE as a function of distance from the monument, after accounting for any overall change in CPUE post expansion (*12*). The results are shown in Fig. 1, B and C. The color scale represents the number of standard deviations away from the mean value of pre-expansion CPUE for each species. The results are suggestive of a spillover benefit for bigeye tuna and yellowfin tuna, with a stronger effect for the latter as CPUE for yellowfin increases by ~0.55 standard deviations as a vessel moves 600 nmi closer to the monument boundary.

Next, we examine temporal patterns in CPUE for the 100-, 200-, and 300-nmi region radius

[1]Cooperative Institute for Marine and Atmospheric Research, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, HI, USA.
[2]Department of Economics and UHERO, University of Hawai'i at Mānoa, Honolulu, HI, USA. [3]Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI, USA.
*Corresponding author. Email: lynham@hawaii.edu

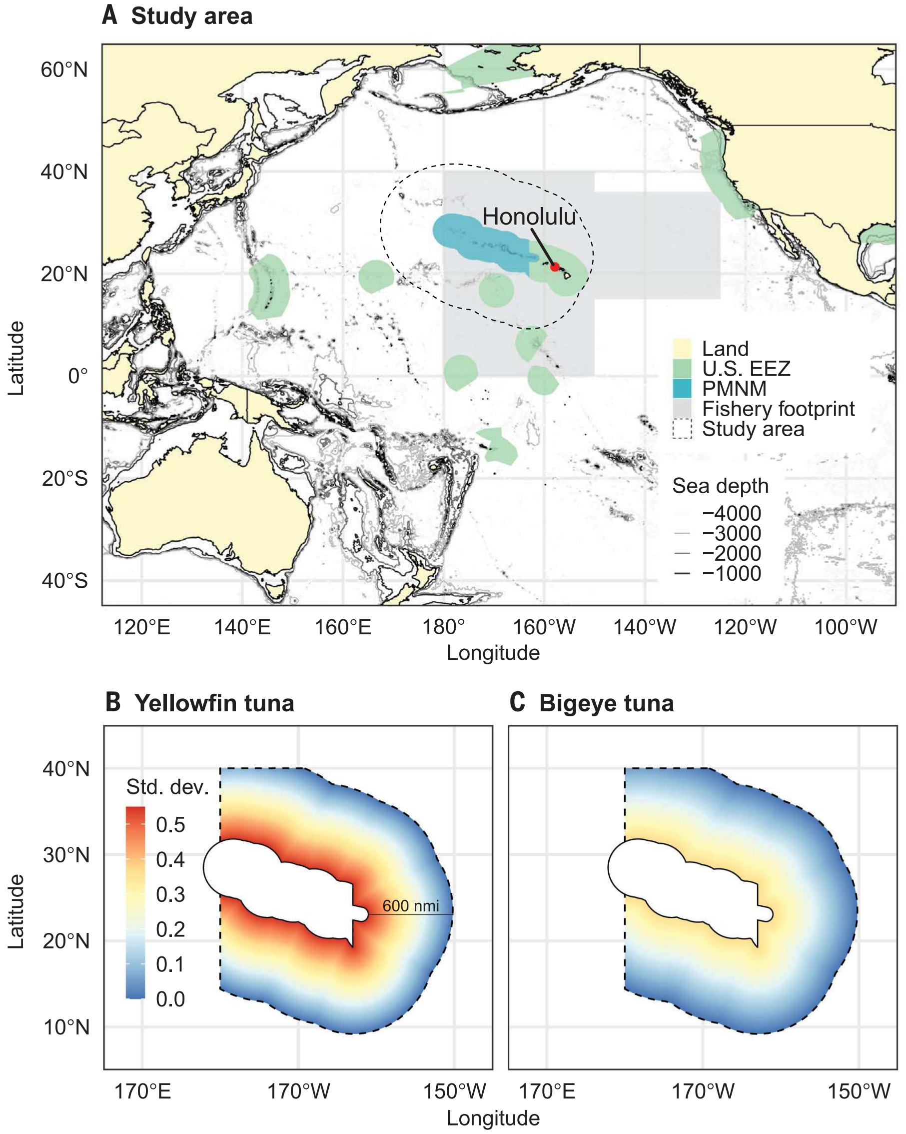

Fig. 1. Increase in standardized CPUE over 1-nmi increments from the PMNM border. (**A**) Map of PMNM surrounding the northwest Hawaiian islands. The exclusive economic zone (EEZ) is an area of coastal water and seabed within 200 nmi of a country's coastline, to which the country claims exclusive rights for fishing, drilling, and other economic activities. PMNM is part of the U.S. EEZ. Fishery footprint refers to the full spatial extent of Hawai'i-based deep-set longline fishing activity during the study period (2010 to 2019). The study area comprises a 600-nmi buffer around the PMNM. (**B** and **C**) Difference between pre- and post-expansion standardized CPUE within the study area; units are the number of standard deviations above the mean value of pre-expansion standardized CPUE and the spatial extent is the part of the study area within the fishery footprint.

specifications (Fig. 2, A, D, and G). For each year in the sample, we calculated the difference between CPUE for the near and far regions for each species (and for all fish species combined). We then standardized each time series based on its pre-expansion moments (subtract the pre-expansion mean and divide by the pre-expansion standard deviation of the difference in CPUE). The results are shown in the second column of Fig. 2, B, E, and H. The vertical axis for each graph represents the number of standard deviations away from the pre-expansion mean difference in CPUE. If the difference in CPUE between the near and far regions remains the same following expansion of the monument (i.e., there is no suggestive evidence of a spillover benefit), then each time series would fluctuate around zero. By contrast, if catch rates increase in the near region more than in the far region (i.e., there is suggestive evidence of a spillover benefit) then each time series will rise above zero. For each species grouping we observe suggestive evidence of a spillover benefit—CPUE is increasing in the near region relative to the far region following monument expansion. The spillover benefit appears strongest for yellowfin tuna, especially for the 100- and 200-nmi region radii. Differences in catch rates for bigeye tuna become more apparent with the 300-nmi radius. For example, by 2019 the difference in CPUE for bigeye tuna between the near and far regions was more than 2 standard deviations larger than the pre-expansion mean difference.

To quantify the effects of the monument expansion on CPUE more precisely and to control for other confounding factors and possible selection bias, we developed a species-specific difference-in-differences linear regression model. We tested the null hypothesis that there was no spillover benefit using the approach proposed by (*11*). We used three model specifications, each imposing additional layers of control variables. The first model is a basic difference-in-differences setup (baseline). The second model adds month-year and vessel fixed effects (time-vessel fixed effects). The final and most restrictive model adds controls related to gear configurations, which can affect catch rates (gear controls). The outcome variable for each model is catch per 1000 hooks for each species or species group, standardized by its pre-expansion mean and standard deviation. This allows for easy comparisons across species and species groups. The estimated difference-in-differences coefficients represent the change in CPUE as a result of the monument expansion, measured in standard deviations above or below the mean value of pre-expansion CPUE. Results are summarized in graphical form in Fig. 3 and in tables S3 to S5. We also show the mean and standard deviation for baseline pre-expansion CPUE, as well as the results using raw CPUE (number of fish caught per 1000 hooks) for the time-vessel fixed effects (preferred) model in table S6.

Across specifications and species, we consistently estimate positive spillover benefits from the monument expansion on CPUE. Focusing on the time-vessel fixed effects (preferred) model (table S4) and the 100-nmi near region, the monument expansion leads to an increase of 0.12 standard deviations in CPUE ($P < 0.1$) for bigeye tuna, 0.291 for yellowfin tuna ($P < 0.01$), and 0.173 for all species ($P < 0.05$). This is equivalent to an increase of 0.5 bigeye tuna per 1000 hooks (with a pre-expansion mean of 4.3 fish per 1000 hooks), 0.6 yellowfin per 1000 hooks (with a pre-expansion mean of 1 fish per 1000 hooks), and 1.9 fish of any species per 1000 hooks (with a mean value of 23.6 fish pre expansion). See table S6 for the same calculations for the 200- and 300-nmi specifications.

To deal with the possibility that the chosen region-radii specifications (100, 200, and

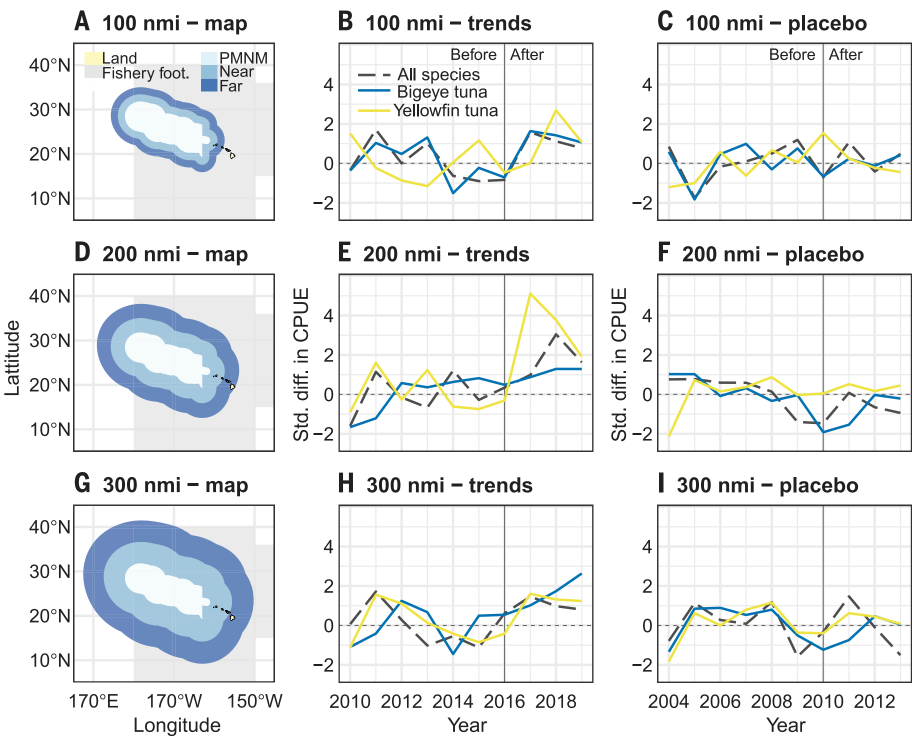

Fig. 2. Standardized difference in CPUE between regions near to and far from the PMNM. The near region extends (0, x] nmi from the monument border and the far region extends (x, 2x] nmi from the monument border, with x equal to 100, 200, and 300 in rows 1, 2, and 3, respectively. Fishery footprint (fishery foot) refers to the full spatial extent of the Hawai'i-based deep-set longline fishery during the study period (2010 to 2019). (**A**, **D**, and **G**) Maps for each radius. (**B**, **E**, and **H**) Standardized differences between pre- and post-expansion CPUE over time. (**C**, **F**, and **I**) Standardized differences in CPUE before and after a monument expansion time placebo date (2010). For (B) and (C), (E) and (F), and (H) and (I), negative values indicate that CPUE was higher in the far area whereas positive values indicate CPUE was higher in the near area.

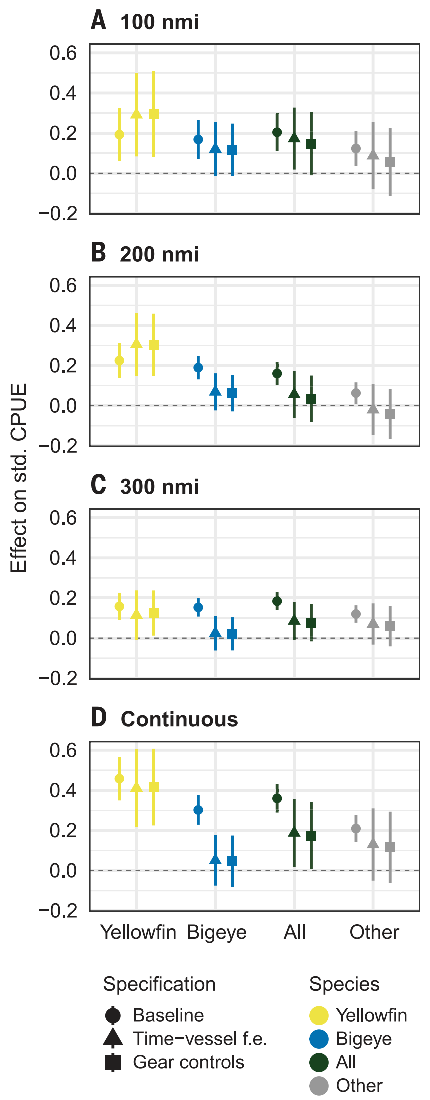

Fig. 3. Coefficient estimates for the effect of the monument expansion on CPUE. (**A** to **C**) Results for the 100 nmi, 200 nmi, and 300 nmi specifications, respectively. (**D**) Results for the continuous distance specification. Results are scaled such that the estimated coefficient represents the effect of moving 500 nmi closer to the boundary of the monument. Symbols indicate point estimates and lines indicate 95% confidence intervals constructed using White heteroskedasticity-robust standard errors.

300 nmi) could be biasing our analysis in favor of finding a positive spillover effect, we also use a continuous distance measure instead of a binary near or far indicator as our treatment variable. By interacting the continuous distance variable with a dummy variable for the post-expansion period (and multiplying by −1), we estimate the change in CPUE of moving closer to the current monument boundary following monument expansion. We estimate this model with the same sets of covariates used in the region-radii specifications above. Results are summarized in graphical form in Fig. 3D (for a movement of 500 nmi) and in tables S3 to S5 (for a movement of 1000 nmi). Across the three specifications, as a fishing vessel moves closer to the monument border (following the expansion of the monument in 2016) CPUE increases for both bigeye tuna and yellowfin tuna. For example, for the baseline specification for yellowfin tuna, moving 1000 nmi closer to the monument results in a 0.92-standard deviation increase in CPUE. For bigeye tuna, the coefficient estimate is only statistically significant for the baseline specification (0.6 standard deviations); the estimate is always statistically significant for yellowfin tuna ($P < 0.01$). The implications of the baseline coefficient estimates are visualized in Fig. 1, B and C.

To test the robustness of our findings, we explored whether the data source affects the results. In addition to the data collected by National Marine Fisheries Service observers, CPUE in this region can also be derived from captains' logbooks. We reconstruct the region-radii and continuous distance specifications explained above for the time-vessel fixed effects (preferred) model using logbook data (tables S7 and S8). The results using logbook data are consistent with the previous results except that we now see stronger evidence of a spillover benefit for bigeye tuna [it is statistically significant ($P < 0.05$) in all specifications]. A common robustness check in analyses of the type presented here is to apply the same methodology in a setting or subset of the data where the expectation is that no effect will be detected—in other words, a placebo test. We conducted a series of temporal placebo tests (*12*), altering the start date of the MPA expansion to be in 2010 instead of 2016 (column 3 of Fig. 2, C, F, and I). These placebo tests failed to detect a statistically significant spillover benefit for bigeye or yellowfin tuna (table S9). Finally, to encourage easy replication, refinement, and criticism of our results, we demonstrate that the general pattern of our findings can be replicated using a nonconfidential but aggregated version of the logbook data (fig. S2).

If a large MPA was providing protection to a number of migratory fish species and subsequently providing a spillover benefit beyond its boundaries, one would expect to observe an increase in CPUE near the MPA relative to any changes in CPUE far from the MPA (*11*). Further, confirmation should be sought that this increase is being observed for the same vessel (or, at the very least, vessels of similar technical efficiency) and not simply because vessels are reallocating their fishing effort across space (*6*) or altering fishing intensity across space. The increase in CPUE should be most pronounced for species that have experienced heavy fishing pressure (*18–20*). The spillover effect should be stronger for species that are less migratory, exhibit stronger site fidelity, and have been documented to spawn in or near the MPA (*21–25*). Finally, the increase should not be immediate but rather should have built up over time (*7*). We observe all of these signals in the data.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S2
Tables S1 to S9
References (*27*, *28*)

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