ARTICLE IN PRESS

Marine Policy xxx (xxxx) xxx

Contents lists available at ScienceDirect

Marine Policy

journal homepage: http://www.elsevier.com/locate/marpol

Economic impacts of Papahānaumokuākea Marine National Monument expansion on the Hawaii longline fishery

Hing Ling Chan [a,b,1]

[a] University of Hawaii Joint Institute for Marine and Atmospheric Research, 1000 Pope Road, Marine Sciences Building 312, Honolulu, HI, 96822, USA
[b] Pacific Islands Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 1845 Wasp Blvd., Building 176, Honolulu, HI, 96818, USA

ARTICLE INFO

Keywords:
Hawaii
Longline fishery
Monument expansion
Economic impacts

ABSTRACT

This study examines the economic impacts of the Papahānaumokuākea Marine National Monument (PMNM) expansion on the Hawaii longline fishery, using difference-in-differences (DID) models with fixed effects. It evaluates the impacts of the PMNM expansion on catch per unit effort (CPUE) and fishing revenue for the group of vessels that had a high portion of their fishing effort inside the Monument Expanded Area (MEA) prior to the expansion in August 2016. The results show that the PMNM expansion caused the CPUE of this group of vessels to decrease by 7%. Revenue per trip decreased by 9%, $3.5 million, during the first 16 months of post-expansion period. One likely reason for the negative impacts is that longline fishers who used to fish inside the MEA have been displaced from their traditional fishing grounds are still in the process of becoming more efficient in finding areas with comparable productivity.

1. Introduction

On August 26, 2016, President Obama created the largest protected area on the planet by quadrupling the size of the Papahānaumokuākea Marine National Monument (PMNM) that was created in 2006, from 139,793 to 582,578 square miles of waters and submerged lands in the Northwestern Hawaiian Islands (Fig. 1). The original PMNM and the new Monument Expanded Area (the MEA) were designed to protect the area from commercial extraction activities, such as fishing and deep-sea mining. Limited activities are allowed with permit, including recreational fishing and removal of fish and other resources for Native Hawaiian cultural practices and scientific research purposes [1]. Among the most affected commercial fishery would be the Hawaii longline fishery.

Hawaii longline fishery is the most economically important commercial fishery in the U.S. Pacific Islands Region. There were 141 active Hawaii longline vessels in 2016, together they deployed more than 51 million hooks, landed more than 33 million pounds of pelagic fish, and generated $111 million in revenue. There are two segments in the Hawaii longline fishery, a deep-set longline fishery targeting bigeye tuna, and a shallow-set longline fishery targeting swordfish. Among the 1522 trips that occurred in 2016, 1476 (97%) were deep-set trips, and 46 (3%) were shallow-set trips. For recent trends of the fishing activities in Hawaii longline fishery, refer to Ayers et al. [2].

The Hawaii longline fishery is governed by numerous regulations, which vary substantially by gear type, fishing area, vessel permit, and vessel size. The fishery's operation is significantly affected by the fleet-wide bigeye catch limits for both deep-set and shallow-set longline fisheries (combined) and turtle interaction caps for the shallow-set longline fishery. The fleet-wide bigeye catch limits are managed by two international commissions: the Western and Central Pacific Fishery commission (WCPFC) in the western Pacific (WCPO) since 2009, and the Inter-American Tropical Tuna Commission (IATTC) in the eastern Pacific (EPO) since 2004. Since catch limits have been in place, the fishery has been closed five times in WCPO with more closure days in recent years (39 days in 2017). The Hawaii longline vessels are subject to different bigeye catch limits in EPO for vessels over 24 m. Vessels 24 m or less are not subject to any catch limits in EPO. The EPO fishery closed in the latter part of the year from 2013 to 2107 for vessels greater than 24 m (32 days in 2017) [2].

The shallow-set longline fishery is managed by several regulations, including annual interaction caps for loggerhead and leatherback turtles, gear restrictions to reduce or mitigate interactions with turtles and marine mammals, and 100% observer coverage since the fishery was

E-mail address: hingling.chan@noaa.gov.

[1] Hing Ling Chan is a senior fisheries economic project manager at the University of Hawaii Joint Institute for Marine and Atmospheric Research (JIMAR), c/o NOAA Fisheries Pacific Islands Fisheries Science Center, NOAA IRC, NMFS/PIFSC/ESD, 1845 Wasp Blvd., Building 176, Honolulu HI 96818.

https://doi.org/10.1016/j.marpol.2020.103869
Received 4 January 2019; Received in revised form 16 January 2020; Accepted 4 February 2020

Please cite this article as: Hing Ling Chan, *Marine Policy*, https://doi.org/10.1016/j.marpol.2020.103869

reopened in 2004 after a three-year closure enacted in response to litigation related to turtle interactions [3]. The shallow-set longline fishery has been closed three times between 2004 and 2018 as a result of reaching the annual turtle interaction limit.

Given the heterogeneity of the Hawaii longline fleet and regulations that govern the fishery, different segments of the fishery may experience different socioeconomics impacts [2,4,5]. The newly expanded waters of the PMNM add another layer to the already complex regulations, and the potential economic impacts of the PMNM expansion have generated great concern among the longline fishers. Because not all the Hawaii longline vessels fished inside the MEA, it is expected that the PMNM expansion would impact different segments of the fleet in diverse ways. No vessels are permitted to fish inside the MEA since the expansion. As a result, fishing effort must divert to areas outside the MEA. An internal report by Pacific Islands Fisheries Science Center [6] used historical data (2010–2015) to estimate the upper bound of potential direct economic impacts by assuming full loss of revenue from the PMNM expansion without spatial reallocation of effort. That report estimated the loss at $7.8 million per year. The objective of this study is to assess the economic impacts of the PMNM expansion on the Hawaii longline fishery, taking into account potential relocation of longline vessels from the MEA using retrospective data.

Total fishing activity inside the area that would become the MEA was not particularly high in the Hawaii longline fishery before the PMNM expansion. Table 1 shows the number of hooks set inside the MEA between 2007 and 2016 for all trips, shallow-set trips, and deep-set trips, relative to the total hooks set for all trips. For the past 10 years, before the PMNM expansion, the percent of annual hooks set inside the MEA was 9% in 2008 and 2011 and gradually dropped to 2% in 2016 (before the PMNM expansion), and the majority of the hooks set inside the MEA were from deep-set trips. However, fishing inside the MEA was important for the shallow-set fishery, with 11%–15% of annual shallow-set hooks set inside the MEA between 2010 and 2013 (Fig. 2). There was large variation in monthly effort inside the MEA and distinct seasonal patterns for both deep-set and shallow-set trips. Fishing inside the MEA was opportunistic in nature because bigeye tuna CPUE was higher in the northwestern and northeastern part of Pacific Ocean in the third quarter of the year [7]. Therefore, almost no deep-set fishing effort occurred inside the MEA between July and September. And the highest deep-set activity occurred inside the MEA during the winter, with 16% of effort in November, 14% in December, and 9% in January. For shallow-set trips, the monthly effort inside the MEA was as high as 21% in April, 37% in May, and 29% in June. From August to January there was no shallow-set fishing activity inside the MEA (Fig. 3).

If the MEA is particularly productive compared with outside areas, then banning fishing inside the MEA due to the PMNM expansion would negatively impact the Hawaii longline fishers. Table 2 shows the productivity inside and outside the MEA from 2007 to 2016. Productivity, defined as number of fish kept per 1000 hooks, was higher inside the MEA most years. Productivity defined as pounds of fish kept per 1000 hooks, was consistently higher inside the MEA, particularly between 2007 and 2011. This suggests that the fish landed inside the MEA, on

Table 1
Distribution of hooks set inside and outside the Monument Expanded Area: all trips, deep-set trips, and shallow-set trips, 2007–2016 (before the PMNM expansion).

	Number of hooks set inside MEA			Number of hooks set inside and outside MEA
	Deep-set trips	Shallow-set trips	All trips	All trips
2007	1,657,758	122,004	1,779,762	40,181,068
2008	3,530,582	133,339	3,663,921	41,580,233
2009	2,727,286	129,056	2,856,342	39,492,259
2010	1,554,300	273,851	1,828,151	38,594,203
2011	3,652,828	171,968	3,824,796	42,145,177
2012	2,956,042	185,385	3,141,427	45,450,757
2013	2,640,653	111,443	2,752,096	47,800,201
2014	2,013,133	92,081	2,105,214	47,030,006
2015	1,753,574	116,025	1,869,599	48,668,380
2016	605,596	26,050	631,646	33,206,858

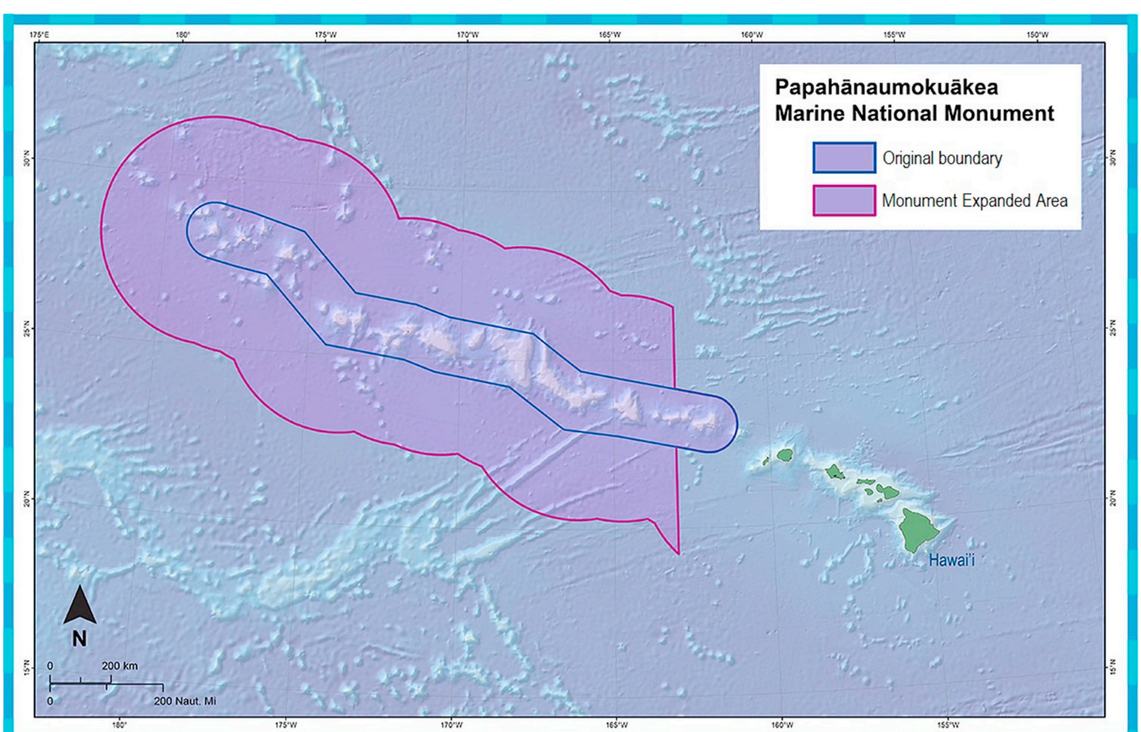

Fig. 1. Map of Papahānaumokuākea Marine National Monument: Original boundary and Monument Expanded Area. Credit: NOAA

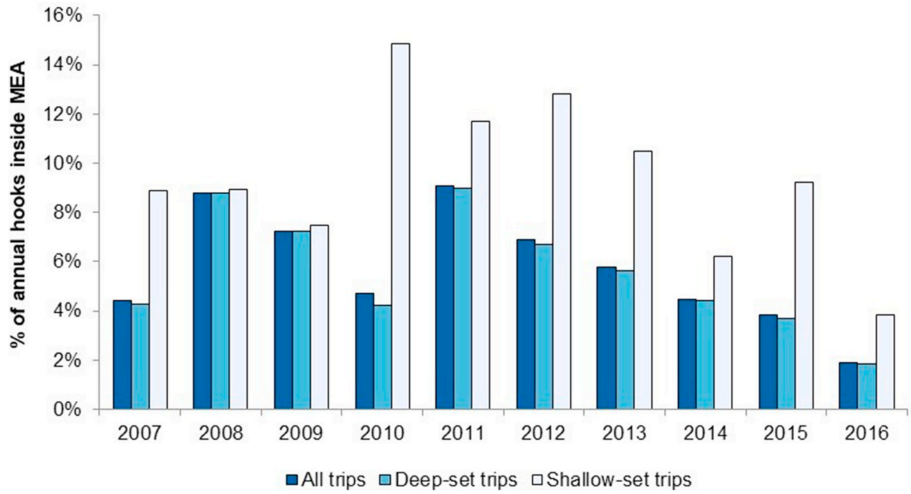

Fig. 2. Annual distribution of hooks inside the Monument Expanded Area for all trips, deep-set trips, and shallow-set trips, 2007–2016 (before the PMNM expansion).

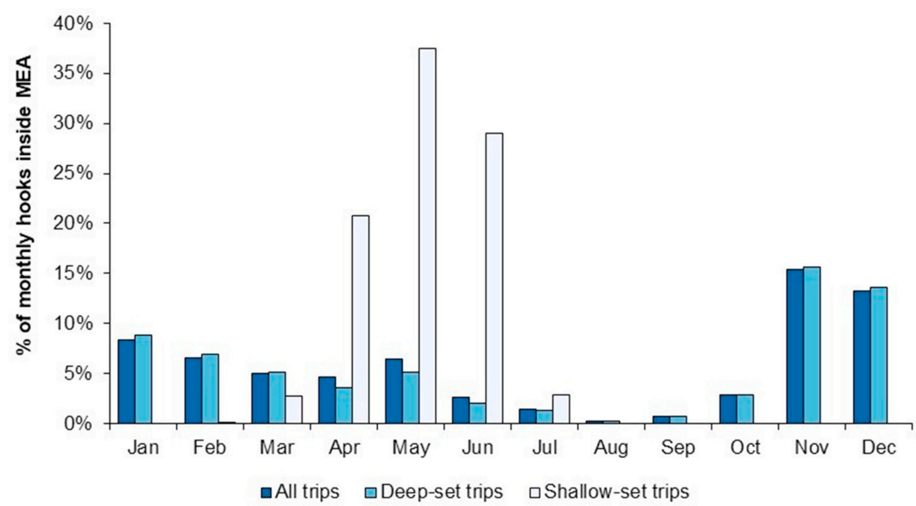

Fig. 3. Seasonal distribution of hooks inside the Monument Expanded Area between 2007 and 2016 (before the PMNM expansion) for all trips, deep-set trips, and shallow-set trips.

Table 2
Productivity inside vs. outside the MEA, 2007–2016 (before the PMNM expansion).

	CPUE			Pounds kept per 1000 hooks			Pounds per fish			Revenue per 1000 hooks		
	MEA	Outside MEA	% difference	MEA	Outside MEA	% difference	MEA	Outside MEA	% difference	MEA	Outside MEA	% difference
2007	11.5	10.5	9%	745	610	22%	64.9	58.0	12%	1800	1630	10%
2008	12.4	10.4	19%	764	635	20%	61.6	60.9	1%	2079	1766	18%
2009	9.4	9.2	2%	620	558	11%	66.3	60.8	9%	1578	1497	5%
2010	10.4	10.6	−3%	797	597	33%	77.0	56.1	37%	2199	1818	21%
2011	12.5	11.2	11%	710	620	15%	56.9	55.1	3%	2138	1957	9%
2012	11.1	10.7	4%	609	569	7%	54.7	53.2	3%	2043	2119	−4%
2013	11.5	11.1	4%	626	567	10%	54.4	51.3	6%	1932	1932	0%
2014	12.0	11.8	2%	677	631	7%	56.6	53.6	6%	1927	1847	4%
2015	11.7	12.1	−4%	786	704	12%	67.4	58.2	16%	1992	2108	−6%
2016	9.3	11.4	−18%	682	678	1%	73.6	59.6	23%	2372	2332	2%

average, were larger than the fish landed outside the MEA. Revenue per 1000 hooks generated from fish kept inside the MEA was also consistently higher before 2011. The comparative advantage of fishing inside the MEA started to drop in 2012 which could explain the decrease in fishing effort inside the MEA at this time.

Studies evaluating the economic impacts of regulatory policies on the Hawaii longline fishery have been undertaken. Most of these studies developed fishery models using one year of data as a base year and simulated economic impacts from regulatory policies [8–12]. However, there is often a large discrepancy between the predicted and observed outcomes. Sweeney et al. [13] improved upon this by developing a Positive Mathematical Programming model that closely replicated the observed activities at the individual vessel level using one year of cost-earnings information and simulated the impacts on the fishery under different policy scenarios. Other studies used an input-output approach to assess the statewide economic impacts from the Hawaii longline swordfish closure [14,15].

Instead of building a theoretical model, difference-in-differences (DID) estimation is a common approach to evaluate the policy impacts using before and after data. The DID approach has been broadly used in applied economics literature to evaluate economic, environmental, and health care policy intervention, and recently it has been used to evaluate the impacts of marine policies [16–18]. Cunningham et al. [16] developed DID models with fixed effects and found a catch share program in New England caused spillover effects of increased landings into adjacent Mid-Atlantic fisheries. In addition to individual vessel's fixed effects, their models also controlled for fluctuations in landings due to seasonal variation, annual variation, and monotonic changes in catch over the entire study period. Pfeiffer and Gratz [17] used DID estimation with vessel fixed effects to evaluate the effects of catch shares management on fishermen's risk-taking behavior. Chan and Pan [18] used DID approach to estimate the spillover effects of sea turtle interactions due to environmental regulations in the Hawaii longline swordfish fishery. Jardine et al. [19] examined the effects of Cooper River Fishermen's Cooperative on salmon prices and product quality, using a neighboring salmon fishery as the control. Abbott and Wilen [20] included vessel-specific fixed effects to examine the success of the participation of a private program, Sea State, that integrated and communicated bycatch information to participants, using nonparticipants as the control group. Hallstein and Villas-Boas [21] included product- and store-specific fixed effects to estimate the impacts of a seafood advisory for sustainable seafood on sales in regional supermarket chain.

DID approach often involves retrospective analyses, using data before and after the actual policy was enacted. It is common to use retrospective analyses to evaluate the impacts of marine reserve on fisheries. This approach basically compares the fishery status before and after the policy, often using treatment and control groups for comparison. Recent studies include Smith et al. [22] that used the program evaluation approach to quantify the effects of marine reserves on changes in CPUE in the Gulf of Mexico reef fish fishery. They developed models to measure the differences in CPUE between treatment and reference groups before and after the marine reserve, with the treatment group containing areas within marine reserves and the reference group included areas far away from the reserves. To isolate the effects of marine reserves, their models took into account variation in fishing gear, vessel fixed effects, fish stocks in different zones, seasonality in fish abundance, impacts of other regulatory policies, and the announcement effects of marine reserves. Mason et al. [23] also used retrospective analyses to examine the changes in fishing effort and spatial distribution of effort in the California groundfish trawl fishery following implementation of a marine reserve off the California coast. Their study demonstrated how to use the level of effort in the reserve as a guideline to categorize vessels and evaluate the impacts of marine reserve.

This study uses DID approach with fixed effects to conduct retrospective analyses of the PMNM expansion. It evaluates whether and to what extent the PMNM expansion affected the Hawaii longline fishery's CPUE and revenue. In this study, CPUE is defined as total number of fish kept per 1000 hooks. Using confidential fishery-dependent data at the individual vessel level and comparing the CPUE and revenue between treatment (vessels with high effort inside the MEA) and control (vessels not utilizing the MEA historically) groups, before versus after the PMNM expansion, and taking into account the differences in vessel characteristics, annual and seasonal effects, gear usage, spatial and temporal variations in effort and fish abundance, the effects of other coexisting management policies, and other trip specific factors, the average treatment effects from the PMNM expansion can be found. The results of this study should convey the economic impacts of the PMNM expansion on the Hawaii longline fishery to the fishery managers. The next section discusses the empirical models and data used for this study. The third section presents the results and conducts robustness checks. The final section provides some discussion and conclusions.

2. Models and data

To quantify the economic impacts of the PMNM expansion on the Hawaii longline fishery, DID models with fixed effects are developed, using fishery-dependent data at the individual vessel level. The DID models quantify the causal impacts of the PMNM expansion on CPUE and revenue by defining treatment and control groups and measuring the CPUE and revenue before and after the PMNM expansion. Vessels are grouped based on their fishing effort within the MEA prior to the expansion. The treatment group is defined as vessels that had a high portion of their fishing effort within the MEA before the expansion and the control group is defined as vessels that had little or no fishing effort inside the MEA.

To define treatment and control groups, distribution of the percent of fishing effort (hooks) within the MEA between 2012 and 2016 (before the PMNM expansion on August 26, 2016) is used (Fig. 4). Effort inside the MEA fluctuated greatly prior to 2012 and continuously decreased after 2012 (Fig. 2). Therefore, using 2012 to 2016 data provides a good representation of recent effort inside the MEA. The effort distribution shows an aggregation of vessels that had 5% or less effort inside the MEA; therefore, a cutoff point of 6% is used to classify "higher effort group". There is another group of vessels that had little to no effort (0%–1%) inside the MEA between 2012 and 2016 and it is classified as "no effort group". The group of vessels between these two extremes fished inside the MEA occasionally at a low level (2%–5%), but not consistently over time and it is classified as "lower effort group". Based on their past fishing patterns, they are less likely to be impacted by the PMNM expansion since they have other fishing location choices besides the MEA. The higher effort group is considered the treatment group, the no effort group is considered the control group, and the lower effort group is excluded in the analysis.

To better estimate the impact of Monument expansion on the higher effort group, vessels that fished inside the MEA opportunistically in one year and vessels that did not fish in the whole study period are excluded. Among the 44 vessels initially identified as higher effort group, 7 vessels are excluded as they only fished inside the MEA for one year between 2012 and 2016, and had 0%–4% of effort inside the MEA in other years. For the 38 vessels that were initially identified as no effort group, 6 did not fish in 2017 and 3 only fished in 2016; therefore, all 9 are excluded making the no effort group 29 vessels.

Table 3 shows the trip characteristics for the treatment and control groups before and after the PMNM expansion. To examine any changes in trip characteristics like trip length, effort, catch, and revenue after the Monument expansion and also in relative terms between the two groups, significance tests were conducted to compare the means before and after the expansion for each group, and also between two groups for each period. Before the PMNM expansion, the higher effort group had significantly higher effort and better performance when compared with the no effort groups as their trip length was longer, they used more hooks and kept more fish, and had higher CPUE and revenue per trip. After the PMNM expansion, the higher effort group increased their hooks per trip significantly, by 7%, but the number of fish kept dropped by 8%. As a result, their CPUE and revenue per trip dropped significantly, by 14% and 7%, respectively, and they were comparable to the no effort group's CPUE and revenue per trip. Although the CPUE for no effort group also dropped significantly after the PMNM expansion, their pounds kept per trip actually increased significantly (indicating bigger fish caught) and as a result, no significant changes in revenue per trip.

For a DID model to generate unbiased estimators, several conditions must be met. First, treatment must be exogenous to factors that affect the variable of interest [24]. For example, if the variable of interest is CPUE and the assumption is that the PMNM expansion was caused by a

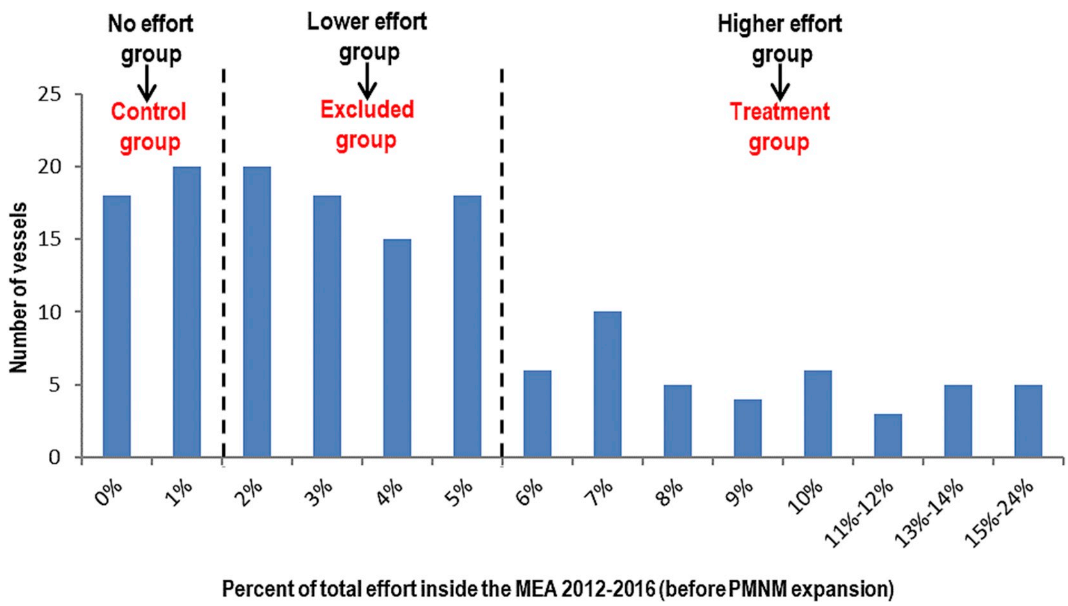

Fig. 4. Distribution of percent of hooks within the Monument Expanded Area by vessels between 2012 and 2016 (before the PMNM expansion).

Table 3
Average effort, catch, CPUE, and revenue per trip before and after the PMNM expansion for higher and no effort groups.

	Higher effort group		No effort group	
	Before expansion	After expansion	Before expansion	After expansion
Vessel length	22.8		20.7	
Percent of deep-set trip	96%[a]	99%*[b]	93%	95%*
Trip length	23.4[a]	22.1*[b]	22.0	21.3*
Hooks per trip	35,638[a]	38,114*[b]	32,327	34,854*
Fish kept per trip	432[a]	398*[b]	358	367
CPUE per trip	12.1[a]	10.4*	11.1	10.5*
Pounds kept per trip	23,598[a]	23,213	20,941	23,247*
Revenue per trip	$76,385[a]	$71,164*	$67,583	$70,424
Number of trips	1755	521	1233	430

* Significant at 5% level, before vs. after the PMNM expansion.
a Significant at 5% level, higher effort group vs. no effort group, before the PMNM expansion.
b Significant at 5% level, higher effort group vs. no effort group, after the PMNM expansion.

collapse of bigeye stock, the models must control for this shock because the collapse of bigeye stock independently impacts CPUE. In reality, the expansion of the PMNM was mainly due to interests in protecting biodiversity conservation, not in response to activity of the Hawaii longline fishery. As the Pacific bigeye tuna is not subject to overfishing, the primary target of the deep-set component of the longline fishers, the Monument expansion was not expected to impact bigeye tuna status.

Second, the treatment must not influence the control group indirectly, in other words, the parallel trends assumption between treatment and control groups is satisfied [19]. In this case, it means the PMNM expansion did not influence the no effort group's CPUE and revenue indirectly. Figs. 5 and 6 show similar monthly trends of CPUE and revenue for the higher and no effort groups before the PMNM expansion.

However, it is possible that after the PMNM expansion, the no effort group was impacted by spatial spillovers. Spatial spillovers could happen if the higher effort group relocated to areas where the no effort group was fishing so their fishing areas were overlapped, causing increased competition and affecting no effort group's performance. Or if the higher effort group moved to a fishing area where the no effort group previously fished, displacing no effort group's fishing location before the expansion and changing its fishing behaviors. Note, however, that if either of these scenarios happened, the DID estimators would be likely downward-biased. Whether the no effort group was impacted by spatial spillovers is essentially unprovable because the counterfactual never happened. It is unknown what would have happened to the no effort group's performance or fishing location if there were no PMNM expansion. The best can be done is to provide support for corollary of the parallel trends assumption; on intuitive grounds by examining the no effort group's fishing location and performance after the expansion; and performing falsification tests to check the pre-treatment trends (in section 3.2). Fig. 7 shows that some of the fishing areas for higher and no effort groups overlapped, but not in the hotspot where the higher effort group relocated to after the expansion. Before the PMNM expansion, the higher effort group had a higher concentration of effort (red areas) inside and below the MEA (between 10°N and 20°N and west of 160°W). On the other hand, the no effort group had a higher concentration of effort occurred east of 160°W. After the PMNM expansion, the higher effort group continued to concentrate their effort below the MEA and one obvious movement was the relocation of effort around the edge of the lower part of the MEA (between 19°N and 22°N, and 160°W and 163°W). The no effort group continued to fish extensively east of 160°W but they did not fish in the hotspot where the higher effort group relocated to (both before and after the expansion). The relocation of effort close to the edges of a reserve (fishing the line) is consistent with Mason et al. [23] and Murawski et al. [25] who argued that fishermen tried to capture spillover of biomass at the edge of the protected area. To quantify the fishing effort in different areas for higher and no effort groups, Table 4 shows their distribution of fishing effort adjacent to the MEA (defined as the right boundary of the MEA, i.e., west of 163°W, and the bottom and the top of the MEA, i.e., between 19.25°N and 26.55°N), inside the PMNM (i.e., the original PMNM plus the MEA), and outside the MEA. It shows that the higher effort group increased their fishing effort around the edge of the MEA from 3.4% before the PMNM expansion to 6.1% after the expansion, whereas the no effort group decreased their effort from 2.1% to 1.1% in this area between the two periods. To examine the possibility of spatial spillovers, Fig. 8 shows the areas that fishing sets overlapped daily in 1 by 1° between the higher

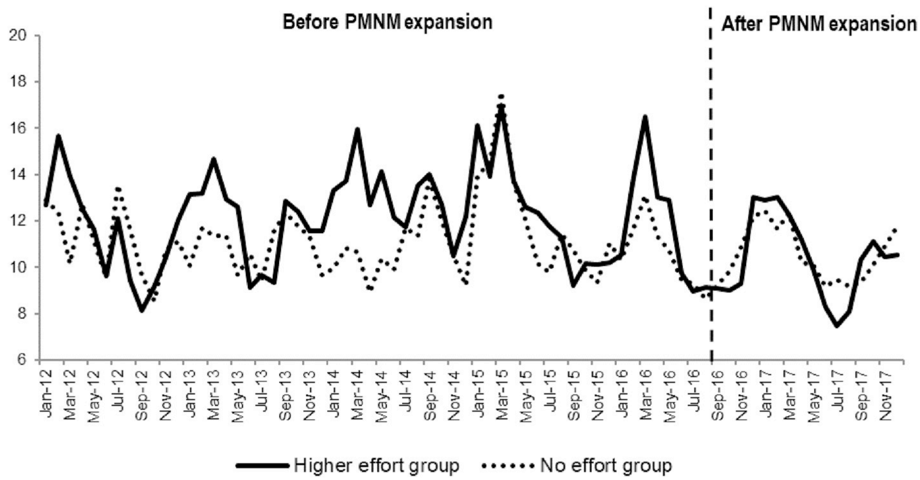

Fig. 5. Average CPUE by month by effort group, 2012–2017.

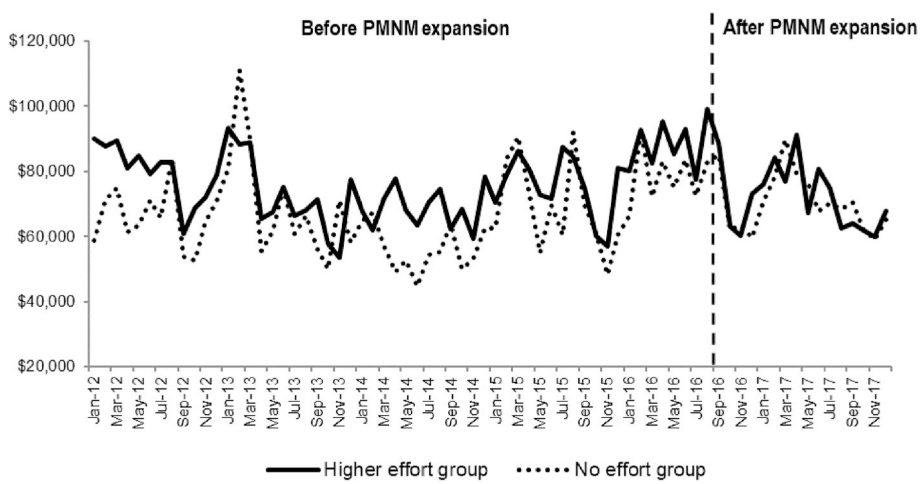

Fig. 6. Average per trip revenue by month by effort group, 2012–2017.

and no effort groups. If spillover occurred, it is expected that the overlap area to increase (when higher effort group displaced no effort group's locations) or decrease (when higher effort group flocked to the productive locations where no effort group was fishing). The overlap areas did not change after the PMNM expansion, they remained at 30% of all fishing areas. Although a higher concentration of overlap area below the main Hawaiian Islands (between 15°N and 19°N, and 156°W and 164°W) after the expansion could be a sign of spillovers, but the fact that the no effort group's yield improved significantly after the expansion (increased pounds kept per trip in Table 3) did not support that the no effort group was suffered from increased competition. Nevertheless, to mitigate the possible spillover effects in some fishing areas, a covariate that represents the number of fishing vessels in 1 by 1° is added to the DID models.

Third, the treatment and control groups must be as comparable as possible so that they are subject to similar shocks and trends that affect the dependent variable [19]. In this case, the treatment and control groups were in the same fishery, they targeted the same species and therefore impacted by the same environmental factors such as El Nino. Majority of the landings were sold at the Honolulu Fish Auction, so both groups were exposed to similar market conditions that impacted fish prices.

Fourth, the composition of the treatment group and control group must remain stable over time, so that no individuals selected themselves in or out of the treatment and control groups based on policy treatment [26]. In this study, the selection of treatment and control groups was based on their portion of fishing effort inside the MEA before the expansion. The treatment group includes all vessels that had a high portion of effort inside the MEA and fished consistently inside the MEA before the expansion and continued to operate after the expansion. No effort group includes all vessels that had little to no effort inside the MEA and had fishing activities in the whole study period. Essentially there was no selection bias as all vessels in both groups were included in the models. The models measure the average changes in CPUE and revenue for the entire population of vessels that were impacted by the PMNM expansion.

The DID models can control for variations in CPUE and revenue that are time-invariant and time-dependent. Time-invariant effects include factors that differ across vessels such as captain's skill and experience, vessel length, and horsepower. These factors influence CPUE and revenue. As demonstrated in Kalberg and Pan [27], larger vessels generated higher revenue and total profit than smaller vessels in the Hawaii longline fishery. Time-invariant factors are represented as individual vessel specified fixed effects in the models.

Time-dependent effects are unique in a time period but impact all vessels equally. Vector of year dummy variables are included in the

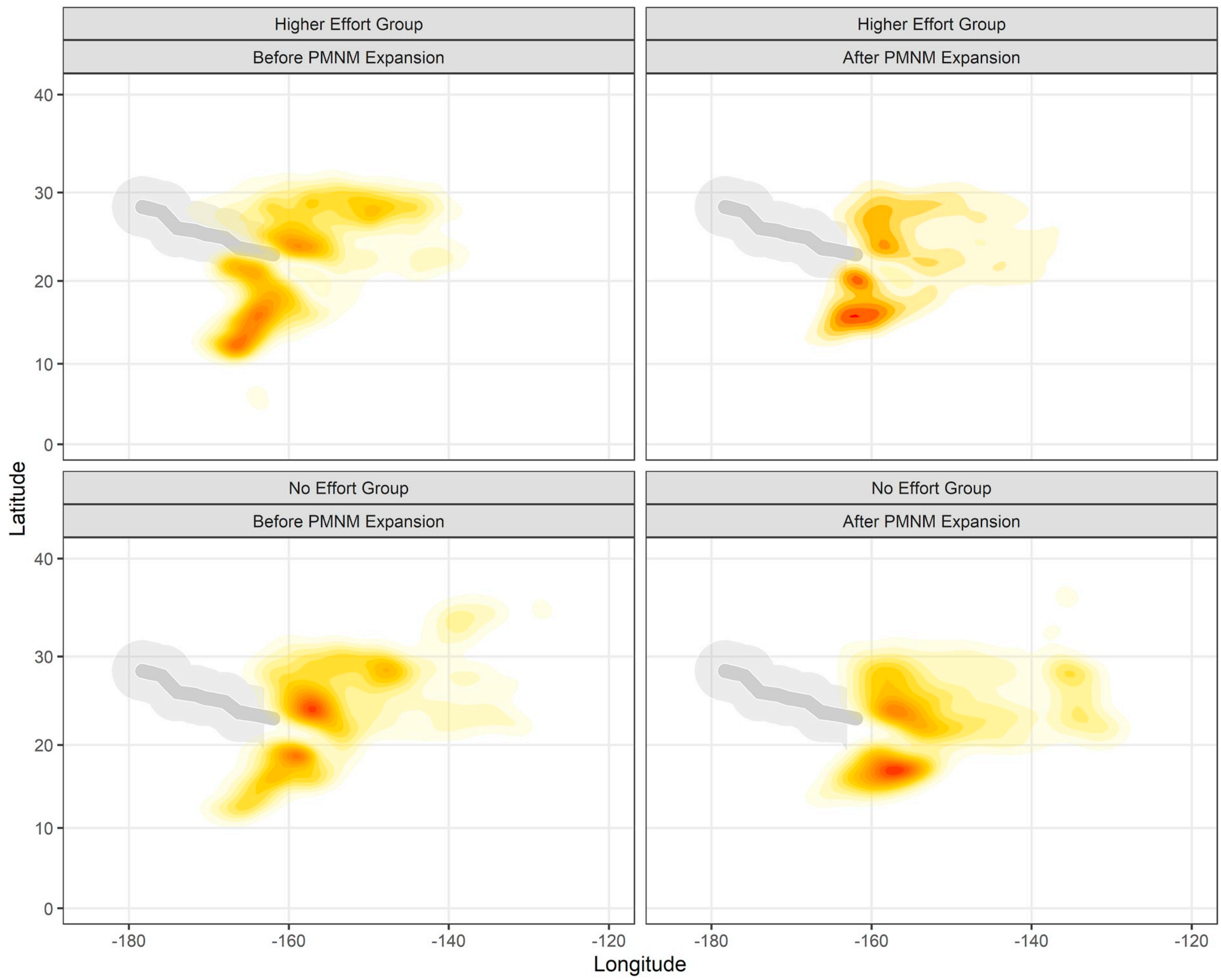

Fig. 7. Density of fishing sets by higher effort and no effort groups, before and after the PMNM expansion. Note: Data records with effort by less than three individual vessels in 5 × 5° are removed to meet confidentiality requirements.

Table 4
Distribution of fishing effort (number of hooks) adjacent to the MEA, inside original PMNM and the MEA, and outside the MEA for higher and no effort groups, before and after PMNM expansion.

	Higher Effort Group		No Effort Group	
	Before PMNM expansion	After PMNM expansion	Before PMNM expansion	After PMNM expansion
Adjacent to the MEA	3.4%	6.1%	2.1%	1.1%
Inside original PMNM and the MEA	10.1%	0.1%	0.5%	0.0%
Outside the MEA	86.5%	93.8%	97.4%	98.9%
Total	100.0%	100.0%	100.0%	100.0%

models to control for variations in CPUE/revenue that are unique to a particular year. Monthly dummy variables are also included in the models. They capture the monthly-specific shocks to the CPUE/revenue, independent of the year. It is very important to control for seasonal variation in outcomes as there is seasonal variation in catch, fishing effort, and fishing location in the Hawaii longline fishery [7]. The monthly dummy variables can also control for inter-seasonal variations due to fluctuations in biological conditions and fishing effort for the entire fishing ground. Failing to account for the monthly patterns could produce bias in the estimation of the treatment effects if vessels allocate their effort differently across seasons.

Another important factor that impacts CPUE/revenue is gear type (deep-set and shallow-set). Logbook data showed CPUE and catch of Hawaii longline fleet varied by gear type and fishing area [28]. As demonstrated in Chakravorty and Nemoto [8], catchability varied by species targeted and gear use. Kalberg and Pan [27] also found CPUE and revenue changed greatly by gear type in the Hawaii longline fishery. Therefore, a gear-type dummy variable is included in the models to account for the variations in CPUE/revenue due to gear type.

Variation in CPUE/revenue could be also impacted by spatial and temporal patterns of fishing by gear type. The deep-set and shallow-set longline fisheries have different spatial and seasonal distribution of effort due to seasonal variation in fish abundance [8,9]. Shallow-set longline fishery operates in certain temporal and seasonal patterns with the fishing effort concentrated at relatively high latitudes (30°N) above the main Hawaiian Islands in the first two quarters of the year [29]. Deep-set longline fishery covers much larger fishing grounds in the central North Pacific Ocean, ranging from 180°W to 120°W and from equatorial waters to around 40°N [7]. The deep-set fishery operates all year-round, with more effort observed in the fourth quarter of the year [30].

Studies have found the Hawaii deep-set longline fishery exhibits shifting in spatial and seasonal distribution of effort over time. Woodworth-Jefcoats et al. [7] divided the Hawaii deep-set longline fishing grounds into five sub-areas (northeast (NE), southeast (SE), northwest (NW), central west (CW), and southwest (SW)) and found the

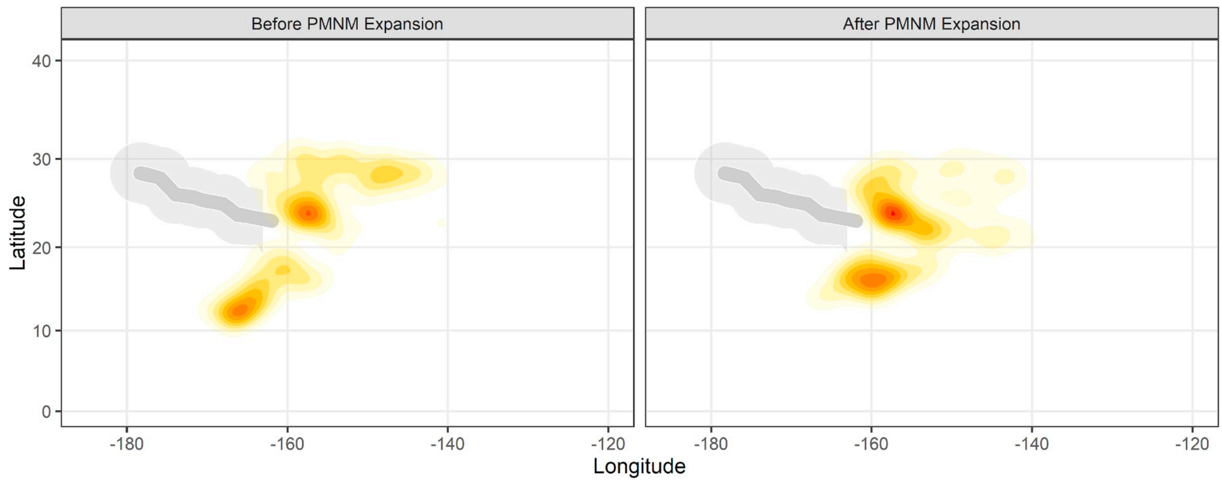

Fig. 8. Density of fishing sets overlapped daily in 1 by 1° between higher effort and no effort groups, before and after the PMNM expansion.

Hawaii longline fishery exhibited geographical shifts in fishing effort in different quarters of the year. They found that in the first quarter of the year most of the fishing effort was concentrated in SW and CW regions. In the second quarter, effort was concentrated in SW and NW regions. The fishing effort shifted dramatically to the NE region in the third quarter and CW region in the fourth quarter. Oceanographic variability results in disparate catch rates by region at different time periods, therefore impacting the location of fishing effort. Woodworth-Jefcoats et al. [7] discovered a steady increase in the Hawaii deep-set longline fishery's effort in the NE and NW regions since 2005. The highest expansion was found in the NE region during the third quarter, because bigeye tuna's preferred thermal habitat vertically overlaps with the depth range of deep-set hooks and with waters that contain appropriate oxygen concentrations. In addition, there was little competition from international fleets in this region. In other regions, such as the SE, the oxygen concentrations do not match the preferred thermal habitat of bigeye tuna, and catch rate was low in this region. Similarly, Gilman et al. [30] found the Hawaii deep-set longline fishery expanded effort to the northeast and southwest of the main Hawaiian Islands and increased the proportion of effort in the third quarter of the year. To take into account the spatial and temporal variations in fishing effort by different gear type, the model includes dummy variables for the five sub-areas as defined in Woodworth-Jefcoats et al. [7] and dummy variables for area-month, area-gear, and gear-month interactions to take into account the variability of CPUE/revenue due to spatial, temporal, and gear factors.

Besides the MEA restricting Hawaii longline fishing, there are policies that coexist and restrict the fishery, including bigeye catch limits in WCPO and EPO. When the bigeye catch limits in WCPO are reached, the longline fishery will be closed until the end of the year unless prior arrangements allowing contribution of bigeye tuna catch to a U.S. territory are in place.[2] Also, the catch limit in each area applies differently depending on vessel permit status and vessel size. During a bigeye tuna closure in WCPO, a Hawaii longline vessel which also holds a valid American Samoa longline permit (dual permitted vessel) may land bigeye tuna in Hawaii, provided that the fish were not caught in the portion of the U.S. EEZ surrounding the Hawaiian Archipelago. In the EPO, only vessels greater than 24 m are subject to bigeye catch limits of 500 mt. Because these policies affect the fishery differently depending on permit status and vessel size, two policy indicator variables are incorporated in the models to flag the fishery closures for a specified time period, area, dual permit status, and vessel size. Owning both Hawaii and American Samoa longline limited entry permits provides the potential for a competitive advantage over vessels that own Hawaii permits only, as dual-permitted vessels are allowed to fish outside the U. S. EEZ during the bigeye closure in WCPO. To demonstrate the effects of dual permit ownership on CPUE/revenue, a dummy variable is added in the models to indicate vessels operating with dual permits at particular time period.

The models also include two covariates to account for trip-specific characteristics that are not controlled by vessel specified fixed effects and spatial effects. The first covariate is the number of vessels fishing in 1 by 1° grids, which takes into account the potential crowding effects (negative) or seasonal effects (positive) in finer scale than monthly and five area levels. The second covariate is trip length. Nguyen and Leung [31] found a significant negative relationship between daily revenue and trip length due to fishermen seeking target revenue goal for a fishing trip. They also suggested the more productive a fishing trip, the shorter the trip length as fishermen achieve the target revenue goal. The other possible reason for a negative correlation between revenue and trip length is the decreasing returns to scale conditions, due to reduced fish quality impacting prices received for landings. Adding trip length as a covariate will capture the impacts of trip length variation on CPUE/revenue.

2.1. Data

Fishery data used in the models include federal logbook data for the Hawaii longline permitted vessels that record fishing location, fishing effort, and catch at set level [32] and dealer data from Hawaii Division of Aquatic Resources that record commercial fish sales [33]. These data are not publicly available, and their use requires meeting Federal confidentiality requirements. The evaluation period is from January 1, 2012, to December 31, 2017. There are 3939 trips recorded in the logbook during the study period for higher and no effort groups. Because the models are using a daily index; effort, catch, and revenue for a trip are distributed evenly across the days of a trip to convert them into daily variables. This process increases the number of observations to 92,977 trip days. Note that the transformation of trip data into daily indices requires standard errors to be clustered at the fishing trip level (at a minimum).

[2] National Marine Fisheries Service (NMFS) regulations under 50 CFR 300.224(d) provide an exception to the closure for bigeye tuna caught by U.S. longline vessels identified in a valid specified fishing agreement under 50 CFR 665.819(c). Further, 50 CFR 665.819(c)(9) authorized NMFS to attribute catches of bigeye tuna made by U.S. longline vessels identified in a valid specified fishing agreement to the U.S. territory to which the agreement applies.

2.2. Models

The DID models with fixed effects are used to examine the economic impacts of the PMNM expansion on the higher effort group, and they are defined as follows[3]:

$$Y_{ijt} = \beta_1 M_t + \beta_2 H_i M_t + V_i + E_y + E_m + G_{it} + A_j + A_j E_m + A_j G_{it} + G_{it} E_m + \\ + C1_{it} + C2_{it} + P_{it} + W_{tx} + L_{it} + \varepsilon_{ijt} \tag{1}$$

- Y_{ijt} is the CPUE or revenue per day for individual vessel i in time t at area j, where t is in daily interval and area (j) is defined as in variable Aj below.
- M_t is a dummy variable that equals one for observations in period after the PMNM expansion, i.e., after August 24, 2016, and zero for period before the PMNM expansion.
- H_i takes the value of 1 for higher effort group, 0 for no effort group.
- The interaction term $H_i M_t$ takes the value of 1 for higher effort group in time period after the PMNM expansion. Thus, β_2 is the DID estimator, representing the average effect of the PMNM expansion on higher effort group's CPUE/revenue per day.
- V_i are individual vessel specific fixed effects.
- E_y are year dummy variables, and E_m are monthly dummy variables, where y = year and m = month.
- G_{it} represents gear type used in a trip, $G_{it} = 1$ for deep-set trips and 0 for shallow-set trips.
- A_j are the five areas used to divide the Hawaii longline fishing grounds in areas, where j = NE, NW, CW, SE, and SW.[4] A_j takes the value of 1 for each of the five areas.
- $A_j E_m$, $A_j G_{it}$, $G_{it} E_m$ represent area-month, area-gear, and gear-month interactions terms, respectively.
- $C1_{it}$ and $C2_{it}$ take the value of one when bigeye tuna closures were in effect that impacted vessel i in period t (based on vessel's dual permit status and size), and 0 otherwise. There was no closure of the shallow-set fishery between 2012 and 2017.

o $C1_{it}$ represents bigeye closure in WCPO

o $C2_{it}$ represents bigeye closure in EPO.

- P_{it} equals one for vessels i having dual permits in period t that allows Hawaii-based vessels to fish for bigeye tuna during an otherwise closed WCPO bigeye closure. It is indexed by t because vessels may be dual permitted for a particular period of time.
- W_{tx} represents the number of vessels fishing in a $1 \times 1^\circ$ grid x at time period t, i.e., a fishing density or congestion variable.
- L_{it} represents the trip length.
- ε_{ijt} is the error term; with the assumption that it is normally distributed with a mean of zero.

In order to control for both observation errors that are correlated within fishing trips (due to expansion of the number of observations from trips to days), and also serial correlation and heteroscedastic errors at the vessel level, double clustered standard errors at the fishing trip and vessel levels were used.

[3] Classic DID specification includes variable *Hi* to control for time-invariant treatment group-specific differences in outcome of interest; however, due to the inclusion of individual vessel specific fixed effects *Vi* that are time-invariant, this term was dropped to avoid perfect collinearity.

[4] The entire fishing ground was divided between two fishing convention areas at 150°W with the east of 150°W dividing into northeast (NE) and southeast (SE) at 20°N. The west of 150°W was divided into northwest (NW), central west (CW), and southwest (SW); with latitude at 26°N dividing NW and CW and latitude at 20°N dividing CW and SW.

3. Results

3.1. Model results

Table 5 shows the model results, with CPUE and revenue per day as the dependent variables. Both models show significant and negative effects of the PMNM expansion (treatment effect) on the higher effort group. There is a drop of 0.87 fish/1000 hooks in CPUE on average for the higher effort group as a result of the PMNM expansion. Using their average CPUE before the PMNM expansion (12.13 fish/1000 hooks), this translates into a 7% drop in CPUE. Revenue per day decreases by $301.62 post expansion. Using the average trip length of 22.1 days for the higher effort group after the PMNM expansion, this translates into a $6666 decrease in revenue per trip (9% drop per trip). With 521 trips operated by the higher effort group after the PMNM expansion until the end of 2017, this represents a $3.5 million loss in revenue during the 16-month post-PMNM expansion period, which is lower than the upper bound estimate of $7.8 million loss in revenue per year in PIFSC [6]. This is reasonable given the PMNM expansion only restricts fishing inside the MEA, but vessels can reallocate their effort spatially, which PIFSC [6] did not estimate. Post-expansion data show the higher effort group increased their fishing effort after the PMNM expansion and also reallocated their effort spatially to the edge of the MEA. The results suggest that the higher effort group was exploring new fishing grounds but was less successful in finding fishing areas with comparable productivity relative to the MEA.

Some of the year dummy variables are significant (on revenue but not CPUE) and most of the monthly and area dummy variables are significant. The interaction terms for area-month, area-gear, and gear-month interactions are jointly significant, supporting the importance of controlling for temporal and spatial variations and their interactions with gear use in the models. Policy dummy variables for catch limits in WCPO is negative and significant on CPUE, meaning when the longline fishery was closed in WCPO due to catch limits, it negatively impacted the CPUE. Having dual permits has a positive impact on revenue but no significant impact on CPUE. The number of vessels per grid has positive impacts on CPUE and revenue, possibly representing the seasonal effects when vessels follow seasonal changes in abundance in finer scale than monthly patterns, five fishing areas, and their interactions [22]. Longer trip length has negative impacts on both CPUE and revenue.

3.2. Robustness checks

A set of robustness checks are conducted on the DID models specified above. One critical assumption in the DID model is that in the absence of a policy (treatment), the differences in the variables of interest between the treatment and control groups remain the same over time. Falsification tests are conducted by running the same DID models but assuming that the PMNM expansion occurred one, two, and three years before the actual expansion date on August 26, 2014. Data after the actual PMNM expansion are dropped, and the period between the "proxy" treatment dates and August 25, 2016 are considered as the new treatment periods. Note that testing the pre-treatment trends cannot prove the post-treatment trends would have developed the same as this is an untestable assumption. Checking the pre-treatment trends is "a test of a possible corollary of the assumption" [34]. Because there was no actual treatment during the "proxy" treatment periods, there should be no statistically significant treatment effects shown in the DID models. Table 6 (columns 2 to 4) shows the treatment effects are insignificant for all three proxy treatment scenarios. Another robustness check is to test whether the treatment group is identified properly. The same DID models are run by considering that the lower effort group is the treatment group, and the no effort group remains as the control group. Table 6 (column 5) shows the treatment effects are not statistically different from zero.

As additional robustness checks on the DID model specification,

Table 5
DID models with fixed effects estimation.

	Dependent variable = CPUE				Dependent variable = Revenue per day			
	Parameter estimate	Standard error	t statistic	p value	Parameter estimate	Standard error	t statistic	p value
Period after expansion	0.39	0.35	1.11	0.27	−217.79	143.14	−1.52	0.13
$H_i\,M_t$ Treatment effect	−0.87	0.42	−2.10	0.04	−301.62	132.34	−2.28	0.02
2013	0.31	0.36	0.86	0.39	−123.26	86.98	−1.42	0.16
2014	0.47	0.42	1.12	0.26	−435.47	80.42	−5.41	0.00
2015	0.42	0.43	0.96	0.34	−108.69	81.35	−1.34	0.18
2016	−0.64	0.43	−1.47	0.14	322.95	100.34	3.22	0.00
2017	−0.97	0.54	−1.80	0.07	338.80	129.36	2.62	0.01
Month_2	0.73	0.24	3.04	0.00	233.00	133.48	1.75	0.08
Month_3	1.42	0.40	3.55	0.00	105.16	158.08	0.67	0.51
Month_4	−1.55	0.32	−4.79	0.00	−107.85	117.15	−0.92	0.36
Month_5	−1.94	0.46	−4.18	0.00	−385.15	131.04	−2.94	0.00
Month_6	−3.31	0.39	−8.60	0.00	−374.79	120.10	−3.12	0.00
Month_7	−3.08	0.41	−7.56	0.00	−625.33	147.88	−4.23	0.00
Month_8	−3.44	0.39	−8.87	0.00	−383.92	150.07	−2.56	0.01
Month_9	−3.29	0.48	−6.91	0.00	−618.09	158.53	−3.90	0.00
Month_10	−3.32	0.45	−7.38	0.00	−684.60	139.99	−4.89	0.00
Month_11	−2.72	0.42	−6.48	0.00	−514.00	114.89	−4.47	0.00
Month_12	−1.41	0.28	−5.04	0.00	−263.31	99.38	−2.65	0.01
SE	−3.40	1.37	−2.49	0.01	−540.18	163.04	−3.31	0.00
CW	−4.07	0.31	−12.99	0.00	−199.20	106.71	−1.87	0.06
NW	−2.34	0.46	−5.10	0.00	−157.45	116.62	−1.35	0.18
NE	−1.11	0.85	−1.30	0.19	432.78	286.39	1.51	0.13
Catch limit in WCPO	−1.33	0.24	−5.43	0.00	64.35	97.94	0.66	0.51
Catch limit in EPO	−0.17	0.30	−0.55	0.58	−110.21	91.82	−1.20	0.23
Dual permits	−0.08	0.35	−0.24	0.81	314.89	103.75	3.04	0.00
Number of vessels per grid	0.09	0.03	3.29	0.00	39.72	10.50	3.78	0.00
Trip length	−0.13	0.02	−7.18	0.00	−84.62	7.95	−10.64	0.00
44 area-month interactions	Jointly significant $F_{[44,\ 92708]} = 14.28$, p value < 0.01				Jointly significant $F_{[44,\ 92708]} = 34.81$, p value < 0.01			
3 area-gear interactions	Jointly significant $F_{[3,\ 92708]} = 13.37$, p value < 0.01				Jointly significant $F_{[3,\ 92708]} = 3.23$, p value < 0.05			
11 gear-month interactions	Jointly significant $F_{[11,\ 92708]} = 3.38$, p value < 0.01				Jointly significant $F_{[11,\ 92708]} = 13.33$, p value < 0.01			
R-squared	0.40				0.36			
Observations	92,859				92,859			

Note: These variables are restricted for identification: 2012 dummy variable, month_1 dummy variable, SW region, SW & monthly dummy variables, SE & month_1, CW & month_1, NW & month_1, NE & month_1, 5 areas & deep-set dummy variables, SW & shallow-set, deep-set & monthly dummy variables, shallow-set & month_1. SE & shallow-set has no data and therefore dropped. G_{it} is dropped in the estimation as it is highly collinear with the area-gear and gear-month interactions. Standard errors are clustered at fishing trip and vessel levels.

Table 6
Robustness checks I.

	Dependent variable = CPUE					Dependent variable = Revenue per day				
	(1) DID model	(2) Expans-ion on August 26, 2013	(3) Expans-ion on August 26, 2014	(4) Expans-ion on August 26, 2015	(5) Lower effort group is treatment group	(1) DID model	(2) Expans-ion on August 26, 2013	(3) Expans-ion on August 26, 2014	(4) Expans-ion on August 26, 2015	(5) Lower effort group is treatment group
$H_i\,M_t$ Treatment effect	−0.87* (0.42)	1.18 (0.74)	0.09 (0.55)	−0.15 (0.49)	−0.20 (0.41)	−301.62* (132.34)	94.78 (137.49)	29.95 (125.40)	56.41 (145.88)	−133.88 (132.04)
R-squared	0.40	0.39	0.38	0.39	0.35	0.36	0.38	0.38	0.38	0.33
Observations	92,859	71,584	71,584	71,584	132,376	92,859	71,584	71,584	71,584	132,376

Note: numbers in parenthesis are clustered standard errors at fishing trip and vessel levels.
*p < 0.05.

several alternate model specifications are estimated by dropping some of the variables, including areas, area-month interactions, area-gear interactions, and gear-month interactions. Table 7 (columns 2 to 5) shows that dropping some controls in the models does not significantly affect the point estimates of the treatment effects; the treatment effects under all scenarios are still negative and significant.

Another robustness check on the DID models is to test the seasonal impact of the PMNM expansion. This is to test whether the impact of the PMNM expansion was more acute in certain months such as key months with high effort inside the PMNM prior to expansion, i.e., November to January for deep-set fishery and April to June for shallow-set fishery (Fig. 3). Instead of using the interaction term $H_i\,M_t$ that represents the average effect of the PMNM expansion on the higher effort group, three-way interaction terms are used to represent the monthly effect of the PMNM expansion on the higher effort group ($H_i\,M_t\,E_m$). Table 8 shows the model results that almost all of the three-way interaction terms are negative (except for CPUE in December and revenue in April, but they are not significant), and some are insignificant. The most acute significant effects appear in July and August for CPUE, and August and May for revenue. This can be explained by the changes in monthly effort by the

Table 7
Robustness checks II.

	Dependent variable = CPUE					Dependent variable = Revenue per day				
	(1) DID model	(2) No area dummies	(3) No area, area-month dummies	(4) No area, area-month, area-gear dummies	(5) No area, area-month, area-gear, gear-month dummies	(1) DID model	(2) No area dummies	(3) No area, area-month dummies	(4) No area, area-month, area-gear dummies	(5) No area, area-month, area-gear, gear-month dummies
$H_i M_t$ Treatment effect	−0.87* (0.42)	−0.90* (0.42)	−1.01* (0.46)	−1.05* (0.45)	−1.23** (0.46)	−301.62* (132.34)	−300.13* (132.26)	−285.95* (134.17)	−273.31* (137.07)	−279.21* (142.87)
R-squared	0.40	0.38	0.32	0.32	0.29	0.36	0.36	0.33	0.33	0.32
Observations	92,859	92,859	92,859	92,859	92,859	92,859	92,859	92,859	92,859	92,859

Note: numbers in parenthesis are clustered standard errors at fishing trip and vessel levels.
*$p < 0.05$.
**$p < 0.01$.

Table 8
Robustness checks III.

	Dependent variable = CPUE				Dependent variable = Revenue per day			
	Parameter estimate	Standard error	t statistic	p value	Parameter estimate	Standard error	t statistic	p value
Period after expansion	0.27	0.36	0.74	0.46	−229.33	139.92	−1.64	0.10
$H_i M_t$ Month_2	−0.85	0.70	−1.21	0.23	−191.43	232.03	−0.83	0.41
$H_i M_t$ Month_3	−1.89	0.64	−2.95	0.00	−343.16	231.00	−1.49	0.14
$H_i M_t$ Month_4	−0.61	0.61	−1.00	0.32	515.70	302.50	1.70	0.09
$H_i M_t$ Month_5	−1.55	0.60	−2.58	0.01	−428.74	177.60	−2.41	0.02
$H_i M_t$ Month_6	−0.99	0.51	−1.96	0.05	−39.12	272.04	−0.14	0.89
$H_i M_t$ Month_7	−3.13	0.53	−5.87	0.00	−169.42	280.45	−0.60	0.55
$H_i M_t$ Month_8	−2.64	0.61	−4.35	0.00	−641.85	222.88	−2.88	0.00
$H_i M_t$ Month_9	−0.60	0.67	−0.90	0.37	−189.64	192.48	−0.99	0.32
$H_i M_t$ Month_10	−0.70	0.44	−1.58	0.11	−295.48	174.01	−1.70	0.09
$H_i M_t$ Month_11	−1.01	0.49	−2.08	0.04	−315.84	189.31	−1.67	0.10
$H_i M_t$ Month_12	0.38	0.56	0.68	0.50	−377.41	181.12	−2.08	0.04
2013	0.31	0.36	0.88	0.38	−121.74	87.38	−1.39	0.16
2014	0.46	0.42	1.10	0.27	−436.25	80.06	−5.45	0.00
2015	0.44	0.44	1.00	0.32	−106.50	81.06	−1.31	0.19
2016	−0.65	0.43	−1.50	0.13	330.85	100.42	3.29	0.00
2017	−0.66	0.57	−1.16	0.24	308.52	137.73	2.24	0.03
Month_2	0.83	0.25	3.35	0.00	248.29	134.50	1.85	0.06
Month_3	1.63	0.42	3.84	0.00	139.50	160.56	0.87	0.38
Month_4	−1.48	0.33	−4.52	0.00	−146.62	124.88	−1.17	0.24
Month_5	−1.79	0.49	−3.67	0.00	−344.51	129.68	−2.66	0.01
Month_6	−3.21	0.38	−8.34	0.00	−363.96	127.14	−2.86	0.00
Month_7	−2.71	0.40	−6.73	0.00	−590.70	155.62	−3.80	0.00
Month_8	−3.07	0.39	−7.83	0.00	−291.81	158.27	−1.84	0.07
Month_9	−3.16	0.48	−6.54	0.00	−580.84	159.00	−3.65	0.00
Month_10	−3.23	0.45	−7.18	0.00	−642.15	149.76	−4.29	0.00
Month_11	−2.62	0.45	−5.87	0.00	−477.10	119.71	−3.99	0.00
Month_12	−1.59	0.29	−5.45	0.00	−218.46	97.52	−2.24	0.03
SE	−3.41	1.39	−2.45	0.01	−549.43	163.23	−3.37	0.00
CW	−4.09	0.32	−12.97	0.00	−213.14	107.28	−1.99	0.05
NW	−2.48	0.46	−5.44	0.00	−193.56	118.49	−1.63	0.10
NE	−1.15	0.85	−1.35	0.18	419.21	287.88	1.46	0.15
Catch limit in WCPO	−1.43	0.24	−5.87	0.00	45.74	98.31	0.47	0.64
Catch limit in EPO	−0.22	0.30	−0.72	0.47	−103.41	95.77	−1.08	0.28
Dual permits	−0.08	0.36	−0.23	0.82	297.95	103.99	2.87	0.00
Number of vessels per grid	0.08	0.03	2.97	0.00	39.49	10.62	3.72	0.00
Trip length	−0.13	0.02	−7.08	0.00	−84.54	7.93	−10.65	0.00
44 area-month interactions	Jointly significant $F_{[44,\ 92698]} = 13.99$, p value < 0.01				Jointly significant $F_{[44,\ 92698]} = 31.19$, p value < 0.01			
3 area-gear interactions	Jointly significant $F_{[3,\ 92698]} = 13.37$, p value < 0.01				Jointly significant $F_{[3,\ 92698]} = 3.37$, p value < 0.05			
11 gear-month interactions	Jointly significant $F_{[11,\ 92698]} = 3.00$, p value < 0.01				Jointly significant $F_{[11,\ 92698]} = 14.16$, p value < 0.01			
R-squared	0.40				0.36			
Observations	92,859				92,859			

Note: Standard errors are clustered at fishing trip and vessel levels.

higher effort group after the PMNM expansion. The higher effort group increased their monthly effort sharply in March, May, July, and August in 2017 and they were at the highest level across years (Fig. 9). This suggests that the higher effort group not only relocated their fishing location after the PMNM expansion, but also increased their fishing effort during the low activity months. This is understandable given each

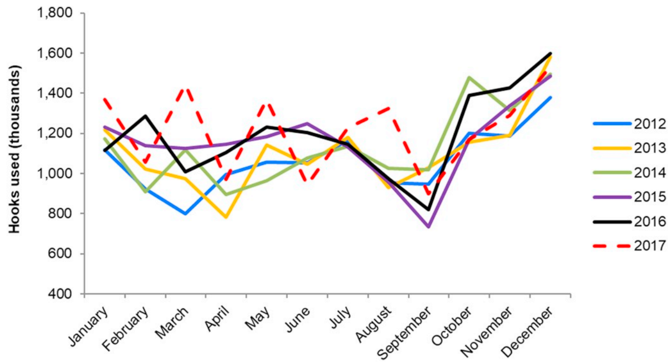

Fig. 9. Seasonal distribution of hooks used by higher effort group by month and year, 2012–2017.

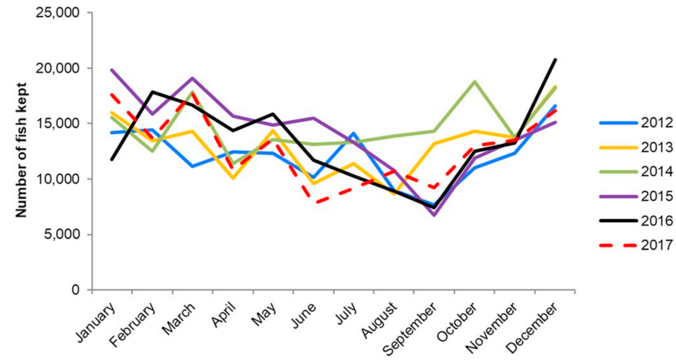

Fig. 10. Seasonal distribution of number of fish kept by higher effort group by month and year, 2012–2017.

vessel is constrained by its capacity; effort cannot be increased too much in the months when it is operated near maximum capacity, e.g. during winter months. But in the summer months the CPUE is relatively low, that is why higher negative impacts on CPUE are found in the summer months. On the other hand, significantly negative impacts are found in the winter months (November for CPUE and December for revenue). This can be explained by the relocation of effort to areas outside the MEA that are relatively less productive. Although fishing effort increased in November 2016 (highest across years) and winter 2017 (Fig. 9), the number of fish kept did not increase proportionately (Fig. 10), and therefore yielding lower revenue.

The results of these robustness checks all support the conclusion that the PMNM expansion had negative impacts on CPUE and revenue of the higher effort group.

4. Conclusions and discussion

This study examines the economic impacts on the Hawaii longline fishery from the PMNM expansion in 2016, using DID models with fixed effects. These models used individual vessel level fishery-dependent data before and after the PMNM expansion and controlled for the effects of vessel characteristics, annual and seasonal effects, gear usage, spatial and temporal variations in effort and fish abundance, the effects of other coexisting management policies, and other trip specific factors. The results show that the PMNM expansion imposed negative effects on the higher effort group in both CPUE and revenue. Specifically, CPUE dropped by 7% and revenue dropped by 9% per trip valued at \$3.5 million during the first 16 months of post-expansion period. One likely reason for the negative impacts is that longline fishers who previously fished inside the MEA are still in the process of becoming more efficient in finding areas with comparable productivity relative to those found in their traditional fishing grounds. This is demonstrated by the fishing effort data after the PMNM expansion. The higher effort group escalated fishing effort through an increase in hooks set, during the low activity months, but the number of fish kept and CPUE per trip decreased. In the longer term, when longline fishers find productive fishing areas outside the MEA, they will likely become more efficient and the negative economic impacts have the potential to decline. An alternate reason is that the area within the MEA is particularly productive. Restricting fishing inside the Monument area would lower the higher effort group's productivity. It would be valuable to do a follow-up analysis in the future to examine how the higher effort group performs. Nevertheless, this study provides fishery managers the first economic impact analysis of the PMNM expansion on the Hawaii longline fishery using post-expansion data and allows them to strategize policies to alleviate the economic impacts on the fleet.

Some research on marine reserves has found positive economic benefit due to spillover effects of increased productivity adjacent to the marine reserve [35,36], but this is not likely to happen in the case of the PMNM expansion since the MEA is not a nursery or spawning grounds for the target species in the Hawaii longline fishery [37]. Theoretically, Apostolaki et al. [38] demonstrated that marine reserves could improve yield even for underexploited fisheries and highly mobile species if effort was redistributed from the reserve area to the rest of the fishing grounds. Those models did not consider the "adjustment time" for fishers to relocate their effort. In the Hawaii longline fishery, fishers not only increased their effort after the PMNM expansion but relocated to areas with which they were not familiar, leading to decreased productivity and revenue.

This study did not research fishing trip costs associated with the PMNM expansion. It is hard to determine whether they would increase or decrease after the expansion as there were several counteractive factors affecting trip costs. The data show that after the expansion, the higher effort group increased their hook use and, therefore, trip costs increased. However, trip length decreased slightly which would lower fuel costs. We do not know whether vessels spent more time searching for lucrative fishing areas which would increase fuel costs. Future work could estimate travel distance for each fishing trip and associated trip costs related to search time. A complete economic impact analysis would incorporate these changes in fishing costs (trip costs and fixed costs) and compare them with the observed changes in revenue. However, the change in trip costs appear to be relatively minor, legitimizing the evaluation of the economic impact of the PMNM expansion on the Hawaii longline fleet using changes in revenue only.

Declaration of competing interest

None.

Acknowledgements

The author especially thanks PingSun Leung and Samuel Pooley for their advices and comments. The author also thanks Jennifer Raynor, Malia Chow, and Richard Hall for their review and feedback that improved this research, and Johanna Wren for her help to enhance the look of the maps. Funding for this study was provided to Joint Institute for Marine and Atmospheric Research (JIMAR) via National Oceanic and Atmospheric Administration (NOAA), grant number NA11NMF4320128. The funding source did not have a role in the preparation of this manuscript. The author declares that there are no conflicts of interest. The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or any of its subdivisions.

References

[1] Executive Office of the President, Papahānaumokuākea Marine National Monument. https://www.federalregister.gov/documents/2016/08/31/2016-211

38/papahamacrnaumokuamacrkea-marine-national-monument-expansion, 2016. (Accessed 3 January 2018).

[2] A.L. Ayers, J. Hospital, C. Boggs, Bigeye tuna catch limits lead to differential impacts for Hawaii longliners, Mar. Pol. 94 (2018) 93–105, https://doi.org/10.1016/j.marpol. 2018.04.032.

[3] NOAA, Fisheries off West Coast States and in the Western Pacific; Western Pacific Pelagic Fisheries; Hawaii-based Pelagic Longline Area Closure, 2001. https://www.federalregister.gov/documents/2001/02/22/01-4492/fisheries-off-west-coast-states-and-in-the-western-pacific-western-pacific-pelagic-fisheries. (Accessed 28 January 2018).

[4] S. Allen, The importance of monitoring the social impacts of fisheries regulations, Pelagic Fish. Res. Program 12 (3) (2007) 4–8.

[5] L. Richmond, D. Kotowicz, J. Hospital, Monitoring socioeconomic impacts of Hawaii's 2010 bigeye tuna closure: complexities of local management in a global fishery, Ocean Coast Manag. 106 (2015) 87–96, https://doi.org/10.1016/j.ocecoaman.2015.01.015.

[6] PIFSC, Potential Economic Impacts of the Papahānaumokuākea Marine National Monument Expansion. PIFSC Internal Report IR-17-06, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, Honolulu, Hawaii, 2017.

[7] P. Woodworth-Jefcoats, J.J. Polovina, J.C. Drazen, Synergy among oceanographic variability, fishery expansion, and longline catch composition in the central North Pacific, Fish. Bull. 116 (2018) 228–239, https://doi.org/10.7755/FB.116.3.2.

[8] U. Chakravorty, K. Nemoto, Modeling the effects of area closure and tax policies: a spatial-temporal model of the Hawaii longline fishery, Mar. Resour. Econ. 15 (2001) 179–204, https://doi.org/10.1086/mre.15.3.42629301.

[9] M.L. Pan, P.S. Leung, S.G. Pooley, A decision support model for fisheries management in Hawaii - a multilevel and multi-objective programming approach, N. Am. J. Fish. Manag. 21 (2) (2001) 293–309, https://doi.org/10.1577/1548-8675(2001)021<0293:ADSMFF>2.0.CO;2.

[10] N.C. Pradhan, P.S. Leung, Incorporating sea turtle interactions in a multi-objective programming model for Hawaii's longline fishery, Ecol. Econ. 60 (1) (2006) 216–227, https://doi.org/10.1016/j.ecolecon.2005.12.009.

[11] N.C. Pradhan, P.S. Leung, Sea turtle interactions with Hawaii's longline fishery: an extended multiobjective programming model incorporating spatial and seasonal dimensions, Appl. Econ. 40 (2008) 2121–2134, https://doi.org/10.1080/00036840600949355.

[12] R. Yu, S. Railsback, C. Sheppard, P.S. Leung, Agent-Based Management Model of Hawaii's Longline Fisheries (FMMHLF): Model Description and Software Guide, 2013. SOEST Publ 13–01, http://www.soest.hawaii.edu/pfrp/soest_jimar_rpts/yu_leung_abm_2013.pdf. (Accessed 27 May 2018).

[13] J.R. Sweeney, R. Howitt, H.L. Chan, M.L. Pan, P.S. Leung, How do fishery policies affect Hawaii's longline fishing industry? Calibrating a positive mathematical programming model, Nat. Resour. Model. 30 (2) (2017) 1–15. https://arxiv.org/pdf/1707.03960.

[14] P.S. Leung, S.G. Pooley, Regional economic impacts of reductions in fisheries production: a supply-driven approach, Mar. Resour. Econ. 16 (4) (2002) 251–262, https://doi.org/10.1086/mre.16.4.42629336.

[15] J.N. Cai, P.S. Leung, M.L. Pan, S.G. Pooley, Economic linkage impacts of Hawaii's longline fishing regulations, Fish. Res. 74 (2005) 232–242, https://doi.org/10.1016/j.fishres.2005.02.006.

[16] S. Cunningham, L. Bennear, M. Smith, Spillovers in regional fisheries management: do catch shares cause leakage? Land Econ. 92 (2) (2016) 344–362, https://doi.org/10.3368/le.92.2.344.

[17] L. Pfeiffer, T. Gratz, The effect of rights-based fisheries management on risk taking and fishing safety, Proc. Natl. Acad. Sci. U.S.A. 113 (10) (2016) 2615–2620, https://doi.org/10.1073/pnas.1509456113.

[18] H.L. Chan, M.L. Pan, Spillover effect of environmental regulation for sea turtle protection in the Hawaii longline swordfish fishery, Mar. Resour. Econ. 31 (3) (2016) 259–279, https://doi.org/10.1086/686672.

[19] S. Jardine, C. Lin, J. Sanchirico, Measuring benefits from a marketing cooperative in the Copper River fishery, Am. J. Agric. Econ. 96 (4) (2014) 1084–1101, https://doi.org/10.1093/ajae/aau050.

[20] J. Abbott, J. Wilen, Voluntary cooperation in the commons? Evaluating the Sea State Program with reduced form and structural models, Land Econ. 86 (1) (2010) 131–154, https://doi.org/10.3368/le.86.1.131.

[21] E. Hallstein, S. Villas-Boas, Can household consumers save the wild fish? Lessons from a sustainable seafood advisory, J. Environ. Econ. Manag. 66 (2013) 52–71, https://doi.org/10.1016/j.jeem.2013.01.003.

[22] M.D. Smith, J. Zhang, F.C. Coleman, Effectiveness of marine reserves for large-scale fisheries management, Can. J. Fish. Aquat. Sci. 63 (2006) 153–164, https://doi.org/10.1139/f05-205.

[23] J. Mason, R. Kosaka, A. Mamula, C. Speir, Effort changes around a marine reserve: the case of the California Rockfish Conservation Area, Mar. Pol. 36 (5) (2012) 1054–1063, https://doi.org/10.1016/j.marpol.2012.03.002.

[24] T. Besley, A. Case, Unnatural experiments? Estimating the incidence of endogenous policies, Econ. J. 110 (2000) 672–694, https://doi.org/10.1111/1468-0297.00578.

[25] S. Murawski, S. Wigley, M. Fogarty, P. Rago, D. Mountain, Effort distribution and catch patterns adjacent to temperate MPAs, ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 62 (6) (2005) 1150–1167, https://doi.org/10.1016/j.icesjms.2005.04.005.

[26] R. Blundell, T. MaCurdy, Labor supply: a review of alternative approaches, Handb. Labor Econ. 3 (1999) 1559–1695, https://doi.org/10.1016/S1573-4463(99)03008-4.

[27] K. Kalberg, M.L. Pan, 2012 Economic Cost Earnings of Pelagic Longline Fishing in Hawaii, U.S. Dep. Commer, NOAA Tech. Memo., 2015, https://doi.org/10.7289/v5/tm-pifsc-56.

[28] NMFS, The Hawaii Limited Access Longline Logbook Summary Report January to December 2016. PIFSC Data Report DR-17-009, 2017. https://repository.library.noaa.gov/view/noaa/14385. (Accessed 4 June 2018).

[29] W.A. Walsh, K.A. Bigelow, K.L. Sender, Decreases in shark catches and mortality in the Hawaii-based longline fishery as documented by fishery observers, Marine Coast. Fish. Dyn. Manag. Ecosyst. Sci. 1 (2009) 270–282, https://doi.org/10.1577/C09-003.1.

[30] E.L. Gilman, M. Chaloupka, A. Read, P. Dalzell, J. Holetschek, C. Curtice, Hawaii longline tuna fishery temporal trends in standardized catch rates and length distributions and effects on pelagic and seamount ecosystems, Aquat. Conserv. Mar. Freshw. Ecosyst. 22 (2012) 446–488, https://doi.org/10.1002/aqc.2237.

[31] Q. Nguyen, P.S. Leung, Revenue targeting in fisheries, Environ. Dev. Econ. 18 (5) (2013) 559–575, https://doi.org/10.1017/S1355770X13000144.

[32] PIFSC, Fisheries Monitoring and Analysis Program, Hawaii Longline Logbook from 2007-2017, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, Honolulu, Hawaii, 2018. https://inport.nmfs.noaa.gov/inport/item/2721.

[33] PIFSC, Western Pacific Fisheries Information Network, Hawaii DAR Dealer Reporting System Data from 2012-2017, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, Honolulu, Hawaii, 2018. https://inport.nmfs.noaa.gov/inport/item/5610.

[34] S. Cunningham, Causal Inference: the Mixtape, V.1.7, TUFTE-LATEX.GOOGLECODE.COM, 2018.

[35] C. Roberts, J. Bohnsack, F. Gell, J. Hawkins, R. Goodridge, Effects of marine reserves on adjacent fisheries, Science 294 (5548) (2001) 1920–1923, https://doi.org/10.1126/science.294.5548.1920.

[36] E. Sala, C. Costello, D. Dougherty, G. Heal, K. Kelleher, J. Murray, A. Rosenberg, R. Sumaila, A general business model for marine reserves, PloS One 8 (4) (2013), https://doi.org/10.1371/journal.pone.0058799.

[37] Western Pacific Regional Fishery Management Council (WPRFMC), Workshop on Pacific Bigeye Movement and Distribution, 2014. http://www.wpcouncil.org/wp-content/uploads/2014/11/Final-Bigeye-Workshop-Report.pdf. (Accessed 28 January 2018).

[38] P. Apostolaki, E. Milner-Gulland, M. McAllister, G. Kirkwood, Modelling the effects of establishing a marine reserve for mobile fish species, Can. J. Fish. Aquat. Sci. 59 (2002) 405–415, https://doi.org/10.1139/f02-018.