High-Seas Closures Can Be Enforced but Deliver Limited Conservation Benefits

Juan Carlos Villaseñor-Derbez[1] and John Lynham[3]

[1]Rosenstiel School of Marine, Atmospheric, and Earth Sciences and Institute for Data Science and Computing, University of Miami

[3]Department of Economics, University of Hawai'i at Manoa

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Abstract

Can large-scale marine protected areas (LSMPAs) be effective on the high seas? We address this question by evaluating the world's first large-scale spatial closure implemented in areas beyond national jurisdiction. In the Western and Central Pacific Ocean, two large high-seas pockets were closed to industrial purse-seine fishing in 2010 to reduce bycatch of juvenile bigeye tuna, while longline fishing was allowed to continue. Nearly two decades later, the empirical consequences of this intervention remain unknown. Using two decades of spatially explicit catch and effort data and a preregistered causal research design, we test whether the closure (i) eliminated purse-seine fishing effort within the high-seas pockets, (ii) benefited longline vessels targeting adult bigeye tuna, and (iii) generated spillover benefits to purse-seine fisheries operating near pocket boundaries. We find that the closure permanently eliminated purse-seine fishing within the high-seas pockets. Longline vessels operating within the closed area experienced a modest increase in bigeye catch per unit effort measured in numbers of fish, but no detectable increase when measured in biomass. We find no evidence that the closure increased catch rates for purse-seine fleets operating near the pocket boundaries. Our findings demonstrate that area-based conservation can be enforced on the high seas when backed by strong regional governance. However, they also show that partial high-seas closures may be insufficient to deliver substantial fishery benefits. As nations begin implementing marine protected areas under the High Seas Treaty, our results highlight the importance of protection level, ecological context, and governance arrangements in shaping conservation outcomes.

Significance statement: Marine protected areas are central to global efforts to conserve ocean biodiversity, yet their effectiveness on the high seas remains largely untested. We provide the first comprehensive empirical evaluation of a large-scale high-seas spatial closure by analyzing two decades of fishing data from the Western and Central Pacific. We show that the closure successfully eliminated industrial fishing within its boundaries but produced only modest biological benefits and no detectable spillover to adjacent fisheries. These results indicate that enforcement of high-seas protections is feasible, but that partial closures alone may not deliver the outcomes observed in fully protected areas within national waters. Our study offers timely, evidence-based guidance for the design of future high-seas marine protected areas under the High Seas Treaty.

1 Introduction

More than 190 governments have committed to protecting 30% of the world's oceans by 2030 using Marine Protected Areas and other area-based conservation measures [1]. Thanks to the recently adopted High Seas Treaty this goal can now extend to areas beyond national jurisdiction, which increases the total amount of marine environment to be protected [2]. The latest assessments indicate that less than 10% of the marine environment is currently under some form of protection [3]. Clearly, if we are to extend conservation to the high seas, large-scale MPAs-–areas larger than 100 km^2[4, 5]– will have to be part of the strategy.

Large-scale MPAs (LSMPAs) already account for more than half of total area-based marine conservation, and the largest 100 MPAs account for 89% of all conserved areas [3]. By virtue of the habitats they protect, LSMPAs most often restrict fishing effort of pelagic fisheries, such as those targeting tuna, billfish, and sharks [6]. Previous work has found that tuna fisheries operating near LSMPA boundaries may see increases in their catch rates [7, 8, 9], which may prompt nations to think strategically when designing LSMPAs on the high seas. For instance, nations may implement LSMPAs immediately outside their exclusive economic zones as a way to boost catch rates in their waters [10, 11]. However, not all LSMPAs are created equal, and it is not yet clear whether LSMPAs in the high seas may successfully curtail fishing effort and whether they will produce the same benefits that LSMPAs within national jurisdictions. Here, we fill this crucial gap in policy-relevant knowledge by studying the first known case of large-scale area-based marine conservation on the high seas.

We focus on the Western and Central Pacific Ocean, an area known for its exceptionally effective management of tuna stocks under the Western and Central Pacific Fisheries Council [12, 13, 14]. Tuna fishing vessels in the region use two main gears to target different tuna species. The longline fleet primarily catches albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*), and yellowfin tuna (*Thunnus albacares*). The purse seine fleet mainly catches skipjack (*Katsuwonus pelamis*) and yellowfin tuna, with some by-catch of juvenile bigeye associated to the use of drifting fish aggregating devices [15, 16, 17].

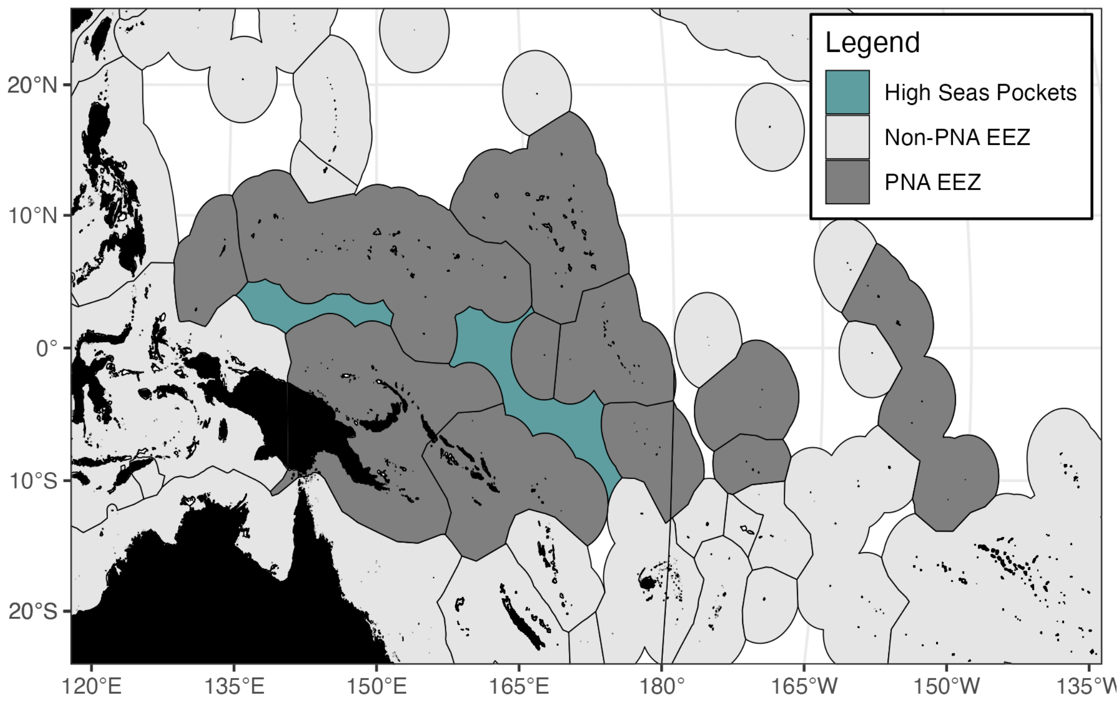

Figure 1: Map of the Western and Central Pacific. Light gray polygons show the Exclusive Economic Zones of all nations. Dark gray polygons highlight the Exclusive Economic Zones of PNA nations (Federated States of Micronesia, Kiribati, Nauru, Palau, Papua New Guinea, Republic of the Marshal Islands, Solomon Islands, Tuvalu) and Tokelau. The two teal polygons show the High Seas Pockets—the "doughnut holes" formed by the surrounding Exclusive Economic Zones–where purse seine fishing has been prohibited since 2010.

The Parties to the Nauru Agreement–a group of eight nations in the region– and Tokelau jointly manage tuna fisheries in their waters using market-based approach known as the vessel-day scheme [18, 12]. By-catch of juvenile tuna by the purse seine fleet presented a major problem to the longline fleet [15, 16, 17], particularly in the two high seas pockets formed between the PNA's exclusive economic zones (Figure 1). In an effort to reduce the purse-seine fleet's by-catch of *juvenile* bigeye tuna, an externality affecting longline vessels targeting *adult* bigeye tuna, purse seine fishing was prohibited in the high seas pockets since 2010 [19]. These pockets are roughly 360,000 km^2 and 780,000 km^2, so they are very much in line with the size of LSMPAs in the region, like the Palau National Marine Sanctuary

($475{,}077^2$) or the now-demoted Phoenix Island Protected Area (408,422 km^2). In closing the high seas pockets to industrial tuna purse seine fisheries, this intervention effectively created the first partially protected *de facto* large-scale MPA in areas beyond national jurisdiction.

There are only a few examples of high seas closures implemented before the adoption of the high seas treaty, and their potential effectiveness remains contested or unevaluated [20]. One of the main arguments is that reducing or eliminating fishing effort in areas beyond national jurisdiction hinges on weak regulatory frameworks, meaning many fishing vessels may not necessarily comply with the measures. And even if fishing effort can be reduced, previous work indicates that the benefits of high seas closures to tuna populations would be limited. For example, work by Sibert et al. [21] used hind-cast simulations to estimate the impact that the PNA's high seas closures would have on Bigeye and Skipjack populations, finding that they would have a negligible effect. However, nearly two decades later, empirical evidence on the the effectiveness of this spatial intervention remains untested. More importantly, recent empirical work on LSMPA within national jurisdictions has found that catch rates tend to increase in areas near LSMPA boundaries, which could be [7, 8, 9]. The recent push for implementing high seas protected areas, along with contrasting evidence from simulation and empirical work call for a rigorous empirical assessment of the high seas pocket closure implemented by the PNA.

Our objective is to test for the effectiveness of this one-of-a-kind policy intervention with the goal of providing the first empirical evaluation of the consequences of the first large-scale spatial closure in the high seas. We compile a multi-decadal (2000-2020) and spatially explicit on catch and effort by tuna and longline fisheries using publicly available data form the Western and Central Pacific Fisheries Council (WCPFC; see subsection 3.1). We divide our analysis in three parts. First, we ask whether the intervention actually reduced fishing effort in the high seas pockets. Then, we ask whether the reduction of purse seine fishing effort benefited the longline fleet. Finally, we explore whether the high seas pockets, acting as a *de facto* marine protected area, provide spillover benefit to tuna fisheries fishing outside but near the high seas boundaries. We answer these questions following our preregisted study design, available at **cite prereg here**. As we will show, the intervention wa successful at eliminating purse seine fishing from the high seas pockets, but we detect weak evidence that this led to a benefit to Bigeye populations. We believe our findings can help inform the design and implementation of forthcoming LSMPAs on the high seas.

2 Results and Discussion

2.1 Reducing fishing effort by purse seiners

The closures sought to eliminate purse seine fishing effort from two high seas pockets. Consequently, we begin by testing for changes in purse seine fishing effort in the high seas pockets. A visual inspection of trends in the data shows that, in the 10 years leading to the closure, total annual fishing effort by purse seiners oscillated around 2,187 ± 770 days (mean ± standard deviation) or 1,766 ± 634 sets (Table 1A-B). After the closure, fishing effort in the pockets dropped to zero starting in 2010, except for a few events recorded in 2013 and 2019[1]. These patterns, however, don't account for other factors that could also explain the observed changes, such as region-wide changes in the environment or management policies.

To credibly say that the closure caused vessels to vacate the area, we must compare trends in fishing effort inside the high seas to trends in fishing effort in other comparable areas. These "control" areas must subject to the same environmental fluctuations and changes in management, thus providing a counterfactual of the expected levels of fishing effort, had the closure not been implemented. Our formal test compares annual changes in fishing effort for all 1°x1° grid cells in the high seas pockets (N = 40) to other high seas grid cells that fall under the WCPFC convention area and lie between 20°N–20°S (N = 151; Figure S3). We use a two-way fixed effects regression model that accounts for differences across grid cells and

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[1] 41.4 days (47 sets) reported in 2013, 9.4 more days in 2019. Check on this: I remember reading that WCPFC was considering lifting the closure around 2013? Perhaps this is why some ventured in? Check this non-compliance

years (See subsubsection 3.4.1). We find that the measure dramatically reduced fishing effort in the high-seas pockets, with an estimated annual reduction of 18.78 days or 16.77 sets per grid cell ($p < 0.01$), relative to trends observed for other high-seas areas in the region. We also estimate a model with dynamic treatment effects that show the annual change in fishing effort. These event-study models corroborate two important factors. First, that coefficient estimates before the closure are not statistically different from zero, indicating that effort in our treated and control areas followed similar trends before the closure. And second, that all years since 2010 had significantly less fishing effort than what would have been expected had the closure not been implemented ($p < 0.01$; Figure 2C-D). Additional test in alignment with our preregistration are shown in section 3.4.3.

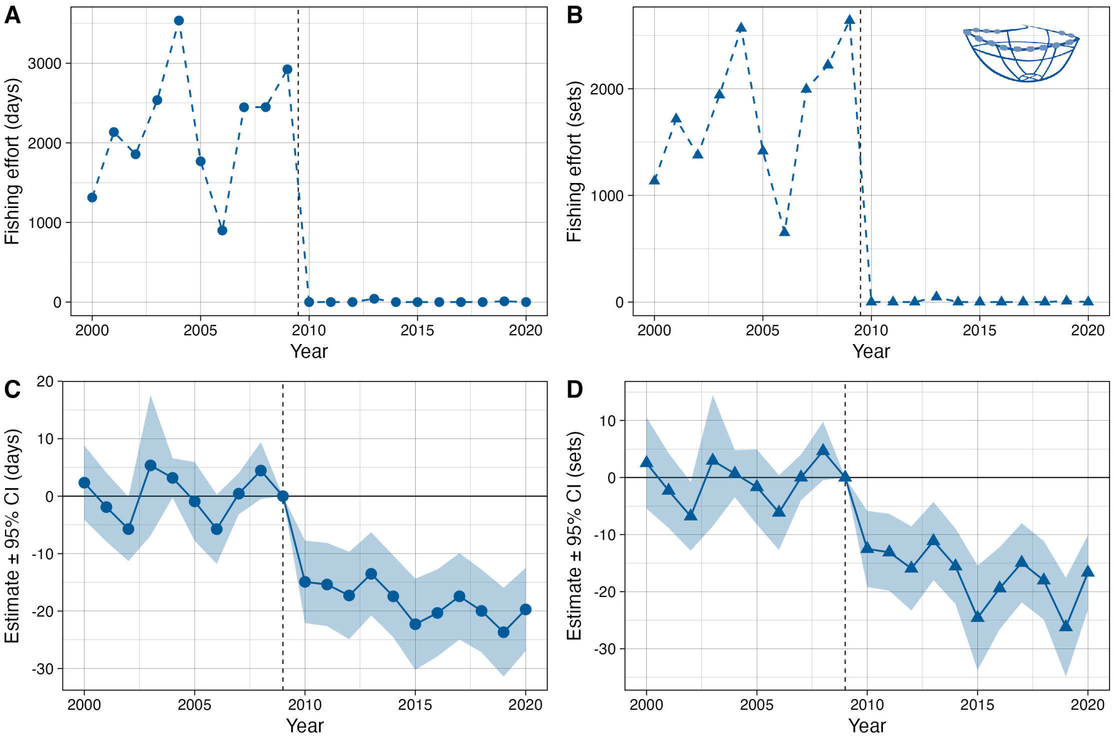

Figure 2: Changes in purse seine fishing effort in the high seas pocket. Panels A and B show time series of total fishing effort in days and number of sets, respectively, across all grid cells in the high seas pocket. Panels C and D show coefficient estimates for the change in fishing effort in the high seas pocket since the closure was enacted, relative to fishing effort in other high seas areas in the WCPFC convention area.

Table 1: Coefficient estimates for change in fishing effort inside the high seas pocket after the closure, relative to changes in fishing effort observed for other high seas areas in the WCPFC convention area.

	Effort (days)	Effort (sets)
Post x Treated	-18.781***	-16.770***
	(2.466)	(1.920)
$\bar{Y}_{pre}$	18.193	14.690
Num.Obs.	5478	5478
R2 Adj.	0.270	0.190

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius. $\bar{Y}_{pre}$ indicates the mean of each outcome variable in the pre-closure period.

2.2 Benefits to longlines and BET

In the 10-yrs before closure (2000-2009), tuna purse seines caught an average of 3,200, 48,500, and 13,800 metric tons (mt) of Bigeye, Skipjack, and Yellowfin tuna every year (Figure S1). Our results so far show that purse seine fishing effort was effectively eliminated in the high seas pockets. It follows, then, that so was catch by purse seiners. Recall that the longline fleet has always been allowed to operate in the high seas pockets, so now we ask: Did reducing purse seine fishing mortality in the high seas pocket benefit the longine fleet?

We focus on Bigeye tuna because the closure was motivated by high by-catch rates of juvenile Bigeye in the purse seine fishery (See section 3.4.3 for results on all other species). We measure benefits to the longline fleet using catch-per-unit-effort (CPUE) of Bigeye tuna. Specifically, we measure CPUE in number of fish for every hundred hooks and metric tons for every hundred hooks. These can be understood as proxies for abundance and biomass. Two time series of Bigeye CPUE from the longline fleet operating in the high seas pockets are shown in Figure 3A-B. Both measures show a steady decline in CPUE during the ten years before the exclusion of purse seiners. After the closure, the decreasing trend slows down and CPUE shows relative stability, particularly when measured in number of fish per hundred hooks. Note, too, that there was a sharp increase in CPUE starting around 3 years after the closure, peaks at around 5 years, and then retuning to baseline levels 7 years later.

As before, a formal test requires that we compare trends in CPUE in the high seas pockets to a counterfactual. In this second test we retain all 5°x5° grid cells that fall in the high seas pocket (our "treated" cells; N = 16) and all high seas grid cells in the WCPFC convention area that lie between 20°N–20°S (N = 69; Figure S4). We now estimate annual changes in bigeye CPUE in high seas pocket grid cells, relative to changes observed in our counterfactual grid cells (See subsubsection 3.4.2). We detect a modest increase in bigeye CPUE of 0.07 fish per hundred hooks ($p < 0.05$), and no change in CPUE when measured in tons per hundred hooks Table 2. These results suggest that fishers may have caught more fish, on average, between 2010 and 2020, but that these fish were not necessarily larger. Our event-study estimates echo these results: the annual number of Bigeye tuna caught per every hundred hooks exhibits a slightly positive trend since 2010, but we observe no change in Bigeye CPUE when measured in metric tons per hundred hooks (Figure 3C-D). Notably, bot CPUE measures for 2020 are not distinguishable from those in 2009. Similar tests for other species caught by the longline fleet and other model specifications are persented in section 3.4.3.

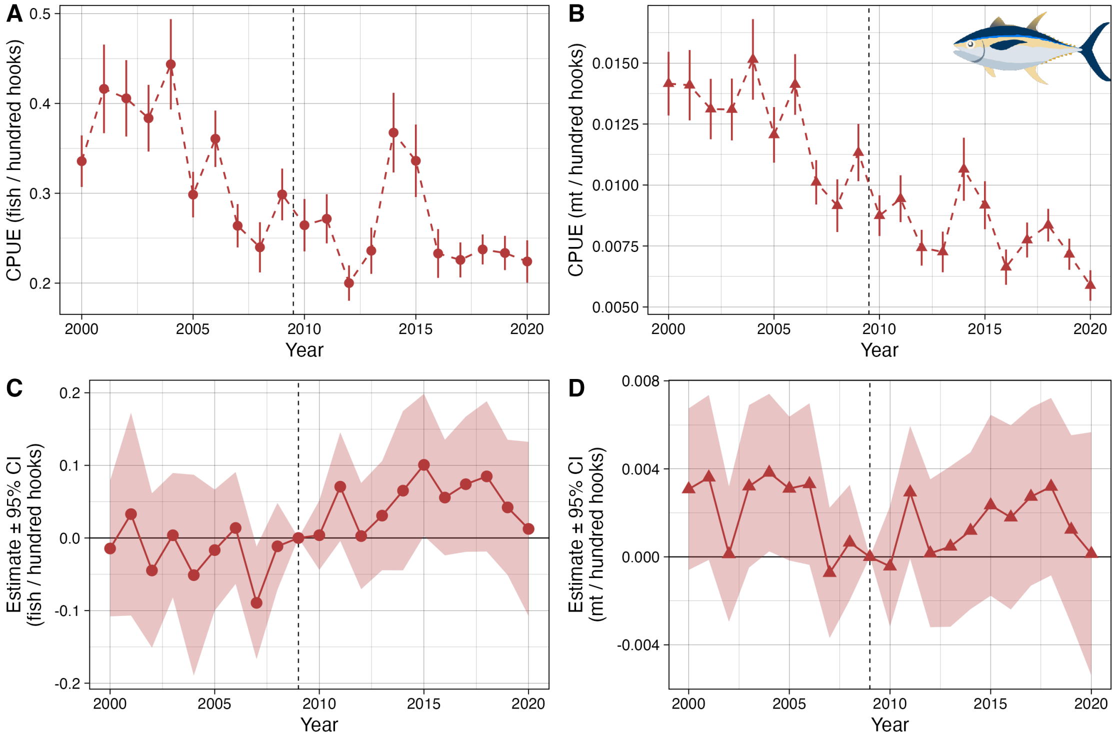

Figure 3: Changes in catch-per-unit-effort (CPUE) of Bigeye tuna in the longline fleet operating in the high seas pocket. Panels A and B show time series of mean CPUE in number of fish per 100 hooks and metric tons per 100 hooks, respectively, across all grid cells in the high seas pocket. Panels C and D show coefficient estimates for the change in Bigeye tuna CPUE in the high seas pocket, relative to CPUE in other tropical (20°S - 20°N) high seas areas in the WCPFC convention area.

Table 2: Coefficient estimates for change in Bigeye tuna CPUE in the high seas pocket after the closure, relative to changes in Bigeye tuna CPUE observed for other tropical (20°S - 20°N) high seas areas in the WCPFC convention area.

	fish / 100 hooks	mt / 100 hooks
Post x Treated	0.070**	0.000
	(0.035)	(0.001)
$\bar{Y}_{pre}$	0.344	0.013
Num.Obs.	12 606	12 606
R2 Adj.	0.547	0.645

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 1100km radius. $\bar{Y}_{pre}$ indicates the mean of each outcome variable in the pre-closure period.

2.3 Spillover benefits to tuna purse seines

Skipjack tuna are only targeted by the purse seine fleet. When the high seas pockets were closed to purse seine fishing, the region essentially became a *de facto* no-take zone for Skipjack tuna[2]. Previous work has shown that CPUE of tuna purse seiners tends to increase near large-scale MPAs after their implementation [8]. Therefore, we now ask whether the high seas pockets, in reducing fishing mortality to Skipjack, also produced spillover benefits to tuna purse seine fisheries operating near their borders. A direct examination of a time series of Skipjack CPUE shows two contrasting trends. When measured in tons per day, CPUE within 100 nautical miles of high seas pockets seems to increase since 2010, as compared to pre-closure years (Figure 4A). We observe the opposite opposite when we measure CPUE in mt per set, which shows typically lower CPUE for all years after the closure (Figure 4B).

Following previous work, we formally test for changes in Skipjack CPUE near (within 100 nm; N = 226) the high seas pocket boundaries, relative to changes observed far (100 -

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[2] Try to say something about skipjack catch in the longline fleet, if any, to further substantiate this argument

200 nm; N = 224) from the boundary [7, 8, 9]. We only retain grid cells that fall within PNA countries' waters because purse seine fishing is strictly managed under the vessel-day scheme [18, 8]. Using this Before-After-Near-Far design, we fail to detect changes in CPUE that would be indicative of a spillover effect, with estimated effects of -0.49 tons per day and -0.86 tons per set, on average ($p = 0.45$ and $p = 0.27$, respectivelyTable 3). Our event-study estimates are shown in panels C and D of Figure 4. These highlight that CPUE near the high seas pocket is not different from CPUE observed for 2009. Overall, there is not enough evidence to indicate that closing the high seas pockets produced spillover befits to adjacent purse seine vessels targeting Skipjack tuna. Similar results for other species and additional model specifications are presented in section 3.4.3.

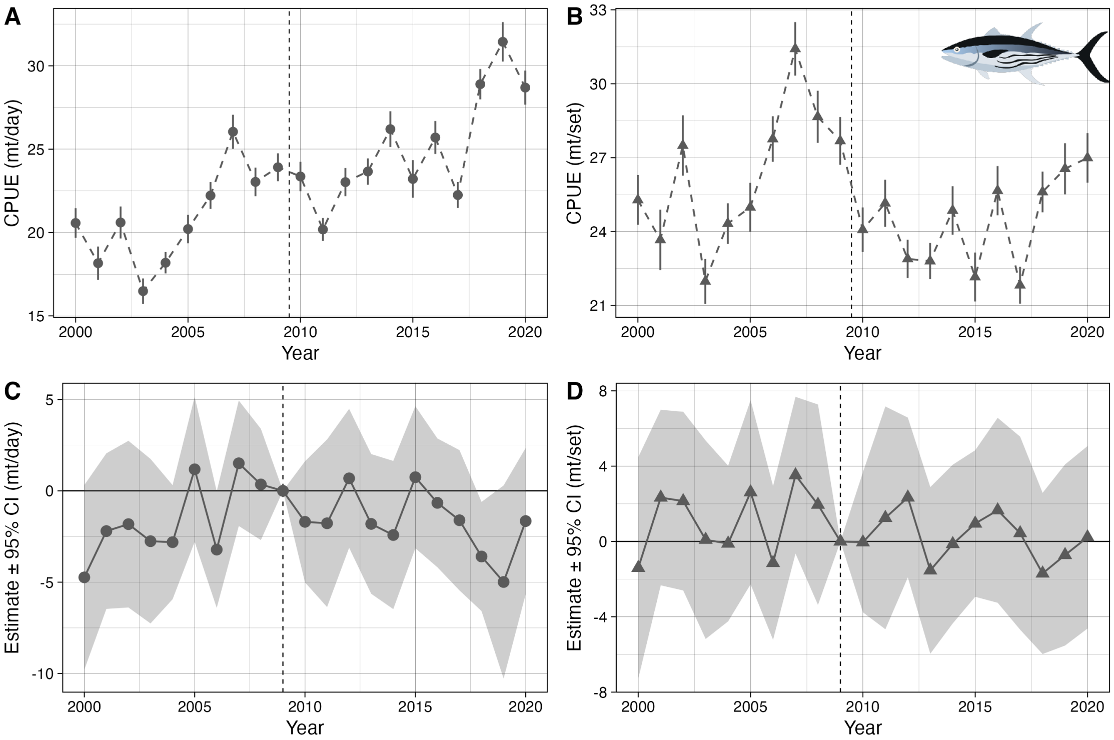

Figure 4: Changes in catch-per-unit-effort (CPUE) of Skipjack tuna in the purse seine fleet operating within 100 nautical miles of the high seas pockets. Panels A and B show time series of mean CPUE in tons per day and tons per set, respectively, across all grid cells within 100 nm of the high seas pocket. Panels C and D show coefficient estimates for the change in Skipjack tuna CPUE near the high seas pockets, relative to changes in CPUE observed in areas further away (100 - 200 nm).

Table 3: Coefficient estimates for change in Skipjack tuna CPUE in areas within 100 nautical miles of the high seas pocket after the closure, relative to changes in Bigeye tuna CPUE observed for areas between 100 and 200 nautical miles and inside PNA nation's Exclusive Economic Zones.

	CPUE (mt/day)	CPUE (mt/set)
Post x Near	−0.496	−0.865
	(0.661)	(0.796)
$\bar{Y}_{pre}$	22.296	27.966
Num.Obs.	24 140	24 140
R2 Adj.	0.148	0.106

* p < 0.1, ** p < 0.05, *** p < 0.01
The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius. $\bar{Y}_{pre}$ indicates the mean of each outcome variable in the pre-closure period.

2.4 Policy Implications for LSMPAs in the High Seas

We evaluated changes in fishing effort and catch-per-unit effort inside and near two high seas pockets where purse seine fishing has not been permitted since 2010. Our results clearly show that purse seine fishing effort was successfully eliminated from the high seas pockets. This intervention led to longliners catching a higher number of bigeye tuna, but not necessarily heavier fish, per unit effort. Interestingly, we fail to find evidence that the closure boosted catch rates of skipjack tuna for purse seine vessels fishing near the high seas pockets. As we discuss below, these results can help guide conversations around forthcoming large-scale MPAs in the high seas [22].

The success in eliminating fishing effort within the high seas highlights the power of power. Thanks to the PNA's exemplary approach to fisheries management via the vessel-day scheme, PNA waters contain some of the most productive tuna fishing grounds in the world [18, 12]. This high productivity gives PNA members bargaining power when negotiating access agreements for foreing fishing vessels interested in fishing in tuna-rich PNA waters. As we have shown, this allowed PNA members to close a portion of the high seas to fishing, well before the High Seas Treaty came into force.

Even though the intervention successfully eliminated purse seine fishing in the high seas pockets, we only find week evidence of benefits to the longline fleet. We find that longliners catch more fish, but not necessarily heavier fish. This is broadly aligned with initial expectations. Because purse seiners are no longer incidentally catching juvenile bigeye, more of these fish are available for harvest by the longline fleet. However, these are still juveniles and therefore do not result in increased total catch. Fishers probably care more about the latter because this dictates the amount of catch they can sell.

The weak and null effects we detect can also be driven by the resolution of the data. Longline data are reported on a 5°x5° grid, which may be too coarse to detect the expected small effects [21]. Unfortunately, the WCPFC does not make higher resolution data publicly available, but in principle these exist and should allow for a more granular test [23]. This could be because the amount of juvenile by-catch was not an important contributor to total bigeye tuna mortality. Our results lend some support to previous work suggesting that traditional fisheries management–like regulating the use of drifting Fish Aggregating Devices known to aggregate juveniles [21, 17]– would have been more effective.

We also fail to detect a spillover effect to purse seine fisheries operating near the high seas pocket, even when the closure significantly reduced fishing mortality for skipjack tuna in the high seas pockets. This may be because longliners continued operating in the region and may ocassionally catch skipjack tuna. This lingering source of fishing mortality would equate this *de facto* LSMPA to a partially protected MPA, and previous work has shown that fully protected MPAs are the ones most likely to deliver conservation benefits[24]. Future efforts to implement LSMPAs on the high seas should prioritize full protection over partial protection, and maintain the focus on biodiversity conservation rather than fisheries management.

The habitat in the high seas pocket may be also very different from habitat contained by

Large-scale MPAs where spillover has been reported [7, 8, 9]. For example, previous work has shown that pelagic species tend to aggregate around shallow (< 150 m deep) seamounts [25]. The most comprehensive global dataset on seamount location and depth [26, 27] shows that the high seas pockets do not contain any shallow seamounts (Figure S2). This observation would lend support for calls to protect these underwater features [28].

Our results show that PNA members were able to use their bargaining power–rooted in successful fisheries management–to significantly reduce fishing effort within the high seas pockets. This intervention led to the world's first *de facto* large-scale MPA in areas beyond national jurisdiction. We find mixed evidence of the effects of this significant reduction in fishing effort, but our results show that lessons learned form LSMPAs implemented within national jurisdictions may not directly translate to those implemented in the high seas. They also highlight how features such as degree of protection, amount of fishing displaced, and presence of critical habitat may drive potential outcomes of *de jure* MPAs to come. Until more high seas MPAs are implemented, their proponents should carefully manage expectations about the potential benefits that these may yield.

3 Methods

Our methods follow our preregistration, as outlined in **cite the preregistration here?**. We used the template provided by AsPredicted, which states the hypotheses being tested, the outcome variables and units of measurement, and the process by which conditions (e.g. treated vs. control) are assigned.

As stated in our preregistration, we test three hypotheses: (1) The PNA's closure of the high-seas pocket to purse seine fishing reduced purse seine fishing effort within the high seas pocket. (2) Reducing purse seine fishing effort within the high seas pocket will increase catch-per-unit-effort of tuna, especially Bigeye tuna (*Thunnus obesus*), for the longline fleet operating within the high seas pocket. And (3), the closure will also increase catch-per-unit-effort of Bigeye (*Thunnus obesus*), Skipjack (*Katsuwonus pelamis*) and Yellowfin tuna (*Thunnus albacares*) to the purse seine and longline fleets operating in PNA waters within 100 nautical miles of the high seas pocket. The methods below describe the steps we take to build our panel data and test our hypotheses.

3.1 Data sources

We use publicly available data from the Western and Central Pacific Fisheries Commission (WCPFC). We download data from the WCPFC Public Domain Aggregated Catch/Effort data website [3]. Specifically, purse seine data come from: *Aggregated data, grouped by 1°x1° latitude/longitude grids, YEAR and MONTH* (WCPFC_S_PUBLIC_BY_1x1_MM5). Longline data come from: *Aggregated data, grouped by 5°x5° latitude/longitude grids, YEAR and MONTH*

(WCPFC_L_PUBLIC_BY_YR_MON_3). All catch and effort data were downloaded on Oct 31, 2025.

3.2 Dataset construction

3.2.1 Outcomes of interest

Our two outcomes of interest are fishing effort and catch-per-unit-effort (CPUE). We measure fishing effort by the purse seine fleet in days and sets per grid cell and year. We measure CPUE per grid cell and year as the sum of the total catch and total effort reported, accommodating for gear-specific differences. Longline CPUE is measured in number of fish per hundred hooks and tons per hundred hooks. For purse seines, CPUE is measured in tons per day and tons per set.

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[3] `www.wcpfc.int/wcpfc-public-domain-aggregated-catcheffort-data-download-page`

3.3 Conditions

All tests have periods for before / after high seas closure (effective January 2010), as well as treatment and control groups. The definition of treatment and control groups varies by test. When testing for changes in purse seine fishing effort, we define treated grid cells as those within the high seas pocket, and control grid cells as other high seas grid cells that fall under the WCPFC convention area and lie between 20°N–20°S. When testing for changes in CPUE to the longline fleet operating in the high seas pocket, we consider grid cells inside high seas pocket as "treated" and other high seas grid cells that fall under the WCPFC convention area and lie between 20°N–20°S as considered "control". Finally, when testing for spillover benefits, we follow the same Before-After-Near-Far design used to test for spillover benefits from large-scale marine protected areas [7, 8]. Specifically, grid cells within 100 nautical miles of the high seas pocket boundary are labeled as treated. Grid cells between 100 and 200 nautical miles of the high seas pocket boundary are labeled control. For the purse seine fishery, we only retain grid cells that fall within PNA countries to account for the sharp difference in management between vessels that operate under a vessel-day scheme vs loosely regulated high seas [18, 12, 29].

3.4 Identification and Estimation

3.4.1 Testing for changes in fishing effort in the high seas pocket

Let E_{it} be purse seine effort (measured in sets or days) in pixel i at time t. We first test for changes in fishing effort in the high seas pocket with a simple linear regression that does not account for changes in region-wide fishing effort. The linear regression with the form:

$$E_{it} = \sum_{t \neq 0} \beta_t \mathrm{T}_t + \mu_i + \epsilon_{it} \tag{1}$$

Where T_t are indicators for periods relative to year of treatment, such that $\mathrm{T}_t = 0$ corresponds to the last year when purse seine fishing was allowed, 2009. Negative values of T_t

are pre-closure years, and positive values of T_t are post-closure years. The parameter of interest is β_t, which is a vector of coefficients capturing changes in effort inside the high seas pocket relative to the last year when fishing was allowed (2009). Then, μ_i are fixed-effects by pixel and ϵ_{it} is the error term, which accounts for spatio-temporal autocorrelation via Conley standard errors. These results are shown in Table S1.

Our main-text specification estimates changes across time relative to changes in effort in other high seas pixels with a regression of the form:

$$E_{it} = \sum_{t \neq 0} \beta_t \left(\mathrm{T}_t \times \mathrm{D}_i \right) + \mu_i + \tau_t + \epsilon_{it} \tag{2}$$

Here, $D_i = 1$ indicates pixel i falls within the high seas closure and $D_i = 0$ otherwise and τ_t are fixed-effects by year. This model allows us to account for region-wide trends in fishing effort, and under standard assumptions allows us to derive a causal estimate of the intervention.

Nested models, such as $E_{it} = \beta \mathrm{Post}_t + \mu_i + \epsilon_{it}$ and $E_{it} = \beta \mathrm{Post}_t \times \mathrm{D}_i + \mu_i + \tau_t + \epsilon_{it}$, were also estimated. In this context Post_t is a dummy variable that takes the value of 1 or 0 if the observation comes from after or before the implementation period, respectively.

Our pre-registration stated that we would estimate models using log-transformed outcomes. However, due to the large number of zeroes in our data, we instead use an inverse-hyperbolic sine transformation (asinh), considered a standard alternative for our case [30].

3.4.2 Testing for change in CPUE inside

Let y_{it} denote longline catch-per-unit-effort (CPUE) in pixel i at time t. We estimate:

$$y_{it} = \sum_{t \neq 0} \beta_t \left(\mathrm{T}_t \times \mathrm{D}_i \right) + \mu_i + \tau_t + \epsilon_{it} \tag{3}$$

All regressors have the same definitions as above. The coefficient of interest, β_t, captures the change in CPUE within the high seas pocket relative to changes observed in other high seas pixels where purse seine effort was not curtailed. A pre-post model with the form $y_{it} = \beta \text{Post}_t \times \text{D}_i + \mu_i + \tau_t + \epsilon_{it}$ will also be estimated to test for aggregate effects. Log-linear models will also be estimated.

3.4.3 Testing for spillover benefits:

Let y_{it} denote longline or purse seine catch-per-unit-effort (CPUE) in pixel i at time t. We estimate:

$$y_{it} = \sum_{t \neq 0} \beta_t \left(\text{T}_t \times \text{D}_i \right) + \mu_i + \tau_t + \epsilon_{it} \tag{4}$$

The coefficient of interest, β_t, captures the dynamic treatment effect of the high seas closure on CPUE within 100 nautical miles of the high seas pocket, relative to changes observed in other grid cells between 100 and 200 nautical miles of the high seas closure. A pre-post model with the form $y_{it} = \beta \text{Post}_t \times \text{D}_i + \mu_i + \tau_t + \epsilon_{it}$ will also be estimated to test for aggregate effects; log-linear models will also be estimated.

By construction, $y_{it} = \frac{\sum_{j \in (i,t)} \text{Catch}_j}{\sum_{j \in (i,t)} \text{Effort}_j}$, so $\text{Var}(y_{it}) \propto \frac{1}{\text{Effort}_{it}}$. We therefore assume

$$\text{Var}(\epsilon_{it} \mid X) = \frac{\sigma^2}{\omega_{it}}, \qquad \omega_{it} = \text{Effort}_{it},$$

and estimate all models using normalized measures via weighted least squares using effort as weights.

All data cleaning and sample construction was performed with the tidyverse (v4.5.1) in R and RStudio (2026.01.0+392 ”Apple Blossom” Wickham et al. [31]). All models were fit using the fixest package (v 0.13.2, Bergé [32]). Regression tables were built using the modelsummary package (v1.3.0, Arel-Bundock [33]), and event-study plots were built with ggfixest (v0.4.0, McDermott [34]) and customized with ggplot2 (v4.0.0, [31]).

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Supplementary Materials for: Large Scale Marine Protected Areas in the High Seas

Supplementary Figures and Tables

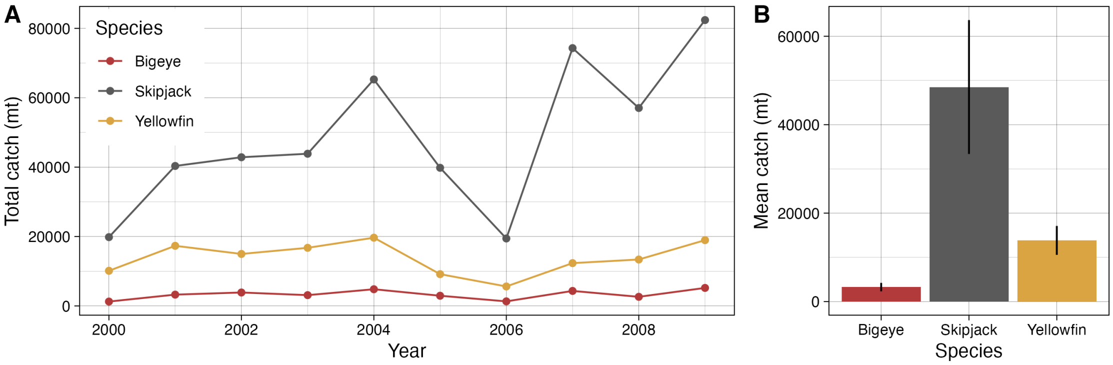

Figure S1: Historical (2000-2009) catch of Bigeye, Skipjack, and Yellowfin tuna by tuna purse seiners fishing in the high seas pocket before its closure. Panel A shows a time series of catch by species, panel B shows mean (± SD) catch by species.

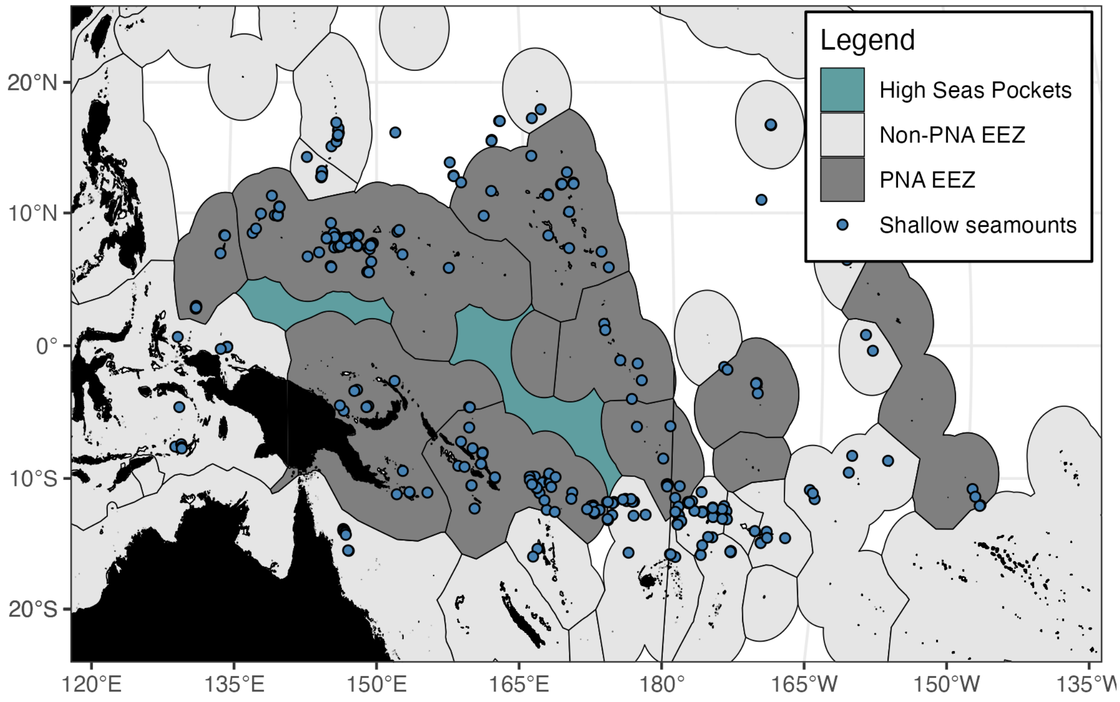

Figure S2: Map of shallow seamounts in the Western and Central Pacific. Blue points indicate the centroid of shallow (¿ -150 m deep) seamounts. Light gray polygons show the Exclusive Economic Zones of all nations. Dark gray polygons highlight the Exclusive Economic Zones of PNA nations. The two teal polygons show the High Seas Pockets closed to purse seine fishing starting in 2010.

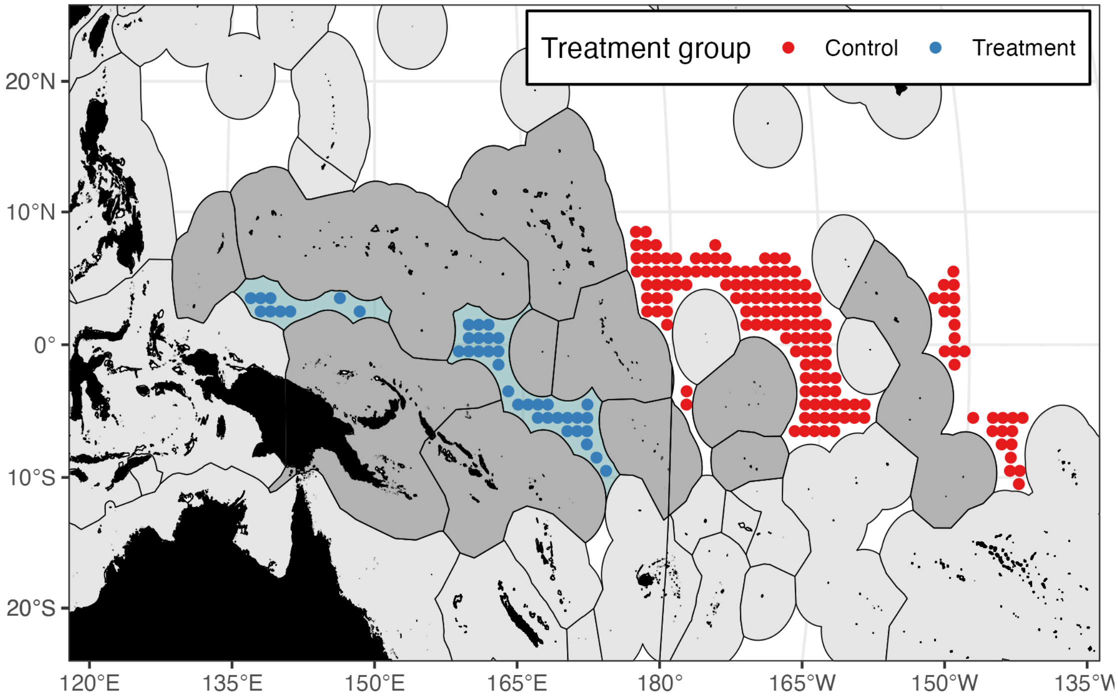

Figure S3: Map of location of treatment and control grid cells used in our test of changes in purse seine fishing effort in the high seas pockets.

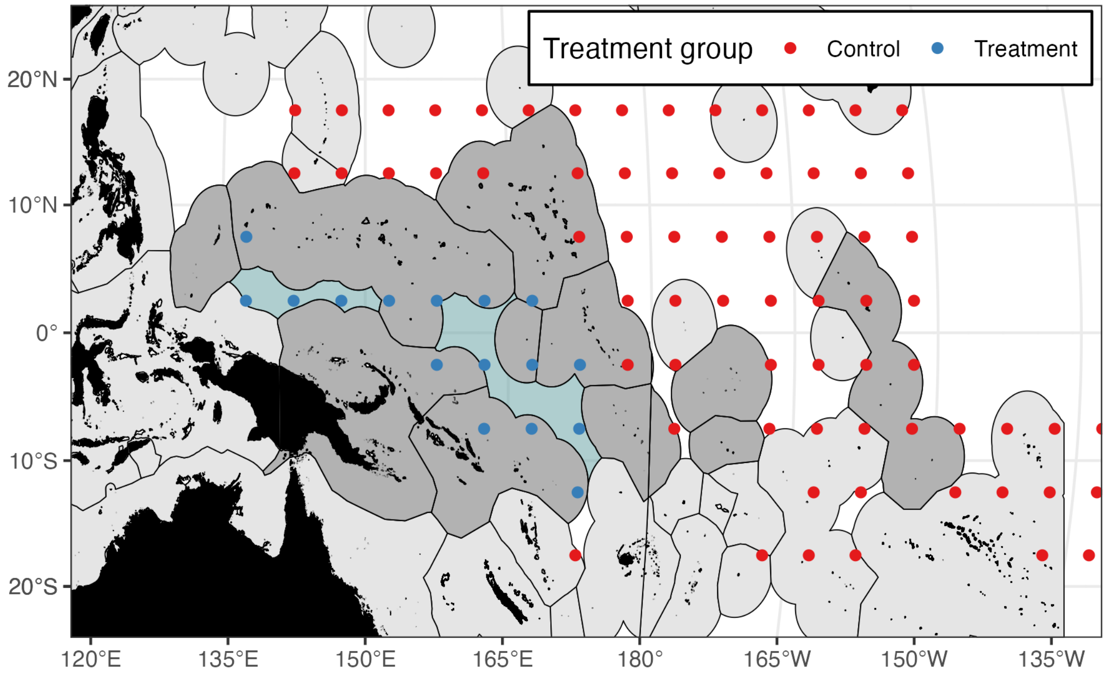

Figure S4: Map of location of treatment and control grid cells used in our test of changes in CPUE for the longline fleet operating in the high seas pockets.

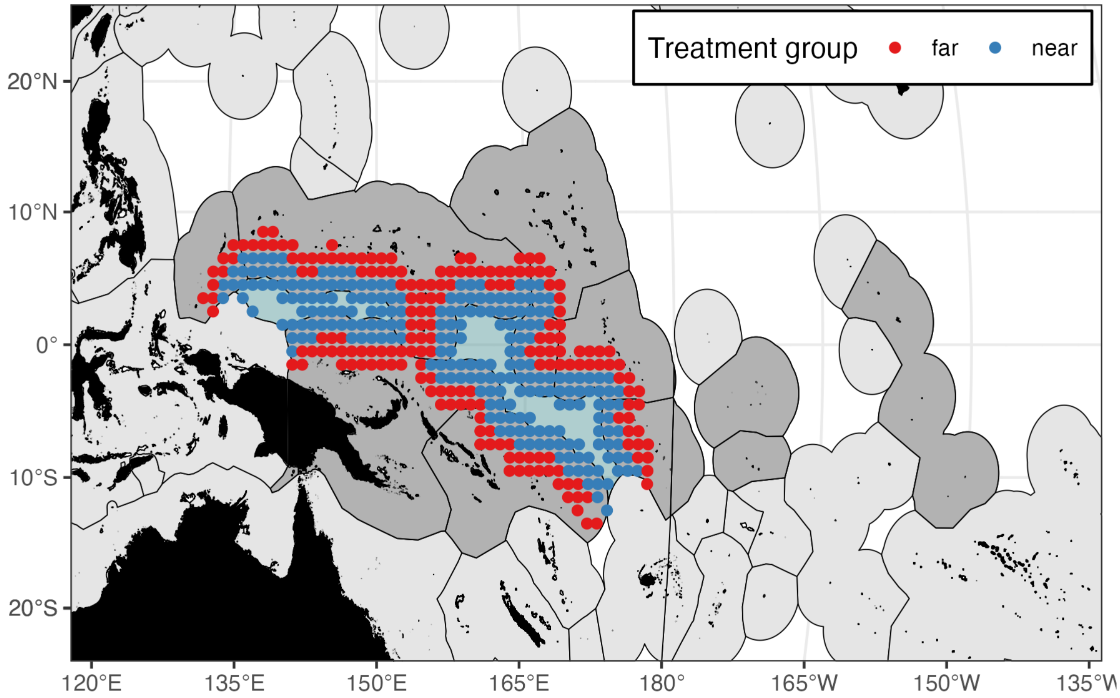

Figure S5: Map of location of treatment and control grid cells used in our test of a spillover effect to the purse seine fleet.

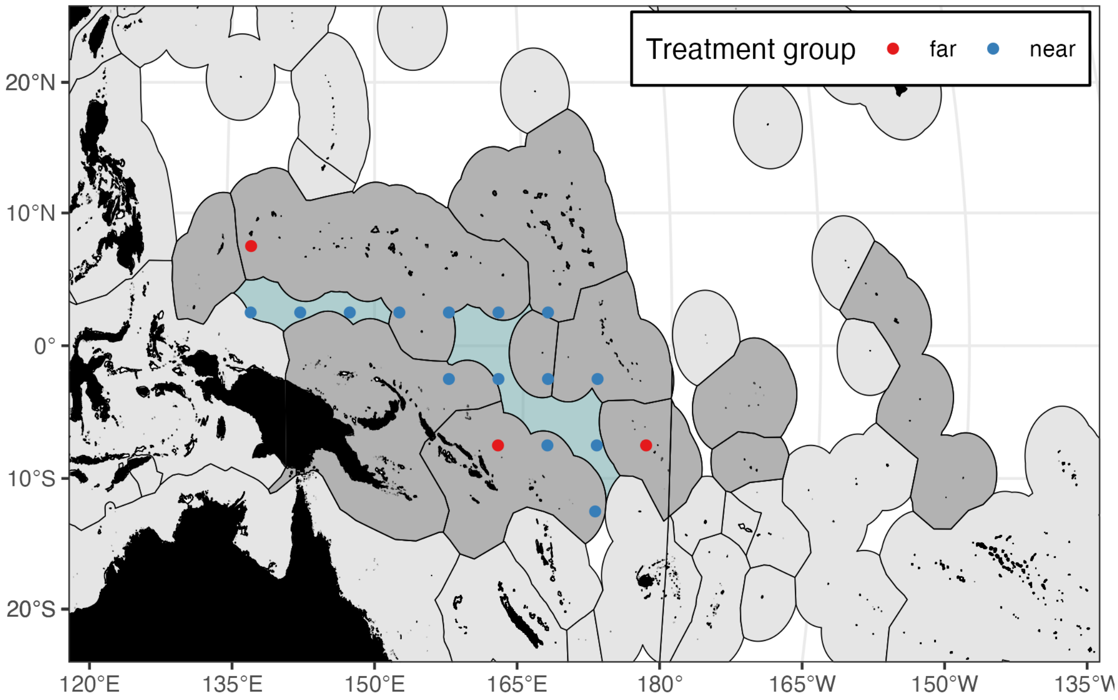

Figure S6: Map of location of treatment and control grid cells used in our test of a spillover effect to the longline fleet.

Robustness Tests and Accompanying Results

Decrease in purse seine effort in high seas pockets

Table S1: Change in fishing effort inside the high seas pockets

	(1)	(2)
A) Levels		
Post	-16.735***	-13.592***
	(2.469)	(1.820)
R2 Adj.	0.207	0.156
B) Inverse-hyperbolic sine transformation		
Post	-2.882***	-2.640***
	(0.204)	(0.178)
R2 Adj.	0.702	0.657
Num.Obs.	1643	1643

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

Table S2: Change in fishing effort inside the high seas pockets relative to other high seas areas

	(1)	(2)
A) Levels		
Post x Treated	-18.781***	-16.770***
	(2.466)	(1.920)
R2 Adj.	0.270	0.190
B) Inverse-hyperbolic sine transformation		
Post x Treated	-3.401***	-3.207***
	(0.240)	(0.218)
R2 Adj.	0.563	0.533
Num.Obs.	5478	5478

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

Change in longline CPUE in high seas pockets

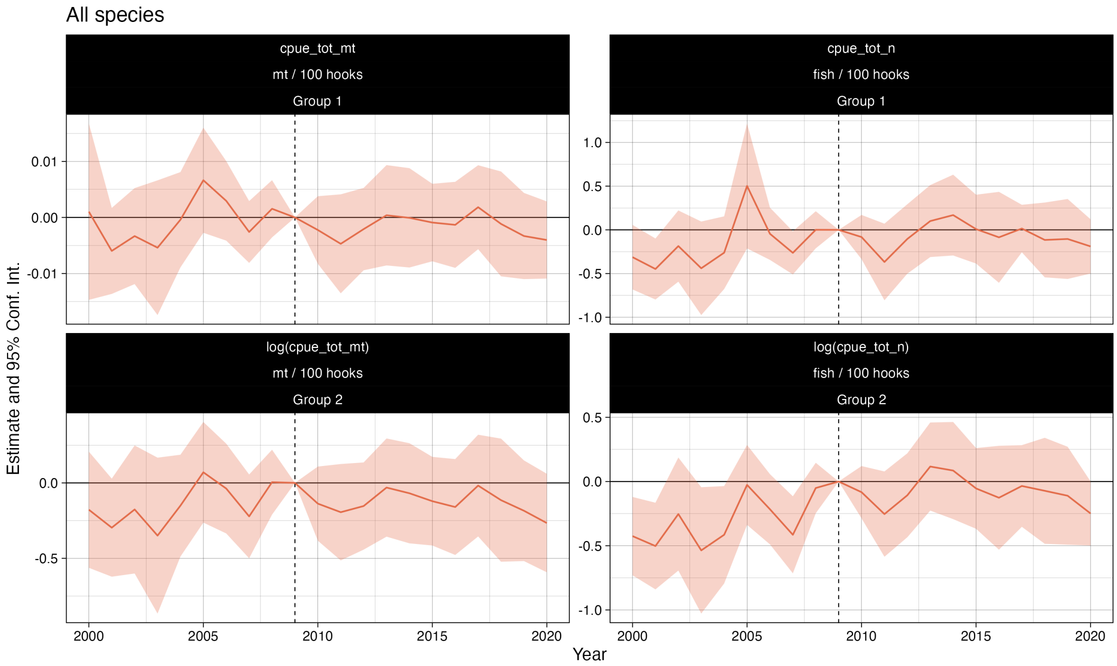

Figure S7: Caption

Table S3: Change in CPUE for all tuna species caught by the longline fleet in the high seas pockets

	fish / 100 hooks	mt / 100 hooks
A) Levels		
Post x Treated	0.066	-0.001
	(0.156)	(0.003)
R2 Adj.	0.357	0.295
B) Log-transformed		
Post x Treated	0.188	-0.001
	(0.130)	(0.083)
R2 Adj.	0.479	0.404
Num.Obs.	12626	12626

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 1100km radius.

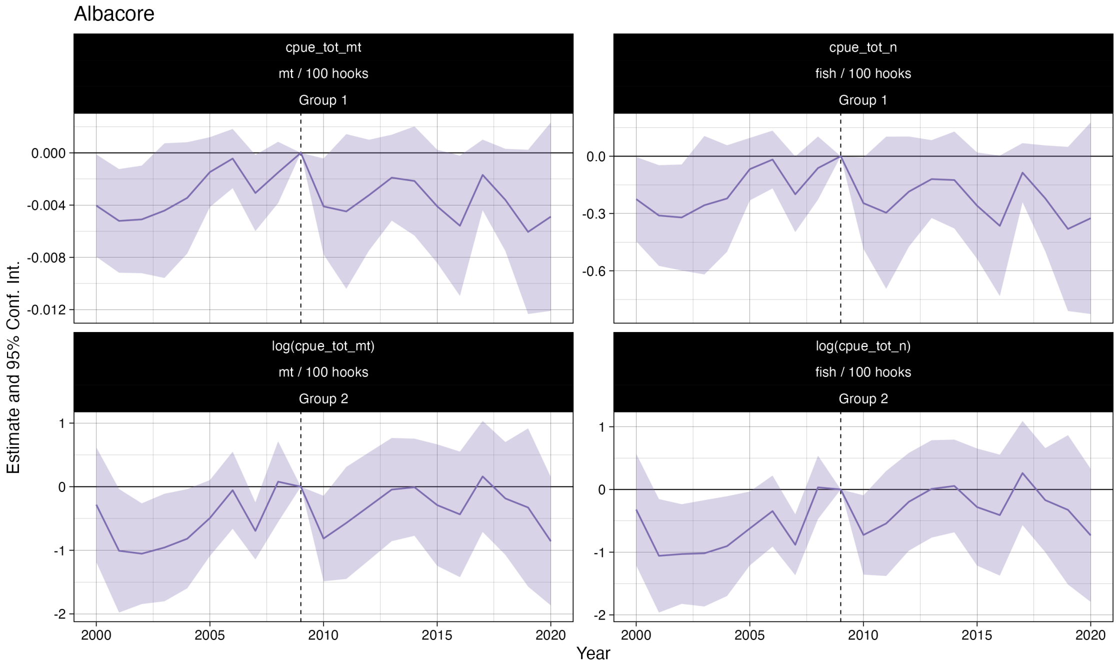

Figure S8: Caption

Table S4: Change in CPUE for Albacore tuna caught by the longline fleet in the high seas pockets

	fish / 100 hooks	mt / 100 hooks
A) Levels		
Post x Treated	-0.074	-0.001
	(0.081)	(0.001)
Num.Obs.	11746	11746
R2 Adj.	0.708	0.703
B) Log-transformed		
Post x Treated	0.326	0.190
	(0.328)	(0.317)
Num.Obs.	11742	11685
R2 Adj.	0.702	0.686

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 1100km radius.

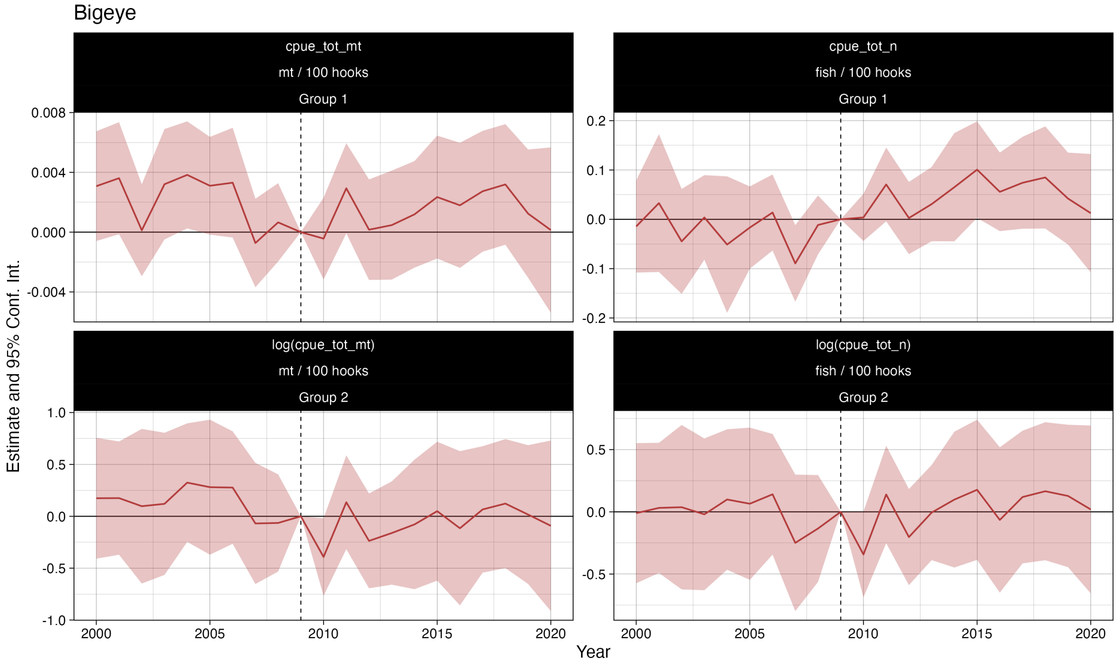

Figure S9: Caption

Table S5: Change in CPUE for Bigeye tuna caught by the longline fleet in the high seas pockets

	fish / 100 hooks	mt / 100 hooks
A) Levels		
Post x Treated	0.070**	0.000
	(0.035)	(0.001)
R2 Adj.	0.547	0.645
B) Log-transformed		
Post x Treated	0.037	-0.170**
	(0.092)	(0.081)
R2 Adj.	0.706	0.749
Num.Obs.	12606	12606

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 1100km radius.

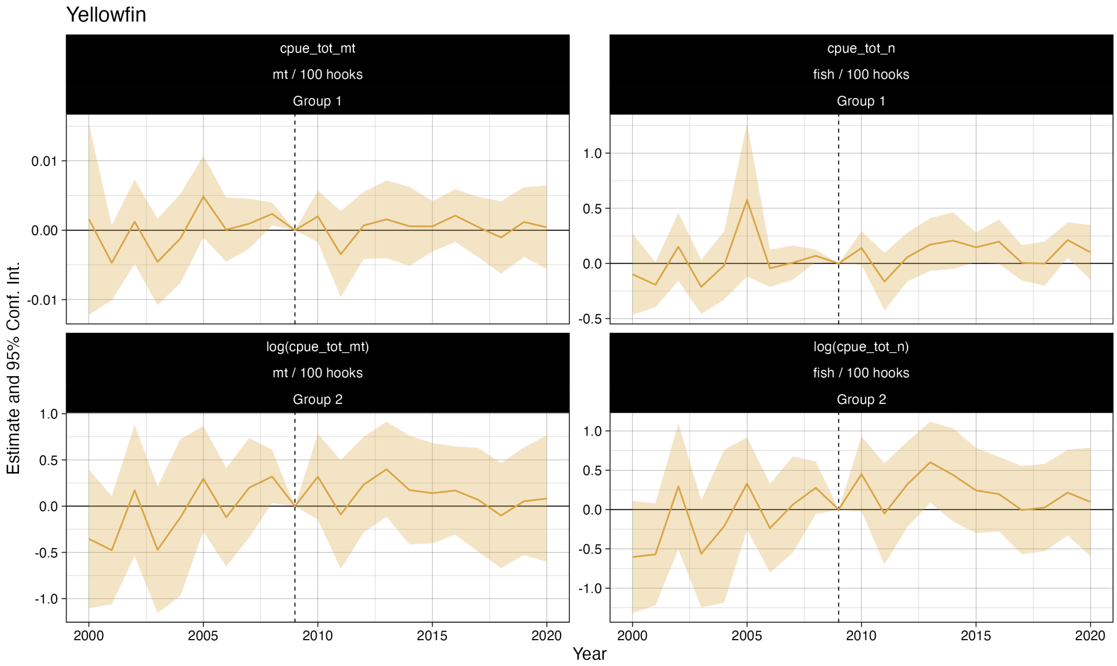

Figure S10: Caption

Table S6: Change in CPUE for Yellowfin tuna caught by the longline fleet in the high seas pockets

	fish / 100 hooks	mt / 100 hooks
A) Levels		
Post x Treated	0.060	0.000
	(0.083)	(0.002)
R2 Adj.	0.228	0.380
B) Log-transformed		
Post x Treated	0.319**	0.160
	(0.139)	(0.112)
R2 Adj.	0.467	0.453
Num.Obs.	12620	12620

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 1100km radius.

Spillover benefits to fisheries adjacent to high seas pockets

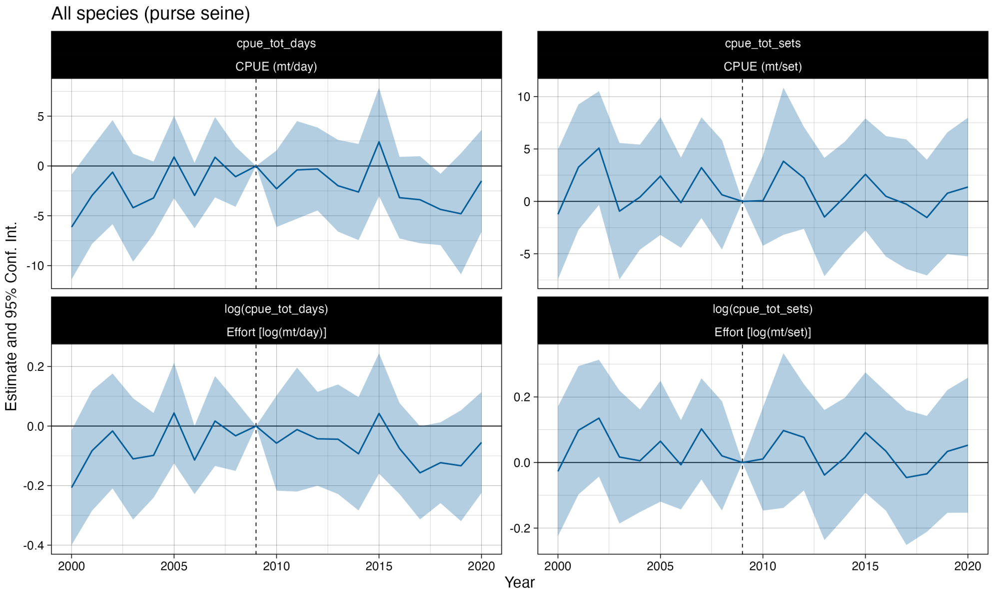

Figure S11: Caption

Table S7: Change in CPUE for all tuna species caught by the purse seine fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	-0.294	-0.468
	(0.805)	(1.022)
Num.Obs.	24140	24140
R2 Adj.	0.108	0.083
B) Log-transformed		
Post x Near	-0.012	-0.014
	(0.030)	(0.035)
Num.Obs.	24140	24140
R2 Adj.	0.091	0.082

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

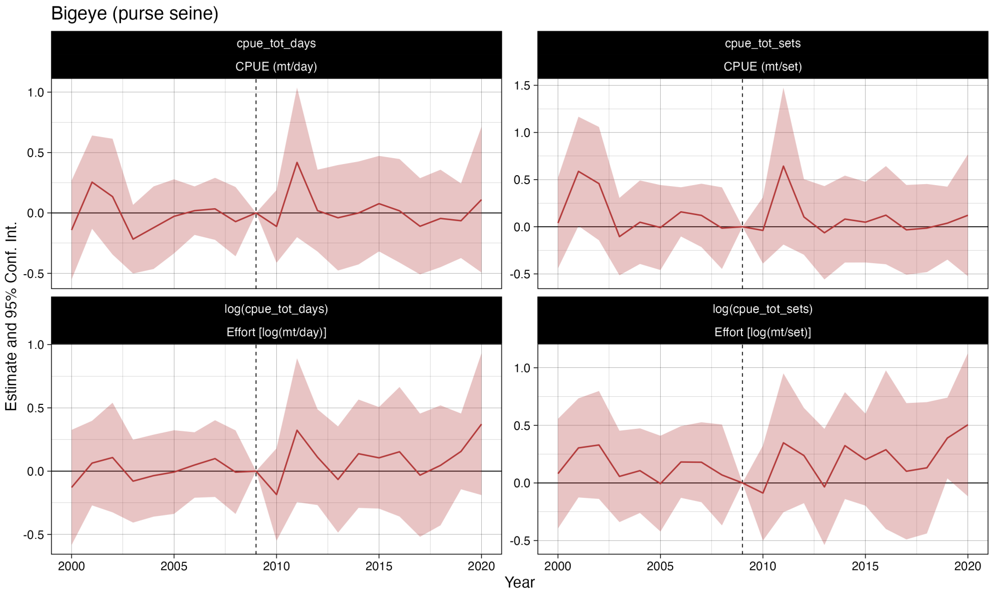

Figure S12: Caption

Table S8: Change in CPUE for Bigeye tuna caught by the purse seine fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	0.061	0.001
	(0.102)	(0.118)
Num.Obs.	23839	23839
R2 Adj.	0.071	0.093
B) Log-transformed		
Post x Near	0.088	0.088
	(0.087)	(0.096)
Num.Obs.	23839	23839
R2 Adj.	0.097	0.137

* p < 0.1, ** p < 0.05, *** p < 0.01

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

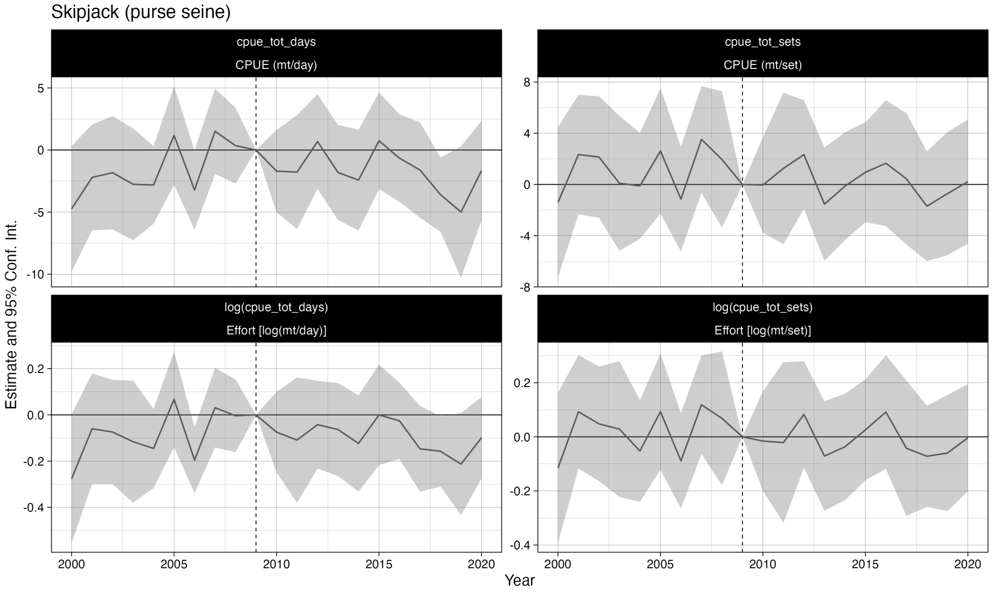

Figure S13: Caption

Table S9: Change in CPUE for Skipjack tuna caught by the purse seine fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	-0.496	-0.865
	(0.661)	(0.796)
Num.Obs.	24140	24140
R2 Adj.	0.148	0.106
B) Log-transformed		
Post x Near	-0.026	-0.036
	(0.033)	(0.038)
Num.Obs.	24140	24140
R2 Adj.	0.131	0.098

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

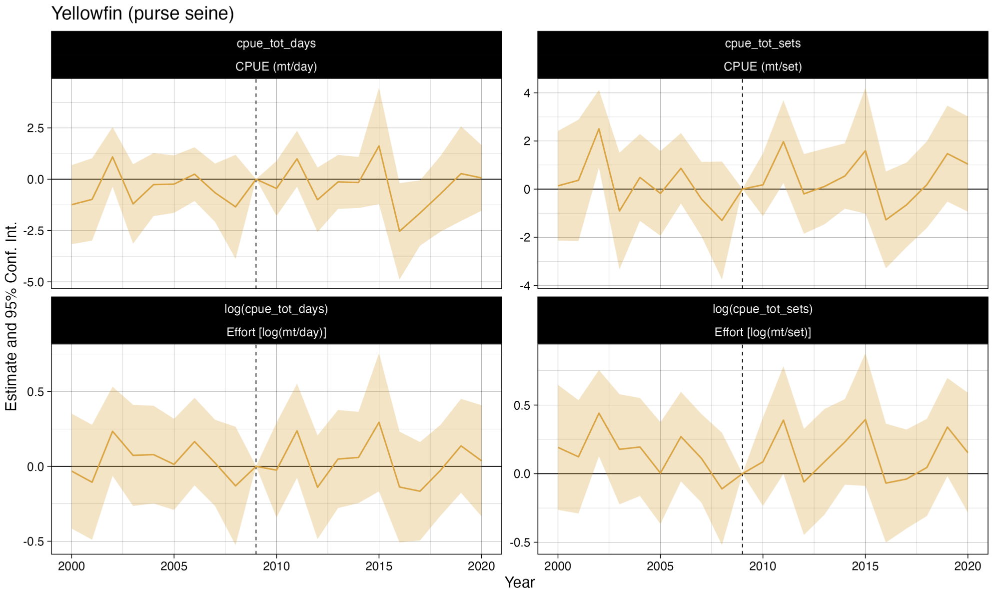

Figure S14: Caption

Table S10: Change in CPUE for Yellowfin tuna caught by the purse seine fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	0.146	0.402
	(0.273)	(0.292)
Num.Obs.	24111	24111
R2 Adj.	0.105	0.141
B) Log-transformed		
Post x Near	-0.004	0.012
	(0.040)	(0.050)
Num.Obs.	24111	24111
R2 Adj.	0.122	0.170

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

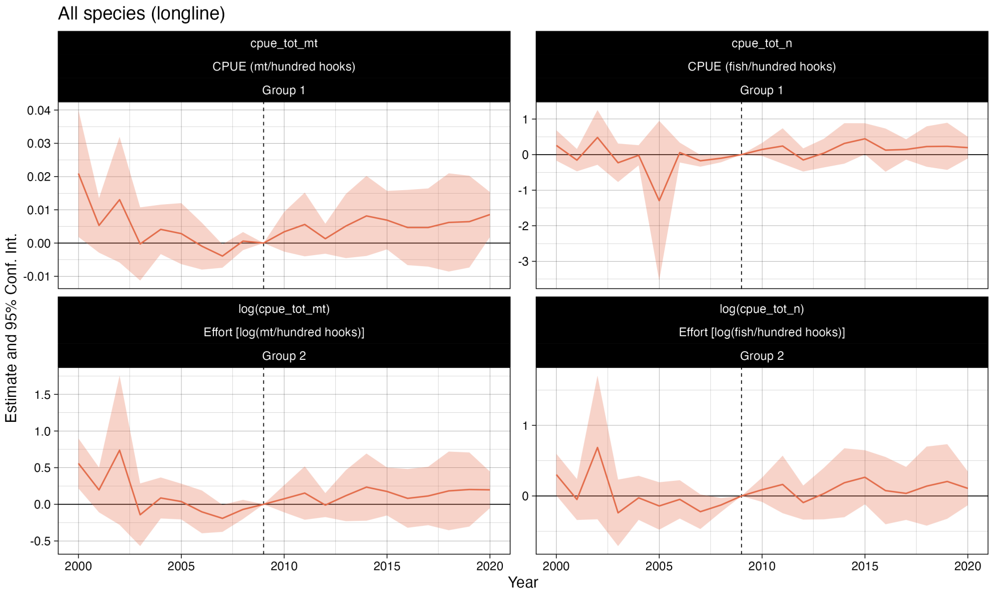

Figure S15: Caption

Table S11: Change in CPUE for all tuna species caught by the longline fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	0.298	0.001
	(0.277)	(0.004)
Num.Obs.	3229	3229
R2 Adj.	0.264	0.228
B) Log-transformed		
Post x Near	0.080	0.028
	(0.130)	(0.100)
Num.Obs.	3229	3229
R2 Adj.	0.454	0.231

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

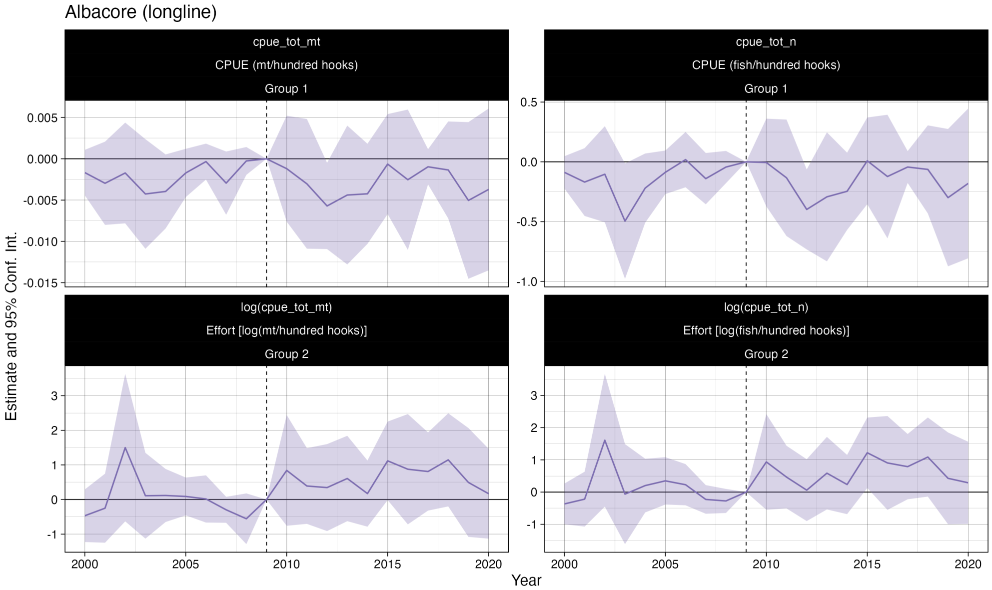

Figure S16: Caption

Table S12: Change in CPUE for Albacore tuna caught by the longline fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	-0.058	-0.001
	(0.131)	(0.002)
Num.Obs.	2855	2855
R2 Adj.	0.740	0.755
B) Log-transformed		
Post x Near	0.480	0.597
	(0.388)	(0.490)
Num.Obs.	2852	2855
R2 Adj.	0.742	0.710

* p < 0.1, ** p < 0.05, *** p < 0.01

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

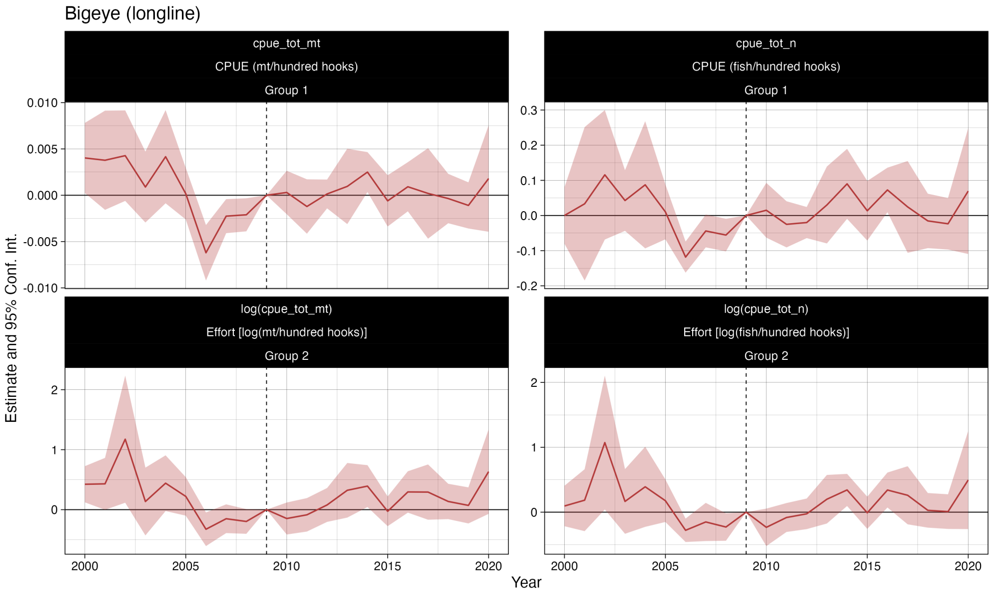

Figure S17: Caption

Table S13: Change in CPUE for Bigeye tuna caught by the longline fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	0.014	-0.000
	(0.041)	(0.001)
Num.Obs.	3228	3228
R2 Adj.	0.492	0.542
B) Log-transformed		
Post x Near	-0.029	-0.029
	(0.117)	(0.123)
Num.Obs.	3228	3228
R2 Adj.	0.608	0.672

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.

Figure S18: Caption

Table S14: Change in CPUE for Yellowfin tuna caught by the longline fleet within 100 nm of the high seas pockets

	(1)	(2)
A) Levels		
Post x Near	0.335	0.003
	(0.204)	(0.003)
Num.Obs.	3229	3229
R2 Adj.	0.124	0.238
B) Log-transformed		
Post x Near	0.239	0.195
	(0.150)	(0.164)
Num.Obs.	3229	3229
R2 Adj.	0.302	0.284

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The unit of observation is a grid cell by year. All model specifications include fixed effects by year and grid cell. Numbers in parentheses are Conley standard errors with a 220km radius.