FISHERIES

Evidence of spillover benefits from large-scale marine protected areas to purse seine fisheries

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Global tuna fisheries are valued at more than $40 billion, with the majority of this value derived from purse seine fisheries. Recently created large-scale marine protected areas are potentially big enough to protect highly migratory species such as tuna, possibly leading to increases in abundance (a conservation benefit) and consequent spillover near protected area boundaries (an economic benefit). Using publicly available data from nine large-scale marine protected areas across the Pacific and Indian oceans, we find that catch-per-unit-effort in tuna purse seine fisheries has increased by an average of 12 to 18% near protected area boundaries, and this increase declines with distance from the boundaries. The increase is larger for bigeye tuna (*Thunnus obesus*) than for skipjack tuna (*Katsuwonus pelamis*), in line with fisheries science simulation models.

In 2004, there was only one large-scale marine protected area (MPA) (typically defined as a contiguous no-take zone larger than 100,000 km^2) on Earth. At present, there are 21, and most of them occur in areas where tuna fisheries operate (Fig. 1 and table S1). This presents an opportunity to test what the impact has been, so far, of these new large-scale MPAs. In particular, what have the impacts been on commercially valuable tuna species, such as bigeye tuna (*Thunnus obesus*), skipjack tuna (*Katsuwonus pelamis*), and yellowfin tuna (*Thunnus albacares*)? These species support a global industry valued at more than $40 billion (*1*) and provide essential direct and indirect employment in many coastal and island nations (*2*). Understanding the interactions between large-scale MPAs, tuna stocks, and tuna fisheries is especially timely given international goals to protect 30% of the world's ocean area by 2030 and the recent approval of the Agreement on Marine Biodiversity of Areas beyond National Jurisdiction by the United Nations. Together, these may lead to the creation of new large-scale MPAs in the pelagic environment.

It has traditionally been argued that most tuna species are too migratory to be protected by large-scale MPAs and that such measures are inferior compared with more standard fisheries management approaches, such as catch limits and temporary closures (*3*, *4*). Recent work has argued that there is limited evidence of large-scale MPAs having any impact on the pelagic environment (*4*) and that when it comes to fisheries, the evidence of spillover from these protected areas is lacking or mixed at best (*5*–*10*). This lends support to criticism of global simulation studies that implicitly assume spillover benefits from MPAs (*11*, *12*). There is clearly a need for a robust and reproducible test of the central motivation behind large-scale MPAs: Do they lead to a recovery of the pelagic ecosystems that they are designed to protect?

To this end, we used publicly available data to test for changes in catch rates that have been caused by the creation of large-scale MPAs. More precise details are provided in the supplementary materials (*13*), but, in short, we combined four publicly available datasets on tuna catch and effort from the Atlantic, eastern Pacific, Indian, and western Pacific oceans. We then combined these geo-coded datasets with spatial polygons of large-scale MPAs located near areas with tuna fisheries (Fig. 1 and tables S1 to S4). Finally, we followed the standard methodology (*14*–*17*) for testing for a spillover benefit from an MPA. Specifically, controlling for changes in fishing effort, we investigated whether a particular type of fishing gear caught more in an area near the MPA—after the formation of the MPA—than it would have caught had the MPA never been established. To do this, we defined a near zone of 0 to 100 nautical miles from the boundaries of each large-scale MPA and a far zone of 100 to 200 nautical miles from each large-scale MPA. Figure 1 displays each MPA individually along with the boundaries of the near (MPA boundary to dashed line) and far (dashed line to solid line) zones. We then calculated the catch-per-unit-effort (CPUE) (in metric tons of tuna per set) in the near zone and the far zone both before the MPA was created and the same calculations after the MPA was created, and we tested for changes in the CPUE near the MPA boundary relative to any changes observed in the far zone. Under a set of identification and estimation assumptions (*13*), this before-after-control-impact (or, in this specific context, before-after-near-far) design allows us to make causal statements about the effect of large-scale MPA implementation on tuna spillover. Our work focuses on purse seine fisheries because this gear accounts for the majority of landings (67%) and end value (57%) associated with tuna fisheries (*1*) and because the spatial resolution of publicly available longline data is too coarse for this type of analysis [(*13*); but see fig. S1 and table S5 for longline-specific results].

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Evidence of spillover benefits

Figure 2 summarizes these calculations using the raw data for relevant purse seine fisheries (see also table S2 and fig. S2). Figure 2A shows that purse seine CPUE near large-scale MPAs has increased by 22.5% but that it has only increased by 8.7% far from MPAs, which suggests a spillover benefit of a 13.8% increase in tuna CPUE near the boundaries of large-scale MPAs. We explore this observation in more detail by calculating the change in CPUE as a function of distance from the MPA. Estimation of this spillover gradient is standard in evaluations of smaller nearshore MPAs (*18*–*20*). Figure 2B shows that the increase in purse seine CPUE is declining as a function of distance from the MPA boundary.

Taken as a whole, Fig. 2 is indicative of spillover benefits. However, these figures are just aggregate summaries of the raw data; there is no attempt to control for other factors that influence CPUE across time and space. We now turn to our main analysis, which is a regression-based approach that allows us to control for other factors that may confound a simple graphical analysis [such as year-to-year fluctuations in tuna abundance and country-specific differences in fishery practices and regulations (*13*)]. Our main results are divided into three parts: First, a spillover test for all large-scale MPAs in our dataset. Second, a test of spillover benefits for a subset of relevant MPAs with a balanced design (i.e., with multiple observations before, after, near, and far). Third, we present MPA- and species-specific test results.

Full sample results

Table 1 presents our main regression results, pooling all our data, and for different sets of control variables. Panel A includes nine different large-scale MPAs from across the Pacific and Indian oceans ("initial analysis"). Panel B is a subsample that only includes six large-scale MPAs with enough data for a balanced design ("main analysis"; see table S2). In column 1, we start with a basic regression model that includes an indicator variable for post-MPA establishment, an indicator variable for near the MPA, and an indicator variable for the product of the two (Post × Near), which gives the before-after-control-impact or "difference-in-differences" estimate of interest. There are no additional control variables. Using this somewhat naïve model to estimate the impact of large-scale MPAs on tuna CPUE, we conclude that the spillover benefit is a 32% increase in CPUE (because the outcome variable in the

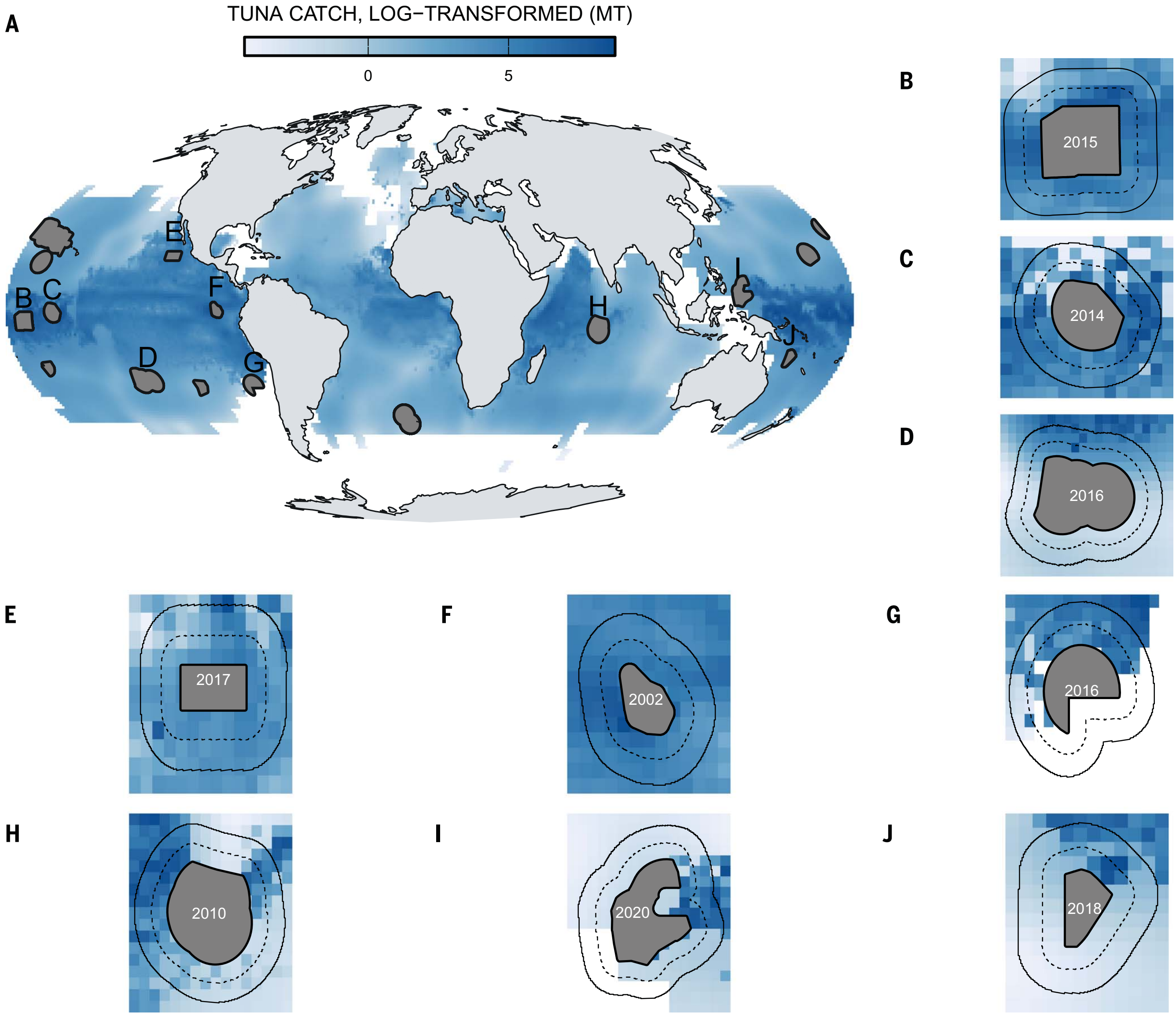

Fig. 1. Large-scale MPAs and the world's tuna fisheries. (**A**) Global map of average tuna catch as reported by four regional fisheries management organizations between 2011 and 2021 and polygons for 15 large-scale MPAs located near tuna fisheries (table S1). Catch data reported on a 5° by 5° grid (10.5%) were resampled onto a 1° by 1° grid using cubic spline interpolation and then combined with data reported on a 1° by 1° grid (89.5%). MT, metric tons. (**B** to **J**) The nine large-scale MPAs considered in this study and all catch within 250 nautical miles of their boundary. Subplots are ordered from west to east, as shown by labels in the main map in (A): Phoenix Islands Protected Area (Kiribati) (B), Pacific Remote Islands - Jarvis (USA) (C), Pitcairn Islands Marine Reserve (UK) (D), Revillagigedo (Mexico) (E), Galápagos (Ecuador) (F), Nazca-Desventuradas Marine Park (Chile) (G), Chagos MPA (UK) (H), Palau National Marine Sanctuary (Palau) (I), and Coral Sea Marine Park - National Park Zone (Australia) (J).

regression model is logged CPUE, the coefficients can be interpreted as approximate percentage changes—e.g., +0.1 implies a roughly 10% increase in CPUE; for the exact percentage change, take the exponent of the coefficient and subtract 1). These estimates (panels A and B) are statistically significant at the 1% level.

In columns 2 to 4, we include step-wise sets of additional controls (fixed-effects by grid cell, by fleet flag, and by MPA-year). These specifications control for unobserved differences in CPUE across space, unobserved differences across fishing fleets, and time-varying unobserved factors influencing CPUE around an MPA over time (e.g., changes in ocean conditions or regional trends in tuna abundance). The estimated spillover benefit is attenuated but still positive (ranging from 12 to 13%) and remains statistically significant at the 5% level. Column 4 in Panel B is our preferred estimate because it includes the most complete set of controls.

We also include results from a specification that incorporates linear and quadratic effects of mean annual Oceanic Niño Index anomalies for each MPA (column 5). This specification addresses concerns that specific changes in environmental conditions [such as El Niño (*21*)] may be causing the increases in CPUE observed outside large-scale MPAs. In essence, this controls for the impact of El Niño–Southern Oscillation on tuna CPUE around each MPA. The spillover benefit is still estimated to be 12% and is significant at the 5% level. The results in Table 1 are also robust to different specifications and definitions of near-far areas (different radius, table S6; binned distances, fig. S3; and continuous distances, table S7),

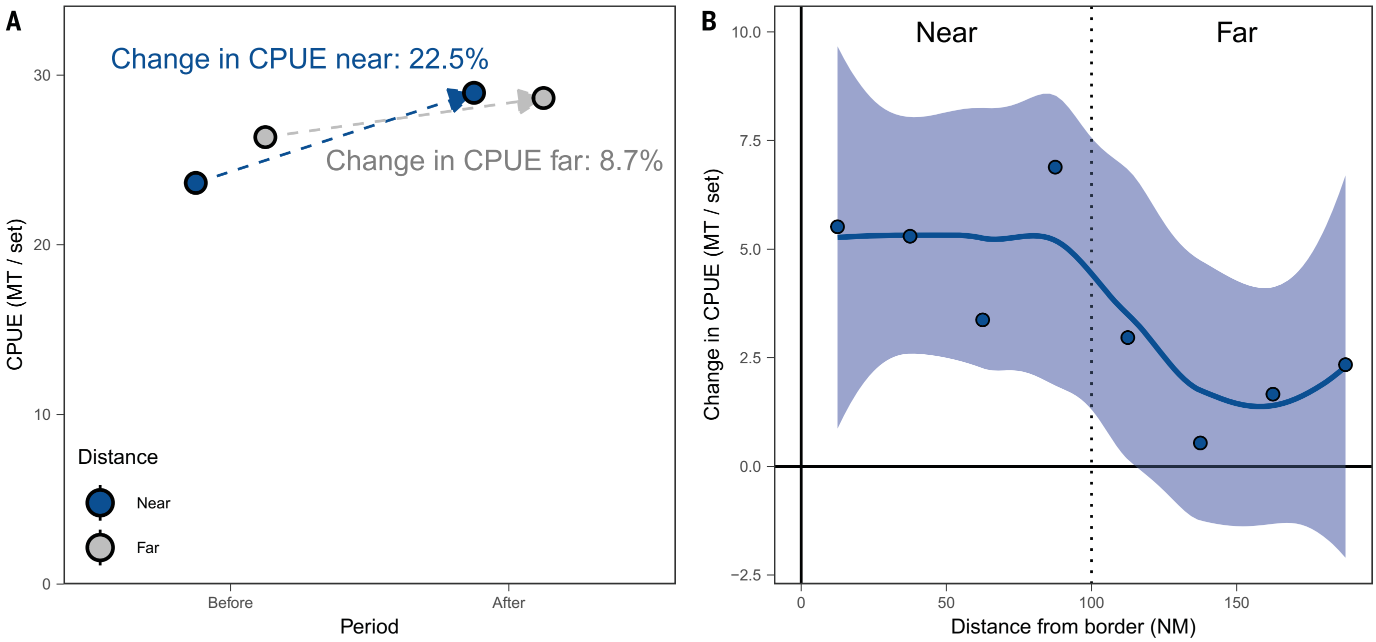

Fig. 2. Aggregate effect of large-scale MPAs on CPUE of adjacent tuna purse seine fisheries. (**A**) Mean CPUE (in metric tons per set) in a before-after-control-impact framework, with points showing the group averages and error bars the standard errors. Text insets show the percentage change in CPUE for near (blue) and far (gray) areas. (**B**) Binned scatter plot showing how the change in CPUE declines as a function of distance from MPA boundaries. Individual points are the mean change in CPUE for each distance bin [8 bins, every 25 nautical miles (NM)], the smoothed line is a locally fitted polynomial, and the shaded areas show standard errors. Both panels use all data available within a 10-year window around the time of implementation of five large-scale MPAs: Galápagos, Jarvis, Nazca-Desventuradas, Phoenix Islands, and Revillagigedo. Data from the Chagos Islands MPA are excluded from these visualizations because they are reported in units different from those used in the rest of the world. Figure S2 shows before-after-near-far plots for each individual MPA.

Table 1. Effect of large-scale MPAs on CPUE of tuna purse seine fisheries. Coefficients are difference-in-differences estimates for the percentage change in CPUE, with associated standard errors shown in parentheses. Column 1 is the simplest specification, with no fixed effects. Column 2 includes fixed effects by grid cell. Column 3 includes fixed effects by grid and by flag. Column 4 shows a full specification, with fixed effects by grid, by flag, and by MPA-year. Column 5 then incorporates linear and quadratic terms for the Oceanic Niño Index interacted with MPA and removes MPA-year fixed effects but retains MPA fixed effects. *N* indicates number of observations, R^2 Adj. is the adjusted coefficient of determination, and SE is the method or assumption used to calculate standard errors. IID, independently and identically distributed; FE, fixed effects. Conley (200 km) are Conley standard errors accounting for spatial correlation using a 200-km cutoff. Dashes indicate not applicable.

Parameter	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Panel A: All data (nine large-scale MPAs)					
Post × Near	0.320*** (0.046)	0.133** (0.054)	0.124** (0.055)	0.117** (0.057)	0.119** (0.055)
N	10407	10407	10407	10407	10407
R^2 Adj.	0.020	0.512	0.526	0.545	0.530
SE	IID	Conley (200 km)	Conley (200 km)	Conley (200 km)	Conley (200 km)
Panel B: Subsample of relevant large-scale MPAs (six MPAs)					
Post × Near	0.317*** (0.047)	0.132** (0.054)	0.123** (0.055)	0.117** (0.057)	0.119** (0.055)
N	10273	10273	10273	10273	10273
R^2 Adj.	0.022	0.512	0.526	0.546	0.530
SE	IID	Conley (200 km)	Conley (200 km)	Conley (200 km)	Conley (200 km)
FE: Grid ID	–	X	X	X	X
FE: Flag	–	–	X	X	X
FE: MPA-Year	–	–	–	X	–
FE: MPA	–	–	–	–	X

**$P < 0.05$; ***$P < 0.01$.

using random effects models instead of fixed-effects models (table S8) and extending the sample to all after-implementation data available (spillover benefits are larger, 16 to 18%, and all are statistically significant at the 1% level; table S9).

Effects by MPA and species

We next explore these estimated effects in terms of individual MPAs and separately for different tuna species. Starting at the individual MPA level (Fig. 3 and table S10), we find that five of the six MPAs in our main analysis have positive spillover coefficients. The effects are moderate but precise for well-studied MPAs (Galápagos, Phoenix Islands Protected Area, and Revillagigedo) and corroborate previous insights (*9*, *22*, *23*). The results are more mixed for MPAs that did not displace a lot of fishing effort after implementation (Jarvis, Nazca-Desventuradas, and Chagos)—a negative coefficient, a positive coefficient with a large confidence interval, and a small positive coefficient, respectively. The coefficient for Chagos is much larger (12% instead of 3%) and closer to statistical significance if we exclude data from 2015 onward for this particular MPA [there was a court ruling in 2015 challenging the legality of the MPA (*24*)]. Figure S2 shows before-after-control-impact plots for each large-scale MPA (similar to Fig. 2A): For all six MPAs, the percentage change in the near area is greater than the percentage change in the far area. Overall, these results demonstrate that the combined estimate is not being driven by one single outlier area and is instead primarily driven by three that are known to have displaced large amounts of fishing effort (fig. S4).

Results across species are relatively consistent, with all species showing some evidence of positive spillover (ranging from 2 to 11%; table S11). Again, this means that our combined estimates of spillover benefits are not being driven by one single species. It is interesting to note the larger coefficient on bigeye tuna CPUE. Purse seine vessels catch large numbers of juvenile bigeye tuna (*25*). This increase in juvenile bigeye tuna abundance outside the boundaries of large-scale MPAs would be consistent with a recruitment effect (*26*, *27*), but this is far from definitive evidence and further highlights concerns about catch of juvenile bigeye in purse seine fisheries (*25*, *28*). The other noticeable fact about the coefficient on bigeye tuna is its size relative to the estimated spillover effect for skipjack tuna. This is consistent with predictions from high-resolution models of large-scale MPAs in the western and central Pacific Ocean, an area dominated by purse seine fisheries (*23*, *28*). Simulating the impact of the Phoenix Islands Protected Area (*23*) predicts that the abundance of skipjack tuna inside the MPA would increase by 2.58% but the abundance of bigeye tuna inside would increase by 15.32% (and generally finds that the increase in bigeye abundance inside large-scale MPAs in the Pacific Ocean is always larger than the increase in skipjack abundance). Our estimate for skipjack tuna is a 2.1% increase and that for bigeye tuna is an 11.2% increase in the spillover zones outside the MPAs (five of the six large-scale MPAs included in our main analysis are in the Pacific Ocean, including the Phoenix Islands Protected Area). See figs. S5 and S6 for the same MPA-, species-, and year-level analysis but without including any fixed effects.

Who reaps the benefits?

We have shown that large-scale MPAs can produce spillovers that benefit adjacent tuna purse seine fisheries. But who reaps these benefits? Is it possible that a nation closing large swaths of ocean territory imposes large costs on their own fleet (e.g., by closing most of their exclusive economic zone so as to push their fleet into the high seas), just to have a foreign fleet reap the spillover benefits that we document in this work? This is a crucial question posed by nations that are hesitant to engage in large-scale marine conservation. We find that, to date, nations that engage in conservation are also the ones that reap most of the benefits (Fig. 4). Consider the example of two MPAs implemented by nations with large tuna fishing fleets: Galápagos (in Ecuador) and Revillagigedo (in Mexico). In these instances, Ecuadorian- and Mexican-flagged purse seiners account for 65% and 100%, respectively, of tuna caught near the MPAs since their implementation. This suggests that these nations' commitments to large-scale marine conservation directly benefit their tuna fishing fleets.

The same may be true even for nations that lack a large industrial fishing fleet or those with MPAs so large that they extend to the edge of their exclusive economic zone. For example, Kiribati and eight other Pacific Island nations jointly manage their purse seine fisheries through a vessel-day scheme (*29*). In line with findings from previous work (*23*), we detect spillover from the Phoenix Islands Protected Area (in Kiribati) that enhances the profitability of tuna fisheries in surrounding waters. Because foreign fleets pay upward of $10,000 for the rights to fish for a single day in these waters, this spillover benefit may make their waters more attractive to foreign tuna purse seiners (*29*–*31*).

Discussion

This work presents an empirical evaluation of the fisheries impacts of large-scale MPAs on an ocean-wide but not fully global scale. Previous work focused on a single large-scale MPA has either found positive effects (*8*, *22*, *32*) or no effects (*6*, *7*, *9*, *33*). Using publicly available data and a before-after-control-impact methodology, we find evidence of economically meaningful spillover benefits. The average increase in CPUE outside large-scale MPAs ranges from 12 to 18%, with 12% being the most credible estimate. Overall, the results are consistent with the amount of fishing effort displaced from each MPA, the life history of the species affected, and previous simulation studies (*23*, *28*) and are stable across a range of specifications and robustness tests. Note that a spillover benefit does not, by itself, imply that a fish stock is now more abundant overall or that an affected fishery is more profitable; we are simply confirming the existence of one of many benefits that MPAs can provide and that have been demonstrated at smaller scales (*14*) or in single case studies (*8*).

Our estimates of spillover by MPA and by species show some variation. However, the patterns observed are in agreement with the previous literature. For example, Jarvis, Chagos, and Nazca-Desventuradas displaced little-to-no fishing effort or have limited enforcement (*34*, *35*). These large-scale MPAs exhibit weak or very imprecise estimates that are not robust to different specifications (fig. S5). On the other hand, Revillagigedo, the Phoenix Islands, and Galápagos displaced large amounts of fishing effort and were subject to stiff opposition from the fishing sector (*9*, *22*, *36*). These MPAs show positive and precise spillover effects that are correlated with the age and size of the MPA, a pattern not observable for the other three (fig. S4). Although these patterns are in agreement with previous findings from the literature (*37*), we note that caution is warranted because these patterns are derived from just three MPAs.

There are, of course, caveats to drawing conclusions from results obtained using observational data. Large-scale MPAs were not randomly assigned to different locations across the globe, and they were not implemented in randomly determined years: Five of the six MPAs in our main analysis are all in the Pacific Ocean, and four were implemented between 2014 and 2017. It always remains a possibility that some unobserved factor could be correlated with the timing and location of MPA implementation. For example, it is possible, but unlikely, that the increase in CPUE outside the Galápagos Marine Reserve was caused by some change in ocean conditions that only began to manifest its impact on tuna abundance after 2002 and only affected abundance within 100 nautical miles of the MPA but did not affect abundance 100 to 200 nautical miles away from the MPA. However, it should be stressed that the real strength of our contribution is that we are able to move beyond single case studies (which are more susceptible to confound bias) and present a set of results where the same patterns are being observed at different locations and at different points in time.

Another caveat is the quality of the data. The spatial resolution is low: A single grid cell comprises an ocean area of ~12,000 km^2. It is challenging to detect effects that are most likely occurring on a scale of around <100 nautical miles when data are aggregated into such large grid cells. The other issue with aggregation is that it masks possible changes in fishing behavior that could bias estimates of spillover, either upward or downward. For example, if the creation of a large-scale MPA causes vessels with typically higher values of CPUE to fish farther

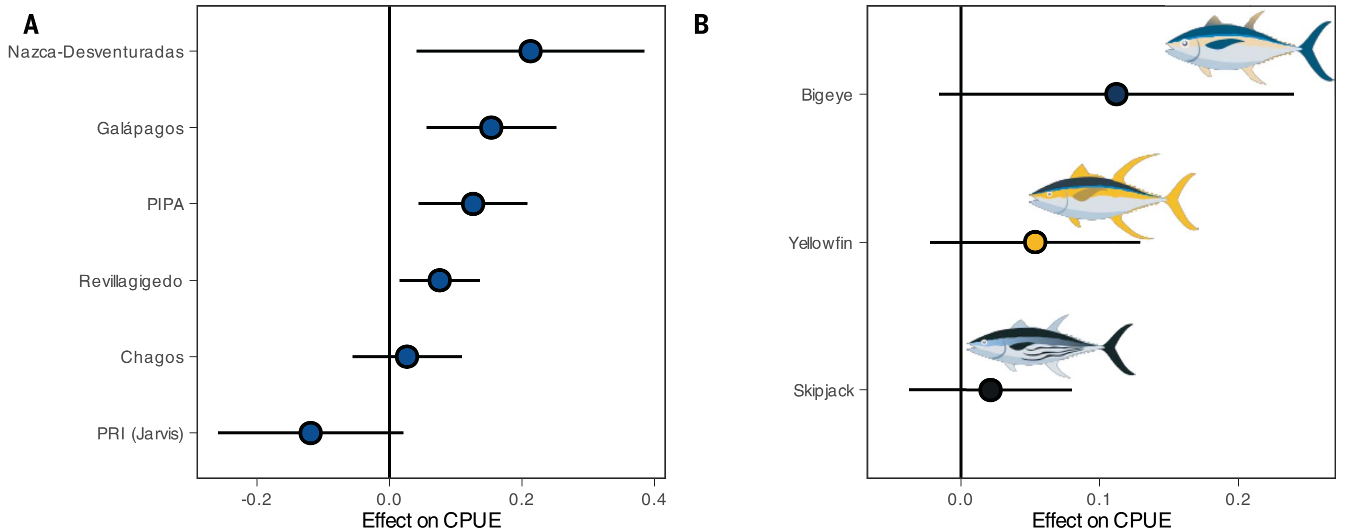

Fig. 3. Spillover effects by large-scale MPA and species. (**A**) Effect of each large-scale MPA on the CPUE of purse seine fleets operating in MPA-adjacent waters. (**B**) Effect of MPAs on the CPUE for different species [bigeye tuna (*T. obesus*), skipjack (*K. pelamis*), and yellowfin tuna (*T. albacares*)]. In all panels, error bars are Conley standard errors using a 200-km cutoff. Note that, within each subplot, large-scale MPAs and species are ranked by effect size. Regression tables for data shown here are presented in tables S10 and S11. PIPA, Phoenix Islands Protected Area; PRI, Pacific Remote Islands Marine National Monument.

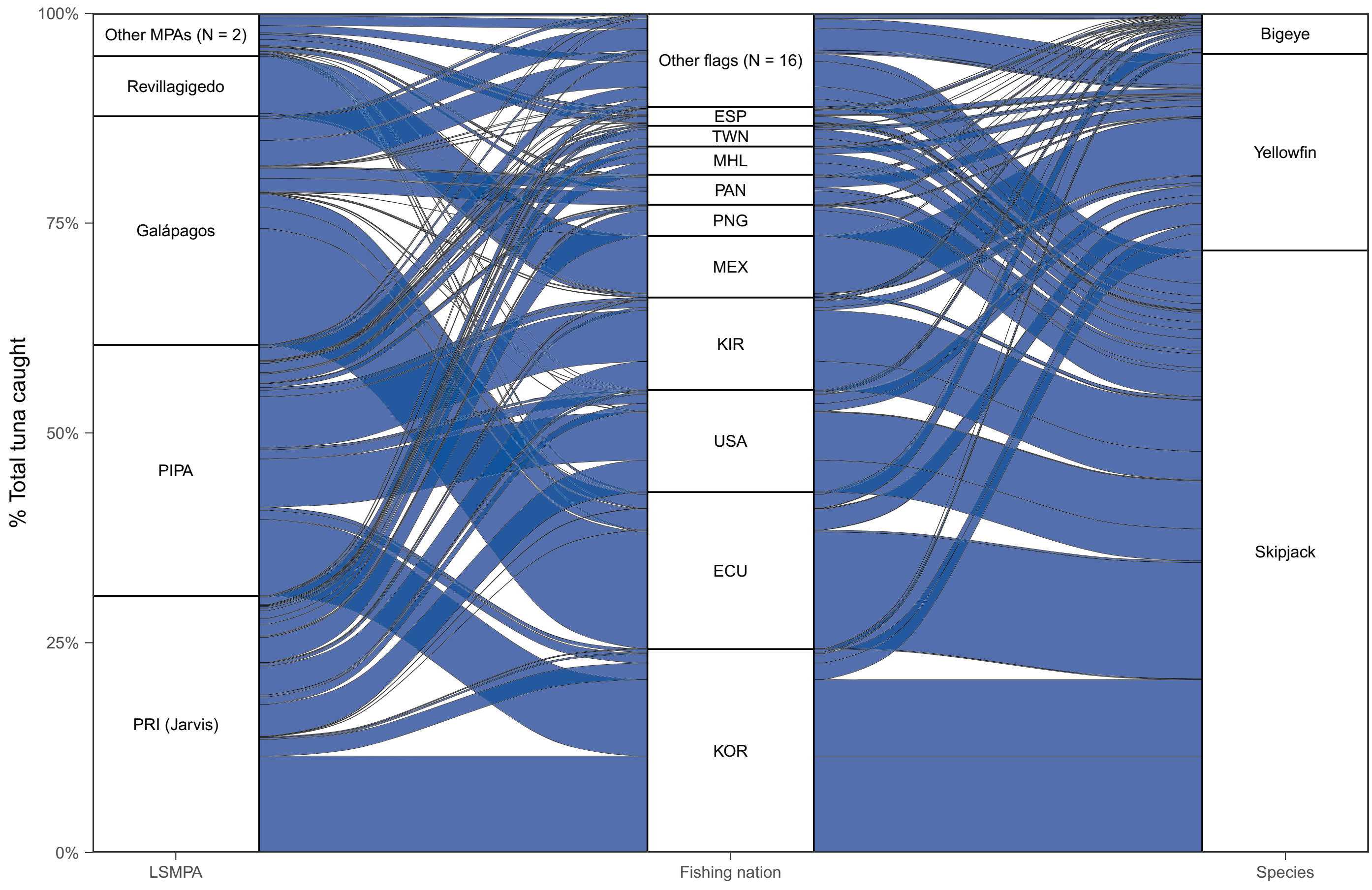

Fig. 4. Distribution of spillover benefits across fishing nations. This alluvial diagram shows how catch (*y* axis; percentage of total) reported within 200 nautical miles of a large-scale MPA (LSMPA) boundary (left column) flows into fishing nations (center column) and species (right column). For example, skipjack account for more than 50% of all tuna catch occurring within 200 nautical miles of all large-scale MPAs considered in our study. Alternatively, ~30% of all tuna caught within 200 nautical miles of a large-scale MPA in our sample is caught outside the Phoenix Islands Protected Area (PIPA). PRI, Pacific Remote Islands Marine National Monument; ESP, Spain; TWN, Taiwan; MHL, Marshall Islands; PAN, Panama; PNG, Papua New Guinea; MEX, Mexico; KIR, Kiribati; ECU, Ecuador; KOR, South Korea.

away from the MPA than they used to, then this would increase CPUE in the far zone, leading to a smaller estimate of the spillover effect than what would be obtained using data reported at the individual vessel level. Reassuringly, the few case studies that do exist on vessel redistribution after large-scale MPA establishment have not found any evidence that this is happening on a scale that would bias our estimates (*7*, *8*, *30*, *32*).

Despite the limitations of the data, this does not alter their main redeeming feature: They are all publicly available. The primary motivation behind this work was to test for evidence of spillover effects using only publicly available data and open-source code. Much of the work on large-scale MPA impacts has relied on either confidential data (*8*, *32*) or proprietary code (*23*). We strongly encourage other researchers to replicate, refine, and critique our analysis.

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Data and materials availability: The underlying data used in this study are available for download on each regional fisheries management organization (RFMO)'s website [Inter-American Tropical Tuna Commission (IATTC), https://www.iattc.org/en-US/Data/Public-domain; Western and Central Pacific Fisheries Commission (WCPFC), https://www.wcpfc.int/node/4648; International Commission for the Conservation of Atlantic Tunas (ICCAT), https://www.iccat.int/en/accesingdb.HTML; and Indian Ocean Tuna Commission (IOTC), https://iotc.org/data/datasets], from the Marine Protection Atlas website (https://mpatlas.org/), and from the World Database on Protected Areas website (https://www.protectedplanet.net). The raw and processed data as well as the R code that supports the findings of this study are available on Zenodo (*38*). The baseline results in column 1 of Table 1 can be replicated with one line of code.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
Tables S1 to S11
References (*39*–*55*)
MDAR Reproducibility Checklist

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