ECOLOGY

A global test of MPA spillover benefits to recreational fisheries

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Marine protected areas (MPAs) have been identified as one of the most effective tools to halt marine biodiversity loss. However, conflicting evidence from disparate, small-scale studies obfuscate a cohesive global picture of the role that MPAs can play in enhancing local fisheries through spillover benefits. We conducted a global analysis of trophy-size fish catches as a proxy for spillover occurring outside of fully protected MPAs, focusing on time series of recreational angling catch records. We show that the accumulation of recreational fishing records accelerates close to MPAs (compared to reference areas) and that this effect grows stronger over time. Our results provide a standardized global assessment of one of the benefits MPAs provide to recreational anglers.

INTRODUCTION

In 2022, 190 countries approved a United Nations agreement to protect 30% of the world's land and oceans by 2030 (*1*). Creating new protected areas in the ocean (only 2% of the global ocean is currently designated as highly or fully protected areas) will involve trade-offs, often between short-run costs (as ocean users are displaced) in return for long-run benefits (as marine ecosystem services are restored) (*2*). Most of the research examining these trade-offs at a global scale has focused on impacts to commercial fisheries and, to a lesser extent, other large-scale industries such as deep-sea mining (*3*). However, in many parts of the world, participation in and economic output generated by recreational fishing exceeds that of commercial fishing (*4*). Recreational fishers represent an important stakeholder group that is sometimes ignored when national and international targets are set for protected areas in the ocean (*5*).

Understanding the true costs and benefits to ocean stakeholders, and when they are likely to occur, is critical to informing progress toward the global 30% by 2030 target (i.e., "30 × 30"). Mirroring trends in psychology (*6*), medicine (*7*), economics (*8*), and ecology (*9*), the field of marine protected area (MPA) science has been experiencing a "replication crisis" resulting, in some cases, in retractions of high-profile scientific studies (*10*, *11*). Some studies (especially those showing spillover benefits from MPAs) have been criticized for being one-off examples that have benefited from favorable environmental or policy conditions that occurred at the same time as MPA establishment (*12*).

Here, we test whether the results of one of the most well-known studies of MPA impacts on recreational fishers can be replicated at a global scale. Published more than 20 years ago, Roberts *et al.* (*13*) examined the oldest fully protected marine reserve in the United States, the Merritt Island National Wildlife Refuge in Florida. Motivated by earlier research showing that the abundance of popular sport fish species was 2 to 12 times higher inside the MPA compared to adjacent areas, Roberts *et al.* (*13*) decided to test the hypothesis that long-established MPAs can supply record-sized fish to recreational fisheries through the occasional spillover of large fish across MPA boundaries. They found that the cumulative number of record-breaking fish caught near the MPA (within 100 km of its boundary) starts to rise rapidly between 8 and 30 years after MPA establishment, relative to similar waters far from the MPA. In particular, the timing of the rapid rise corresponds with the longevity of different species (i.e., records start to accumulate earlier for short-lived species and later for long-lived species).At the time of publication, Roberts *et al.* (*13*) highlighted the uniqueness of the Merritt Island National Wildlife Refuge. At that time, it was one of only 36 fully protected MPAs globally that had been in place for longer than 35 years. Today, spread all across the world (Fig. 1A), at least 400 such MPAs exist. This presents a unique opportunity to test the long-run global impacts of fully protected MPAs on recreational fisheries.

RESULTS AND DISCUSSION

Our methods are explained in more detail in Materials and Methods but, in summary, we obtained data on every official world record–breaking fish caught between 1950 and 2021, along with the location of every MPA that is fully protected, obtained from the Marine Protection Atlas (MPAtlas) dataset (Fig. 1A). We define "fully protected" as follows: an MPA where >0% of the area meets the MPA Guide's definition (*14*) of fully protected: "No impact from extractive or destructive activities is allowed." On average, at least 74.67% of the area in the individual MPAs included in this study meet that criterion. We first attempted to replicate the main result in Roberts *et al.* (*13*) (figure 4 in their paper and the first panel in our Fig. 2), which we were able to do (Fig. 2A), for both the same time period (left) and extending the dataset to the present (right). We then combined the data and graphical analysis used in Roberts *et al.* (*13*) to create a simpler, aggregated summary of their result for the MPA as a whole (Fig. 2B, left). We then devised a simple statistical test to confirm the Roberts *et al.* (*13*) finding using this aggregated (and updated to 2021) dataset: Does the accumulation of records accelerate "near" the MPA *x* years after MPA establishment relative to the accumulation rate "far" from the MPA? This is a variation of a Before-After-Control-Impact design where the outcome is not the total number of record-breaking fish, but rather the slope (or speed) of record accumulation over time. See the two blue and yellow lines in the second panel of Fig. 2B for a visual explanation. This panel shows the accumulation of record-sized fish near and far from an MPA in Costa Rica (i.e., Marino Ballena National Park). Comparing the yellow and blue lines pre-1992 (the year of MPA establishment),

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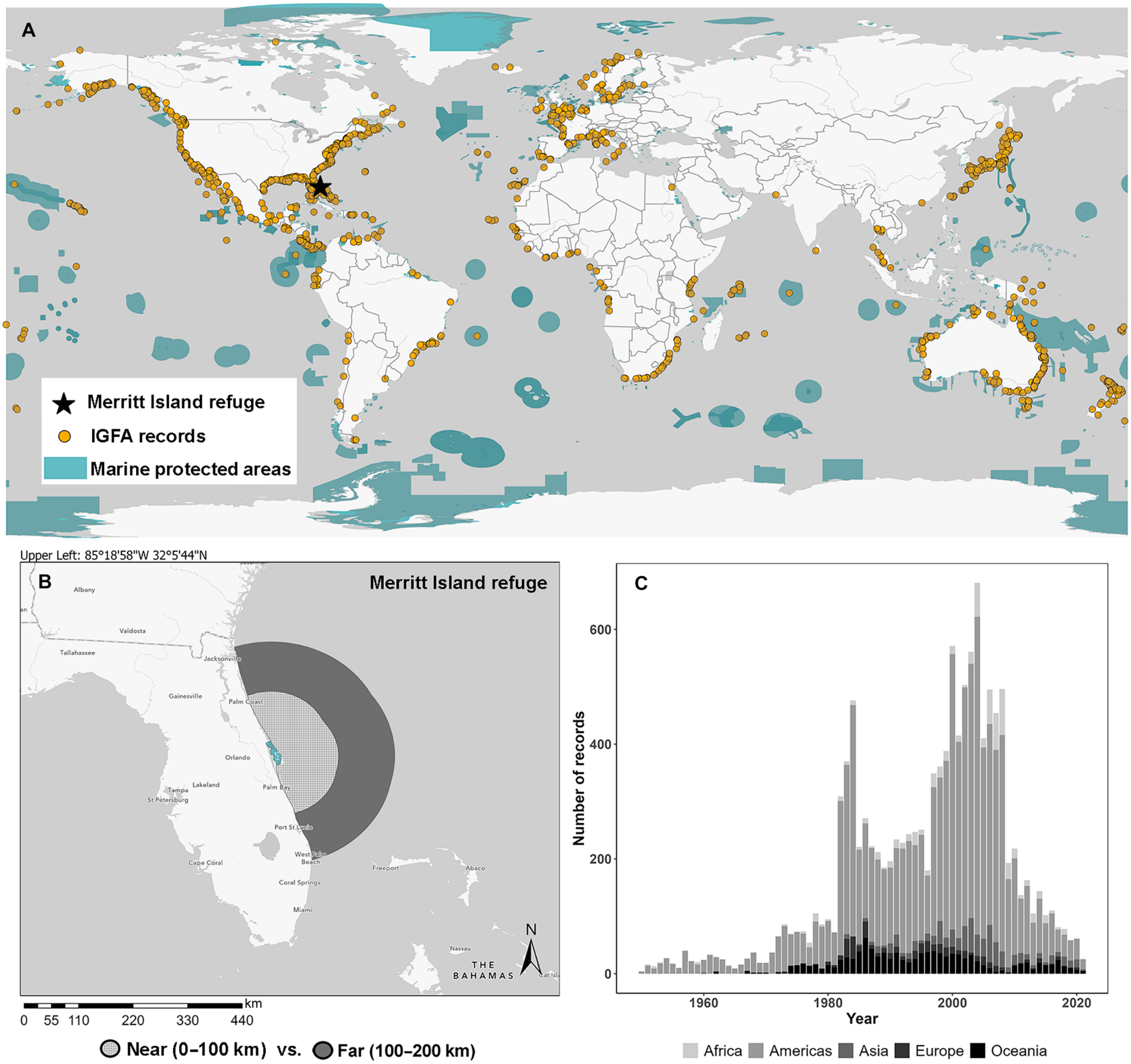

Fig. 1. Spatial distribution and International Game Fish Association (IGFA) world records and marine protected areas. (**A**) Global distribution of the coastal dataset for the IGFA world records (orange dots) and MPAtlas marine protected areas dataset (blue polygons). The Merritt Island National Wildlife Refuge's location is marked by a black star. (**B**) Merritt Island National Wildlife Refuge (Florida, USA). The two highlighted areas represent the near zone (0 to 100 km; light gray) to the far zone (100 to 200 km; dark gray), respectively, in agreement with the study of Roberts *et al.* (*13*). (**C**) Number of IGFA world records by continent and year from 1950 to 2021, shown here as a stacked barplot.

records accumulated at about the same rate (the yellow and blue lines' slopes are very similar). After the MPA is established, the number of record-sized fish caught near the MPA starts to accelerate and the light blue line is much steeper than the yellow line after MPA establishment. This is consistent with the MPA providing a spillover of record-sized fish. Our test is a regression-based hypothesis test of the null hypothesis that the difference in slopes (between yellow and light blue) before MPA implementation is the same as the difference in slopes (between yellow and light blue) after MPA implementation. Another way of saying this is that a statistically significant positive coefficient on the "near acceleration post-MPA" term in our regression model provides empirical evidence that the record accumulation rate has accelerated more near the MPA compared to far from the MPA. This allows for a simple and easy-to-replicate

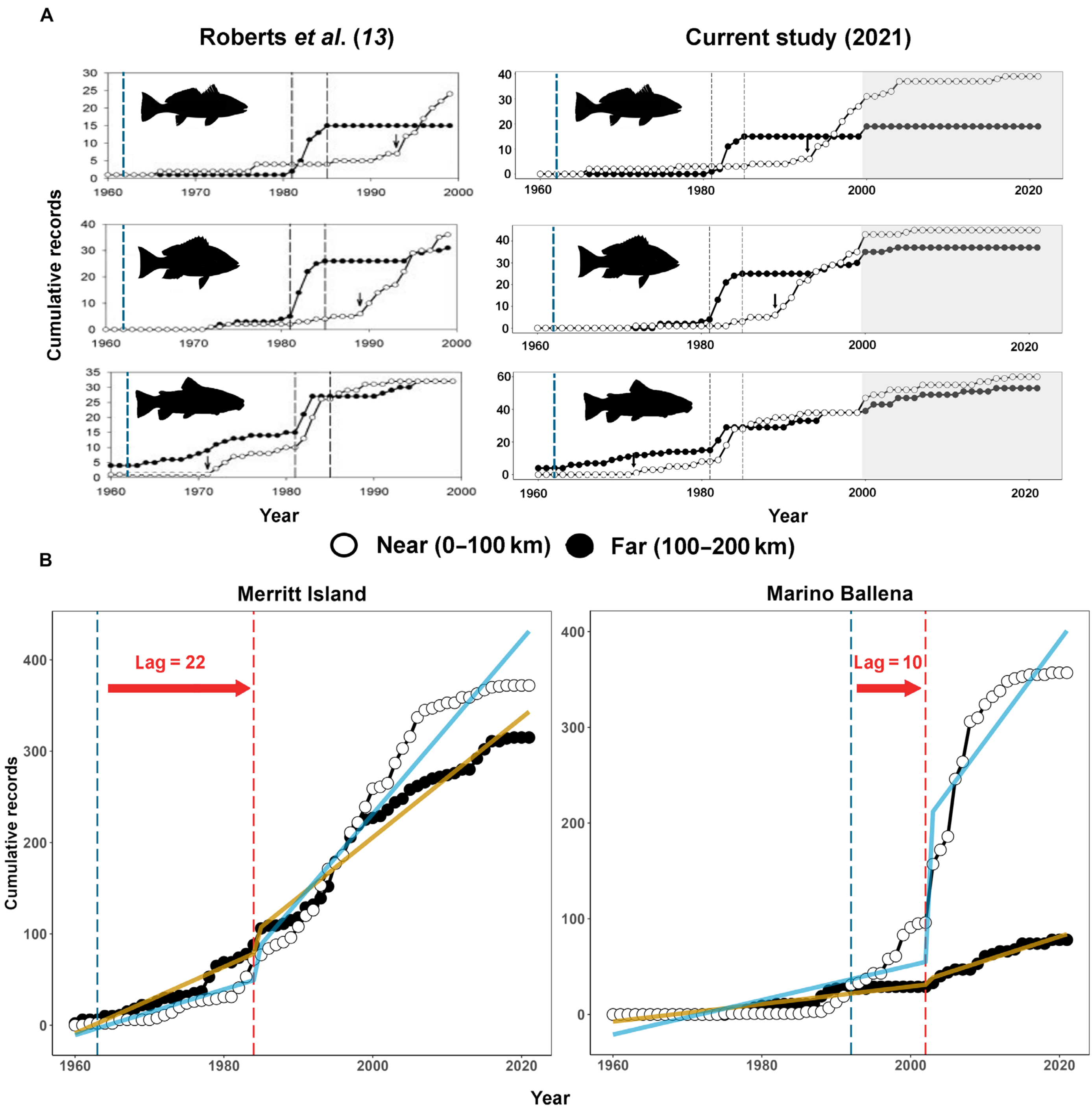

Fig. 2. Cumulative game fish world records near Merritt Island National Wildlife Refuge and Marino Ballena National Park. (**A**) Comparison of cumulative game fish world records in the 200-km coastal section near the Merritt Island National Wildlife Refuge, comparing the original Roberts *et al.* (*13*) study (left) to the current study (right). This result underscores the consistency and validity of the two datasets for comparison. Cumulative world records shown for (from top bottom) black drum (*P. cromis*), red drum (*S. ocellatus*), and spotted seatrout (*C. nebulosus*). Open circles and dark circles represent records within 0 to 100 km and between 100 and 200 km from the MPA boundary, respectively. Vertical dark blue dashed lines mark the time of protection from fishing within the refuge. Vertical gray dashed lines show a period of rapid accumulation of new records after addition of new fishing line categories by the IGFA. Black down arrows mark the points at which there was a rapid increase in accumulation of new records for each species from areas around the Merritt Island National Wildlife Refuge. Gray areas on the right plots represent cumulative records for the same three species updated to 2021. (**B**) Cumulative game fish world records for Merritt Island National Wildlife Refuge and the Marino Ballena National Park. White and black dots represent catches in the near and far areas, respectively. Vertical dark blue dashed lines represent the year of MPA establishment. Vertical red dashed lines represent the lag time after records started accumulating rapidly in the near area. The cumulative record slopes are represented for the far and the near areas by the yellow and light blue lines, respectively.

statistical test of the primarily visual test originally performed by Roberts *et al.* (*13*). We performed this same statistical test on every MPA with enough data before, after, near, and far to estimate four different slope coefficients (and four different intercept coefficients).

We start by calculating the number of MPAs that appear to replicate the main result in Roberts *et al.* (*13*). Figure 3 shows the number of MPAs globally (for different lag times) for which we observe a faster accumulation of records near the MPA, after controlling for any preexisting differences in record accumulation pre-MPA. The inset panel includes all MPAs in our study, while the main graph shows the subset of MPAs that have been established at least 35 years ago. Here, it can be seen that if we set the lag time equal to zero (i.e., assume that MPAs will instantly start leading to a spillover of world record–sized fish and measure the change in slope using all years after MPA establishment), then there are around 160 MPAs that produce the same visual pattern as Roberts *et al.* (*13*). If we increase the lag time to 23 years, we see that there are 180 MPAs that replicate the result. If we increase the lag time to 35 years, there are now more than 300 MPAs from around the world where records start accumulating faster near to the MPA.

The inset figure in Fig. 3 displays the same information as the main figure except the number of successful replications is shown as a proportion of all MPAs (and the results are color-coded by whether the estimated change in slope is positive and/or statistically significant). For lag times beyond 25 years, most MPAs globally are producing spillovers of record-sized fish to recreational anglers (~62% for 35 years). It can be seen that most coefficient estimates are not statistically significant, and this proportion is increasing with lag time, which would be expected given that the size of the post-MPA sample decreases with increasing lag time. Bear in mind that we are including every single fully protected MPA listed in the MPAtlas. Many of these may not have been designed with the intention of benefiting recreational anglers.

In Fig. 4, we combine all the fully protected MPAs in the world into one global network of MPAs and estimate the average impact on world records for different lag times. It can be seen that we can strongly reject a null hypothesis of global positive spillover benefits for a lag time of zero years (instantaneous spillover benefits), but over time, the estimated global coefficient starts to increase and switches from negative to positive for a lag time of 26 years. For a lag time of 35 years, the estimated spillover coefficient for the combined

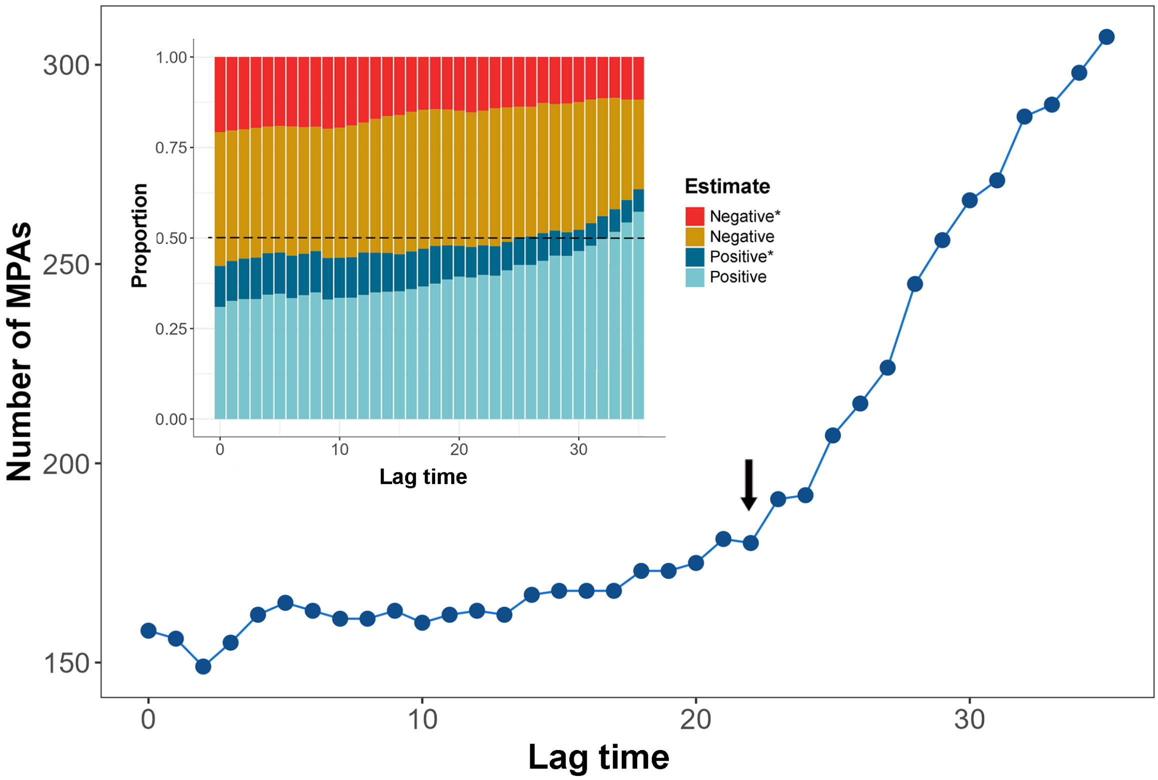

Fig. 3. Cumulative analysis of MPA spillover effects by lag time. Main panel: Cumulative number of 35+-year-old MPAs with estimated positive spillover effects by lag time (blue dots). The black down arrow highlights the point at which a rapid increase in the number of MPAs showing positive spillover effects is observed, corresponding to a lag time of 22 years [see Fig. 2A for the corresponding points for individual species, and a single MPA, in the original Roberts *et al.* paper (*13*)]. Inset panel: Proportion of all MPAs with observed positive (light and dark blue bars; dark blue indicates statistically significant at the 5% level) and negative (orange and red bars; red indicates statistically significant at the 5% level) spillover effects in adjacent areas, by lag time. Positive implies that the slope of the record accumulation line (see Fig. 2B) is steeper for the zone near the MPA following MPA establishment (and controlling for any difference in slopes before establishment). Negative implies the opposite finding. Dashed line denotes 50% of the total MPAs. Both panels' *x* axes range from 0 to 35 years lag time, serving as the lag time value for the 0 to 1 post variable in the regression model (Eq. 1; see Materials and Methods). Total number of MPAs for each lag time is reported in table S1. An analogous plot that only includes MPAs where 100% of the area in the MPA is fully protected is shown in fig. S1.

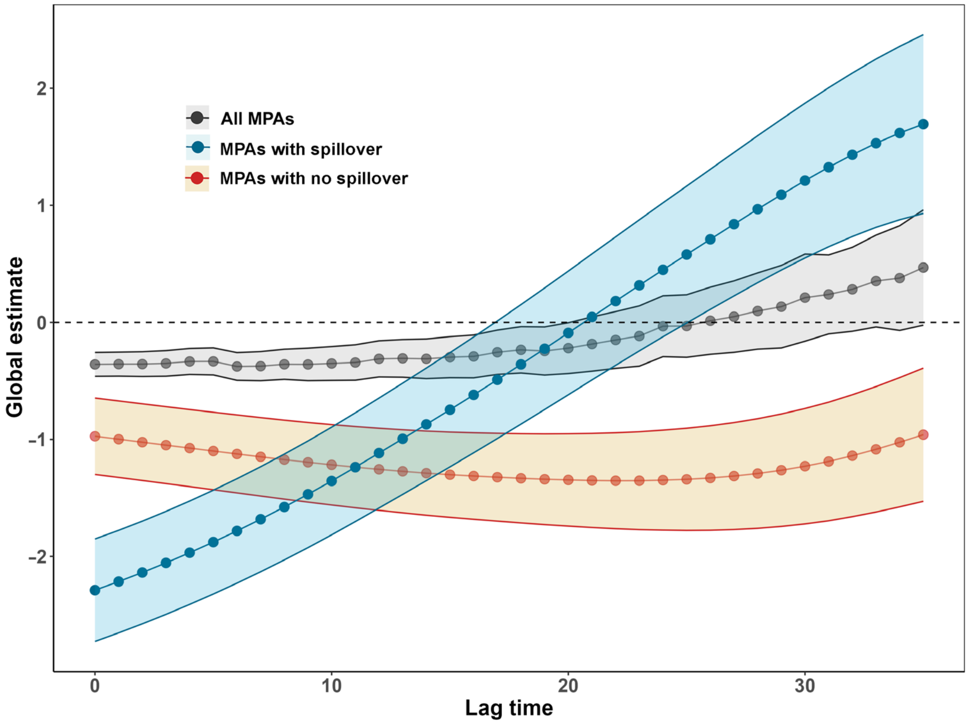

Fig. 4. Average coefficient estimates of cumulative catch records for all locations combined. Black dots represent the average coefficient estimates of all MPAs by lag time. Average coefficient estimates are also shown for MPAs with at least 35 years of post-implementation data that showed a positive (blue dots) and negative (orange dots) spillover effect in the adjacent area at a lag time of 35 years. Sample size for the "blue" positive and "orange" negative MPAs are 308 and 194, respectively. Shaded areas represent 95% confidence intervals.

global sample is borderline statistically significant ($P < 0.065$; 95% confidence interval of −0.024 to 0.961 records year^{-1}). The implication of the estimated coefficient (0.47) is that, on average, after a lag time of 35 years, one more world record–sized fish is caught near an MPA every 2 years relative to similar waters far from the MPA.

Using a robust statistical method that successfully replicates and extends the seminal results of Roberts *et al.* (*13*) (Fig. 2A), we found clear and widespread positive effects of MPAs on angling records. First, worldwide, fully protected MPAs disproportionately produce world record–setting fish catches through the spillover effect of fish from within their protected zones to outside fished areas, benefiting recreational anglers (Fig. 3). These spillover effects increase over time, particularly after 20 to 30 years after reserve establishment (Fig. 3). By 30 to 35 years after establishment, most MPAs globally display positive spillover effects (Fig. 3, inset).

Both the total number and proportion of MPAs exhibiting positive spillover effects increase with MPA age, presumably as some fish continue to evade fishing mortality for longer and longer (Fig. 3). The effect is particularly pronounced after 20+ years after protection. This result is consistent with Robert *et al.*'s work (*13*), where they observed a rapid accumulation of world record–setting fishes caught in nearby areas for the three selected species 22 years (on average) after the establishment of the Merritt Island National Wildlife Refuge, the United States' oldest fully protected marine reserve. This result is also consistent with the findings of many studies (*15*) that previously harvested fish populations within MPAs need years to recover from fishing pressure to rebound. Likewise, many studies have shown at local scales that as populations do rebound, they are more likely to spill over into the areas surrounding the MPAs (*16*), thus benefiting adjacent fisheries through increased abundance (*17*), larval export (*18*), or average body size of catch (*13*). However, it is worth noting that even after 30+ years, some MPAs do not show positive spillover effects (Figs. 3 and 4). MPAs vary widely in enforcement, habitat quality, fisheries management outside of their boundaries, and many other factors (*19*), each of which could affect their potential spillover. Some studies have emphasized that older MPAs with stricter enforcement measures are associated with improved fisheries, particularly in the case of large MPAs (*20*, *21*). However, the success of MPAs in restoring marine ecosystems and biodiversity depends heavily on the compliance of users, especially fishers (*22*). Noncompliance, particularly through illegal fishing, can substantially undermine the intended ecological benefits of MPAs (*23*). It follows that the mere presence of an MPA does not guarantee ecological recovery without the willingness of users to adhere to the MPA regulations, which is affected by their awareness and understanding of the rules, perceived fairness and legitimacy of the regulations, and the economic incentives or pressures they face (*24*). We ran a simple test to illustrate the importance of enforcement and effectiveness: We restricted the sample to just MPAs that are 100% fully protected and do not permit any fishing whatsoever (on the premise that these would be easier to enforce and more effective than mixed-use MPAs) and found that the evidence for spillover benefits is stronger (see fig. S1).

A number of other important caveats should be considered when interpreting these results. First, we filtered the dataset to include only nonpelagic, marine fishes given many pelagic fishes' large home range sizes, which are often far greater than the size of MPAs (*25*). As a result, the degree to which our results might apply to pelagic species remains unclear. Second, many reef-associated or coastal fishes found within MPAs on small remote islands or seamounts would necessarily be more common within the near zone relative to the offshore, far zone that contains little to no shallow habitat. However, our approach of comparing these two zones before and after MPA implementation accounts for this preexisting difference in habitat suitability. Third, the structure of the IGFA dataset is such that fish caught from a boat are recorded at the location of landing (i.e., port), not via the Global Positioning System coordinates of the exact catch location. This lack of precise georeferencing of the exact capture location of record fish catches introduces noise to our analyses, rendering them conservative. To somewhat account for this noise and the effect that it might have on our results, we conducted a sensitivity analysis to determine how the size of the near versus far zones that we delineated affected our results. Doing so is particularly important given that previous research has demonstrated localized spillover dynamics within narrow spatial confines (*26*, *27*). Figure S2 (A and B) visually illustrates the impact of varying spatial resolutions on the observed trends, highlighting the influence of spatial noise within smaller zone radii. However, this bias should not affect our results as it applies both before and after MPA establishment, which serves as our basis for comparison. It can be seen that the general pattern of our results holds for definitions of the near zone ranging from 20 to 100 km. Furthermore, after 35 years, the spillover effect is positive for all zone definitions in fig. S2B, even the most restrictive definition of near (0 to 10 km from the MPA) and far (100 to 110 km from the MPA). Fourth, our metric of record-sized individual fishes is not directly representative of population size or biomass, but it does serve as a proxy for both because population-level metrics such as these scale with individual size. Fifth, by simple geometry, the area of the far zone surrounding each MPA is necessarily slightly larger than the near zone (Fig. 1B). Again, since this difference is not changing over time, it does not bias our results. Sixth, if more recent MPA proposals faced stronger opposition from commercial and recreational fisheries stakeholders [leading them to being placed far from human activity (*28*–*30*)], this could introduce a temporal bias: Newer MPAs are less likely to generate observable spillover benefits. Last, the IGFA database is skewed toward greater representation in developed countries. Nonetheless, we are aware of no a priori reason, other than potential differences in enforcement, to assume that the direction of change that we observed over time in MPA spillover in mainly developed countries would not also be expected to occur in developing countries.

As the global 30 × 30 initiative gets underway, policy-makers and conservation practitioners need clear, easily interpretable evidence from the scientific community for what strategies can most effectively lead to recovery of marine resources and provide benefits for local stakeholders. At present, relatively few MPAs are located in populated coastal areas, many of them are not properly enforced, and local fishing community stakeholders and/or managers may not be fully supportive of them (*31*). This study provides globally relevant guidance for what management agencies, conservation practitioners, and, importantly, recreational anglers can expect over the long term from the establishment of MPAs. The overall message is cautiously optimistic. MPAs are consistently helping anglers to break world records across the globe, but these benefits do not materialize for decades. Advocates for, and managers of, new MPAs need to encourage patience and resist the urge to promise large benefits to recreational anglers that may take 20 years or more to materialize. Overly optimistic predictions about the spillover of record-sized fish will only cause frustration and undermine support for 30 × 30 in the long run. A fruitful avenue for future research would be to explore the MPA characteristics that are likely to lead to more (and earlier) spillover of record-sized fish (or, conversely, those associated with MPAs not producing record-sized spillover), particularly as this knowledge could inform how and where future MPAs are established. In summary, our study represents an important step toward developing a standardized, easily replicable evaluation of one type of MPA benefit and provides fishers, resource managers, and conservation practitioners guidance on the potential spillover benefits that MPAs can provide to recreational fisheries.

MATERIALS AND METHODS

Data

World records

The International Game Fish Association (IGFA) publishes a book every year (*32*) listing all of the world records by fish species and record category [e.g., largest black grouper (*Mycteroperca bonaci*) caught by a male angler using conventional tackle and a 24-kg test line]. These records are also posted on the IGFA's website, with additional details available to IGFA members. Using this dataset, we filtered data to include only saltwater and nearshore or reef-associated species (table S2), resulting in a total of 12,347 records and 454 species (Fig 1, A and C). We excluded highly migratory, pelagic species (such as Atlantic blue marlin, *Makaira nigricans*) because most MPAs are considered too small to provide refuge to pelagic species and the point of landing recorded by the IGFA may be far from the location of where the fish was caught. Following Roberts *et al.* (*13*), we restricted our analysis to the following record categories: 1-, 2-, 4-, 6-, 8-, 10-, 15-, 24-, and 37-kg test line for conventional tackle (for adult male and female anglers) and 1-, 2-, 3-, 4-, 5-, 8-, and 10-kg test line for fly tackle (for adult male and female anglers). In other words, we did not include records for fish caught by children (i.e., the Junior and Smallfry categories) and using the 60-kg test line with conventional tackle, to keep the methodology the same as that implemented by Roberts *et al.* (*13*). The spikes in records observed in Fig. 1C are typically due to the creation of new record categories (e.g., in 1981 and 1998). Each world record includes a text location of where the record was obtained [for example, the world record for red drum (*Sciaenops ocellatus*) caught on a 16-lb (7.25-kg) test line by a male angler was recorded as "Banana River Lagoon, Florida, USA"], and these were geocoded using the Google GEOCODE tool (*33*) to obtain latitude and longitude coordinates for each world record.

MPAs

MPA polygon information was obtained from the MPAtlas global database (*34*), accessed in January 2023 (Fig. 1A). We restricted the set of MPAs analyzed to those defined as fully protected MPAs (*14*). In other words, for some portion (or all) of the MPA area, commercial and recreational fishing is not allowed. This led to an initial candidate list of 1536 MPAs with the percentage of area designated as fully protected ranging from 0.38 to 100% (with a mean value of 74.67%).

Defining before-after-control-impact

We followed the methodology of Roberts *et al.* (*13*) and summed the number of new records every year located near to (0 to 100 km) and far from (100 to 200 km) an MPA boundary (Fig. 1B). This is a slight departure from the near/far definition used by Roberts *et al.* (*13*) they defined near as within 0 to 100 km of the MPA and far as anywhere else in the U.S. state of Florida. This approach would not work for other U.S. states (especially much smaller ones) and certainly not for other countries. Moreover, while the centroid of the MPA was used to calculate the distances between the records and the MPA in Roberts *et al.*'s (*13*) study, we computed the minimum distance between the record coordinates and the MPA's boundary to avoid bias due to differences in the shapes and sizes of different MPAs. The only exception, as detailed in the subsection below where we use the centroid of the MPA to calculate distance from the MPA, is in attempting to replicate Roberts *et al.* (*13*) as closely as possible to test that our metric is comparable. Distances were computed using the *geosphere* function in R. For the purposes of our statistical analysis, only MPAs for which there were at least 10 records in the near and far areas were included. In addition, any MPAs for which there were no IGFA records before the creation of the MPA were excluded.

Modeling framework

Initial calibration

To test the reliability of this new dataset, we ran preliminary analyses on the same study area as Roberts *et al.* (*13*), i.e., the Merritt Island National Wildlife Refuge (Fig. 1B). This test resulted in almost identical results for the three species selected in their work, i.e., black drum (*Pogonias cromis*), red drum (*S. ocellatus*), and spotted seatrout (*Cynoscion nebulosus*) (Fig. 2A). As mentioned above, we calculated distance from the MPA as the distance from the centroid of the MPA because we found some slight visual differences when we initially calculated distance as distance from the boundary of the MPA. For all subsequent figures/tables (i.e., Fig. 2B onward), distance is calculated as the distance from the MPA border.

Regression-based replication test

The accumulation of catch records between near and far areas before and after MPA establishment was analyzed by testing whether the accumulation of records accelerated in the near area after MPA establishment (Fig. 2B). In particular, for each MPA, the following linear regression model was fitted

$$\begin{aligned}\sum^{t} x_{it} = {} & \beta_0 + \beta_1 year_t + \beta_2 near_i + \beta_3 post_t \\ & + \beta_4 year_t * near_i + \beta_5 year_t * post_t \\ & + \beta_6 near_i * post_t + \beta_7 year_t * near_i * post_t + e_{it}\end{aligned} \quad (1)$$

where $\sum^{t} x_{it}$ is the cumulative number of records in year t either near or far from the MPA (i). The variable $year_t$ is the year, which allows for a linear accumulation of records over time. The $near_i$ variable is a 0-1 binary value describing whether the records occurred in the far ($i = 0$) or near ($i = 1$) area. The $post_t$ variable is a 0-1 binary value describing if the records occurred before (0) or after (1) MPA establishment. The other terms are interactions of these binary (or "dummy") variables that allow for different trends over time and space and also allow for testing different hypotheses about how records are accumulated differentially either near/far or before/after. The $year_t * near_i$ variable allows for the accumulation of records (in both the before and after time periods) to be different in the near zone. In other words, the coefficient β_4 represents a statistical test of the hypothesis that the rate of record accumulation in the near and far regions was the same before MPA implementation. The $year_t * post_t$ variable allows for an acceleration (or deceleration) in the record accumulation rate in both the near and far zones after MPA establishment. This is a common feature of the data, especially for older MPAs, because awareness of the IGFA and the ease of confirming records has presumably improved over time. The $near_i * post_t$ variable tests whether the mean number of cumulative records is higher in the near area after MPA implementation, controlling for preexisting differences in mean records between the near and the far region and any general trends over time. Thus, β_6 would be the coefficient evaluated in a standard Before-After-Control-Impact (BACI) or Difference-in-Differences design. The $year_t * near_i * post_t$ variable tests whether the rate at which records accumulate changes in the near area after MPA implementation. In other words, it is a test of whether the slope of the white circle lines in Fig. 2B changes after MPA establishment relative to any change in the slope of the black circle lines after MPA establishment. Thus, a positive coefficient for β_7 implies that world records accumulated faster in the near area after MPA establishment and a negative coefficient implies that world records accumulated faster in the far area after MPA establishment. Take the right panel of Fig. 2B (Marino Ballena National Park) as an example. Clearly, the accumulation of records accelerated in both the near and far regions after 1992 but the slope (or rate of accumulation) was steeper (faster) in the near region. Hence, the estimated β_7 that corresponds to that figure is 7.08 with a P value <0.01. The slope of the light blue line is seven records per year steeper than the yellow line, after controlling for the fact that the two lines had slightly different slopes to begin with.

One of the key points illustrated by Roberts *et al.* (*13*) is that different life histories and movement patterns could affect how quickly spillover effects might start to appear outside MPAs. MPAs are known to require several years or more for detectable fish population recovery (*35*) and significant spillover effects may not be observed for many years after MPA establishment. In particular, when we are considering world record–sized fish, it may take decades for an MPA to provide enough protection to long-lived, slow-growing fishes to reach a point that some individuals might be large enough to be record-breaking. In Roberts *et al.* (*13*), the acceleration in records for spotted seatrout did not start until 1971 (see black, downward-pointing arrow in Fig. 2A), 9 years after MPA establishment. The acceleration in records for red drum did not start until 1989 (see black, downward-pointing arrow in Fig. 2A), 27 years after MPA establishment. Moreover, the acceleration in records for black drum did not start until 1993 (see black, downward-pointing arrow in Fig. 2A), a full 31 years after MPA establishment. These turning points almost perfectly correspond with what is known about the growth rates and life history of these species: spotted seatrout have a longevity of 15 years, red drum have a longevity of 35 years, and black drum have a longevity of 70 years. Thus, it is expected that the average lag time until records started accumulating rapidly outside the Merritt Island National Wildlife Refuge was 22.33 years.

To take this issue into account, we re-ran the regression model above for each MPA and added a lag time to the date the MPA was established to calculate the effects on catch record accumulation based on different "post" time periods. For example, when the lag time is 22 years, this defines the post-MPA period as after 1984, 22 years after the MPA was established in 1962. We summarize the estimated regression coefficients for β_7 for all locations with 35 years or more of post-MPA data at different lag time values in Fig. 3. In Fig. 4, we combine all data on all MPAs into a single regression model, which allows us to estimate the average global impact of MPAs on record accumulation, along with an appropriate standard error. To place all

MPAs on the same time scale, we redefined the year variable to be the number of years before or after MPA implementation. Thus, a $year_t$ value of −5 indicates 5 years before MPA implementation, 0 indicates the year the MPA was implemented, and a value of 10 indicates 10 years after MPA implementation.

Supplementary Materials

This PDF file includes:
Figs. S1 and S2
Tables S1 and S2

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