Conservation Biology

Research Note

Tracking the response of industrial fishing fleets to large marine protected areas in the Pacific Ocean

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Abstract: Large marine protected areas (MPAs) of unprecedented size have recently been established across the global oceans, yet their ability to meet conservation objectives is debated. Key areas of debate include uncertainty over nations' abilities to enforce fishing bans across vast, remote regions and the intensity of human impacts before and after MPA implementation. We used a recently developed vessel tracking data set (produced using Automatic Identification System detections) to quantify the response of industrial fishing fleets to 5 of the largest MPAs established in the Pacific Ocean since 2013. After their implementation, all 5 MPAs successfully kept industrial fishing effort exceptionally low. Detected fishing effort was already low in 4 of the 5 large MPAs prior to MPA implementation, particularly relative to nearby regions that did not receive formal protection. Our results suggest that these large MPAs may present major conservation opportunities in relatively intact ecosystems with low immediate impact to industrial fisheries, but the large MPAs we considered often did not significantly reduce fishing effort because baseline fishing was typically low. It is yet to be determined how large MPAs may shape global ocean conservation in the future if the footprint of human influence continues to expand. Continued improvement in understanding of how large MPAs interact with industrial fisheries is a crucial step toward defining their role in global ocean management.

Keywords: commercial fishing, fisheries, marine protected areas, spatial management, vessel tracking

Seguimiento a la Respuesta de las Flotillas de Pesca Industrial a las Grandes Áreas Marinas Protegidas Extensas

Resumen: Recientemente se han establecido grandes áreas marinas protegidas (AMPs) de tamaños nunca vistos en todos los océanos del mundo; sin embargo, se sigue debatiendo su habilidad para lograr los objetivos de conservación. El debate se centra en los siguientes temas importantes: la incertidumbre por la capacidad de las naciones para hacer cumplir las vedas de pesca en regiones vastas y remotas y la intensidad del impacto humano antes y después de la implementación de una AMP. Usamos un conjunto de datos de rastreo de navíos recientemente desarrollado (producido usando detecciones mediante el Sistema Automático de Identificación) para cuantificar la respuesta de las flotillas de pesca industrial ante cinco de las AMPs más grandes establecidas en el océano Pacífico desde 2013. Después de su implementación, las cinco AMPs mantuvieron exitosamente los esfuerzos de pesca industrial a niveles excepcionalmente bajos. El esfuerzo de pesca detectado ya se encontraba bajo en cuatro de las cinco grandes AMPs previo a la implementación, particularmente en relación con las regiones próximas que no reciben protección formal. Nuestros resultados sugieren que estas grandes AMPs pueden presentar oportunidades importantes de conservación en ecosistemas relativamente intactos con un impacto inmediato bajo para las pesquerías industriales, pero las grandes AMPs que consideramos con frecuencia no redujeron significativamente el

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Article impact statement: Large marine protected areas in intact ecosystems may have positive conservation effects and low immediate impact on industrial fisheries..
Paper submitted December 6, 2019; revised manuscript accepted July 3, 2020.

Conservation Biology, Volume 34, No. 6, 1571–1578

DOI: 10.1111/cobi.13584

esfuerzo de pesca porque la línea base de la pesca con frecuencia ya era baja. Todavía se debe determinar cómo las grandes AMPs pueden moldear la conservación mundial de los océanos en el futuro si la huella de la influencia humana continúa expandiéndose. La mejoría continua del entendimiento de cómo las grandes AMPs interactúan con las pesquerías industriales es un paso importante hacia la definición de su papel en el manejo mundial de los océanos.

Palabras Clave: áreas marinas protegidas, manejo espacial, pesca comercial, pesquerías, rastreo de navíos

Introduction

More ocean area has been formally protected in the last decade than in all preceding history (O'Leary et al. 2018). This trend is driven by rising interest in establishing exceptionally large marine protected areas (MPAs) ($>$100,000 km^2) in which commercial fishing is restricted to achieve conservation and fisheries management goals (Wilhelm et al. 2014). The number of MPAs has increased over the past several decades, but the supersizing of MPAs is a recent occurrence. The mean size of new MPAs has increased 10-fold in the last decade; the largest reserves now exceed the size of France ($>$1 million km^2) (McCauley et al. 2015).

This pattern has great potential to constitute a meaningful step toward global protection targets (e.g., Aichi Target 11) (Boonzaier & Pauly 2016). Large MPAs may be necessary to protect entire marine ecosystems, which benefits some highly mobile species in ways that smaller MPAs cannot (White et al. 2017; O'Leary et al. 2018). Large MPAs are often placed at some of the most remote, pristine ecosystems on the planet, thus, preserving valuable biodiversity assets and reference sites for comparison with more degraded regions (Friedlander et al. 2014). The large size of recent MPAs is also thought to bolster their ability to protect biodiversity as climate change shifts species distributions (Davies et al. 2017, Roberts et al. 2017).

However, the conservation value and socioeconomic impact of large MPAs has been debated in academia, governments, and conservation organizations. Critics of large MPAs often contend that remote zones experience minimal fishing effort—even prior to formal protections—so resources are misplaced when greater threats to biodiversity lie in coastal regions (Magris & Pressey 2018). The response of fishing vessels to large MPAs is another central point of debate. Recently, it has been suggested that large MPAs may undermine conservation objectives in the short term by displacing effort onto other regions or attracting fishing effort in the time between when the MPA is announced and when protections take effect (Dueri & Maury 2013; McDermott et al. 2018). Additionally, nations' abilities to enforce fishing bans across vast, remote regions are questioned (Pala 2013). Degazettement, or removal of protections, of large MPAs has received increased momentum as these debates proceed unresolved. For example, U.S. President Donald Trump ordered a review of several large MPAs in U.S. waters to evaluate removing protections (Bruno et al. 2018).

Both supporters and skeptics of large MPAs acknowledge that empirical evidence to evaluate protection at this scale remained scarce until recently (Kaplan et al. 2013; Friedlander et al. 2016). Traditional tools of marine ecologists are challenging to implement at the scale of large MPAs (Kaplan et al. 2013). High-resolution data on the catch and effort of fisheries near protected regions can offer powerful insights (Boerder et al. 2017), but these data sets are typically kept private by governments. Publicly available data sets released by regional fisheries management organizations (RFMOs) are often too coarse (e.g., 5° grid cells) to evaluate the effects of large MPAs.

The recent proliferation of publicly available vessel tracking data provides an opportunity for empirical investigation of these points of contention. High-resolution tracks of over 70,000 industrial fishing boats have been produced by analyzing satellite detections of vessel Automatic Identification System (AIS) signals—a system originally designed for navigational and safety purposes (Kroodsma et al. 2018). The resulting data set of 2.2×10^9 detections captures approximately 50-75% of global fishing effort in offshore regions, where the vast majority of large MPAs are located (O'Leary et al. 2018). This data set does not capture the activity of most small-scale fishing vessels, because relatively few vessels smaller than 24 m are required to use AIS, or of vessels that fish illegally while not transmitting AIS. Analyses of AIS data reveal patterns of fishing effort near individual MPAs (McCauley et al. 2016; White et al. 2017; McDermott et al. 2018), but broader views across multiple MPAs are needed to improve understanding of this recent trend in marine conservation.

We used vessel tracking to generate views of industrial fishing before and after fishing restrictions were implemented in 5 of the largest MPAs in the Pacific Ocean. Together these 5 focal large MPAs amount to over 4.3 million km^2—or approximately half the land area of the United States. To partially control for drivers of fishing that are not influenced by protection status (e.g., remoteness, regional oceanography, species distributions), we also examined fishing activity in nearby EEZs that permit industrial fishing. High-resolution data let us identify patterns that may have been obscured previously by aggregate data sets or lack of data. We sought to inform

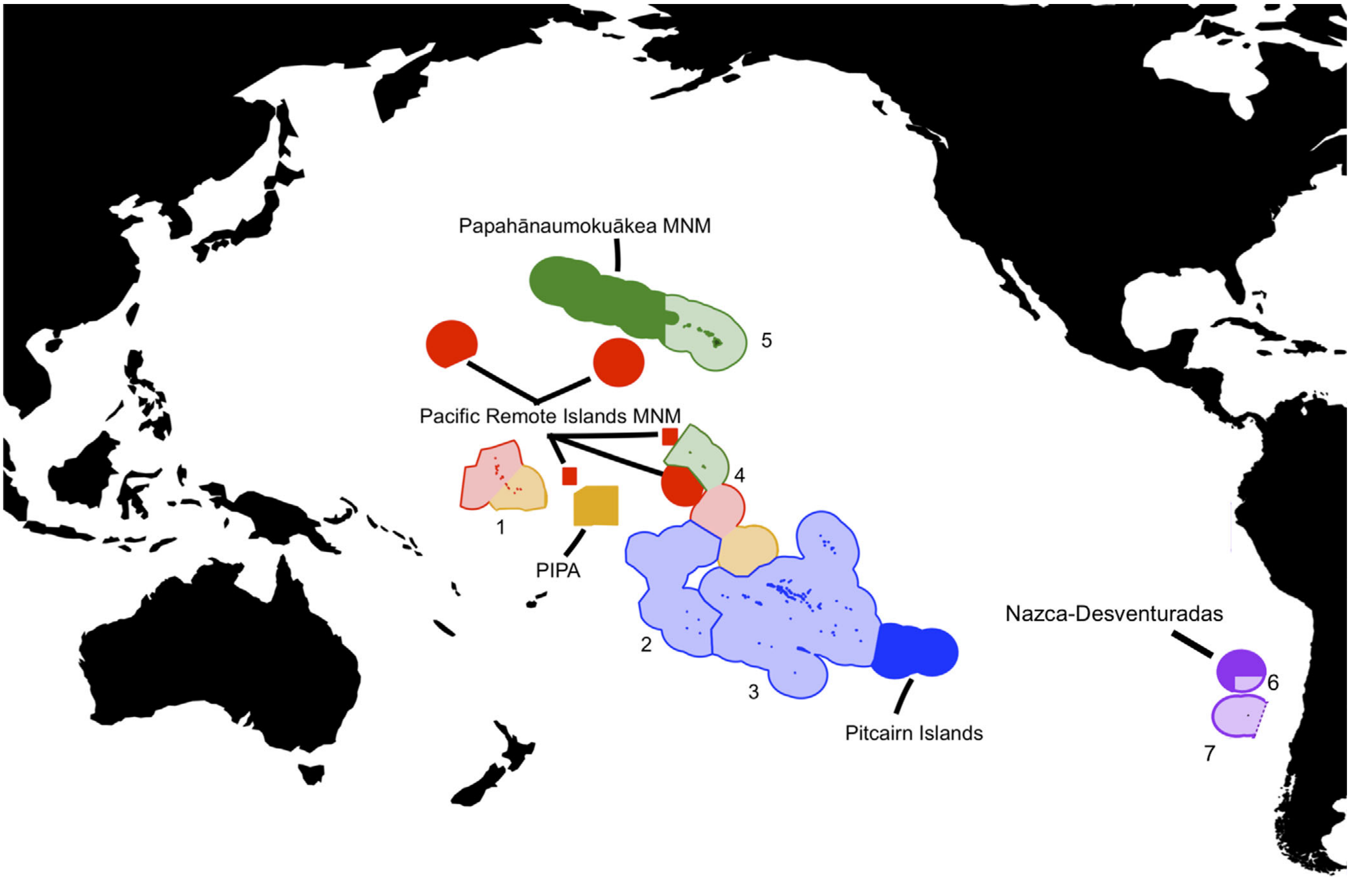

Figure 1. Five large marine protected areas (MPAs) (opaque colors) and associated control sites that permitted fishing during the study period (transparent colors) used for comparative analyses of fishing effort (yellow, Phoenix Islands Protected Area; green, Papahānaumokuākea Marine National Monument; blue, Pitcairn Islands Marine Reserve; red, Pacific Remote Islands Marine National Monument; purple, Nazca-Desventuradas Marine Park; control exclusive economic zones that allow fishing: 1, Kiribati, Gilbert Islands; 2, Cook Islands, 3, French Polynesia; 4, Kiribati, Line Islands; 5, United States, Hawaii; 6, Chile, San Felix and San Ambrosio Islands; 7, Chile, Juan Fernandez Islands).

ongoing discussions over the value of large MPAs in protecting marine biodiversity.

Methods

Study Area

We analyzed fishing effort near large MPAs that fit 4 criteria: no-take MPAs (i.e., all industrial fishing prohibited); MPAs $>$100,000 km^2 (Friedlander et al. 2016; McCauley et al. 2016); MPAs in national waters; and MPAs implemented from 1 January 2013 to 1 January 2017. This date range was chosen to ensure sufficient coverage of our data set of industrial fishing effort (Kroodsma et al. 2018). These criteria resulted in the selection of 5 focal MPAs located in the Pacific Ocean (Fig. 1), out of approximately 10 fully protected large MPAs in this basin (O'Leary et al. 2018). We focused on national waters because all large, no-take MPAs except 1 (the Ross Sea Region Marine Protected Area) have been established in national waters, so we avoided generalizing international MPAs based on this lone case. The processes and policies that govern the creation of large MPAs in international waters are rapidly evolving and may be subject to ongoing negotiations at the United Nations, although they will likely be drastically different from those governing MPAs in national waters (Visalli et al. 2020).

Industrial Fishing Effort

We analyzed satellite detections of industrial fishing vessels to assess their response to newly created large MPAs. We accessed the Global Fishing Watch data set, which uses convolutional neural networks and AIS detections to identify global fishing effort (Kroodsma et al. 2018). The convolutional neural network uses characteristics of vessel tracks (e.g. speed, course) to identify fishing effort with $>$90% accuracy (Kroodsma et al. 2018).

Table 1. The year that no-take fishing restrictions were implemented, total area, and establishing country for each of the 5 large marine protected areas included in this study.

Marine protected area	*Year restrictions implemented*	*Total area (km^2)*	*Country*
Nazca-Desventuradas Marine Park	2016	300,035	Chile
Pacific Remote Islands Marine National Monument	2009, expanded 2014	1,271,526	United States
Papahānaumokuākea Marine National Monument	2006, expanded 2016	1,508,737	United States
Pitcairn Islands Marine Reserve	2016	836,064	United Kingdom
Phoenix Islands Protected Area	2015	408,225	Kiribati

Approximately 50-75% of active fishing vessels larger than 24 m transmit AIS signals (Kroodsma et al. 2018).

We analyzed the tracks of all detected fishing vessels that entered a bounding box extending 1° beyond either each large MPA boundary or its encompassing EEZ. We extended our maps 1° beyond the relevant boundary for plotting purposes so boundaries would not overlap with map edges. To identify spatial changes in fishing effort following MPA implementation, we created maps of annual fishing effort for 1 year before and 1 year after fishing restrictions took effect (Table 1). This 2-year window was selected to balance study duration and sample size of total MPAs that could be included in this study (i.e., requiring a longer time series would extend beyond our available AIS data for some MPAs, thus excluding them) (see Supporting Information for longer term, 4-year trends). We calculated total monthly fishing effort in MPA boundaries over this 2-year window. We also calculated the difference in annual fishing hours, defined as the elapsed time between positions identified as fishing, for each 0.5° grid cell in our study region. The GPS-resolution vessel tracks were used to determine whether vessels were inside or outside MPAs, as opposed to gridded rasters. Therefore, the 0.5° resolution we selected for visual purposes did not influence estimates of fishing inside MPA boundaries. To test for statistically significant changes in total fishing effort after MPA implementation, we conducted a permutation test on time series of monthly values. For each MPA, we randomly sampled each time series 10,000 times before and after MPA implementation and tested the null hypothesis that these distributions do not differ by calculating the probability that differences in mean values randomly occurred.

To partially control for trends in fishing effort not driven by protection status (e.g., remoteness, regional oceanography), we compared fishing activity detected in large MPAs with the 2 nearest Exclusive Economic Zones (EEZs) that permitted industrial fishing at the time of the comparison. We compared MPAs with nearby EEZs, as opposed to the high seas, because international waters have vastly different management structures than national waters (e.g., regional fisheries management organizations as opposed to national governments [Ban et al. 2014]), although we acknowledge that EEZs will also vary in terms of oceanography, AIS requirements, and management plans. We compared Nazca-Desventuradas Marine Park with oceanic portions of nearby EEZs, as opposed to the entirety of the nearby Chilean and Peruvian EEZs, because these were the only continental EEZs and included coastal fisheries not present in the oceanic MPAs. All other comparative EEZs and MPAs surrounded island ecosystems, so we excluded continental waters from the comparison with Nazca-Desventuradas Marine Park. The EEZ of the Republic of Kiribati is comprised of two fished zones and one protected zone; we compared the protected zone (the Phoenix Islands Protected Area) with the two fished zones (McDermott et al. 2018). We scaled total fishing hours by the total area of the MPA or EEZ to facilitate comparisons between polygons of differing sizes. We reran all analyses with unscaled data for comparison.

Results

Two primary results emerged from our analyses. First, detected fishing effort was exceptionally low in 4 out of 5 large MPAs before they received formal protection, especially relative to nearby regions that permit industrial fishing (Figs. 2 & 3). For 1 year prior to MPA designation, these vast expanses of ocean supported a mean of 11.9 fishing hours per month across these 4 study sites. In contrast, we detected up to 30,000 monthly fishing hours in control regions comprised of EEZs that permit fishing (Fig. 3 & Supporting Information). The Phoenix Islands Protected Area (PIPA) is the exception among these 5 MPAs because up to 15,000 monthly fishing hours were detected in the PIPA's future boundaries prior to MPA implementation.

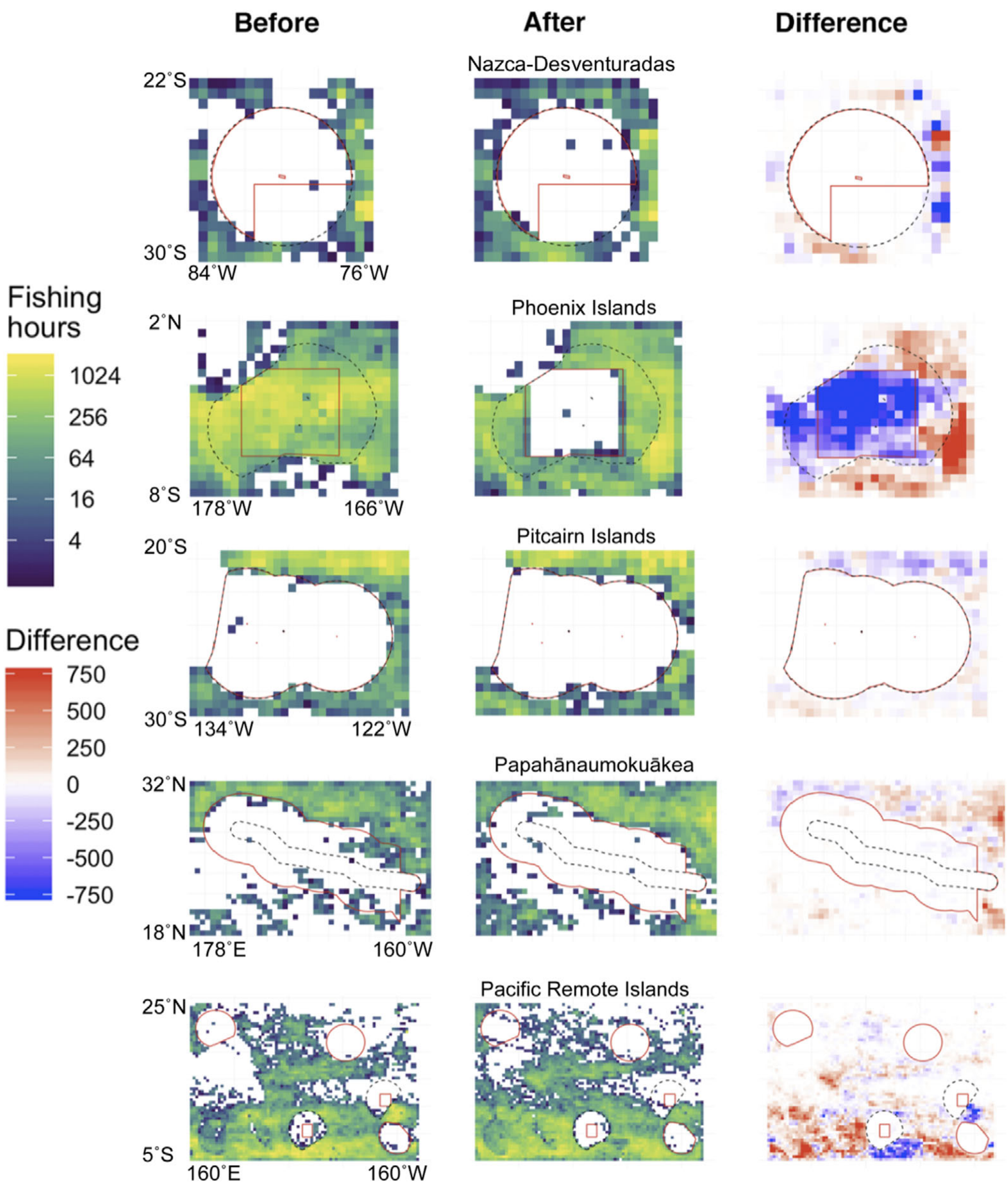

Figure 2. Cumulative, industrial fishing effort for 1 year before and 1 year after the establishment of 5 focal large marine protected areas (MPAs) and their difference (after minus before in units of fishing hours). Fishing effort and the difference in fishing effort between periods is measured in fishing hours, which is the cumulative amount of time all vessels fished in a grid cell as measured via vessel tracking. Maps extend 1° beyond MPA boundaries (solid red) or Exclusive Economic Zone boundaries (black dashes).

Second, we detected virtually no fishing effort in all 5 large MPAs once fishing restricted were implemented (Figs. 2 & 3). Statistically significant declines in fishing effort were detected at PIPA ($p < 0.001$) and Papahānaumokuākea Marine National Monument ($p = 0.002$), although the decline was far greater at PIPA (a decrease of 7715 monthly fishing hours) than Papahānaumokuākea (a decrease of 40 monthly fishing hours, from 40 to 0). Significant trends were not detected at the remaining 3 MPAs because observable fishing was consistently negligible throughout the study period. High levels of fishing effort were generally maintained throughout nearby control regions that did not ban industrial fishing (Fig. 3). These patterns were evident whether or not we scaled fishing hours by study area (Supporting Information).

Discussion

Using a recently developed data set on global fishing effort, we assessed the short-term response of industrial fishing fleets to the implementation of large MPAs in

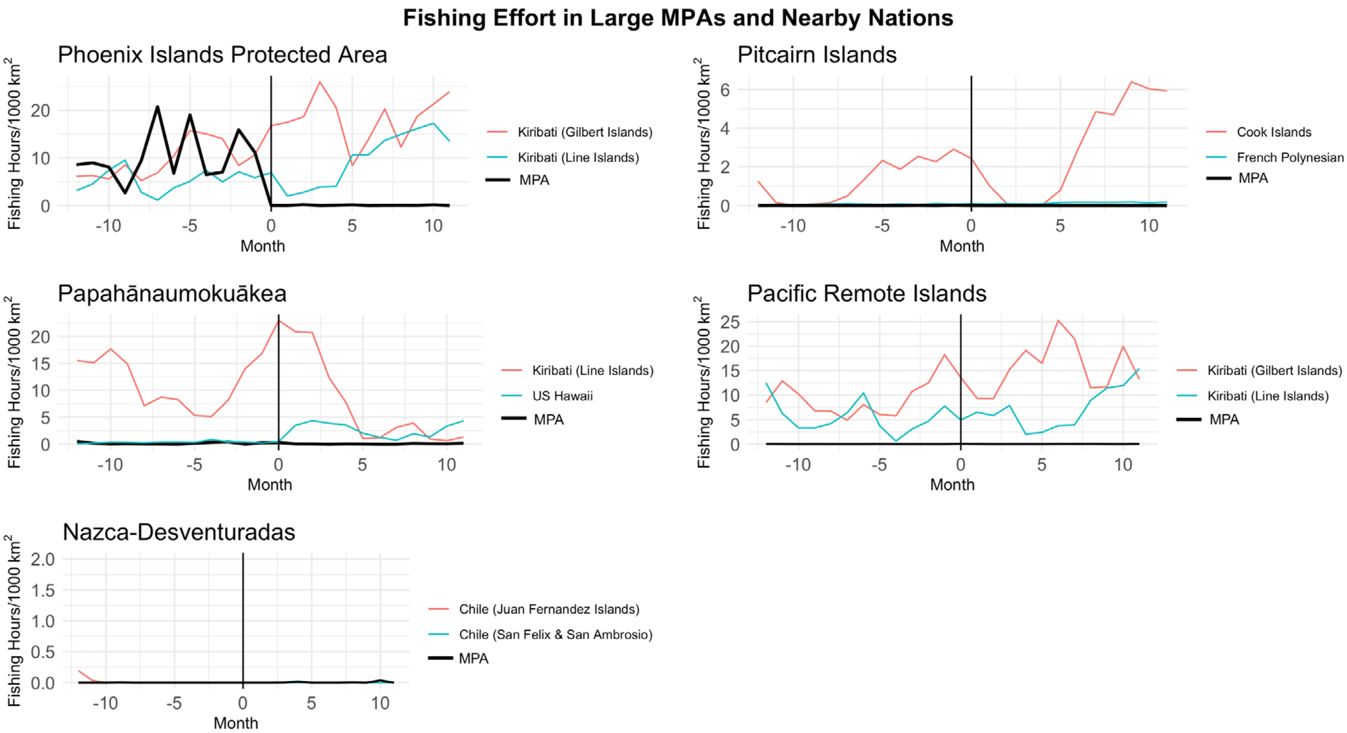

Figure 3. Monthly industrial fishing effort detected in 5 large marine protected areas (MPAs) (black lines) and in nearby Exclusive Economic Zones (EEZs) that permit fishing (colored lines). Fishing hours are scaled by the total area of the MPA or EEZ to facilitate comparisons between polygons of differing sizes.

the Pacific. Our results suggest that large MPAs can effectively maintain fishing effort at remarkably low levels. Virtually no fishing was detected inside all 5 of our focal large MPAs after they were implemented, whereas up to 30,000 monthly fishing hours were observed in nearby EEZs that permit fishing. The ability of large MPAs to restrict industrial fishing is frequently questioned due to concerns over the enforceability of fishing bans across vast, remote regions of the ocean (Magris & Pressey 2018). Our results suggest that most large industrial fishing vessels (because approximately 50-75% of vessels >24 m transmit AIS [Kroodsma et al. 2018]) do respect the boundaries of large MPAs.

With the exception of PIPA, regions where MPAs were placed experienced little fishing effort relative to surrounding areas prior to their formal protection. This indicates that several of the large MPAs considered here maintain low effort relative to surrounding regions, rather than significantly reducing fishing effort within their boundaries. A statistically significant decline in fishing effort was detected at PIPA and Papahānaumokuākea Marine National Monument, though the magnitude of decrease at Papahānaumokuākea (a 40-h reduction in mean monthly fishing hours) was far less than the approximately 7700 mean monthly decrease in fishing hour observed at PIPA. Opponents of large MPAs, or at least the placement of many large MPAs, argue that this allows countries to meet area-based commitments for ocean protection (e.g., Aichi Target 11) but does little to reduce anthropogenic stress on marine ecosystems. Supporters of large MPAs have contended that protecting regions of minimal impact attains conservation success at relatively low socioeconomic cost and impact on food production. They also suggest that that the full worth of these large MPAs as conservation tools may only be realized as the footprint of human activity expands in coming decades including fishing, marine mining, and marine energy (McCauley et al. 2015; Miller et al. 2018). We focused on industrial fishing fleets but acknowledge that large MPAs typically prohibit a broad suite of extractive activities.

Although explanations for the relative absence of fishing in these EEZs prior to MPA implementation may vary by nation and was not a specific focus of this study, this pattern may be partially understood by the international sale of fishing rights. Many Pacific island nations sell access to fishing grounds in their national waters to international fleets. These access fees can comprise over half of the gross domestic product (GDP) of island nations (Havice 2010), which may partially explain why high rates of fishing were observed in PIPA (in the waters of Kiribati) prior to fishing restrictions.

In contrast, the 4 MPAs with minimal initial fishing effort relative to surrounding regions are located in U.S., U.K., and Chilean waters. Unlike Kiribati, these nations prohibit or heavily restrict international fishing activity in their EEZs. International fishing fleets were not permitted to fish the U.S. EEZ before the establishment of the 2 U.S. MPAs considered here, though approximately 4-9% of Hawaii longline sets for bigeye tuna (*Thunnus obesus*) took place in Papahānaumokuākea Marine National Monument prior to MPA implementation and this fleet fished the Pacific Remote Islands Marine National Monument region as well (Lynham et al. 2020). Likewise, Chile prohibits fishing vessels with foreign flags from fishing their EEZ (SUBPESCA 2019), and the Pitcairn Islands, a U.K. Overseas Territory, have generally not issued permits to international fleets in recent decades (Irving & Dawson 2012). Because the GDPs of these 3 nations are each several orders of magnitude greater than that of Kiribati, the annual revenue gained by selling fishing rights (approximately $125 million annually for Kiribati [Villaseñor-Derbez et al. 2020]) may be less important than geopolitical goals, national fishing industry considerations, or environmental costs. Taken together, these regulations and patterns of fishing suggest that waters of these nations received a form of partial protection prior to their implementation as no-take MPAs. Examination of fishing effort outside the boundaries of some large MPAs supports this hypothesis. Significant fishing effort was present outside most MPA boundaries considered here prior to formal establishment. This suggests there may have been fishing effort inside these regions if not for the partial protection afforded by EEZs and large MPAs are not necessarily established in low-quality fishing grounds because the presence of nearby fishing suggests that target species are present, although further investigation is needed to support this hypothesis. Results of prior analyses suggest that fishing grounds outside Papahānaumokuākea Marine National Monument were at least as productive as those in the MPA (Lynham et al. 2020), so it remains challenging to disentangle oceanographic, biological, economic, and policy-related drivers. Combining vessel tracking with species distribution models and animal tracking data sets may help determine whether reductions in fishing at this scale may decrease overlap with threatened species (White et al. 2019). Additional data sets on catch and effort may help determine whether fishing-the-line behavior, where vessels fish near MPA boundaries, are related to MPA creation, prior EEZ designations, or other factors (Villaseñor-Derbez et al. 2020).

Analysis of AIS has dramatically increased capabilities to observe the near-real-time effects of spatial management actions on industrial fishing fleets; 50-75% of large industrial vessels transmit AIS (Kroodsma et al. 2018). The global use of AIS appears highest in the Pacific region (Sala et al. 2018). However, we caution that fishing activity not captured by AIS or undetected illegal, unreported, and unregulated (IUU) fishing, if occurring undetected at a high rate, could have a substantial impact on the effectiveness of large MPAs. Complementary technologies are being explored to improve remote detection of IUU and vessels that lack AIS, ranging from additional satellite data sets (e.g., Synthetic Aperture Radar) to "animal sentinels" equipped with loggers that detect vessels (Weimerskirch et al. 2020).

The continued expansion of publicly available, high-resolution data sets on extractive activities in oceans can help determine whether intervention actions lead to desired outcomes. Insight from these new data can help provide direct empirical evidence that can be used to address several key points of debate around large MPAs. Given the vast areas of the ocean being shaped by the establishment of large MPAs and the large scale and rapid increase of human impact of the global oceans (Halpern et al. 2019), it is critically important that the best available data be used to inform where and how to best use this marine management tool to positively influence marine biodiversity now and in the future.

Acknowledgments

We thank Global Fishing Watch for facilitating remote sensing of fishing effort. We acknowledge support by the National Science Foundation's Graduate Research Fellowship Program (DGE-114747), the National Science Foundation's grant 1736830, NSF NOAA's Graduate Research Internship Program, the Bertarelli Foundation, the Betty and Gordon Moore Foundation, and the Benioff Ocean Initiative.

Supporting Information

Figure S1. Monthly fishing hours observed for 4 years at "control" exclusive economic zones (EEZs) that permit fishing. Fishing hours are scaled by the area of that corresponding EEZ. Open circles at the top of the figure indicate the date of large MPA establishment for reference. PRI = Pacific Remote Islands Marine National Monument, PIPA = Phoenix Islands Protected Area, and PNM = Papahānaumokuākea Marine National Monument.

Figure S2. Monthly industrial fishing effort detected within 30 large MPAs (black lines) and nearby Exclusive Economic Zones (EEZs) that permit fishing (colored lines). Fishing hours are not scaled by the total area of the MPA or EEZ, as they are in Figure 3. All conclusions hold whether or not fishing hours are scaled by area; virtually no fishing is detected within all MPAs after establishment while significant fishing is detected within nearby EEZs, suggesting that low effort in large MPAs is not merely driven by remoteness. Minimal fishing effort is detected in most MPAs prior to establishment. Only the Phoenix Islands Protected Area had notable, initial fishing effort.

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