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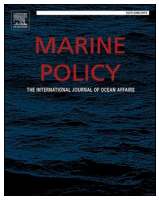

Industrial fishing compliance with a new marine corridor near the Galapagos Islands

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ABSTRACT

Quantifying fishing pressure in under-resourced marine regions remains a challenge to understanding the patterns and impacts of fishing. These issues are compounded in areas with complex marine zoning regulations or those that have changed over time. Here, we use satellite-based fishing vessel positioning to study industrial fishing effort in within Ecuador's Insular Exclusive Economic Zone (I-EEZ), which includes areas open to all fishing, the Galapagos Marine Reserve (GMR) and the newly-established Hermandad Marine Reserve (HMR). From 2019–2023, we identified 145 large, industrial (non-artisanal) fishing vessels (910 gross tonnage on average) from 10 countries fishing within the I-EEZ outside the GMR. Eighty-seven percent of the fishing effort was accounted for by Ecuadorian vessels using tuna purse seines and drifting longlines in equal proportions, while the effort of foreign vessels was accounted for by tuna purse seines. In this time window, we observed 64,626 h of fishing within the I-EEZ. In addition, we studied the effect of a newly declared marine protected area (MPA) in 2022, known as the Hermandad Marine Reserve, which created an additional 60,000 square kilometers of protected area. We documented an 88 % decrease in fishing effort within the Hermandad Marine Reserve after its implementation. Collectively, our results highlight the wide range of fishing activities within and around the HMR marine protected area, especially for migratory marine megafauna.

1. Introduction

Marine protected areas (MPAs) are regions where some level of protection, at least on paper, is offered to an area [14,30,31,43]. There is a large variation in MPA formats, and how they are defined, implemented, and governed, with some completely open to industrial activities and others completely closed to human use [20]. The IUCN defines a protected area as "A clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" [20,48]. Most protected areas fall in the middle of this definition with a mix of human use allowed within marine protected areas [5,19,35]. However, there is often a lack of baseline data and continuous monitoring to examine how fishing or ecosystems respond to new marine management restrictions (G. J. [24,29,13]).

Satellite-based vessel positioning data is useful in improving vessel safety and understanding patterns of trade, tourism, and industrial fishing [3,45]. Data from Automatic Identification Systems (AIS) or Vessel Monitoring Systems (VMS) provides real-time positioning information of vessels across the world [12,22,56]. Data from AIS and VMS combined with ground-truthed machine learning algorithms, can also be used to understand vessel behavior, including the type of fishing being conducted [18,32,34,47]. In turn, satellite-derived estimates of fishing effort have been important for understanding fishing activity across the globe, especially for areas or fleets with limited catch data (T. D. [54]; E. R. [51]). Satellite-derived fishing effort data has been used to understand encroachment into marine protected areas, determine predictors of fishing effort (e.g., oil costs), and help nations with limited enforcement capability monitor their national sovereignty ([34]; T. D. [54]; E. R. [51]). Past work has also shown that fishing effort can increase with the announcement of a new MPA [37]. After MPA implementation, fishing effort may remain the same, increase, decrease, or be displaced

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to a different area [6,10,11,22,54].

To address these knowledge gaps on mixed-use marine areas and regions where new protected areas have recently been established, we studied industrial fishing activity within Ecuador's Insular Exclusive Economic Zone (I-EEZ), which includes areas open to all fishing, the Galapagos Marine Reserve (GMR) and the newly-established (in 2022) Hermandad Marine Reserve (HMR). The Galapagos Islands are also positioned within the larger regional context of the Eastern Tropical Pacific Marine Corridor, a multi-country marine area home to important migratory species and fishing [23,25,39,53,44]. Ecuador's national fishing law and fishing regulation recognize two levels of fishing vessel scale: industrial and artisanal fishing. Industrial fishing is defined as extractive activity carried out by vessels with hydraulic, mechanized fishing that allow the capture of hydrobiological resources as well as the size of vessels allowing for the storage of large quantities of fish [27]. Artisanal fishing is defined as fishing and harvesting activity that is carried out individually, autonomously, or collectively, by men or women, family groups or communities, coastal, riverside, inland and island waters, predominantly carried out manually, to improve their quality of life and contribute to food security, with or without the use of an artisanal vessel (Cochrane and Garcia 2009; FAO 2014).

The GMR is a 138,000 km^2 area that encircles the Galapagos Islands from the archipelago baseline to 40 miles toward the open sea (Fig. 1, [21,1]). The GMR is a mixed-use MPA that regulates several uses such as artisanal fishing, tourism activities and research using a zoning scheme to ensure the conservation of the habitats and biodiversity ([21]; 2016). In 2017, the fishing vessel Fu Yuan Yu Leng 999, flying a Chinese flag, was detained while crossing through the GMR. The vessel contained over 7500 individual sharks [8]. This incident spurred local organizing and the then-Ecuadorian president to commit to expanding the GMR at COP25 in Madrid, Spain. In 2020, a task force was established to facilitate discussions among stakeholders. The Ecuadorian government declared a new MPA in January 2022, the Hermandad Marine Reserve (HMR) of 60,000 km^2, to protect marine ecosystems and their species, especially migratory megafauna [2]. The HMR extends from the northeastern area of the GMR to the maritime border with Costa Rica, covering an area of ocean where movements of Critically Endangered species such as leatherback turtles (*Dermochelys coriacea*) and scalloped hammerhead sharks (*Sphyrna lewini*) have been documented [33]. The HMR has a core no-take zone covering 30,000 km^2, surrounded by zones where longline gear is not permitted totaling a further 30,000 km^2.

After the creation of the GMR in 1998, industrial fishing within its boundaries initially increased, due to a combination of limited enforcement capabilities and delays in the approval of the management plan [9]. Given that the management plan for the HMR was not approved until March 2023 ([38]Ministerio de Ambiente, Agua y Transición Ecológica 2023), and therefore no resources were allocated prior to this date to control and enforcement, we hypothesized that a similar situation to the GMR with increased fishing activity during this first phase of implementation of the MPA may have occurred inside the HMR.

In this study, we use satellite-derived estimates of fishing effort from Global Fishing Watch to examine patterns of industrial fishing (only large vessels $>$ 100 tons) around the Galapagos Marine Reserve. We focus our analyses on fishing patterns within the I-EEZ outside the GMR. We use these data to address three questions: 1) how does fishing effort vary in differently-zoned regions?; 2) how does fishing by different gear types vary spatially; 3) how did fishing fleet behavior change, both across the I-EEZ and with the HMR, before and after the 2022 announcement of the new Hermandad Marine Reserve?

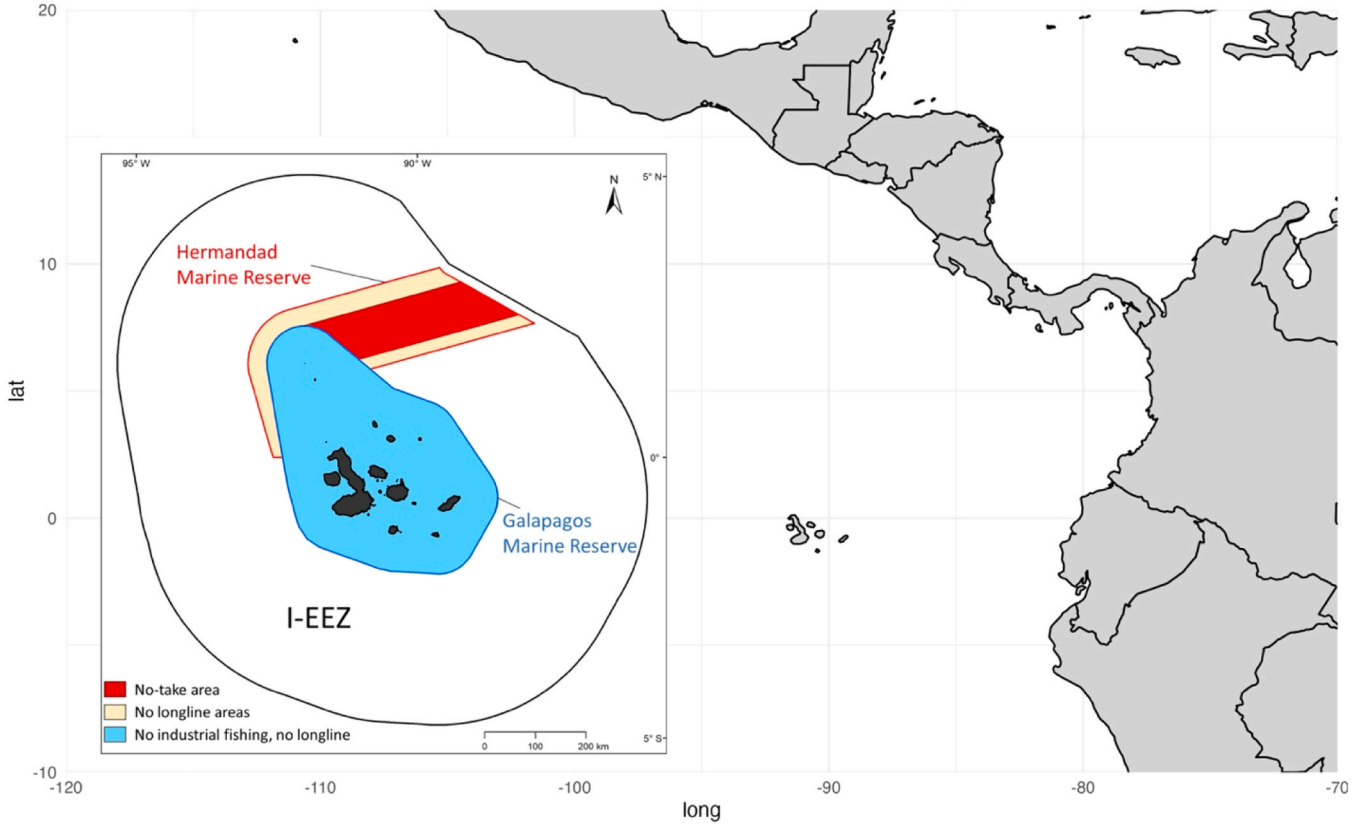

Fig. 1. Map of the Eastern Tropical Pacific with inset map of study area showing the Hermandad Marine Reserve (red contour), with no-take areas (red) and no-longline areas (light orange); the Galapagos Marine Reserve (blue contour), where no industrial fishing nor longline are allowed; and the Ecuadorian Insular Exclusive Economic Zone(I-EEZ) with a black contour.

2. Methods

2.1. Dataset

We used data from the international nonprofit organization Global Fishing Watch (GFW) from January 2019 to August 2023. Global Fishing Watch uses vessel movement data from Automatic Identification System (AIS) transmissions and a set of machine learning approaches to distinguish general vessel movement from different types of fishing [34]. The resulting records include information on the daily fishing effort, in terms of hours spent actively fishing (e.g., setting and hauling gear as opposed to being in transit), in a perimeter gridded by 0.1 ° of longitude and latitude, flag state, gear type, and additional vessel information (e.g., size, registration) [34]. The data only include larger (usually greater than 20 m) vessels. Details on this dataset are found in [34] and on the Global Fishing Watch website (https://globalfishingwatch.org/).

We removed the limited subset of vessels from the GMR artisanal fleet. Currently, this artisanal fleet is not well represented in the Global Fishing Watch dataset since the algorithms are not currently designed for these fleets. Thus, we only studied industrial fishing vessels (>100 tons), which primarily fish outside the GMR given strong enforcement.

We subsetted the Global Fishing Watch fishing effort data for the Insular Exclusive Economic Zone of Ecuador (I-EEZ, i.e., Ecuador's EEZ around the Galapagos Islands), which includes the GMR, and the newer HMR (Fig. 1).

2.2. Analyses

We ran two iterations of a generalized linear model (GLM) with a Poisson error distribution to examine trends in industrial fishing effort over time. First, we used pre-HMR data to project the counterfactual for effort if a reserve was not implemented. Given the limited pre-HMR data (two full years), we approached the modeling cautiously, emphasizing its exploratory nature rather than definitive prediction. To account for seasonality, we included sine and cosine terms for month, using year and month as covariates. We fitted the model to pre-2022 fishing effort data and projected effort for 2022 and 2023, comparing actual fishing effort with these projections to assess potential effects of HMR. We ran separate models for each gear type in these projections. Second, we reran the model to include all years of data to study how seasonality, gear type, and year each explained fishing effort. With both versions of the model, assumptions were verified through residual plot inspections, and we confirmed covariates were not significantly correlated (>0.7) and residuals were not overdispersed.

3. Results

Across the entire I-EEZ outside the GMR, we documented 64,626 h of fishing by 145 unique vessels between 2019 and 2022 (Figs. 2,3, Table S1). Most (92.3 % of hours) of this fishing effort was by Ecuadorian vessels (n = 80 vessels; 59,629 h) from the mainland, but we also observed fishing effort by vessels from Panama (n = 11 vessels; 2776 hours), Venezuela (n = 7 vessels; 1830 hours), Great Britain (n = 1 vessel; 184 h), the USA (n = 4 vessels; 118 h), and limited effort by other countries (Figs. S1). Total fishing hours by Ecuadorian vessels was split between tuna purse seines (46.6 %) and drifting longlines (48.2 %) whereas 99 % of fishing effort by foreign vessels was tuna purse seining (Table S2, Fig. S2). The patterns were similar when examining the number of vessels over time instead of effort (Fig. S3). Effort by longliners was more sporadic time, while tuna purse seine effort peaked in 2021 and has a more strongly seasonal pattern (Fig. 3). Fishing effort was concentrated in the Southwest and Northern parts of the I-EEZ (Figs. 3, S4). Less than 1 % of the total fishing effort by the large vessels studied here occurred within the GMR (Figs. S5-S7).

The HMR was officially declared on January 14th, 2022. Almost all of the fishing within the HMR prior to its implementation was drifting longlines or tuna purse seines (Figs. 4,5). In 2021, only 8 % of the fishing within the I-EEZ was within the HMR area. There was an 88 % decrease in fishing effort within the HMR after its implementation at the start of 2022 (Table S3). While accounting for seasonality, year (β=0.48,

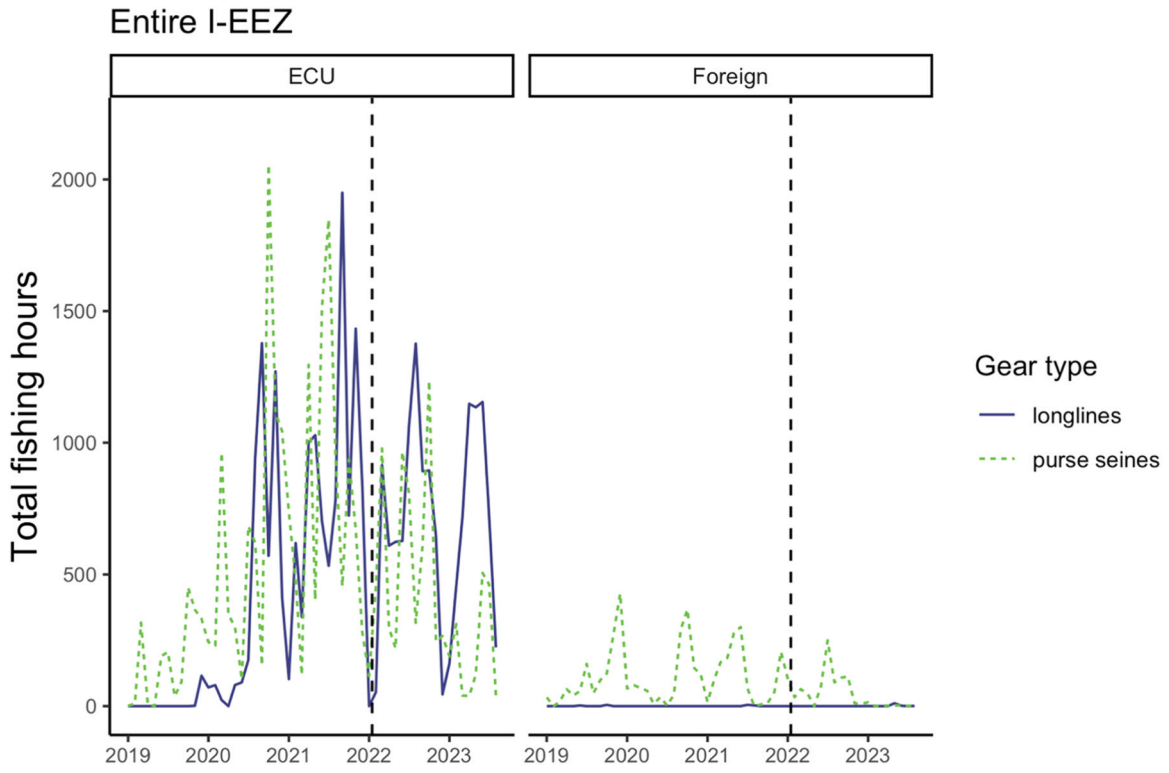

Fig. 2. Total monthly industrial fishing effort (hours) in the Ecuadorian Insular Exclusive Economic Zone (I-EEZ) for different gear types for the Ecuadorian versus all foreign fleets. The vertical dashed line indicates the announcement of the new Hermandad Marine Reserve (which is 10 % of the entire I-EEZ by size).

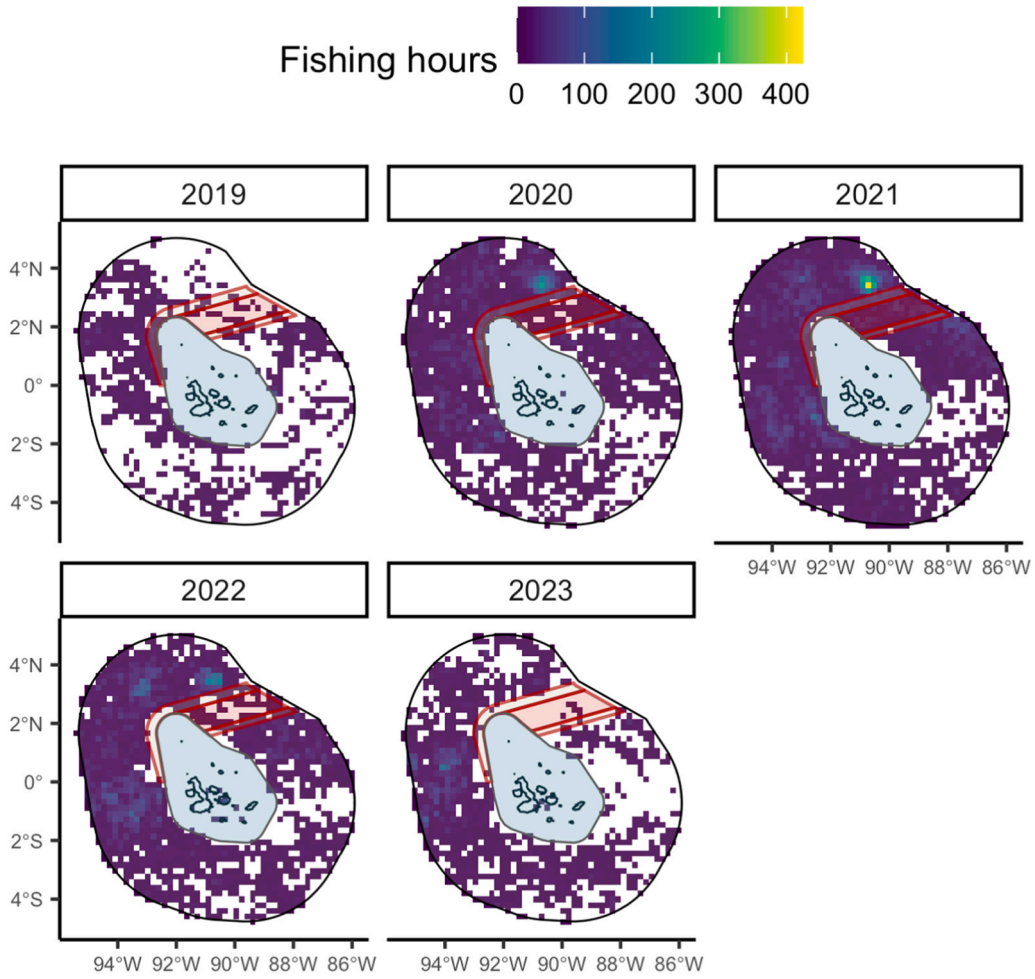

Fig. 3. Spatial distribution of total annual industrial fishing effort in the Ecuadorian Insular Exclusive Economic Zone (I-EEZ) over time. Non-colored cells indicate no recorded fishing activity. 2023 includes only Jan-Aug data.

$p < 0.0001$) and purse seines relative to longlines (β=4.85, $p < 0.0001$) were significant. This effort doesn't appear to have shifted visually elsewhere as total fishing effort in the I-EEZ in 2022 was 23 % less than in 2021. In addition, any remaining fishing effort in 2022 was by Ecuadorian vessels as opposed to foreign boats (Figs. S8, S9, Table S4). In addition, the remaining fishing effort was mostly purse seines and not drifting longlines (Table S5). Fishing effort appeared to decrease outside, but near, the HMR as well (Fig. 3). From 2020–2021, there was a 73 % increase in fishing effort in the region of the future HMR compared to only a 56 % increase in the rest of the I-EEZ. Thus, it is possible that fishing effort increased in the area as it was being proposed.

4. Discussion

Our findings for the newly declared HMR share some similarities, but also stark differences, with past studies on the implementation of no-take areas. Previous work has noted that fishing effort can increase within a protected area when it has been announced, but not yet implemented, and this was indeed the case with the GMR [9]. In line with this past work, we found some evidence of a small increase in fishing effort within the HMR prior to the reserve declaration (Fig. 4). There was a 73 % increase within the HMR (compared to 56 % in the I-EEZ as a whole) in the year prior to its implementation. The increase could be related to the general planning process and anticipation by fishing operations of an upcoming protected area. Similar patterns were observed in the lead up to the Phoenix Islands Protected Area in Kiribati [37].

We also documented an 88 % decrease in fishing effort within the HMR protected area after its declaration at the start of 2022. The dramatic decrease was unexpected as there were no corresponding increases in enforcement. Instead, we suggest it is possible that the well-publicized announcement of the marine protected area near a well-known existing marine reserve was sufficient to deter fishing pressure. We do not know of cases of this phenomenon elsewhere. Additionally, it has been demonstrated that areas along the western GMR boundary receive 4 times more fishing effort density than surrounding areas [7]. Thus, the HMR region was more feasible to be closed to fishing than other areas of the I-EEZ. Fishing effort did not appear to have shifted elsewhere inside I-EEZ after the declaration of the HMR. Instead, total fishing effort in the I-EEZ in 2022 was less than in 2021 and there was no visual increase in "fishing along the line" around the reserve (Fig. 4). In addition, the limited remaining fishing effort in 2022 was by Ecuadorian vessels as opposed to foreign boats (Figs. S8-S9). We suggest that these findings regarding the no-take HMR conflicting with past work [9] may be the result of several factors: the worldwide spotlight on the Galapagos Islands, the heavily managed nature of the region [25], and the distribution of fishing efforts within the protected region and in other areas of the I-EEZ prior to implementation of the HMR (in 2021, only 8 % of the fishing in the I-EEZ was within the HMR). In addition, there were three years of meetings and consensus-building between stakeholders prior to the Hermandad Marine Reserve MPA declaration [33]. Additionally, throughout the duration of the study period, the Ecuadorian purse seine and longline fleets were participating in a Fisheries Improvement Project, to obtain a Marine Stewardship Council (MSC) Blue Fish Label (see

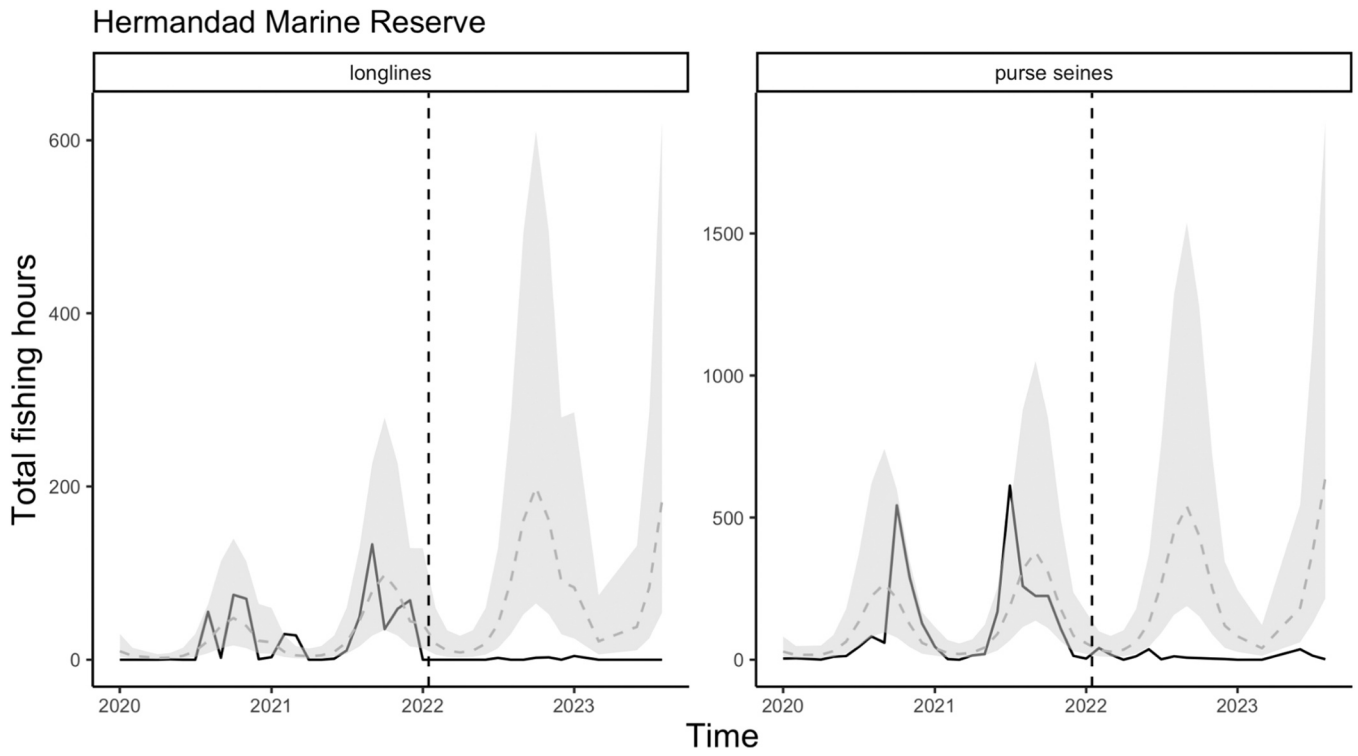

Fig. 4. Total monthly industrial fishing effort (hours) in the area of the Hermandad Marine Reserve for different gear types. The vertical dashed line indicates the announcement of the new Hermandad Marine Reserve. The fitted lighter curve indicates the line of best fit for pre-closure data projected after the closure with one standard deviation around the mean prediction.

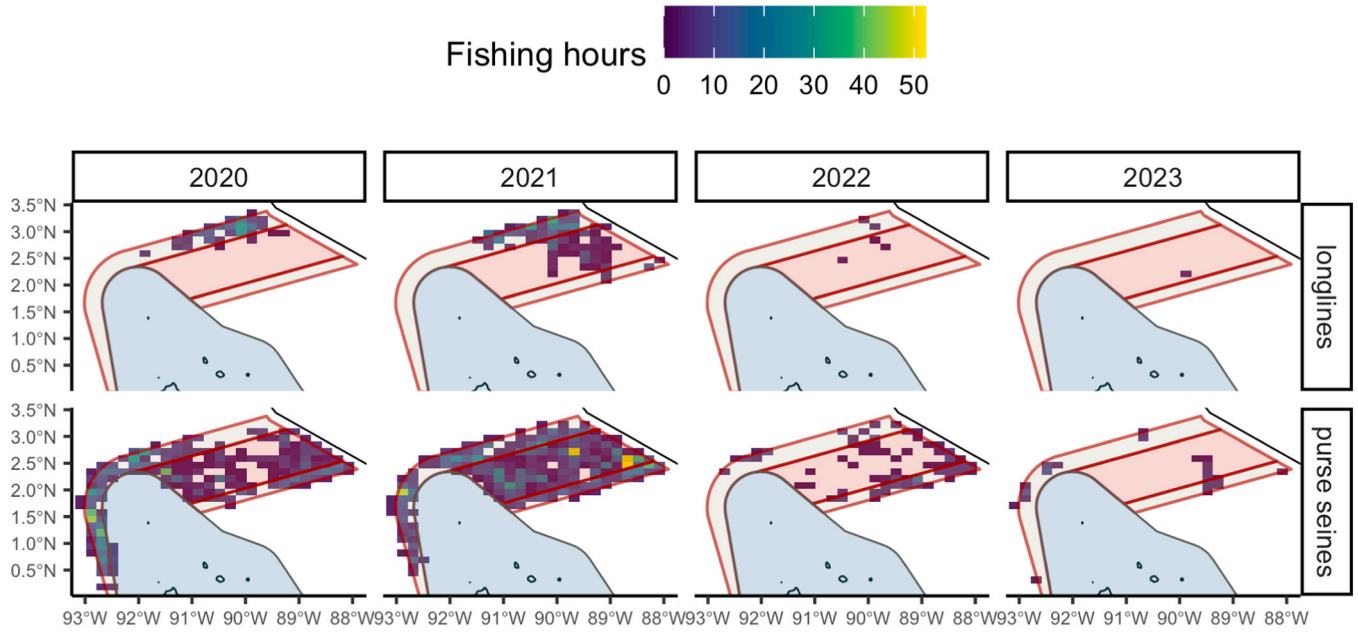

Fig. 5. Total yearly industrial fishing effort (hours) in the area of the Hermandad Marine Reserve for different gear types. The reserve was announced at the start of 2022.

https://www.msc.org/en-us) as a response to the European Commission's issuance of a yellow card for illegal, unreported, and unregulated (IUU) fishing in Ecuador [26]. While participating in this Fisheries Improvement Project, there was likely a focus on eliminating or limiting IUU fishing. The Fisheries Improvement Project is ongoing and is scheduled to conclude in 2026. Our findings would thus support the EU carding system approach to incentivizing non-IUU fishing in Ecuador [46] and, for the first time, its positive impact on compliance with fishing regulations in a recently established marine protected area. In addition, management actions taken by other countries and the COVID-19 pandemic may have affected our results. For example, Panama a new set of fishing laws that clarify rules around licenses, rules for domestic and international vessels, and more [40]. The COVID-19 pandemic, and associate lockdowns, also changed global fishing pressures, with direct health implications for seafood workers [51], decreases in seafood demand in many places [49,52], and increases in

illegal fishing activities [17,41]. In general, more work is needed to investigate how these types of external factors affect the dynamics of fishing in the I-EEZ, including the HMR.

Our analyses centered only on I-EEZ outside the GMR, but including HMR. Future work could examine the broader context of the Eastern Tropical Pacific Marine Corridor, including the exclusive economic zones of other countries and international waters [25], especially, as new MPAs are established in the region. One of the most important sources of fishing pressure in the ETP region is the large presence of squid jigging vessels from nearby and distant countries [36]. Although this new MPA may capture much of the legal fishing (e.g., yellowfin tuna *Thunnus albacares* and Mahi-mahi *Coryphaena hippurus* fisheries) within the Insular Exclusive Economic Zone of Ecuador, our analyses do not account for smaller artisanal vessels. In the supplementary material, we show there were 15 industrial vessels fishing within the GMR compared to 188 active vessels in the Galapagos artisanal fleet [28,42], but more work is needed to understand the interactions between industrial and artisanal fishing.

Our analyses did not address issues related to illegal fishing activity from distant-water fishing fleets that may have disabled their AIS systems, but past work has noted this occurring in our study area [50]. We also were not able to determine long-term trends of fishing effort within the region. Many vessels we examined have only been included in the data recently, limiting our ability to determine if changes in effort over time are real or simply from the inclusion of more vessels. Future work could also study how catch varies spatially and over time as it may differ than fishing effort. Future work would need to assess whether the initial trend of compliance with the newly created Hermandad Marine Reserve is maintained over time. Future work could also examine ecological outcomes from the changing patterns in fishing effort. Recent work has highlighted the possibility of connecting satellite-based measures of fishing effort to actual catch [55,10] which will allow for mapping of catches, and a more thorough understanding of the fishing patterns and potential conservation consequences. Additional fisheries independent surveys in the region could also address the ecosystem-level questions. Our work also highlights that incorporating social factors, by involving many stakeholders into marine spatial planning [15,16,4], may also improve management outcomes, but further work is needed in this area.

5. Conclusions

In line with work in other MPAs, there was a small increase in fishing effort in anticipation of the HMR being announced. However, there was an 88 % drop in fishing effort in the year after the HMR's announcement despite no concurrent increase in enforcement. This unprecedented compliance with a new marine protected area points to the potential importance of a consensus-building approach between scientists, government officials, and fishers. In addition, existing well-enforced marine protected areas in the region, e.g., the GMR, may have had a carry-over effect in driving high compliance. Our work also highlights the importance of satellite-based estimates of fishing effort in regions where other proxies are not available or there is a concern regarding IUU fishing.

CRediT authorship contribution statement

César Viteri-Mejía: Writing – original draft, Writing – review & editing. **Julia Saltzman:** Writing – original draft, Writing – review & editing, Visualization. **Jorge Ramírez-González:** Writing – review & editing, Writing – original draft. **Nicolas Moity:** Writing – original draft, Software, Writing – review & editing, Visualization. **Alex Hearn:** Writing – review & editing, Writing – original draft. **Easton R. White:** Writing – original draft, Software, Validation, Resources, Investigation, Visualization, Supervision, Data curation, Writing – review & editing, Methodology, Formal analysis, Project administration, Funding acquisition, Conceptualization. **María José Barragán-Paladines:** Conceptualization, Writing – original draft, Writing – review & editing. **Sarah Enright:** Writing – original draft, Writing – review & editing.

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Data and code availability

All data used in this paper is publicly available via the Global Fishing Watch website. We also include code and data used in this project at https://github.com/QuantMarineEcoLab/hermandad-galapagos-fishing

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2025.106968.

Data availability

All data is available directly from Global Fishing Watch. We provide code for our analyses at https://github.com/QuantMarineEcoLab/hermandad-galapagos-fishing

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