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Supplementary Information for

Trade-offs between bycatch and target catches in static versus dynamic fishery closures.

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- Supplementary text
- Figures S1 to S17
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Other supplementary materials for this manuscript include the following:

R Code available at: https://github.com/maitepons/MPA_tool

Supplementary Information Text

A diagram describing the factorial design used in the methodology of the paper is presented in Fig. S1. In addition, in Fig. S2 we show the results of the relative changes of bycatch, target catch and effort for the 3 different minimization approaches used. The one presented in the main manuscript is the one that minimizes the ratio Bycatch/Target.

Case studies descriptions

1. Alaskan Eastern Bering Sea Pollock

Walleye pollock (*Gadus chalcogrammus*) in Alaska represents the largest fishery in the United States with annual average landings of ~ 1.2 million metric tons. Targeted using midwater, or pelagic, trawl gear, the eastern Bering Sea fishery (U.S. EEZ only) is consistently valued at more than $1 billion USD (first wholesale) (1). While the fishery is considered to have low bycatch overall, Chinook and chum salmon are designated as prohibited species catches in Alaska groundfish fisheries and have led to closures and bycatch-specific regulations in the pollock fishery (2–4). Major regulatory changes to the groundfish fishery management plans have included abundance-based Chinook salmon quotas (i.e., bycatch quotas are lower in years with lower salmon abundance) and the formation of cooperatives, which include a suite of incentive measures designed to avoid and reduce salmon bycatch. Some of the mechanisms used by these cooperatives include transferable vessel-level Chinook quotas, penalties for higher bycatch rates at the end of the season, and rollover bycatch credits for low salmon catches. One additional avoidance mechanism is an industry-managed voluntary rolling hotspot closure system where catches of salmon are communicated among vessels and small spatial closures (typically ~ one week or less, although the same area will be left closed for longer periods) seek to redistribute effort away from hotspots. The fishery has 100% observer coverage (from which this study's data originated) and since 2011, annual Chinook salmon prohibited species catches (bycatch) have typically been on the order of low tens of thousands while chum salmon are on the order of low hundreds of thousands. Chinook salmon are a choke species with strict quotas that can lead to fishery closures. No such quotas exist for chum salmon.

We explored several different weighting options for Chinook and chum salmon in our analyses. Intuitively, as regulation has targeted Chinook salmon avoidance over chum salmon, one could argue for a greater weight for Chinook salmon. However, the seasonality of salmon bycatch led us to present equal weights because the timing of catches for Chinook and chum salmon are largely different. Typically, higher Chinook bycatch occurs during the winter and late summer / fall months while chum salmon are encountered primarily during summer months. Thus, while managers would prioritize avoidance of Chinook salmon when the species were concurrent, the inter- and intra-annual variability of the relative species occurrences led us to present only the case of equal weighting. However, on-going work in this fishery seeks to better understand the environmental relationships between species-level bycatches, which will help us to improve relative species weightings, as well as resolve how climatic changes may drives shifts in fleet interactions with bycatch in space and time.

Data for this case study were aggregated in 1-degree cells. Historic closures for salmon bycatch have been smaller than those for our study, but they have also, often been irregular polygons. Due to the study design of exploring static versus dynamic, and mosaic closures, we opted for these larger but regular polygons. A targeted study for the pollock fishery alone would likely result in smaller, irregularly shaped polygons.

2. Brazilian longline fishery for tunas and swordfish

The Brazilian longline fishery fleet, focused on catch of tunas and swordfish, has heterogeneous characteristics in structure, fishing strategies, and spatial distributions. This fleet extends its operations within and outside of the Brazilian EEZ. Spatial distribution extends from northern Atlantic international waters (10º N) to a southern limit close to 33º S. A large proportion of the fleet are wooden hulled vessels with total length varying between 12 and 120 m, hold capacity between 9 and 120 metric tons and engine power varying between 111 and 474. As a result of the spatial pattern distribution associated with fishing strategies, ocean characteristics, and animal behaviors, these fleets' interactions with non-target and/or protected species are relatively common, principally in terms of seabirds, marine turtles and sharks.

The data used in this part of the study was provided by “Banco Nacional de Dados da Pesca de Atuns e Afins” (BNDA), which is held by the Brazilian government. This database comprises information provided by logbooks filled by fishing masters from commercial vessels (Rodrigues et al., 2020). Data recorded in this database included information about fishing operations, geographic location, fishing effort and species caught.

For this study's purpose, the observed data collected between 2000 and 2017 were aggregated into 0.5 degree spatial cells, and the number of hooks was used as the measure of nominal fishing effort. Additionally, it was considered as target species the catches of Albacore tuna (*Thunnus alalunga* – weighted 0.29), Bigeye tuna (*Thunnus obesus* – weighted 0.21), Yellowfin tuna (*Thunnus albacares* – weighted 0.21) and Swordfish *(Xiphias gladius* – weighted 0.21), and for non-target species, it was considered the catches of eight species groups, as is: the Atlantic white marlin (*Tetrapturus albidus* – weighted 0.08), Longfin mako (*Isurus paucus* – weighted 0.06), Shortfin mako (*Isurus oxyrinchus* – weighted 0.06), Bigeye thresher (*Alopias superciliosus* – weighted 0.06), Blue shark (*Prionace glauca* – weighted 0.67), Sea turtles (weighted 0.03), Marine mammals (weighted 0.01) and Sea birds (weighted 0.03).

3. Californian swordfish fishery

The California drift gillnet swordfish fishery (DGN) is a federally managed fishery that has operated from 1980 to the present in the national waters of the U.S. west coast. It targets highly migratory species with swordfish the main targeted species (currently contributing ~86% of total revenue; Pacific Fisheries Information Network, PacFIN). The DGN commonly catches non-target species such as blue sharks and molas, and more rarely interacts with marine mammals and sea turtles (7). DGN vessels remain at sea for multiple days before landing their catch, and deploy the gillnet (as a ‘set’) typically overnight (median set duration is 12 h). The exclusive economic zone (EEZ) off California is closed annually to the DGN from 1st February to 30th April, and is closed from the coast to 75 nm offshore from 1st May to 14th August, creating a de facto DGN fishing season from 15th August to 31st January.

The DGN has a complex management history with numerous regulatory changes, and fishery participation has declined considerably over the last 20-30 years (7–9). A number of regulations have been implemented to reduce bycatch, including gear modifications and time-area closures. The National Marine Fisheries Service (NMFS) established a federal observer program for the DGN in 1990, covering 15-20% of fishing trips. This program provides the dates and locations of all sets, set duration, and set-level counts of all caught species; these were the data used in this study. To provide the desired resolution of this analysis, monthly effort and catches were summed in 1-degree square grid cells, such that each grid cell with at least one catch event had an effort value (duration [hours] of all sets that month) and catch values (number of individuals caught of our selected target and bycatch species).

Given the large number of species historically caught as bycatch in the DGN, we decided to simplify the weighting of species, from what was done for the EcoCast tool developed for this fishery (10). Thus, we selected three bycatch species to include a very common species (blue shark) and two protected species (leatherback turtle, sea lions). Given the current focus of spatial closures in the DGN to protect the leatherback turtle (via the large Pacific Leatherback

Conservation Area), this species was given a higher weighting (0.5) than the other two bycatch species (0.25 each). Although the DGN catches multiple marketable species, we simplified to include swordfish as the only target species given its dominant contribution to revenue.

4. EU purse seine tuna fishery in the Atlantic Ocean

The ICCAT Secretariat provided all datafiles needed for the analysis. The files provided included exclusively data for the purse seine tropical tuna fishery, for all flags involved, over the period 1990-2017. Files included ICCAT's Task I Data (nominal catch), which contains nominal catches of Atlantic tunas and tuna-like fish, by year (1990-2017), gear, region, species and flag; Task II Catch & Effort, including catch and effort data by flag country, year, month, one degree square grid, fishing mode and; Task II Catch-at-Size file for the yellowfin tuna (YFT), bigeye tuna (BET) and skipjack tuna (SKJ), including the numbers of specimens caught (numbers measured raised to represent the total catch) by length class bin, species, flag country, year, month, fishing mode, and five degrees square grid.

The above data were used to produce a file that contained catches in weight, effort, and the weight of fish measured according to their maturity stage (immature/mature) and by length class bin, in kilograms, by species, fishing mode (associated school/free-swimming school), locations (5 degree square grid), year (1990-2017) and month. Thus, the number of fish recorded under each length class bin was converted to weight using ICCAT's length-weight equations, as per the ICCAT Manual (Yellowfin tuna[1]: $W = 2.153*10^{-5}*FL^{2.976}$ (19); Bigeye tuna[2]: $W = 2.396*10^{-5}*FL^{2.9774}$ (20); Skipjack tuna[3]: $W = 7.480*10^{-6}*FL^{3.253}$ (21).

The amount of fish immature and mature was assigned using ICCAT's length-at-first-maturity for each of ICCAT's tropical tuna stocks, as recorded in the ICCAT Manual (Yellowfin tuna[4]: 50% of mature females measuring 108.6 cm ((22), Eastern Atlantic); Bigeye tuna[5]: 53% mature females measuring 100 cm ((23), Abidjan). The same authors estimated that 50% mature females measuring 110 cm from samples taken in Dakar. However, data from Abidjan was used as this is the main port of landing for purse seiners in the Atlantic Ocean; Skipjack tuna[6]: 50% mature females measuring 45 cm ((24), Atlantic). Hazin et al. were chosen among the 4 values available for female maturity, with lengths at first maturity ranging from 42 cm to 51 cm, the one chosen being the most recent study.

The data for the different purse seine fleets were aggregated as: PS-EU, including all purse seine fleets operating under the EU catch monitoring scheme (France, Spain, Curaçao, Guatemala, El Salvador, etc.); PS-Ghana, covering purse seine vessels flagged in Ghana and vessels flying other flags that operate as the former; PS-Other: Purse seine vessels flagged to other countries and that do not usually operate in the core area of the purse seine fishery (e.g. Western Central or South Atlantic, Mediterranean Sea, etc.). Only data from the EU-PS fleet, for the period 2003-2017 were used for the analysis. The catches of tropical tunas of the EU group have represented between 77% and 94% (mean 86%) of the total catches of the purse seine component in the Atlantic Ocean. For developing scenarios estimates of current effort and scaling relative to efforts observed in 2016 were used. The selection of 2003-17 as a time-period was made in order to consider recent years of activity of purse seiners and for the recordset to be complete for all three stocks, considering that the last year in which catch-at-size data is available is 2017.

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[1] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_1_YFT_ENG.pdf; Table 2, Page 9
[2] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_2_BET_ENG.pdf; Table 2, Page 35
[3] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_3_SKJ_ENG.pdf; Table 2, Page 59
[4] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_1_YFT_ENG.pdf; Table 3, Page 9
[5] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_2_BET_ENG.pdf; Table 3, Page 35
[6] https://www.iccat.int/Documents/SCRS/Manual/CH2/2_1_3_SKJ_ENG.pdf; Table 3, Page 60

The final file used for the analysis contained total catches of immature and mature tropical tuna in kilograms (BET, YFT and SKJ) taken by EU and assimilated purse seiners and total effort in fishing hours by year, month, fishing method, and 5 degree square grid.

We included juvenile bigeye and yellowfin tuna as bycatch but adults as target catch together with juveniles and adults of skipjack tuna. Because both, adult and juvenile tunas for BET and SKJ were correlated not only in space, but also in time (Fig. 7 in main manuscript), neither area nor temporal closures resulted in high bycatch reductions. For this particular case study, the method for calculating juvenile catches could overestimate this correlation because catch reports are adjusted using samples according to large predefined strata (fishing mode, quarter, areas and weight categories) with all catches within each stratum allocated according to the proportions obtained from sampling.

Weights for bycatch and target categories were based on expert opinion thinking on what we would like to maximize for target species, and what would like to minimize for bycatch species, not what is more valuable or currently observed proportions:

Target:
- adult BET: 0.2
- adult YFT: 0.76
- adult SKJ: 0.02
- juvenile SKJ: 0.02

Bycatch
- juvenile BET: 0.55
- juvenile YFT: 0.45

5. French tuna fishery in the Indian Ocean

Two major sources of data were used for the French purse-seine Indian Ocean case study: (i) captain’s logbook target species catch and effort data and (2) onboard observer data for non-target species. Data were aggregated on 1° × 1° — month strata and this was used as the fundamental spatio-temporal unit for testing the impact of pelagic spatio-temporal closures on catch and bycatch in this fishery.

Target species data

Target species catch and effort data for the Indian Ocean French-flagged purse seine fleet for the period 2012-2018 were derived from fine-scale captain’s logbook data on individual fishing sets (14). Target species included skipjack tuna, juvenile and adult yellowfin tuna, juvenile and adult bigeye tuna, and (more rarely) albacore tuna (for a total of 6 target species categories). Catch for each of these categories was recorded in tons for each fishing set. Data were broken down by fishing mode into free-swimming school sets and floating object school sets, though final target and non-target data were aggregated across fishing mode. The time period 2012-2018 was chosen so as to have a recent time period during which the French fleet was primarily fishing on floating objects and Somali piracy was not a major factor impacting the spatial distribution of fishing. Catch species composition for target species was corrected using the standard T3 methodology for correcting species composition bias in raw captains’ logbook data (15). Only positive fishing sets were considered when calculating target and non-target catch per strata as catch from null sets represented a small fraction of total catch (<2%).

For the purposes of this study, the number of fishing sets was used as the measure of nominal fishing effort. This was chosen instead of fishing search time as search time is deeply flawed as an indicator of fishing effort on fish schools associated with floating objects, the dominant mode of purse seine fishing during the study period, as it does not account for the effort in deploying floating objects. For a discussion of the complexities associated with measuring purse seine fishing effort see Kaplan et al. (16).

The total target species data set consists of 13,965 purse seine fishing sets, of which 56.7% were in areas beyond national jurisdiction.

Non-target species data

Data on non-target species caught in the fishery were obtained from onboard observer data via two observer programs: the European Data Collection Framework (DCF) program, and the industry-managed OCUP observer program (17). These data included species- or genus-level observations of target and non-target species caught in each French purse seine fishing set for which an observer was present. Data come from both French-flagged vessels and from French-associated vessels (i.e., vessels owned by French fishing companies, but flagged in the Seychelles or other nations). Data coverage was low in the initial part of the time series (~10-15% for the period 2012-2013) but increased to ~40-45% after the implementation of the OCUP observer program in 2014 (17). In all, observer data from 7,880 purse seine fishing sets were used, of which 5,109 were on French-flagged vessels (out of a total 13,965 French-flagged fishing sets during the study period).

For the purposes of this study, non-target species catch was grouped into 4 species group: (i) billfish, (ii) sharks and rays, (iii) non-target tunas and (iv) other bony fish. Some potentially interesting species groups, such as catch of turtles or cetaceans, were excluded due to the very low number of observations in the dataset (typically, <10 observations in the entire dataset). Total non-target catch was limited to landed individuals and discarded dead individuals. Non-target catch was measured in numbers of fish for all groups except non-target tunas, for which data was recorded in tonnes.

Extrapolation of bycatch data

As observer data only partially covered French purse seine fishing activity, extrapolation was used to estimate total non-target catch in each $1^\circ \times 1^\circ$ — month strata. Estimates are based on multiplying the ratio of non-target catch to total target catch from observer data by the total target species catch from logbook data (16, 18). As non-target species composition differs significantly by fishing mode, extrapolation was carried out separately for free-swimming school sets and floating object school sets. As the coverage of observer data in certain space-time strata was low, data was aggregated on larger spatial and/or temporal strata until a satisfactory number of observations was available to permit extrapolation. For each nominal $1^\circ \times 1^\circ$ — month strata and fishing mode, data was aggregated in the following order until observer data consisted of at least 10 fishing sets or represented >80% of the total number of fishing sets (i.e., all sets with and without observer coverage) in the aggregation:

$1^\circ \times 1^\circ$ — month (i.e., no additional aggregation)
$5^\circ \times 5^\circ$ — month (i.e., aggregating on a larger 5^∘ spatial scale)
$1^\circ \times 1^\circ$ — climatological month (i.e., aggregated over years for each month)
$5^\circ \times 5^\circ$ — climatological month
Climatological month (i.e., aggregated over all space and years for a given month)

In this way, a non-target to target ratio was estimated for each $1^\circ \times 1^\circ$ — month, which was then multiplied by the logbook-derived total target species catch to obtain the final estimate of non-target catch for each non-target species group.

After extrapolation, catch for all 6 target-tuna categories, all 4 non-target species-groups and fishing effort (i.e., the number of fishing sets) were aggregated across fishing mode to obtain the final catch and effort data for estimating the impact of spatial closures on this fishery.

Definition of bycatch and weightings for case study

For the purposes of this study, each catch category was classified as either “target” or “bycatch.” All target-tuna categories were classified as “target” except juvenile bibeye tuna, which was classified as “bycatch” along with the other non-target catch categories. Whereas juvenile yellowfin tuna is a major component of target tuna catch (e.g., representing ~25% of catch on floating objects), juvenile bibeye tuna is rarer, representing <10% of catch on floating objects. Furthermore, catch of juvenile bigeye tuna is often a source of concern for recruitment limitation of adult bigeye tuna to the longline fishery. As such, juvenile bigeye tuna catch, but not juvenile yellowfin tuna catch, was classified as “bycatch.”

Weights for “target” catch categories were set proportional to the total catch in each “target” catch category (i.e., the weight for adult yellowfin tuna was equal to the fraction of the total catch over the entire study period that was adult yellowfin; similarly, for the other categories). This has the effect of essentially saying that all “target” catch categories have equal value to the fishery. While not precisely true, sale price differences among the different species for conversion into canned tuna (as is the case for almost all purse seine catch) are not large and are generally considered to be insufficient to drive selective fishing by purse seiners (i.e, purse seine vessels are generally assumed to fish on any large tuna school, irrespective of species composition).

Weights for “bycatch” categories were varied based on expert opinion regarding the level of concern for bycatch of each species-group category. Assigned bycatch weights were as follows:

- Sharks & rays: 4/11
- Billfish: 3/11
- Juvenile bigeye tuna: 2/11
- Non-target tunas: 1/11
- Other bony fish: 1/11

Sensitivity tests

In order to assess the sensitivity of the results to methodological choices, additional simulations were carried out for the French tuna purse seine fishery. To test for the impact of the extrapolation scheme for non-target catch data, simulations were done using only fishing sets covered in the observer data (i.e., the subset of fishing sets for which observers were actually onboard). To test for the impact of the details of the weighting scheme, simulations were done with uniform weights for “bycatch” catch categories. In this latter case, juvenile bigeye catch was treated as “target” so as to completely eliminate any dependence of bycatch data from observers on target species catch derived from logbooks. Weighting of all “target” catch categories was as before proportional to the catch in each category (but this time including juvenile bigeye catch). To test for the combined consequences of weighting and aggregating data across fishing modes (free-swimming schools and floating object schools), simulations were done with just the (extrapolated) free-swimming school sets and, separately, just the (extrapolated) floating object school sets using the uniform weighting scheme for “bycatch” categories with all bigeye being treated as catch.

In summary, a total of 6 different simulation runs were carried out (2 catch-effort data sets crossed with 2 weight schemes, plus 2 runs with free-swimming school sets and floating object school sets separated). In all cases, results for the overall impacts of spatio-temporal closures on the Indian Ocean French purse-seine fleet were qualitatively similar except that for just free-swimming schools (Fig. S3 and S4). For example, with a 30% fixed mosaic closure at fixed total effort and no change in fishing efficiency (Fig. S3), a decrease in bycatch between 4% and 29% was observed for all simulations except that including only free-swimming school sets, for which a 70% decrease in bycatch occurred. Given that the great majority of tropical tuna purse seine fishing activity in the Atlantic and Indian Oceans in recent years is on floating objects and that bycatch rates for free-swimming school sets are typically 3-4 times lower than those for floating object sets (3), we decided to only formally present in the paper results for the default simulation using all fishing sets combined across fishing school types, extrapolated non-target catch data and non-uniform weighting of “bycatch” catch categories.

6- 7. Hawaiian bigeye and swordfish fisheries

U.S. and territorial longline fisheries comprise the Hawaii deep-set tuna longline fleet (including several vessels based on the U.S. West Coast) and the Hawaii shallow-set swordfish longline fleet. Longline is a type of fishing gear consisting of a mainline that exceeds 1 nm (6,076 ft) in length that is suspended horizontally in the water column, from which branchlines with hooks are attached. Longline deployment is referred to as “setting,” and the gear, once deployed, is referred to as a “set.” Sets are normally left drifting for several hours before they are retrieved, along with any catch. In shallow-set longline fishing, the gear is configured so that the hooks remain above 100 meters (m) in depth to target swordfish near the surface. In deep-set longline fishing, the gear is configured so that all of the hooks fall below 100 m to target deeper-dwelling tunas. The deep-set fishery targets bigeye tuna in the EEZ around Hawaii and on the high seas at an average target depth of 167 m. The shallow-set fishery targets swordfish (Xiphias gladius), typically to the north of the Hawaiian Islands. Longline vessel operators are required to declare whether they will be making a deep-set or shallow-set trip prior to their departure and are required to carry observers through the Pacific Islands Regional Observer Program (PIROP). A deep-set is defined as a set with 15 or more hooks between floats as opposed to a shallow-set that is characterized by setting less than 15 hooks between floats. Observer coverage through the PIROP is 100% in shallow-set trips and usually 20% (or more) for deep-set trips over the course of a fishing year. NMFS and the Western Pacific Regional Fishery Management Council manage these longline fisheries under a single limited-access permit program, with no more than 164 vessels holding permits at any time.

Fishing locations may vary seasonally based on oceanographic conditions, catch rates of target species, and management measures, among others. The deep-set fishery (Fishery 6) operates in the deep, pelagic waters around the Hawaiian archipelago and on the high seas throughout the year, mostly within 300-400 nm (556-741 km) of the main Hawaiian Islands (MHI). However, federal regulations and other applicable laws prohibit longline fishing inside the 200 nm U.S. EEZ around the Northwestern Hawaiian Islands. Longline fishing within 50 to 75 nm from the shoreline in the MHI is prohibited to minimize the potential for gear conflicts with small boat fisheries and interactions with protected species.

Federal regulations temporarily prohibit longline fishing in the Southern Exclusion Zone (SEZ), an area in the EEZ south of Hawaii (84 FR 5356, February 21, 2019). An SEZ closure is triggered under regulations implementing the False Killer Whale Take Reduction Plan if there are two or more observed serious injuries or mortalities of false killer whales in the EEZ around Hawaii in a given year.

Some limited longline fishing occurred in the U.S. EEZ around U.S. Pacific Remote Island Areas (PRIA) of Kingman Reef and Palmyra Atoll (5° N) prior to 2016. Fig. S5 shows the distribution of fishing effort by the Hawaii deep-set longline fleet as the annual average number of hooks per 5 degree square in millions of hooks over 2019. The distribution of fishing operations over the fishing grounds varies seasonally and from year-to-year. Distribution of fishing effort in 2019 is shown in Fig. S5 and in prior decade 2008-2019 is shown in Fig. S6.

In general, deep-set longline vessels operate out of Hawaii ports, with the vast majority based in Honolulu. Infrequently, deep-set trips originate from other ports such as Long Beach or San Francisco, California, or Pago Pago, American Samoa, and then fishermen land their catches in Hawaii. Fishermen departing from California begin fishing on the high seas, outside the EEZ. Fishermen departing from American Samoa usually begin fishing near the Equator or farther north where they expect higher catch rates of bigeye tuna. The shallow-set longline fishery targeting swordfish (Fishery 7) operates in the U.S. EEZ around Hawaii and on the high seas to the north and northeast of the MHI seasonally.

Weighting:

Target species: for the deep-set fishery that targets bigeye tuna, we considered a weight of 0.9 for bigeye and 0.1 for swordfish. On the other hand, for the shallow-set fishery targeting swordfish, we considered a weight of 0.9 for swordfish and 0.1 for bigeye.

Bycatch species: before assigning weights to the different bycatch species, we grouped them. Separate groups were used for all sea turtles, all albatrosses, manta-rays, dolphins and wales. In addition, silky sharks and oceanic whitetip sharks were not grouped and considered at the species level. Weights were assigned based on conservation concerns and occurrence in each fishery:

For sets targeting swordfish (shallow sets):
- Whales (mainly false killer whales): 0.10
- Sea turtles: 0.40
- Albatross: 0.15
- Dolphins: 0.05
- Manta-rays: 0.05
- Oceanic whitetip sharks: 0.20
- Silky sharks: 0.05

For sets targeting bigeye (deep sets):
- Whales (mainly false killer whales): 0.20
- Sea turtles: 0.15
- Albatross: 0.15
- Dolphins: 0.05
- Manta-rays: 0.20
- Oceanic whitetip sharks: 0.20
- Silky sharks: 0.05

8- 10. Tuna fishery in the Eastern Pacific, IATTC

The Inter-American Tropical Tuna Commission (IATTC) manages tuna and tuna like fisheries in the eastern Pacific Ocean and has the mandate to ensure sustainability of target and non-target species occurring in the convention area. Although a variety of gears exists, longline and purse seine vessels account with most of the tropical tuna catches in the region – Skipjack *Katsuwonus pelamis*, Yellowfin *Thunnus albacares* and bigeye *Thunnus obesus*.

Purse-seine fisheries in the Eastern Pacific takes over 90% of the total reported catches in recent years (around 600,000 metric tons (t) (28)). Purse seiners fish on tunas associated with dolphins (fishery 8), unassociated or free schools (fishery 9) associated with floating objects (fishery 10) (Table S1). For this study's purpose, each set type has been analyzed separately, as they present specific species and sizes composition of target and non-target species.

Since 1993 all Class-6 (carrying capacity greater than 363 t) purse-seine vessels carried observers, who collected detailed data on catches, including non-target species. The observer program evolved, and specific forms were developed for sharks, rays, billfishes, turtles and other important bycatch species in the 90s and early 2000s. For example, the new shark form was implemented in 2004. As such, data corresponding to the period 2004-2019 was used for the present study. Details about the observer program, the role of the IATTC, and other fisheries-related information can be found in IATTC Special Report 13 (29) and SAC-12-03 (28).

Data were aggregated into 1-degree spatial cells, and the fishing set was used as the measure of nominal fishing effort. All tuna catches combined in tons (except Bigeye), were considered target and given a weight of 1. Seven non-target species/groups were considered as bycatch, all in numbers, with the following weights, based on IATTC's conservation and management priorities, vulnerability status and importance to the total catch: silky shark (0.15), other sharks (0.15 – all sharks except silky shark), mobulids (0.2), rays (0.1 – all rays except mobulid rays), sea turtles (0.1), billfishes (0.1), and bigeye tuna (0.2). Bigeye catches in weight were transformed into numbers using the best scientific estimates and averaged weights of the stock assessment outputs by year and modelling area. The idea of considering bigeye tuna as bycatch was used to explore how different seasonal and area closures could help reducing the catch of this species in purse seine fisheries.

11. Small scale tuna and mahi-mahi fishery in the Eastern Pacific

Surface artisanal longline fishing in the Eastern Pacific Ocean (from Peru to Mexico) is very diverse in terms of operational features, gear configuration, types and size of vessels and composition of catch, among others. This fishery is opportunistic targeting pelagic species such as mahi-mahi, billfishes, sharks or a combination of species (multi-species fisheries which is common in tropical waters).

In some countries there is a marked seasonality of fishing effort (i.e. tuna vs mahi-mahi fisheries); however, these fisheries can behave opportunistically, taking commercial advantage of other species such as billfishes and sharks in countries where they are not banned (5, 6).

The data used in this study were collected by observers on board longline vessels from Peru, Ecuador, Panama, Costa Rica, Nicaragua, El Salvador, Guatemala and Mexico. Between 2004 and 2012, trials were conducted to analyze the performance of circle hook in relation to J-hook in these fisheries (5). A total of 536 vessels targeting tuna or mahi-mahi voluntarily carried an observer on board. The total effort observed was 2,749,368 hooks in 7,314 surface sets targeting tuna (827,807 hooks) or mahi-mahi (1,921561 hooks). The average length of the sampled vessels was 9.8 m (range 5 – 31 m) and longline operated in depths ranging 1.83 to 164.7 m., in the area comprising 15° 30´ - 32° 30´N and 71° - 98° W. For the purposes of this study, we aggregated our data into 1-degree spatial cells.

Three scenarios were considered for the purpose of this study based on target species: *i*) sets targeting only tunas; *ii*) sets targeting only mahi-mahi; and *iii*) a combination of all sets targeting tuna and mahi-mahi. The last scenario is the one presented in the main manuscript. The others are presented here as a sensitivity analysis to evaluate differences when assuming different targets (Fig. S7 and S8). Billfishes are considering secondary target species for the tuna fisheries. Sharks were included as bycatch species even though they are legal target species in some countries.

Bycatch were grouped as: turtles (weighted 0.3) including *Chelonia mydas, Eretmochelys imbricata, Lepidochelys olivacea and Caretta caretta*; *Dermochelys coriacea* was included independently (weighted 0.4); pelagic sharks (weighted 0.13) including *Prionace glauca, Alopias pelagicus, Carcharhinus falciformis, Isurus oxyrinchus*, and other shark species (grouped into families due to low numbers or unidentified species: Alopidae, Carcharhinidae, Sphyrnidae); cetaceans (weighted 0.05); birds (weighted 0.02); and mantas/rays (weighted 0.1). For the target catch, a weight of 0.4 was assigned to tunas, 0.4 to mahi-mahi and 0.2 to billfishes for the scenario presented in the main manuscript.

12. South African tuna fishery

South Africa’s longline fishery operates within South Africa’s EEZ and in its vicinity in the Atlantic and Indian Oceans around the southern tip of the African continent, a biodiversity hotspot for seabirds and pelagic sharks. Consequently, the fleet which targets tuna and swordfish has a considerable shark and bird bycatch, which has been reduced by progressively more stringent permit conditions. The longline fleet includes a domestic and a Japanese flagged joint venture component. For the last 15 years the Japanese joint venture vessels have operated under 100% observer coverage. Data are collected per set and include information on the individual gear configuration, bait, start and end position of each setting and hauling operation to a resolution of 0.01 NMI. Catch of 72 species or species groups is recorded on set level. The species data include number and estimated weight for tuniform target species and by-product such as sharks, sailfishes, billfishes and other pelagic teleosts. For charismatic bycatch species such as birds and turtles, information on condition and successful release/discard is also recorded. Being a tuna and swordfish directed fishery, most other species of potential commercial value, in particular sharks, have been relegated to unwanted bycatch and a number of species groups such as threshers, hammerheads and some of the carcharinids have to be released at sea. Species were weighted in three groups, target, by-product and unwanted by-catch. In the target group, yellowfin and bigeye tuna received the highest weighting (0.2), above the less valuable or less common species (0.1). whereas all unwanted byproduct was rated equally low (0.06). In the bycatch group infrequently caught endangered seabirds were weighted 0.1 and all other unwanted bycatch was weighted 0.04.

13. Southern pink shrimp fishery in Brazil

The southern industrial pink shrimp fishery fleet in Brazil operates within Brazilian EEZ, most frequently between the parallels of 20º and 30º S and among the isobaths of 40 and 80 m depth. In general, the fleet operates with approximately 120 wooden-hulled vessels trawlers having an average total length of 18.5 m, average gross tonnage of 55 t and 246 HP engines. The operation characteristics are based on trips with 18 days on average and 4 (4.27 ± 0.87) sets per day with a duration of 4.95 (± 0.78) trawling hours per set. The proportion of pink shrimp (e.g. *Penaeus brasiliensis*; *Penaeus paulensis*) in catches is relatively lower when compared with other components of the catches (e.g. Pink shrimp corresponds to 15% on average of the total catch of each fishing trip). This pattern significantly increases the participation of other species as a byproduct of the fishery. In general, common bycatch and/or byproduct species include Angel shark (*Squatina argentina*; *Squatina guggenheim*; *Squatina occulta*), Picked dogfish (*Squalus acanthias*; *Squalus cubensis*), Freckled catshark (*Scyliorhinus* sp.), Argentine croaker (*Umbrina canosai*), Pink cuskeel (*Genypterus brasiliensis*), Atlantic moonfish (*Selene setapinnis*; *Selene vomer*), Sand sole (*Paralichthys isosceles*; *Paralichthys triocellatus*), Uruguayan lobster (*Metanephrops rubellus*), Brazillian guitarfish (*Pseudobatos horkelii*; *Pseudobatos percellens*; *Zapteryx brevirostris*) and other species.

The data set used in this part of the study was built and maintained by the University of 'Vale do Itajaí' (UNIVALI) as products of a sequence of scientific projects and contracts developed to meet scientific interests on marine resources and regional fisheries (1995 – 2000, (25, 26)), governmental demands for oceanic and deep fisheries development and management (2000 – 2015; (27)) and in support on the licensing processes of the offshore oil and gas exploration activities (2016 onwards; http://pmap-sc.acad.univali.br/). Data collected in these projects included information about the general description of the fishing operation, fishing area, effort, and his respectively catches by species.

For this study's purpose, the observed data collected between 2003 and 2012 were aggregated into 0.5-degree spatial cells, and the hours of trawling were used as the measure of nominal fishing effort. Additionally, it was considered as target species only the catches of Pink shrimp (weighted 1), and for the non-target species, it was considered the catches of only ten distinct species groups, as is: the Angel shark (weighted 0.01), Picked dogfish (weighted 0.005), Freckled catshark (weighted 0.005), Argentine croaker (weighted 0.2), Pink cuskeel (weighted 0.07), Atlantic moonfish (weighted 0.01), Sand sole (weighted 0.53), Uruguayan lobster (weighted 0.15) and Brazillian guitarfish (weighted 0.02).

14. Uruguayan swordfish longline fishery

The Uruguayan pelagic longline fleet operated continuously between 1981 and 2013. During this period, the importance of the target species varied in some years, depending on the vessels, being the following species; swordfish (*Xiphias gladius*), bigeye (*Thunnus obesus*), yellowfin (*T. albacares*), albacore (*T. alalunga*) and pelagic sharks (mainly blue shark *Prionace glauca*). In the period 1991 – 2012, the most important species was swordfish, so most of these vessels employed an American-type longline (monofilament mainline), while some freezer vessels used Spanish longline (multifilament mainline). Further details of longline configuration, materials and characteristics can be found in (30) and (31).

Data used in this study were gathered by the Uruguayan national observer program ("Programa Nacional de Observadores a bordo de la Flota Atunera", PNOFA) of the "Dirección Nacional de Recursos Acuáticos" (DINARA) in the period 2004 – 2012, with approximately 3.5 million hooks observed, and covering a large portion of the southwestern Atlantic Ocean (19° to 48° south, 60° to 20° west). This area encompasses the Uruguayan shelf, slope and deep waters (depths between 200 and 4000 m.), and international waters adjacent to Uruguay, northern Argentina and southern Brazil (depths between 3000 and 4000 m.), waters over the Rio Grande Rise, and deep waters northeast of this Rise.

Data were aggregated on 1° x 1° spatial cells, and for all species, we used number of individuals as the unit of catch. We defined target species as those of interest for the fishermen as it has an important commercial value in the business equation. As mentioned above, target species (corresponding to 83.5% of the total observed captures), were swordfish (weighted 0.3), bigeye tuna (weighted 0.175), yellowfin tuna (weighted 0.175), albacore (weighted 0.175), and blue shark (weighted 0.175). The weightings of the target species were made based on the history of the fishery in recent years, where the main species was swordfish and the rest of the target species varied depending on the companies and the status of the fish values in the regional and international market.

Bycatch was considered as those species or group of species that are always release alive or discarded dead, either because they have no commercial value or because of national or international laws that prohibit their retention. Bycatch species (corresponding to 6.2% of the total observed captures) were aggregated into the following groups: 1) Hammerhead sharks (*Sphyrna* spp., weighted 0.1); 2) Thresher sharks (*Alopias* spp., weighted 0.1); 3) Pelagic stingray (*Pteroplatytrygon violacea*, weighted 0.08); 4) Sunfish (Mola spp., weighted 0.08); 5) Mobulidae (*Mobula* spp., weighted 0.1); 6) Loggerhead turtle (*Caretta caretta*, weighted 0.12); 7) Leatherback turtle (*Dermochelys coriacea*, weighted 0.15); 8) Albatrosses (Diomedeidae, weighted 0.15); and 9) Petrels (Procellariidae, weighted 0.12). The weightings for bycatch were determined based on the vulnerability of the species considered.

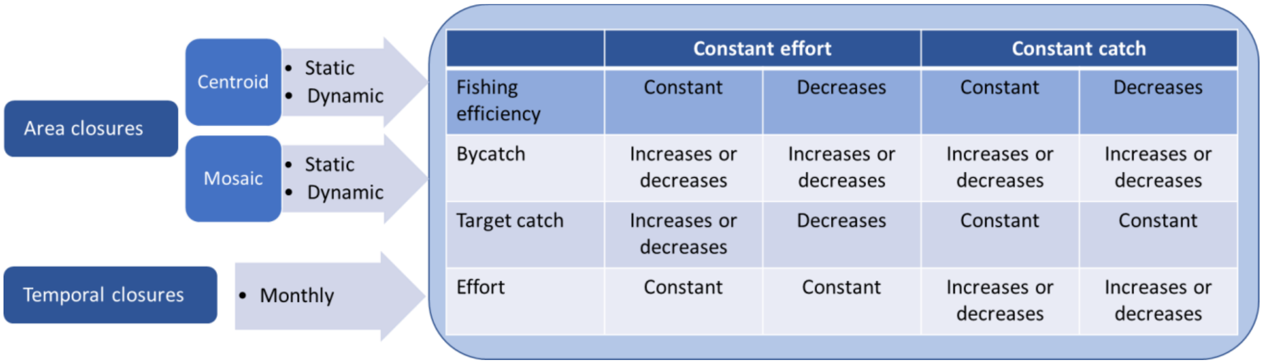
15. US North West Sablefish fishery

The US West Coast limited entry sablefish-endorsed fleet targets sablefish (*Anoplopoma fimbria*) using longlines or pots. For the purposes of this study, we limited the analysis to vessels using longlines because bycatch in pots is generally low. These vessels are typically 10-29 meters in length and most commonly operate out of ports in Oregon and Washington. The primary season runs from 1 April to 31 October, and most fishing occurs in waters >146 meters. Observer coverage in this fleet averages ~30% of landings (11) and the observer data span 2002-2019. Common bycatch species include spiny dogfish shark (*Squalus suckleyi*), Pacific halibut (*Hippoglossus stenolepis*), rockfish species (*Sebastes spp.*), longnose skate (*Beringraja rhina*), blue shark (*Prionace glauca*), and arrowtooth flounder (*Atheresthes stomias*) (12). High-grading of sablefish (i.e. discarding of smaller fish over larger more valuable fish) is also common, so discarded sablefish are treated here as bycatch. In addition to incidental fish catch, the sablefish longline fleet also takes an estimated average of ~70 black-footed albatross (*Phoebastria nigripes*) per year when unobserved effort is accounted for (13). We define a seabird take as “any interaction that was immediately lethal or thought to lead to mortality”. Black-footed albatross are listed as near-threatened by the IUCN, leading to concerns over the impacts of bycatch. In addition, the sablefish longline fleet had one observed incident of short-tailed albatross (*Phoebastria albatrus*) take in 2011. This species is listed as endangered under the US Endangered Species Act. Though we do not include short-tailed albatross in our analysis because we only have a single data point, we consider bycatch risk to black-footed albatross to be a potential proxy for risk to short-tailed albatross.

For the purposes of this study, we aggregated our data into 0.5 degree spatial cells. We aggregated bycatch into the following groups: 1) rockfish (*Sebastes* spp. and *Sebastolobus* spp., weighted 0.3); 2) black-footed albatross (weighted 0.25); 3) Pacific halibut (weighted 0.2), 4) discarded sablefish (weighted 0.15); and 5) elasmobranchs (weighted 0.1). These weightings were chosen following informal discussions with fisheries scientists and other colleagues involved with groundfish fishery management. Though they are subjective, we believe the weightings reflect management-level concerns around economics, conservation, and the recovery of depleted fish species. For target catch, we assigned a weight of 1 to sablefish. Though other species are occasionally retained, they represent a small proportion of the landed catch and are not considered targets of the fishery. For all species, we used metric tons as the unit of bycatch. For black-footed albatross, we converted from numbers of individuals into weights based on observed data.

Sensitivity analysis without weighting

In this section we reproduce the same plots as in the main manuscript but not using any kind of weighting process, just absolute numbers. These figures are shown in Figure 13 x to Figure S17.



	Constant effort		Constant catch	
Fishing efficiency	Constant	Decreases	Constant	Decreases
Bycatch	Increases or decreases	Increases or decreases	Increases or decreases	Increases or decreases
Target catch	Increases or decreases	Decreases	Constant	Constant
Effort	Constant	Constant	Increases or decreases	Increases or decreases

Fig. S1. Factorial design used in the analysis.

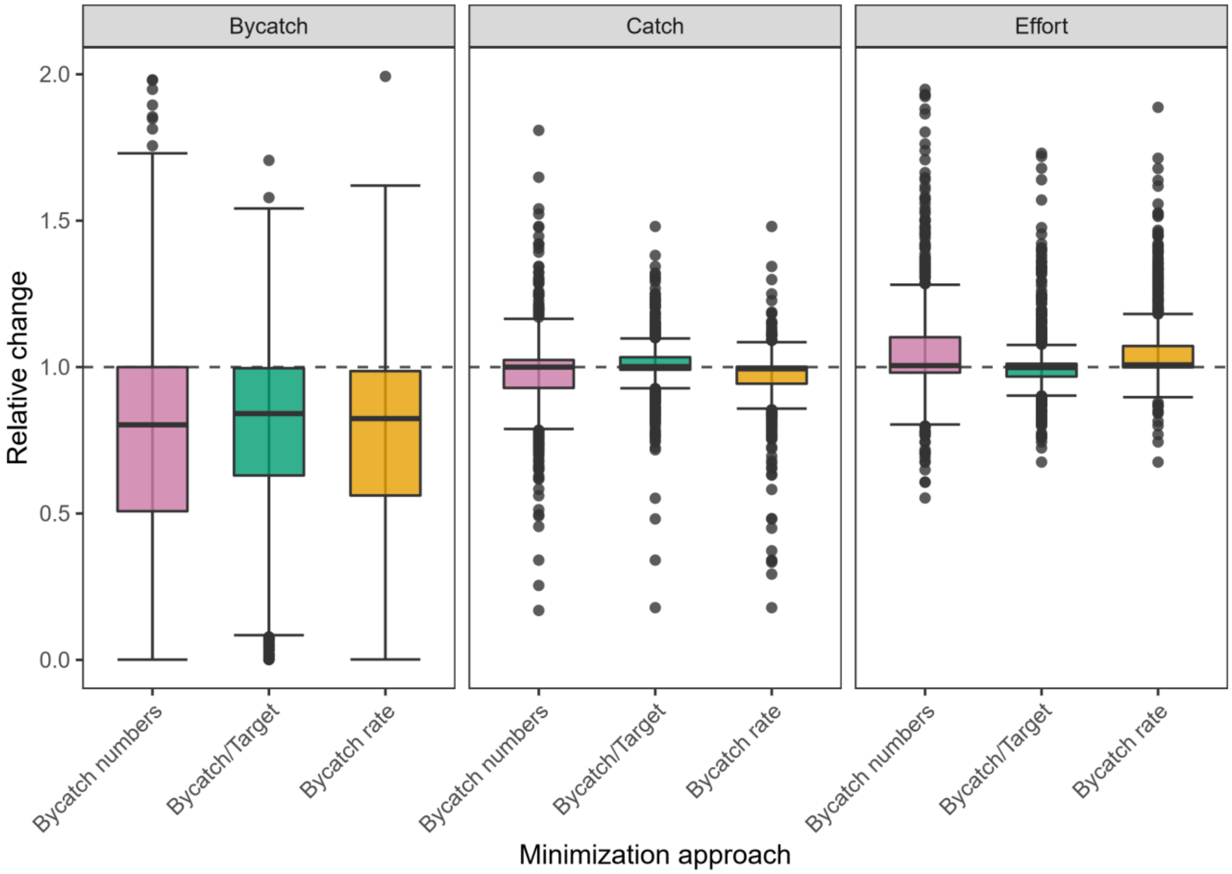


Fig. S2. Minimization approaches used in the study: 1) minimizing bycatch numbers or weight; 2) minimizing bycatch rates; or 3) minimizing the ratio of bycatch to target species. Here, the box represents the quartiles (25, 50, 75 percentiles) where 50% (horizontal line in the box) is the median. The upper whisker is the maximum value of the data that is within 1.5 times the interquartile range over the 75th percentile. The lower whisker is the minimum value of the data that is within 1.5 times the interquartile range under the 25th percentile. Outliers are represented by the dots. No evident differences among minimization approaches exist, so in order to consider minimizing bycatch by maximizing target species, we present the results in the main manuscript for the minimization method that considers the ratio between bycatch and target catch.

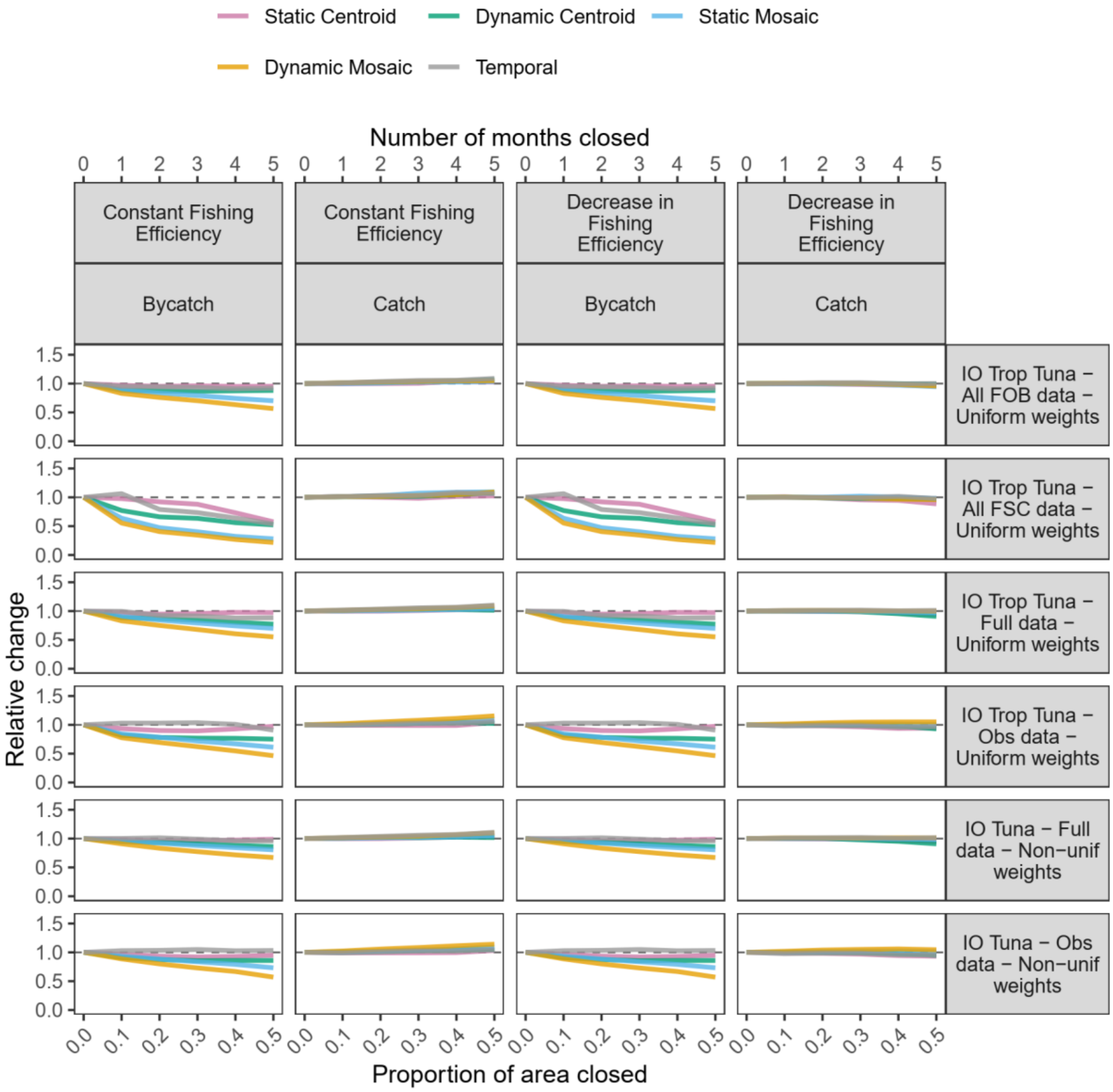


Fig. S3. Relative changes for each type of closure and each scenario (rows) for total bycatch and target catch. These results are for the scenarios when fishing effort remains constant and fishing efficiency decrease (panels on the right) or remain constant (panels on the left) for the French purse seine tuna fleet operating in the Indian Ocean. These comparisons are only part of a sensitivity test. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top. “Obs data” means the subset of fishing sets for which observers were onboard. “Full data” means all extrapolated data. FOB: fishing objects. FSC: free swimming schools. The scenario “IO Tuna – Full data − Non−unif weights” is the one presented in the main manuscript.

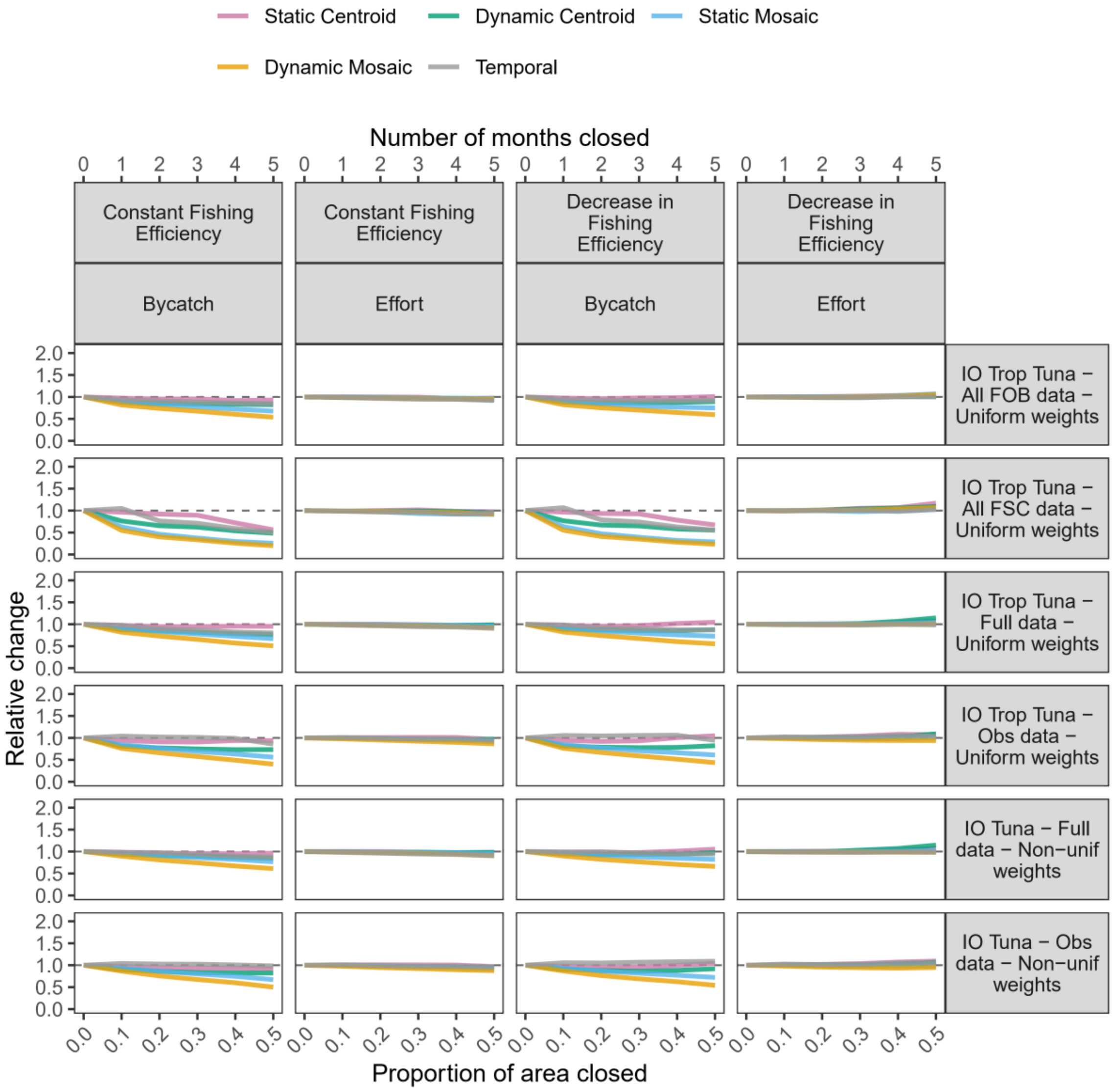


Fig. S4. Relative changes for each type of closure and each scenario (rows) for total bycatch and effort. These results are for the scenarios when total catch of target species remains constant and fishing efficiency decreases (panels on the right) or remains constant (panels on the left) for the French purse seine tuna fleet operating in the Indian Ocean. These comparisons are only part of a sensitivity test. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top. “Obs data” means the subset of fishing sets for which observers were onboard. “Full data” means all extrapolated data. FOB: fishing objects. FSC: free swimming schools. The scenario “IO Tuna – Full data − Non−unif weights” is the one presented in the main manuscript.

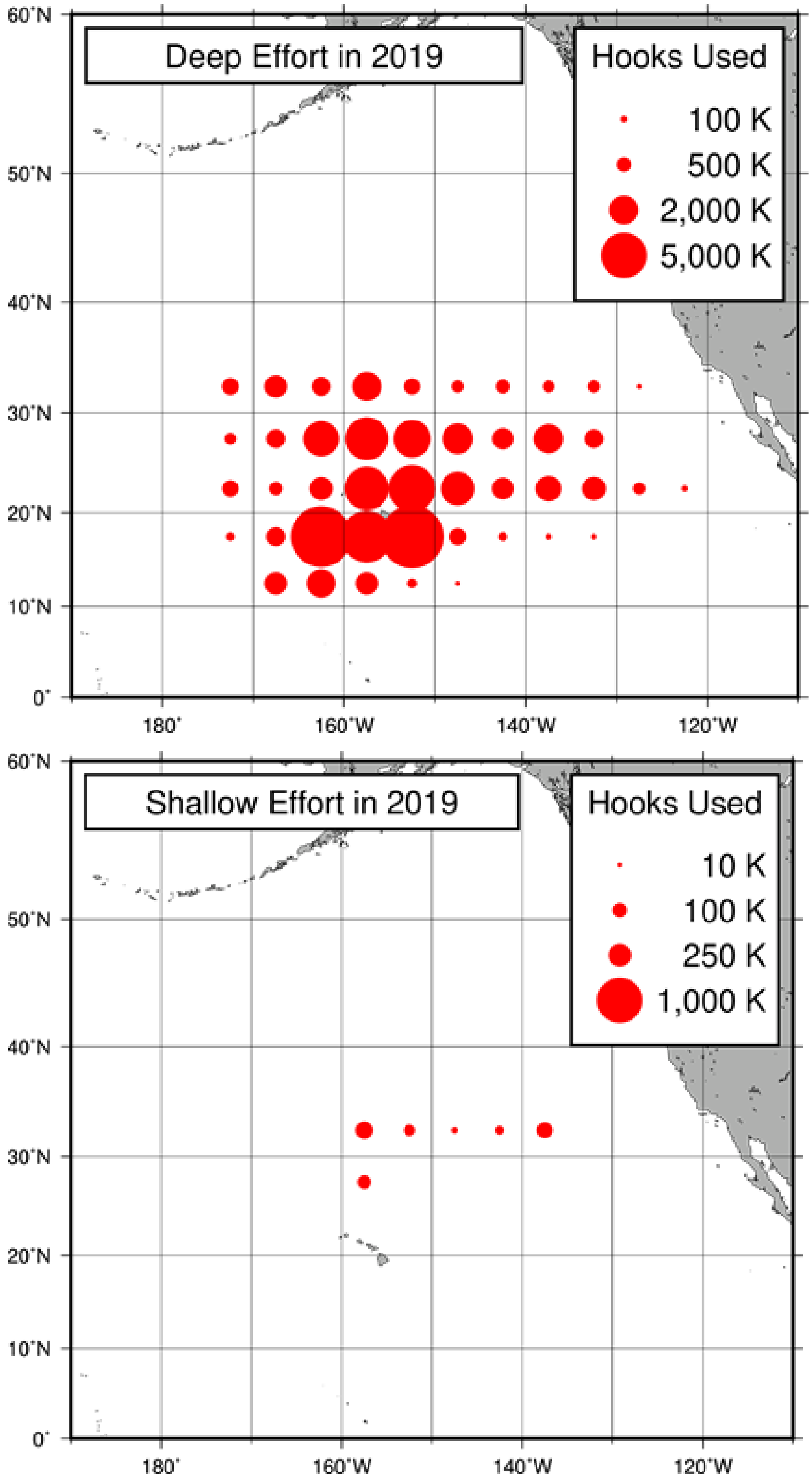


Fig. S5. Top: distribution of deep-set fishing effort (hooks deployed) 2019. Bottom: Distribution of shallow-set fishing effort (hooks deployed) 2019.

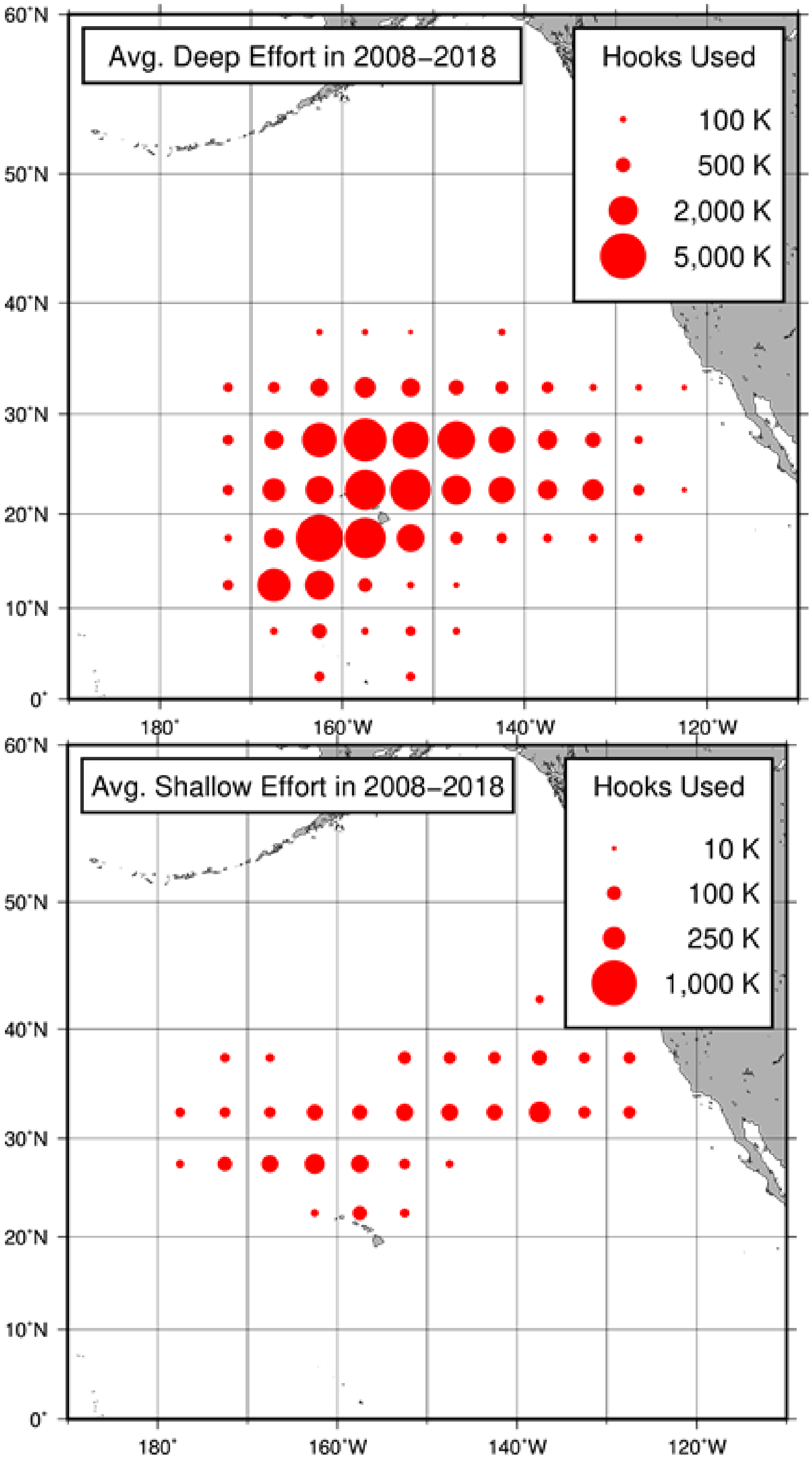


Fig. S6. Top: distribution of deep-set fishing effort (hooks deployed) 2008-2018. Bottom: Distribution of shallow-set fishing effort (hooks deployed) 2008-2018.

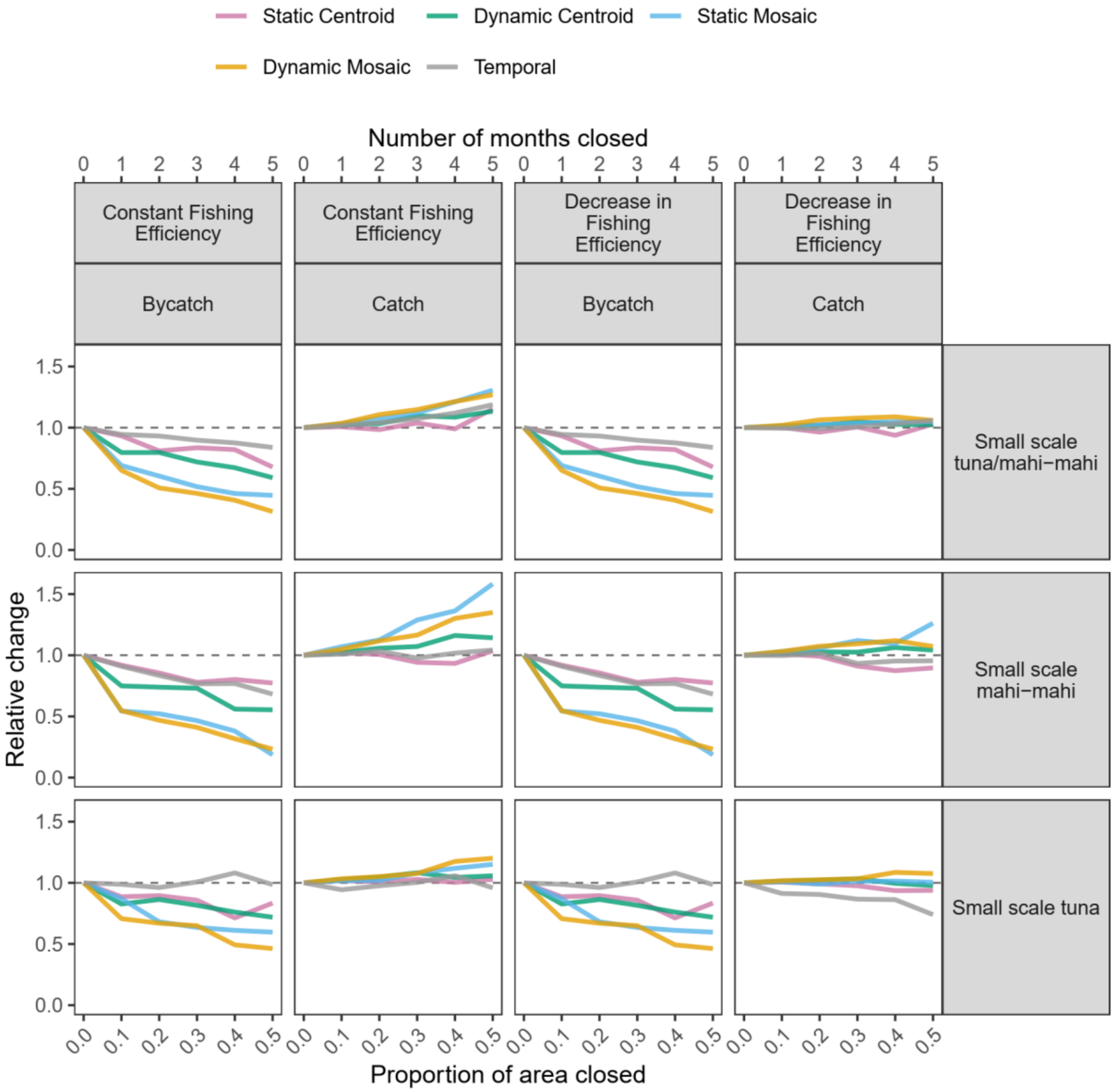


Fig. S7. Relative changes for each type of closure and each scenario (rows) for total bycatch and total target catch. These results are for the scenarios when fishing effort remains constant and fishing efficiency decreases (panels on the right) or remains constant (panels on the left) for the tuna and mahi-mahi fishery operating in the Eastern Pacific Ocean. These comparisons are only for exploratory purposes. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top.

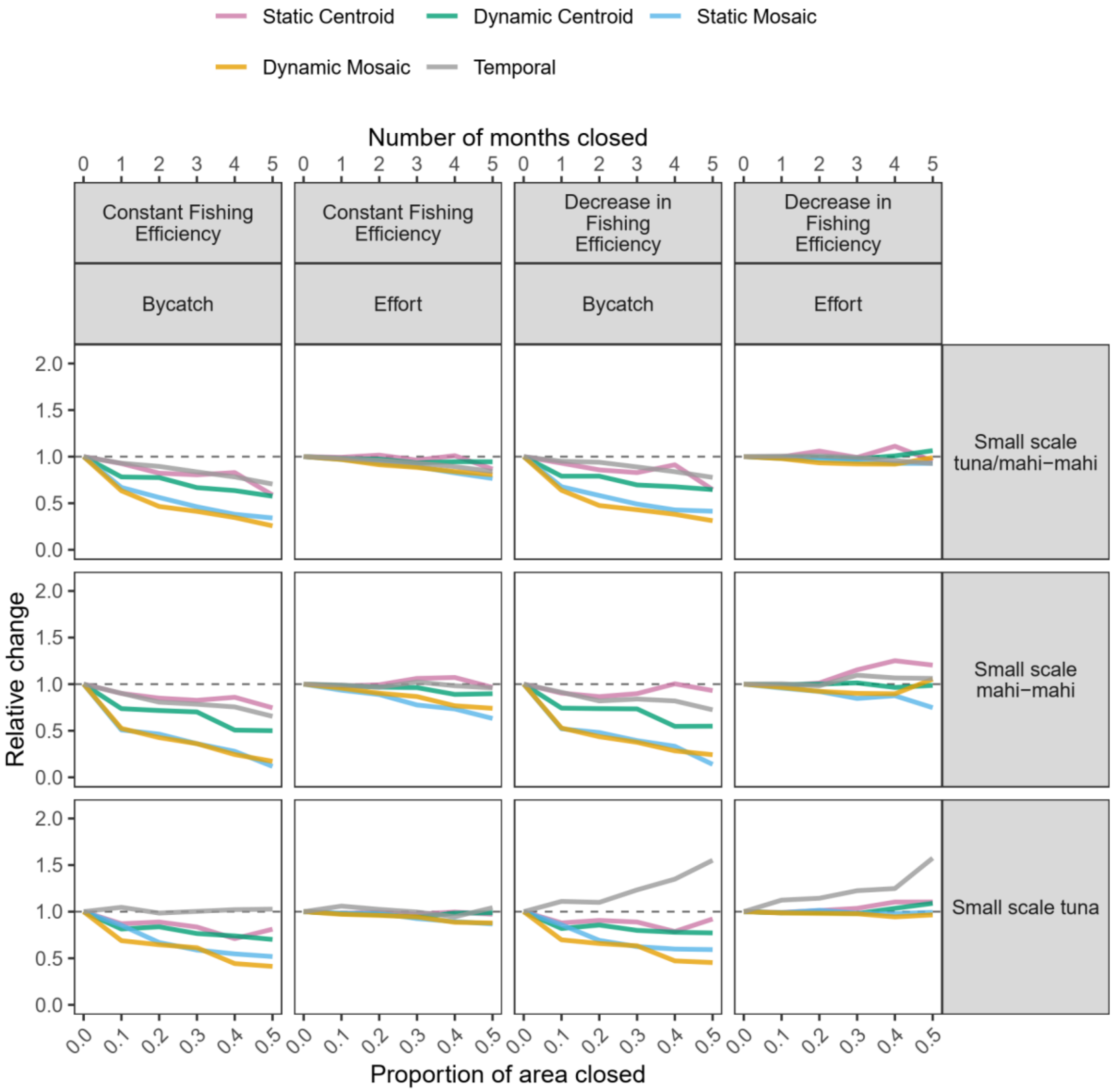


Fig. S8. Relative changes for each type of closure and each scenario (rows) for total bycatch and effort. These results are for the scenarios when target catch remains constant and fishing efficiency decreases (panels on the right) or remains constant (panels on the left) for the tuna and mahi-mahi fishery operating in the Eastern Pacific Ocean. These comparisons are only for exploratory purposes. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top.

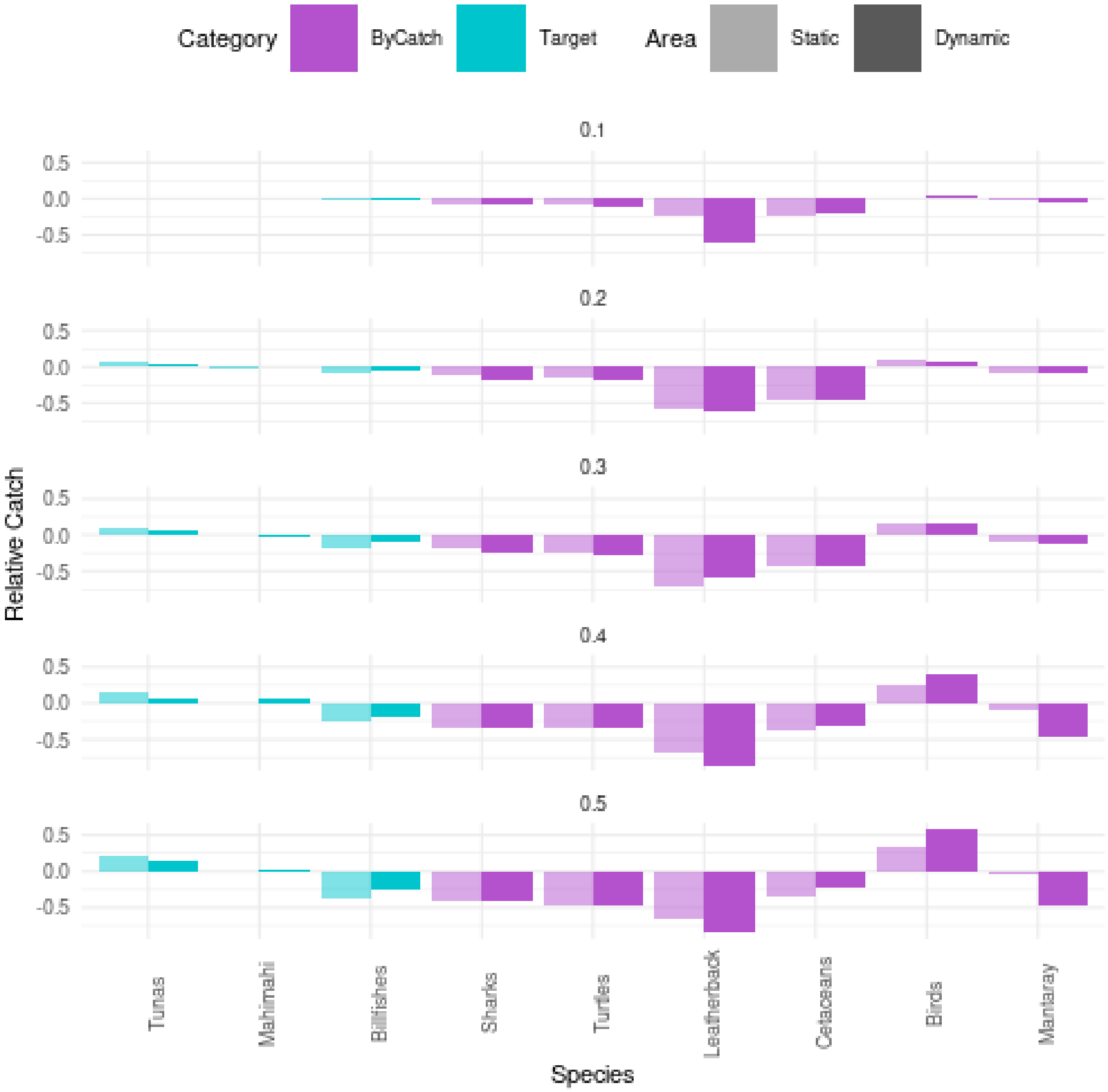


Fig. S9. Results from the mosaic area closures when effort remains constant for the tuna/mahi-mahi fishery in the Eastern Pacific. It shows predicted changes in target catch and bycatch species caused by dynamic and static area closures. Negative values refer to reductions in catch.

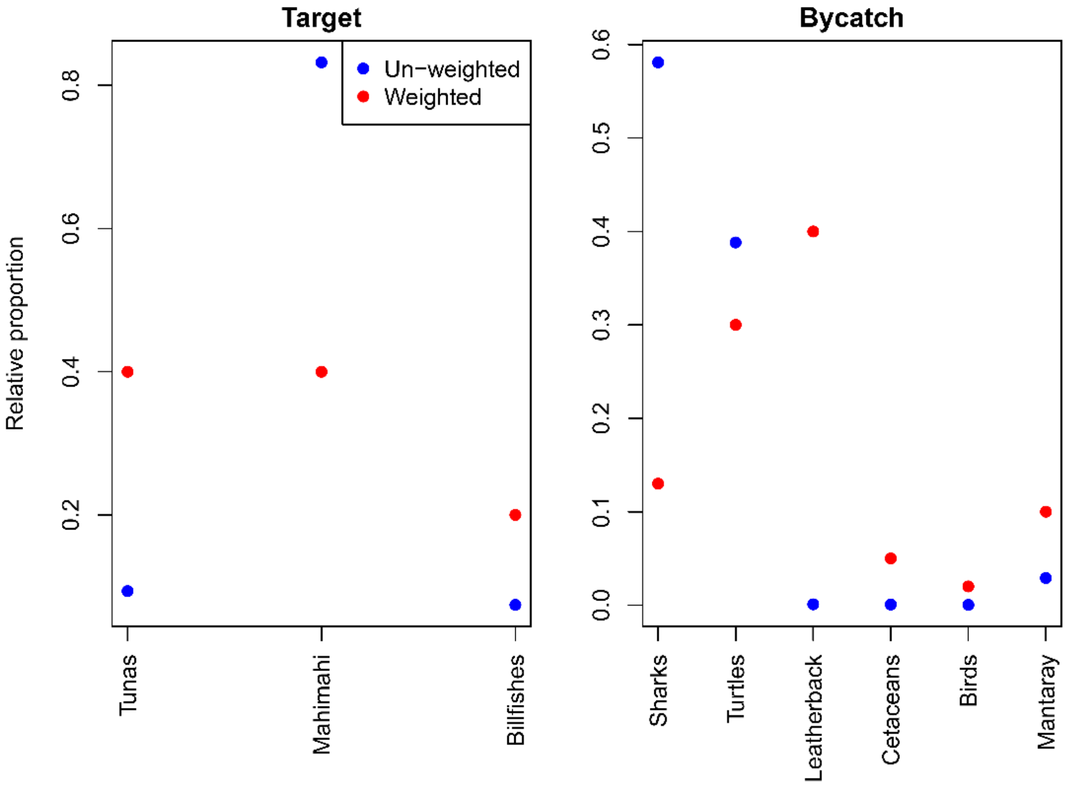


Fig. S10. Proportion of target and bycatch species to the total catch by group before weighting (blue dots) and after weighting (red dots).

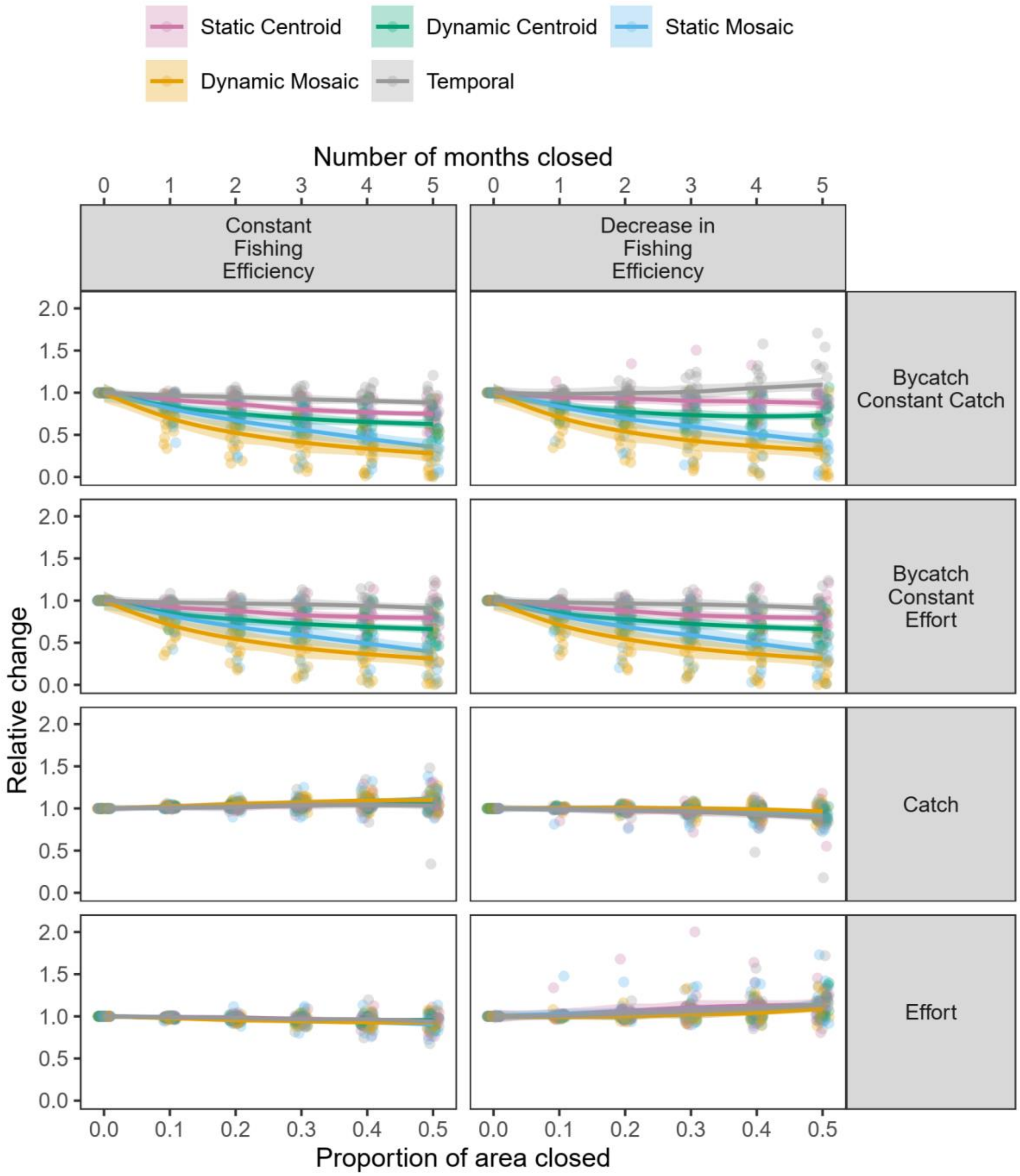


Fig. S11. Relative changes for each type of closure for bycatch (first row for constant catch scenario and second row for constant effort scenario); target catch, for constant effort scenario (third row panels); and effort, for constant catch scenario (bottom panels). Points represent individual case studies; lines are a smooth curve with the band around them representing one standard deviation. The column on the left represents when fishing efficiency remains constant, and the column on the right when fishing efficiency (target CPUE) decreases. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal closures, the number of months closed are represented on the secondary x-axis at the top (grey line only).

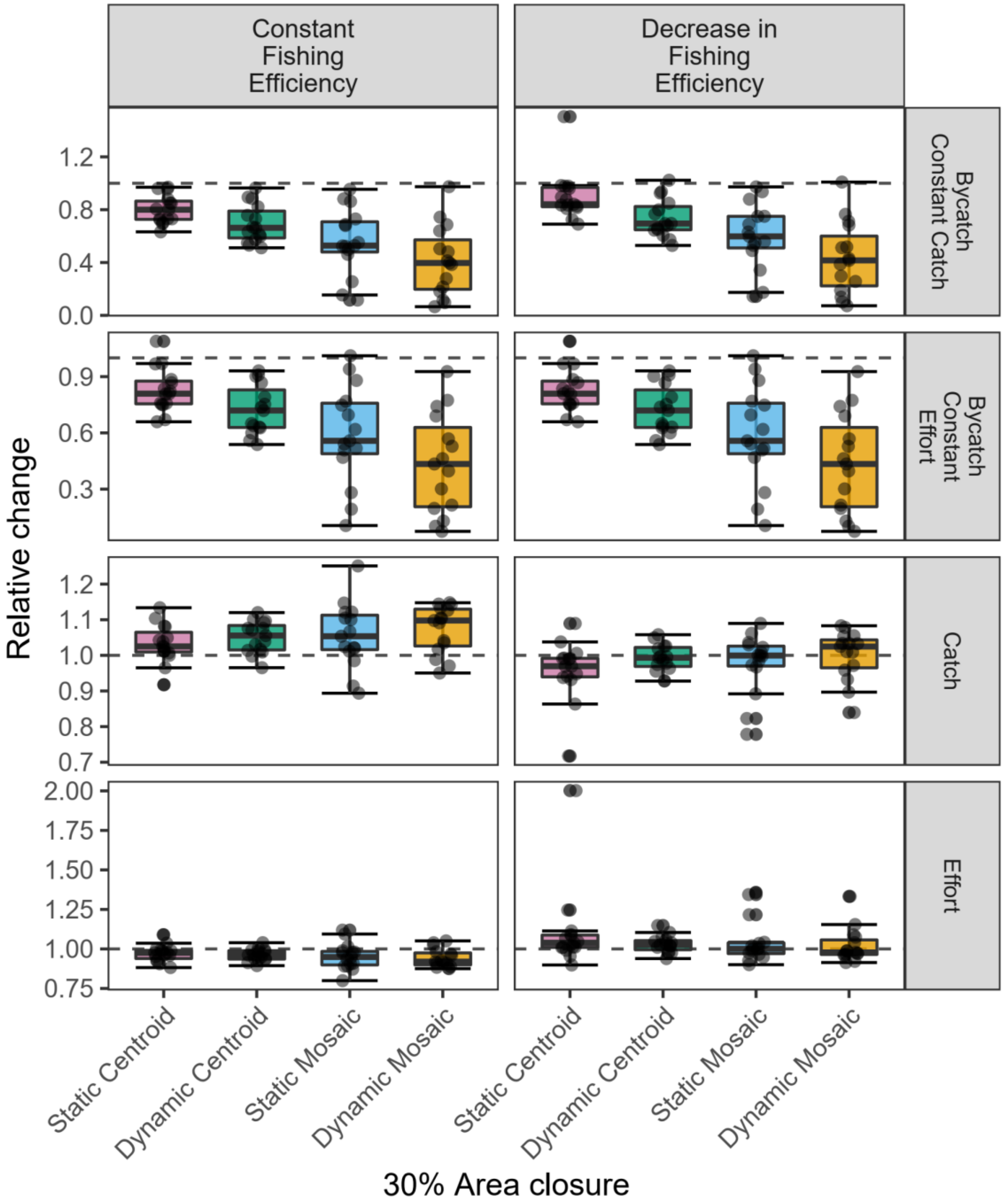


Fig. S12. Relative changes for each type of closure when closing 30% of the total area to fishing for bycatch (first row for constant catch scenario and second row for constant effort scenario); for target catch, for constant effort scenario (third row panels); and for effort, for constant catch scenario (bottom panels). The column on the left represents when fishing efficiency remains unchanged, and the column on the right when fishing efficiency decreases. The box represents the quartiles (25, 50, 75 percentiles) where 50% (horizontal line in the box) is the median. The upper whisker is the maximum value of the data that is within 1.5 times the interquartile range over the 75th percentile. The lower whisker is the minimum value of the data that is within 1.5 times the interquartile range under the 25th percentile. Each case study is represented by the grey dots. The horizontal dashed line is the status quo.

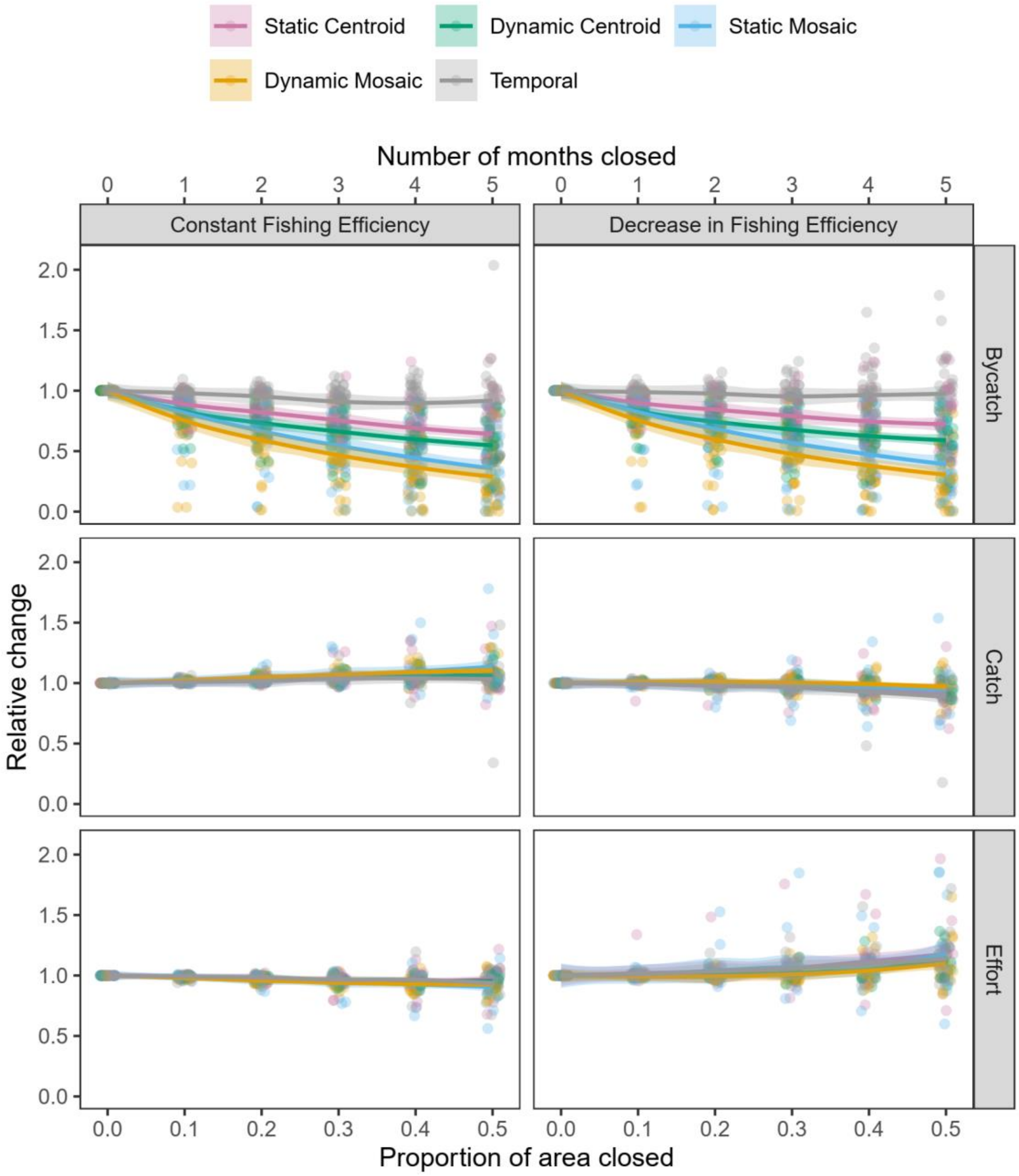


Fig. S13. Analogous to Fig. 3 in the main manuscript but without using weights. It shows the relative changes for each type of closure for bycatch (top panels); target catch, when total effort remains constant (middle panels); and effort, when total catch remains constant (bottom panels). For bycatch relative changes both scenarios, when target catch remains constant, and effort remains constant were combined for simplicity and because there were almost no differences between them. The columns on the left represents when fishing efficiency remains constant, and the columns on the right when fishing efficiency decreases. The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top. There are no large visual differences with Fig. 3 when using weights for each species or group of species.

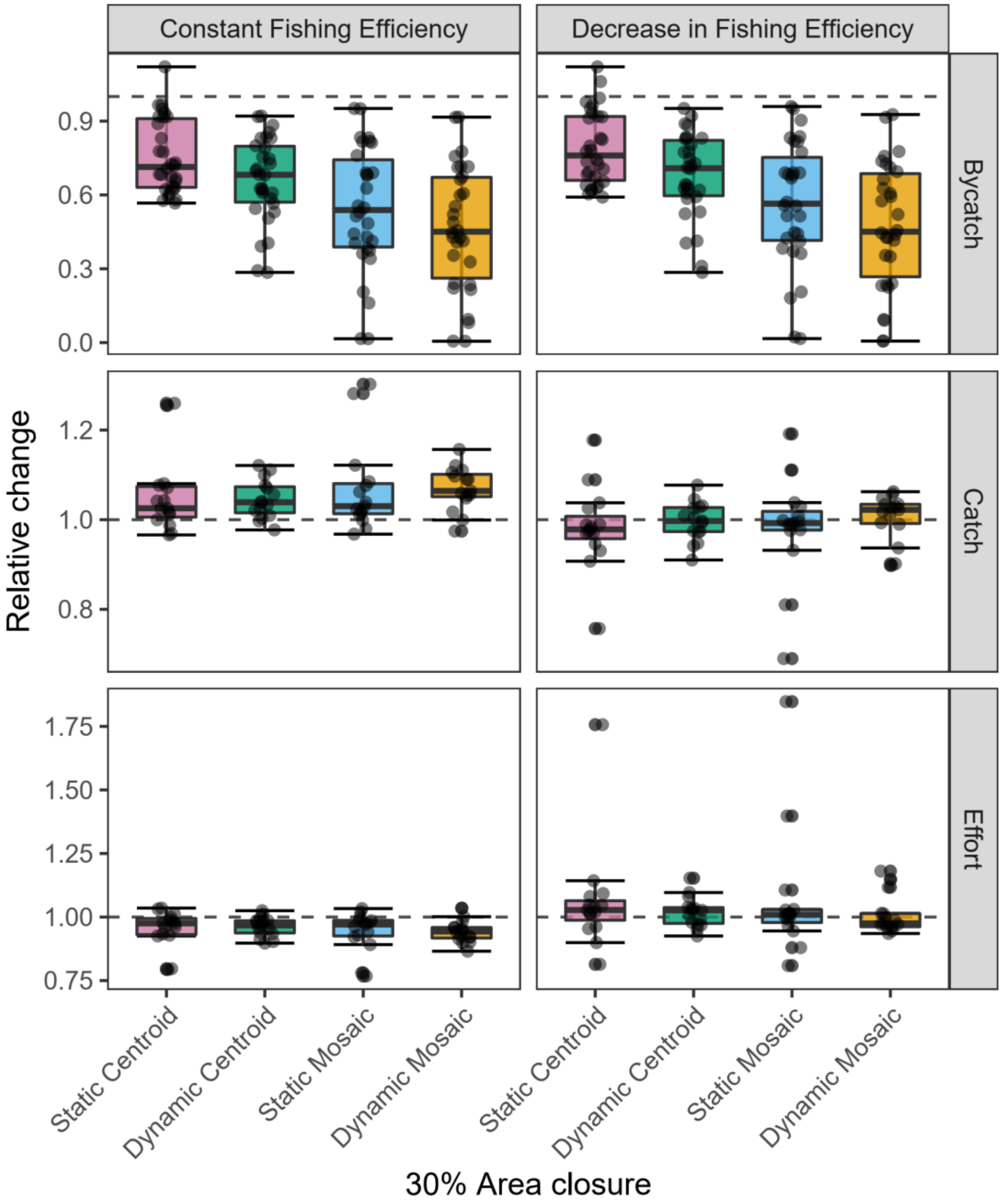


Fig. S14. Analogous to Fig. 4 in the main manuscript but without using weights. It shows the relative changes for each type of closure when closing 30% of the total area to fishing for bycatch (top panels); target catch, when total effort remains constant (middle panels); and effort, when total catch remains constant (bottom panels). For bycatch relative changes both scenarios, when target catch remains constant, and effort remains constant were combined for simplicity and because there were almost no differences between them. The column on the left represents when fishing efficiency remain unchanged, and the column on the right when fishing efficiency decreases. The box represents the quartiles (25, 50, 75 percentiles) where 50% (horizontal line in the box) is the median. The upper whisker is the maximum value of the data that is within 1.5 times the interquartile range over the 75th percentile. The lower whisker is the minimum value of the data that is within 1.5 times the interquartile range under the 25th percentile. Each data point is represented by the grey dots. There are no large visual differences with Fig. 4 when using weights for each species or group of species.

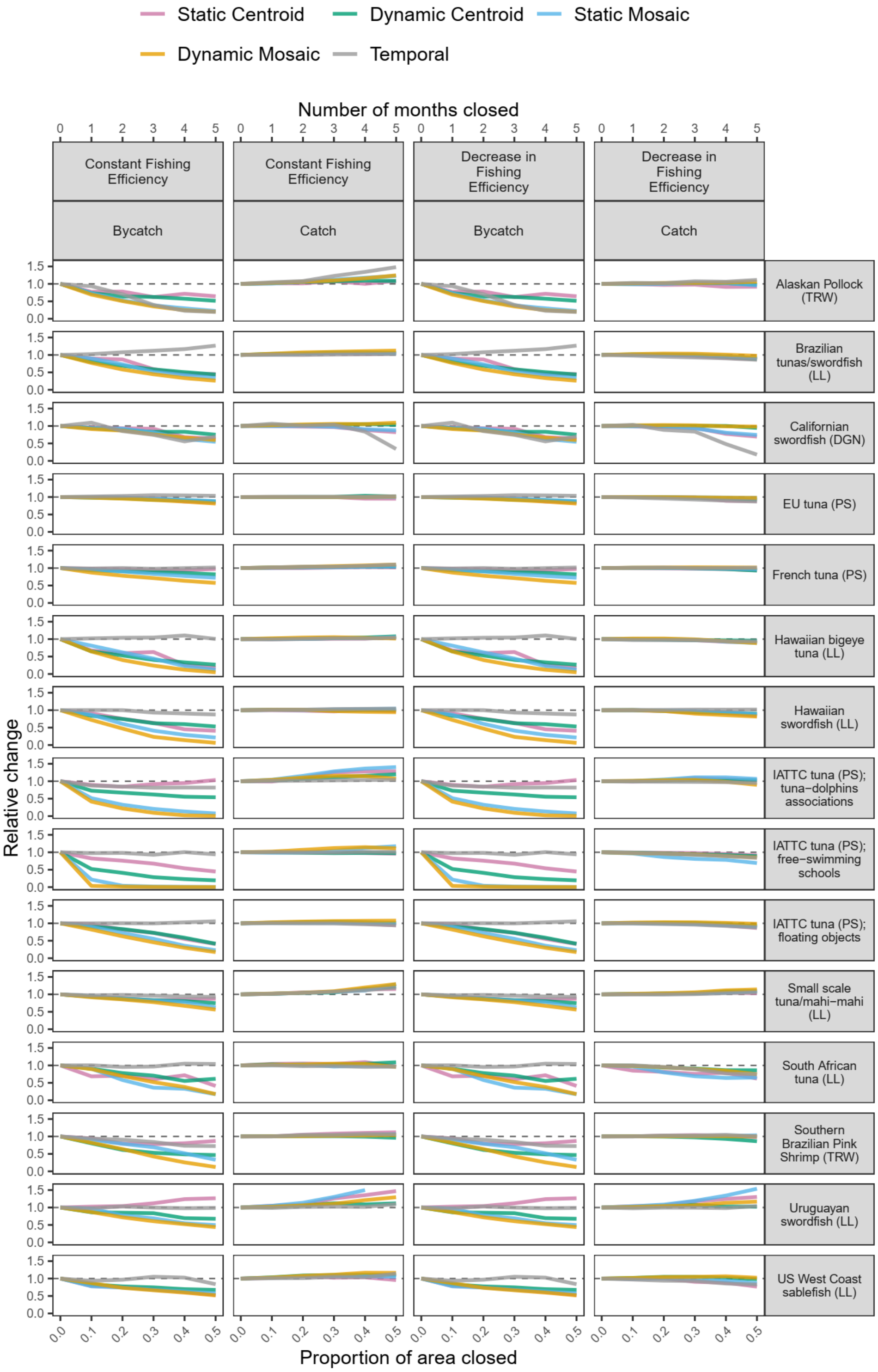


Fig. S15. Analogous to Fig. 5 but without using weights. Relative changes for each type of closure and each case study (rows) for total bycatch and catch of target species. These results are for the scenarios when total effort remains constant and fishing efficiency decreases (panels on the right) or remains constant (panels on the left). The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top. There are no large visual differences with Fig. 5 when using weights for each species or group of species.

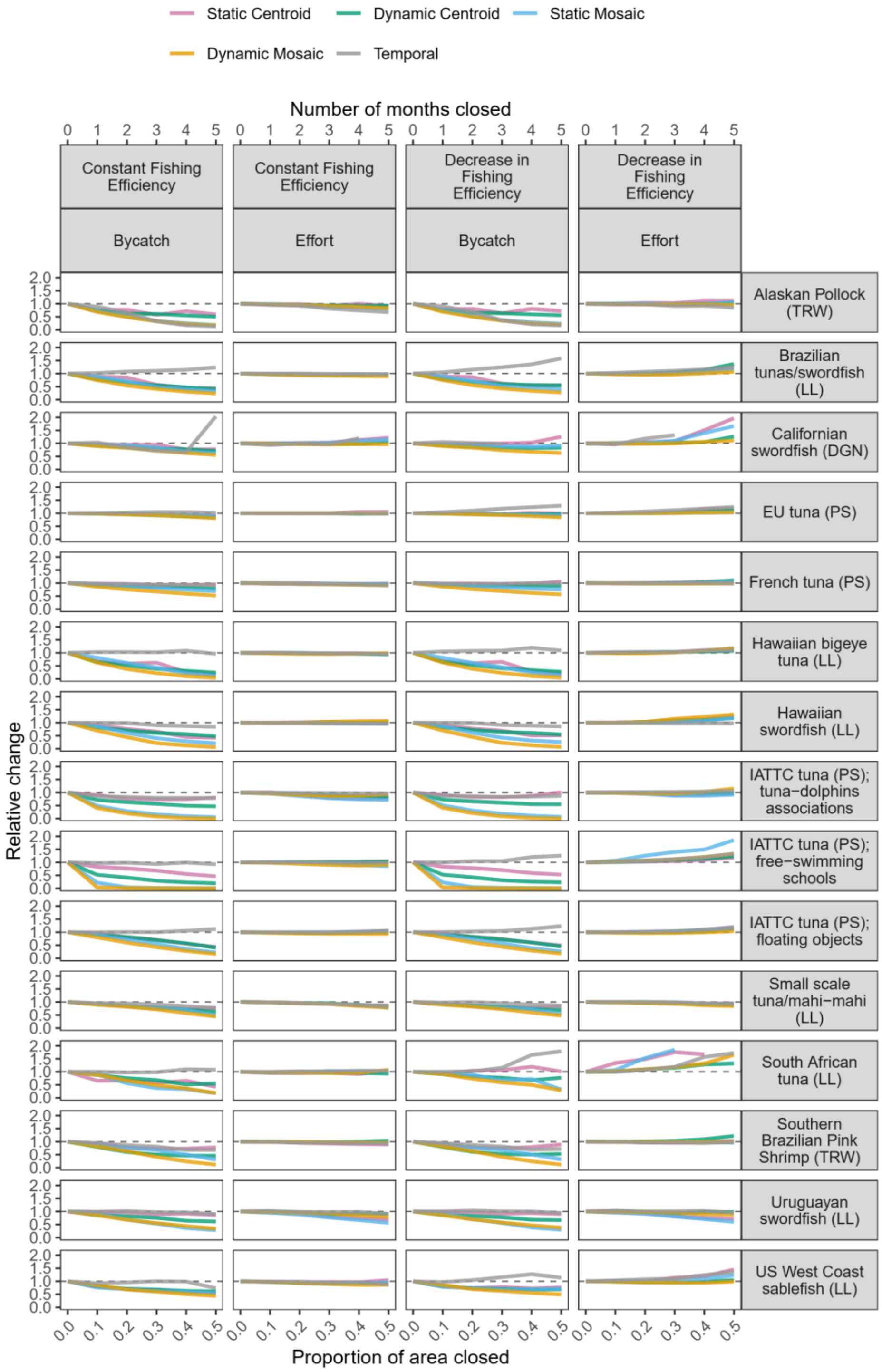


Fig. S16. Analogous to Fig. 6 in the main manuscript but without using weights. Relative changes for each type of closure and each case study (rows) for total bycatch and effort. These results are for the scenarios when total catch of target species remains constant and fishing efficiency decreases (panels on the right) or remains constant (panels on the left). The primary x-axis shows the proportion of area closed from 0.1 or 10% to 0.5 or 50% of the fishing zone. For temporal or seasonal closures, the number of months closed are represented on the secondary x-axis at the top. There are no large visual differences with Fig. 6 when using weights for each species or group of species.

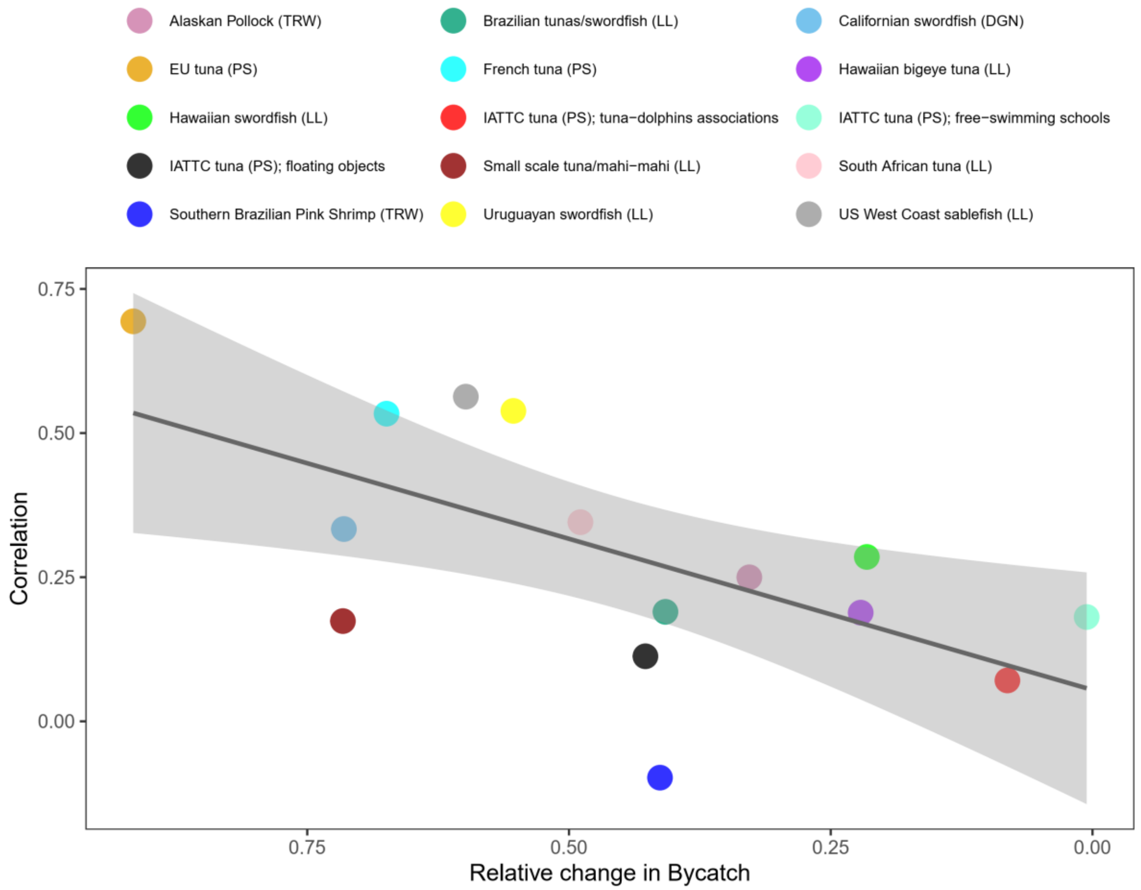


Fig. S17. Analogous to Fig. 7 in the main manuscript but without using weights. Relationship between bycatch reduction in the x-axis and correlation between total bycatch and total target species on the y-axis. Each dot represents a different case study and this plot show, just as an example, the results from a 30% closed area around a centroid and static (traditional marine reserves or no-take MPA). The solid line represents a simple regression and the grey area the 95% confidence interval. There are no large visual differences with Fig. 7 when using weights for each species or group of species.

Table S1. Summary of all case studies considered in this manuscript.

	Name of the fishery	**Region**	**Gear**	**~ % fishing in EEZs vs international waters**	**Target species**	**Effort (units)**	**Main bycatch species**
1	Alaskan pollock	Alaska / Eastern Bering Sea	Pelagic trawl (TRW)	100% EEZ	Walleye pollock	Trawl duration (473,000 hours; 2011 - 2019)	Salmon
2	Brazilian tunas/swordfish	Occidental Atlantic Ocean	Longline (LL)	variable	Tunas and Swordfish	100,498,094 hooks	Sharks, Seabirds and Turtles
3	Californian swordfish	U.S. West Coast, typically Californian waters	Drift gillnet (DGN)	100% EEZ	Predominantly swordfish, but also some sharks and tuna	102,188 hours (total soak time)	Fish and sharks (common), marine mammals and turtles (rare)
4	EU tuna	Atlantic Ocean	Purse seine (PS)	~60% in areas beyond national jurisdictions	tunas	~ 80% of the total effort reported to ICCAT	Juvenile tuna species
5	French tuna	Indian Ocean	Purse seine (PS)	~ 57% in areas beyond national jurisdictions	tunas	13,965 fishing sets	Sharks, billfishes, and juvenile tuna species
6	Hawaiian bigeye tuna	North Pacific Ocean	Longline (LL)	variable	Bigeye tuna	144,550,998 hooks	Sharks
7	Hawaiian swordfish	North Pacific Ocean	Longline (LL)	variable	Swordfish	19,310,240 hooks	Sharks
8	IATTC tuna; tuna-dolphins associations	Eastern Pacific Ocean	Purse seine (PS) associated with dolphins	Mostly in areas beyond national jurisdictions	Primarily yellowfin tuna	152,860 fishing sets	Sharks, rays and billfish
9	IATTC tuna; free-swimming schools	Eastern Pacific Ocean	Purse seine (PS) on free tuna's schools	Mostly in areas beyond national jurisdictions	Primarily skipjack	130,794 fishing sets	Sharks, billfish, and bigeye
10	IATTC tuna; floating objects (FADs)	Eastern Pacific Ocean	Purse seine (PS) associated with FADs	Mostly in areas beyond national jurisdictions	Primarily skipjack and yellowfin tuna	83,048 fishing sets	Sharks, rays, and mobulids
11	Small scale tuna/mahi-mahi	Eastern Pacific Ocean	Longline (LL)	Mainly EEZs	Tunas and mahi-mahi	2,749,368 hooks	Sea turtles and sharks
12	South African tuna	South East Atlantic and South West Indian Ocean	Longline (LL)	variable	Tunas and swordfish	10,240,924 hooks	Pelagic sharks, seabirds
13	Southern Brazilian Pink Shrimp	South-occidental Atlantic ocean	Trawl (TRW)	100% EEZ	Pink shrimp	1,614,235 trawling hours	Demersal sharks, fish and crustaceans
14	Uruguayan swordfish	South West Atlantic Ocean	Longline (LL)	Mainly EEZ	Swordfish	3.5 million hooks	Sharks, Seabirds and Turtles
15	US West Coast sablefish	US West Coast	Longline (LL)	100% EEZ	Sablefish	327,866,210 hooks	fish, seabirds

Table S2. Changes in bycatch, target catch and effort for all scenarios when closing 30% of the area. Numbers are mean changes relative to no closures. So, 0.8 means 20% decrease in bycatch. Numbers above 1 indicate an increase. SD are presented between brackets.

Closure	Shape	Mobility		Constant effort		Constant Catch		
				Constant Fishing efficiency	Decreases in Fishing efficiency	Constant Fishing efficiency	Decreases in Fishing efficiency	Average
Area	**Centroid**	**Static**	**Bycatch**	0.83 (0.12)	0.83 (0.12)	0.80 (0.11)	0.90 (0.19)	**0.84**
			Target catch	1.03 (0.05)	0.96 (0.08)	NA	NA	**0.99**
			Effort	NA	NA	0.97 (0.05)	1.11 (0.26)	**1.04**
		Dynamic	**Bycatch**	0.72 (0.13)	0.72 (0.13)	0.69 (0.14)	0.74 (0.14)	**0.72**
			Target catch	1.05 (0.04)	0.99 (0.04)	NA	NA	**1.02**
			Effort	NA	NA	0.96 (0.04)	1.03 (0.05)	**0.99**
	Mosaic	**Static**	**Bycatch**	0.59 (0.27)	0.59 (0.26)	0.56 (0.25)	0.60 (0.25)	**0.58**
			Target catch	1.06 (0.07)	0.98 (0.09)	NA	NA	**1.02**
			Effort	NA	NA	0.95 (0.08)	1.05 (0.14)	**1.00**
		Dynamic	**Bycatch**	0.44 (0.28)	0.44 (0.27)	0.41 (0.27)	0.43 (0.27)	**0.43**
			Target catch	1.07 (0.07)	1.00 (0.07)	NA	NA	**1.03**
			Effort	NA	NA	0.94 (0.06)	1.02 (0.11)	**0.98**

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