INTER-AMERICAN TROPICAL TUNA COMMISSION

***AD-HOC* PERMANENT WORKING GROUP ON FADS**

8TH MEETING

La Jolla, California (USA)
07-08 June 2024

DOCUMENT FAD-08 INF-A

EVALUATE THE IMPACT OF ALTERNATIVE MANAGEMENT SCENARIOS FOR THE EASTERN PACIFIC OCEAN TROPICAL TUNA SPECIES USING POSEIDON

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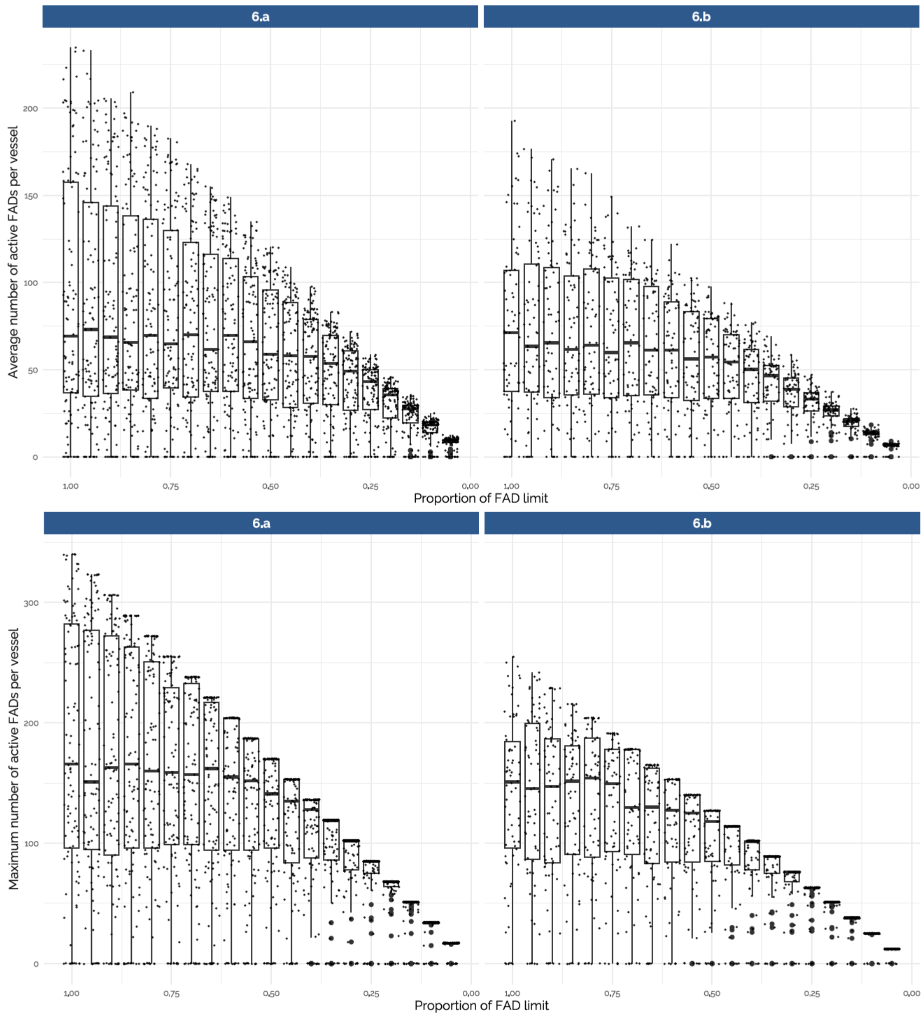
EXECUTIVE SUMMARY

- The eastern Pacific Ocean (EPO) tropical tuna purse-seine fishery catches bigeye tuna (BET), skipjack tuna (SKJ), and yellowfin tuna (YFT). It is a highly dynamic fishery that utilizes an evolving mix of technologies, among them the growing use of fish aggregating devices (FADs) since the early 1990s. Species and fishers' spatial temporal dynamics are strong drivers of this fishery.
- POSEIDON, a coupled agent-based bio-economic model, was adapted to represent the EPO tropical tuna purse seine fishery. The adaptive nature of the agents allows for the simulation and evaluation of complex management scenarios while assessing social, biological, and economic tradeoffs.
- The POSEIDON – EPO tuna model predicts fishery targets (e.g., number of sets, number of FADs) comparable to the IATTC observed data, thus, can be used to compare the impacts of different management scenario. The model predicts that reducing the percentage of active FADs per vessel to 80% of the 2023 active FAD limits in C-21-04 could significantly reduce ecological impacts associated with FADs, such as reduced strandings, while maintaining the total catch at levels consistent with those observed at the current active FAD limit.
- The model predicts that meaningfully reducing the biological impacts of FAD fishing on tropical tuna species populations would require large reductions in the active FAD limits, or regulations covering all three set types. Additionally, combining these measures with spatial regulations could be advisable, especially considering the non-uniform spatial distribution of the three tropical tuna species.



- Figure Summary: Impact of incrementally reducing the active FAD limit for Class 6a (>1200mt) and 6b (<1200mt) vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 (340)) on the distribution of average (top) and maximum (bottom) number of active FADs per vessel outputted by the model POSEIDON.
- Future work should explore the sensitivity of the outcomes to the calibrated FAD aggregation rates for BET and update the biology to reflect the most recent stock assessment year.

The results of this investigation were highly dependent on ecological assumptions (e.g., the aggregation process around the FADs) for which there is still significant uncertainty. As such, this investigation should be considered exploratory and not used for management advice in 2024. Further research will help reduce uncertainty about these ecological assumptions and help strengthen the POSEIDON model predictions.

2. POSEIDON-EPO TUNA AS A TOOL TO SIMULATE AND EVALUATE ALTERNATIVE MANAGEMENT SCENARIOS FOR THE PURSE-SEINE FISHERY

POSEIDON-EPO tuna was designed to assess the socio-economic and biological performance of management scenarios for the sustainability of EPO tropical tuna purse-seine fishery. The model constitutes of 6 modules representing fishers, environment, biology, FADs, market and management (Figure S1). Fishing vessels are modeled as individual ‘agents’ that operate according to a set of behavioral rules that are conditioned on fishing patterns present in the fishery. Simulated fishing agents adapt to the conditions presented in each scenario. The emergent behavior of the fishing agents can help to identify unintended consequences of management interventions and identify tradeoffs across social, ecological, and economic objectives for the fishery. Given the commission's interest in providing scientific advice for the FAD fishery (e.g., Resolution C-19-01, C-23-03), the IATTC staff and the POSEIDON team explored the following hypothetical FAD management scenarios and their effectiveness to achieve these goals, where each scenario corresponds to one level of FAD limit:

1. Simulate reductions of **current individual vessel active FAD limits (by vessel class)** at different levels.
2. Calculate the corresponding % **reduction in global and per vessels' number of active FADs monitored** and some other associated quantities/metrics of interest.
3. Compare two behavioral assumptions one where vessels operate at levels emergent from the POSEIDON model and one where the model pushes fishers to **function at the hypothetical management limits**.

1. Simulation configuration

For each simulation we start with a model calibration that adjusts parameters of the model such that values predicted by the model match the empirical fishery data from the year 2022 (SAC-14-INF-G). The calibrated model is a good fit to the observed data and shows a 2.33% mean error (Figure S2). For each management scenario simulation, the calibrated POSEIDON model is projected 1 year ahead (2023) which allows us to observe the reaction of the fishery to policy changes (see supplementary material for more detailed methods) (Table 3).

This POSEIDON calibration's base state assumes the current IATTC management requirements stating that CPCs shall ensure that purse-seine vessels flying their flag have not exceed the total number FADs, as defined in table 1 (consistent with Resolution C-21-04), active at any one time. In our simulations 100% of the active FAD limit for the forecasted year of 2023 is 340 for Class 6a vessels (>1,200m3) and 255 for Class 6b (<1200m3).

TABLE 1. CPCs allowed number of active FADs at any one time given the IATTC requirements.

Year	Class	Number of Active FADs
2022	Class 6.a (1,200m3 and greater)	400
	Class 6.b (<1,200m3)	270
	Class 4-5	110
	Class 1-3	66
2023	Class 6.a (1,200m3 and greater)	340
	Class 6.b (<1,200m3)	255
	Class 4-5	105
	Class 1-3	64

TABLE 2. Number of vessels used in the daily active FADs analysis in POSEIDON and from IATTC active FAD datasets references.

Vessels	6.b (<1,200m3)	6.a (>=1,200m3)	total
POSEIDON	70	109	179
IATTC (2018-2022, FAD-07-01)	50	65	115

TABLE 3. Simulation configuration of the 2023 model projection.

Total simulations	Assumptions	Scenarios	Stochasticity
160	Deploy at emergent rate from calibrated 2022 model	100 to 0 in 5% increment	8
160	Deploy at maximum rate	100 to 0 in 5% increment	8

The active FAD limits per vessel were reduced from current levels (100%) to zero at 5% intervals (resulting in 20 intervals). Each scenario corresponds to one policy level for which we ran 8 times to account for stochasticity. This is iterated for both behavioral assumptions (Table 3). This resulted in a total of 320 independent simulation runs complete in 16 hours.

All metrics are calculated by taking the average across the 8 stochastic runs for each scenario and assumption combination unless plotted with run variance.

2. Behavior assumptions

We tested two different behavioral assumptions with the POSEIDON model, which projects fishing patterns for 2023. In the first behavioral assumption, vessels deploy FADs at the calibrated rate based on 2021 spin up and 2022 knowledge. In the second behavioral assumption, the "maximize behavior" forces agents to maximize their deployment actions during the fishing planning phase so that vessels attempt to increase their number of active FADs to achieve the maximum allowed under the new hypothetical limits.

As part of the maximized behavior assumption, all vessels that did not use FADs at all in 2022 will continue to not use FADs. Additionally, all vessels with more active FADs than the regulation allows at the start of 2023 (Jan-01-2023) immediately deactivate the FADs with the lowest aggregated biomass. Thus, at the start of 2023, 100% of current FAD limit corresponds to 340 and 255 active FADs for vessel class 6.a and class 6.b respectively.

Both behavior assumptions were then tested against the same active FAD limit and management metrics such as the relationship between active FAD limits and the emergent effects on FAD sets, harvest rates, were developed.

3. RESULTS

1. Baseline conditions

To assess initial conditions, we compared the distribution of active FADs used per class 6 vessel for 2022 between the IATTC buoy data (submitted under Resolution C-21-04; see FAD-07-01 for details) and the

POSEIDON model output (Figure 1). There are slight differences in the two definitions for IATTC and POSEIDON of active FADs, however they remain comparable. According to IATTC definition (C-21-04) a FAD is considered active when it: a) is deployed at sea; and b) activation of the satellite buoy has occurred, and the satellite buoy is transmitting its location and is being tracked by the vessel, its owner, or operator. POSEIDON considers that every FAD deployed at sea is said to have an active satellite buoy transmitting and being tracked by the vessel, it's owner or operator. The distribution of active FADs in both IATTC buoy database (see FAD-07-01) and POSEIDON have most of vessels owning under 150 active FADs per vessel. Fewer vessels had 100 to 200 active FADs in the IATTC buoy databases. However, there are more vessels reaching 300 to 400 active FADs per vessel in the IATTC buoy dataset than in POSEIDON. This discrepancy may come from the model slightly underestimating the number of deployments (Table S2). Note that there is also a difference in number of vessels in class 6a and class 6b vessels between IATTC and POSEIDON (Figure 2, Table 2).

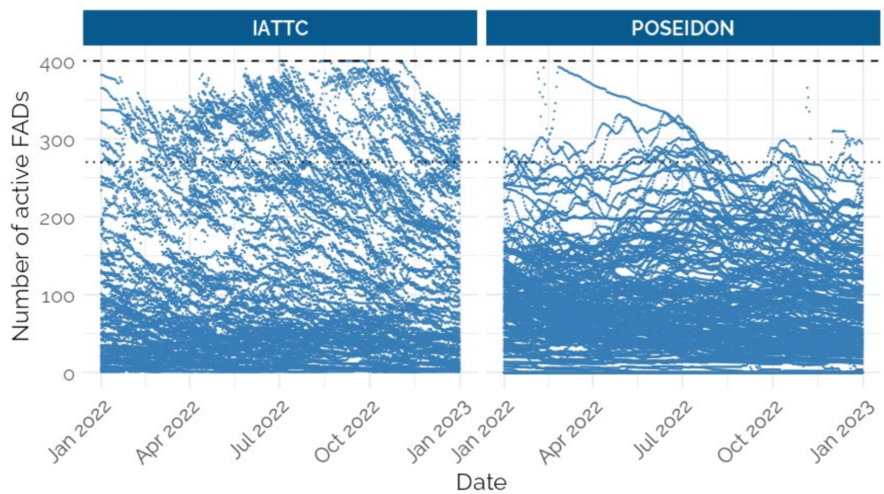


FIGURE 1. Daily active FAD levels comparison between IATTC and POSEIDON, per vessel and for class 6 in 2022. Points are used to show data reporting gaps. The dashed lines represent the limits in Resolution C-21-04 for class 6.a (dash) and class 6.b (point) in 2022.

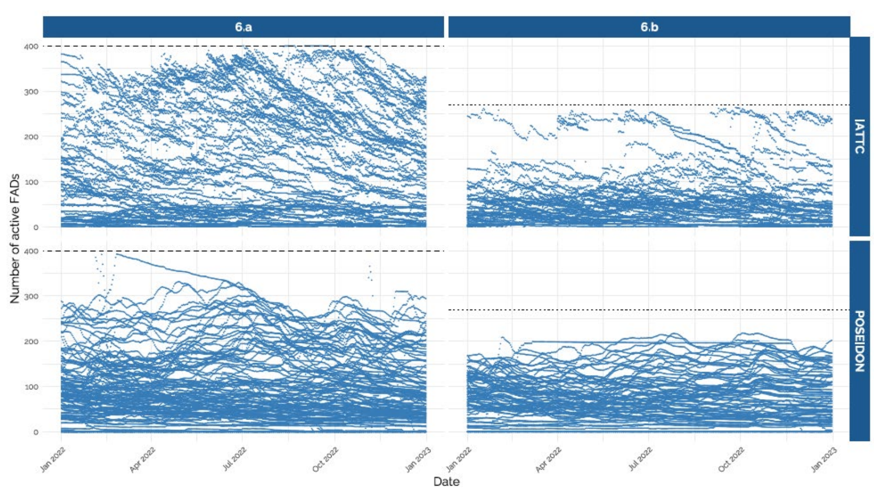


FIGURE 2. Daily active FAD levels comparison between IATTC buoy database and POSEIDON, per vessel and capacity Class 6.a and Class 6.b in 2022. Points are used to show data reporting gaps. The dashed lines represent the limits in Resolution C-21-04.

2. One year ahead projection

Relationship between active FAD limits and active FAD use

From 2022 the maximum trends between IATTC and POSEIDON active FADs are synchronous with respect to the maximum number of active FADs (Figure 3 right panel). The average number of active FADs bimonthly trends are similar. However, there is a difference in the annual trend and numbers of active FADs (Figure 3 left panel) due to the POSEIDON model slight underestimation of deployments. This gives us confidence in the maximum projected annual trends in 2023 for each management scenario with more reserve when it comes absolute average numbers per vessel. The predicted maximum number of active FADs per vessel decreases by 25 active FADs at 90% to plateau at 175 active FADs at 40% of current FADs limit. Then, decrementing equidistantly from 175 to 15 active FADs per vessels from 40% to 5% of current FADs limit respectively.

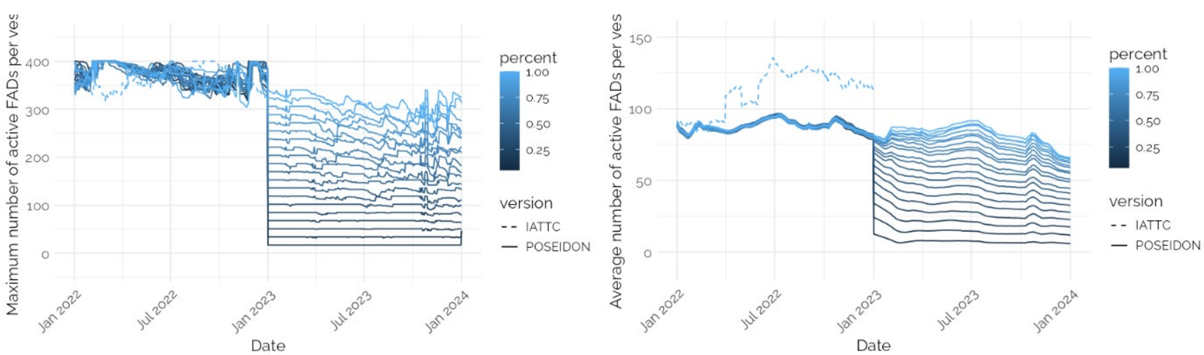


FIGURE 3. Class 6 comparison of average (left) and maximum (right) number of active FADs per vessel from IATTC data (in dashed line light blue) vs POSEIDON model (solid line) for the calibrated year 2022, and the projection year 2023 in response to all scenarios from 100% of current limit to 0% of current limit at 5% intervals.

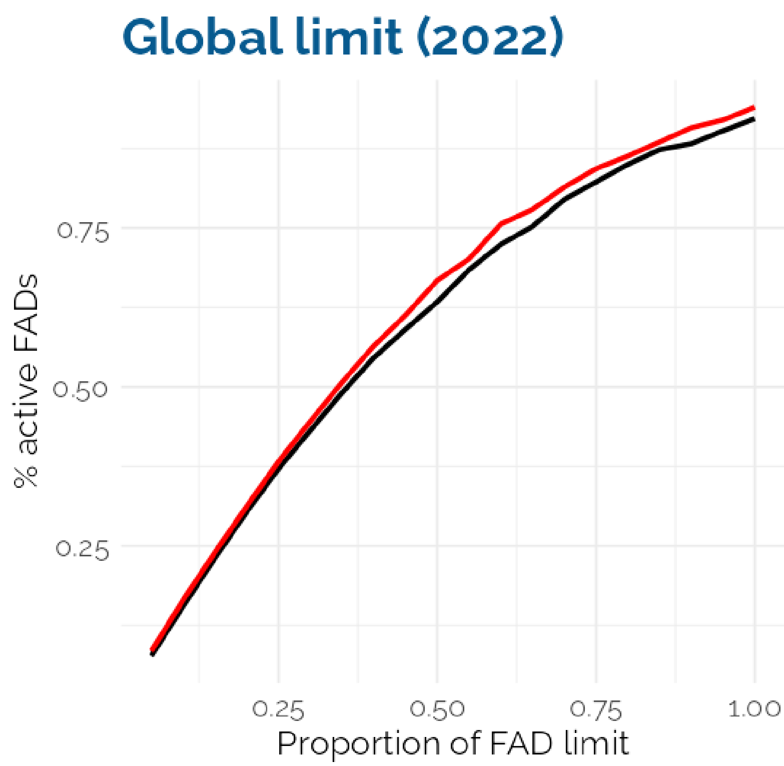


FIGURE 4. Impact of incrementally reducing the active FAD limit for Class 6 vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 in 2022) on the percentage of the total active FADs outputted from the model POSEIDON, calculated using the maximum (black) and average (red) number of active FADs per vessel.

To estimate the level of reduction in active FADs limit needed to achieve a desirable number of active FADs limit we computed the average and the mean of maximum active FAD as a function of the proportion of FAD limit (Figure 4). The average and maximum number of active FADs used per vessel is power proportional to the implemented FAD limit. For example, reducing the proportion of current FAD limit by 25% leads to approximately 12.5% and 10.2% reduction in maximum and average active FAD per class 6 vessel respectively (Figure 4) which corresponds to approximately 60 active FADs per class 6 vessel (Figure 5 right panel) when some boats will operate with the maximum number of 210 FADs (Figure 5 left panel). Figure 4 and 5 equivalent results for Class 6a and Class 6b vessels are available in Figure S9 and S10.

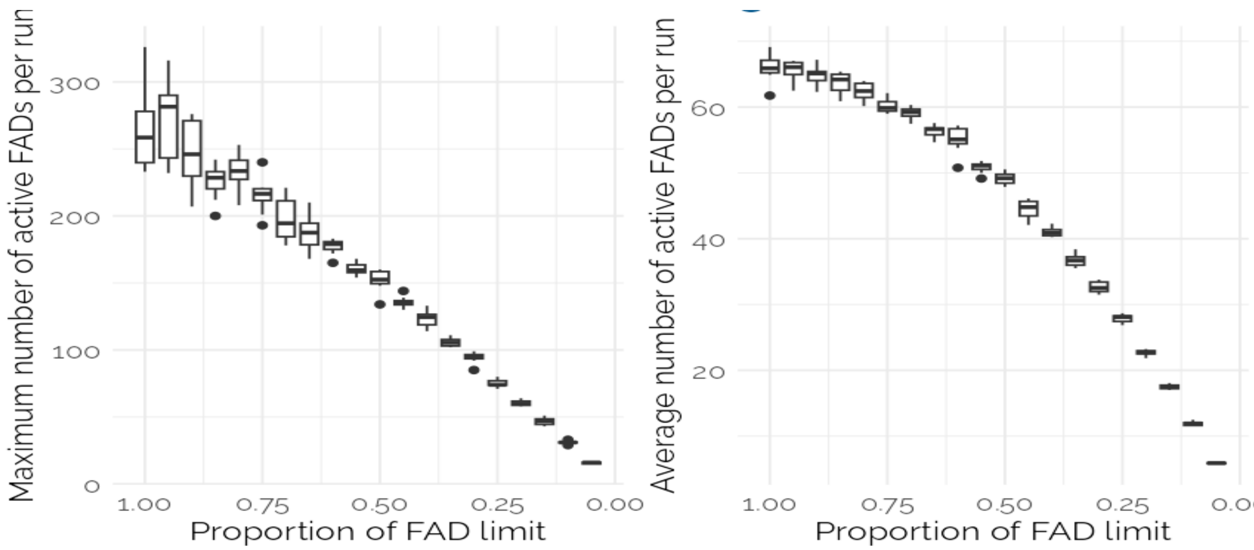


FIGURE 5. Impact of incrementally reducing the active FAD limit for Class 6 vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 in 2023) on the percentage of the average number of active FADs outputted from the model POSEIDON, calculated for each simulation run (n=8).

Effect of FAD limits on OBJ sets and catch

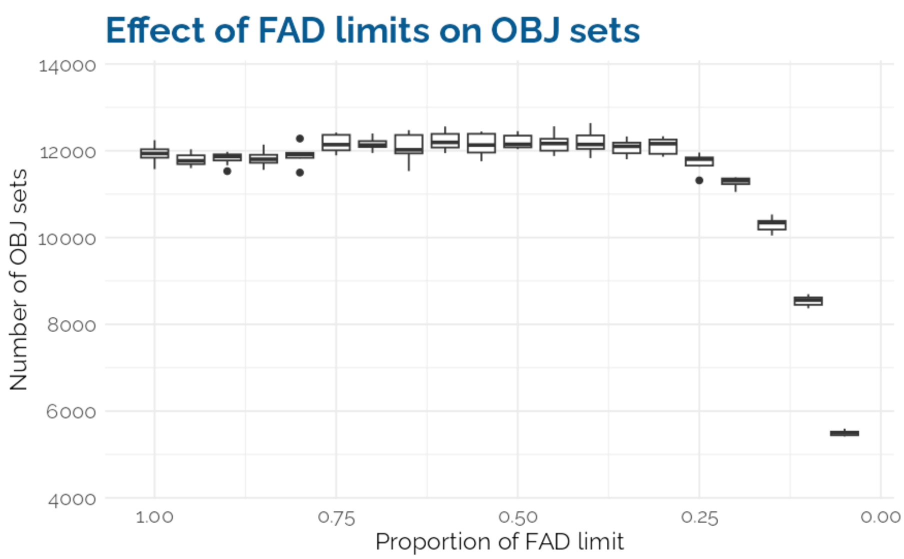


FIGURE 6. Impact of incrementally reducing the active FAD limit for Class 6 vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 in 2023) on the number of OBJ sets outputted by the model POSEIDON.

Unlike the relationship between FAD limits and active FADs, the relationship between FAD limits and OBJ sets was not linear. Simulations between 100% and 30% of current FAD limits all averaged roughly 12,000 OBJ sets. Reducing the FAD limit to between 30% to 5% of current active FADs limit results in a decline in number of object sets. There is little variation between simulation runs which shows stability in the model response to management scenarios (Figure 6).

Total catch remained stable from 100% to 75% of the current FAD limit then increases slowly to culminate at 30% of the current FAD limit. (Figure 7). At 25% of current limit leads to a decrease returning to current catch levels at 12.5% of current FAD limit. From 100% to 50% of the current FAD limit the catch composition remains stable with a majority of skipjack and yellowfin (Figure 7). However, from 50% to 20% the proportion of bigeye slowly increases while the proportion of skipjack slightly decreases.

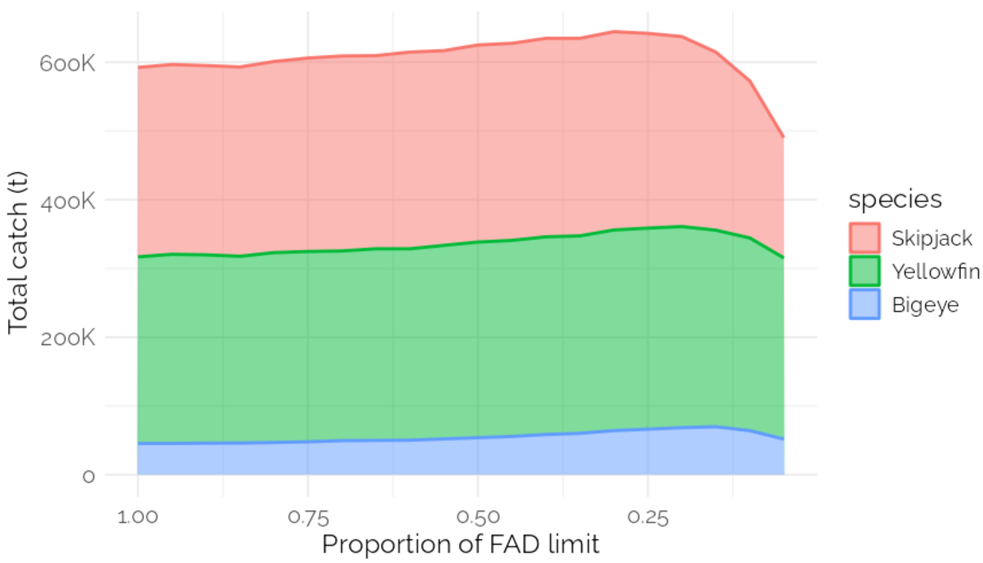


FIGURE 7. Impact of incrementally reducing the active FAD limit for Class 6 vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 in 2023 on the Total catch and catch composition of yellowfin, skipjack and bigeye.

3. Alternative behaviors

The objective of including an additional alternative assumption where fisher maximize their active FADs use, is to analyze the ecological, biological, and effort responses of the system when compelling fishers to operate their vessels at the maximum active FAD limit. By imposing this constraint, we aim to understand the implications on various aspects of the fishery ecosystem. Here we will compare the “default” behavior assumption and the "maximized” behavior assumption:

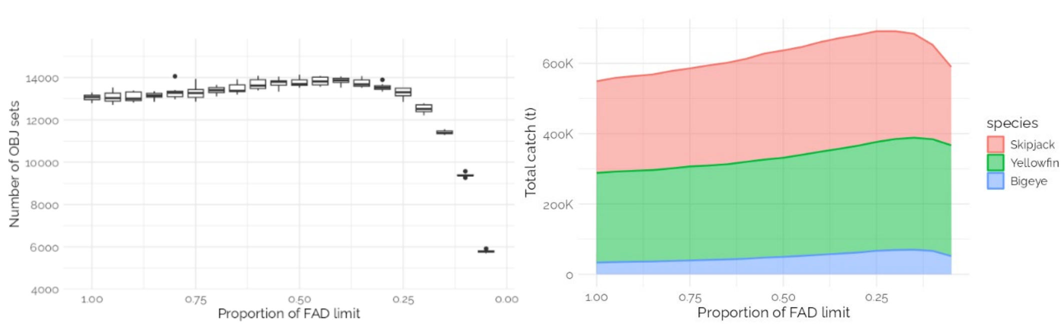


FIGURE 8. Impact of incrementally reducing the active FAD limit for Class 6 vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04 in 2023 on the number of sets outputted by the model POSEIDON (left) and on the total catch and catch composition of yellowfin, skipjack and bigeye (right) when FAD deployment behavior is maximized.

When FAD deployment behavior is maximized, the number of sets and total catch increases drastically culminating at 50% and 25% of current FAD limit respectively to then precipitate. Species composition seem to be having similar outcomes compared to the default behavior assumption.

4. DISCUSSION

As the FAD fishery continues to expand, the necessity for innovative management strategies becomes increasingly imperative. In response, the POSEIDON model was applied to the purse seine tropical tuna fishery (Vert-pre et al., 2023). This spatially explicit agent-based model serves multiple functions: firstly, it is capable of simulating reductions at various levels of current individual vessel active FAD limits and translate that into indicators for all three tropical tuna species simultaneously. Secondly, it facilitates the exploration of the corresponding percentage of reduction in global and per-vessel number of active FADs monitored. Lastly, it offers valuable insights into other associated quantities of interest within the fishery ecosystem including social, behavioral, and economic outcomes.

The model provides consistent annual trends for the year 2023 across various management scenarios, spanning from 100% to 0% of the current active FADs limit. We observe synchronous maximum trends in active FADs between the IATTC buoy database and POSEIDON datasets (Figure 3, left). The Poseidon average active FAD timeseries show variations in annual trends from IATTC, however the seasonal trends are similar as the daily active FADs exhibit variations derived from the two FAD fishing closure starting in end of July and in beginning of November, which mandates a cessation of FAD deployment 15 days prior to closure. Moreover, both the maximum and average number of active FADs per vessel is respectively directly and power proportional to the FAD limit in place (Figure 5). Thus, making implementing FAD limits an efficient way to reducing number of active FAD in the ocean. For example, a 25% reduction in the current FAD limit results in an approximately 12.5% reduction in maximum FADs per class 6 vessel (Figure 5), corresponding to around 60 active FADs per vessel (Figure 6, right), while some vessels may operate at the maximum of 210 FADs. However, it is important to note that not all vessels operate at maximum number of active FAD and thus are not all affected by the reduction in FAD limit. 58% of the vessel are affected from the reduction in limit from 2022 to 2023 and at 70% of 2022 current limit 68% of the vessel are affected and 90% of the vessel are affected when we reach 15% of 2022 FAD limit

For the following metrics all change is compared to the 2023 baseline. Reducing the proportion of active FADs per vessel by 20% of the current FAD limit presents a promising avenue for mitigating environmental impacts linked to FAD loss and stranding, while concurrently maintaining set numbers consistent with those observed at the current limit (Figure 8). Notably, Escalle et al. (2019) estimated that approximately 5.8% of all FAD trajectories in the Western Pacific Ocean. Though we do not have any scientific reference for stranding event in the EPO, there is an increasing interest to this issue. Implementing such an alternative measure could offer a significant step towards addressing this issue.

To address the biological impact on tropical species populations, managers have options to adjust the individual vessel FAD limit. One approach is to reduce the limit to 80% of the current FAD limit, where there is no discernible increase in FAD effort, or to lower it to 12.5% of the current limit, resulting in a significant decrease in effort and curtailing catch levels (Figure 9). Setting the individual vessel FAD limit between 75% and 12.5% of the current FAD limit triggers a shift in fishing behavior from FAD fishing to other types of sets (Figures S4 and S5), accompanied by a slight initial increase in object sets (Figure S6).

POSEIDON fishers undergo a detailed planning process before embarking on a trip, with trips aligning with observed trip lengths. During this planning phase, they can select from various fishing actions, including FAD, dolphin, and unassociated sets, as well as deployments. The behavior model prioritizes FAD sets, reflecting historical fishing patterns. However, when the number of available active FADS is reduced according to the limit, the total biomass under the FAD vulnerable to FAD fishing decreases, leading to an increase in ocean tiles. Consequently, FAD fishing becomes less profitable. To compensate, fishers increase the number of sets and progressively make more dolphin and unassociated sets (Figure S4), which in turn have higher catch rates for Bigeye tuna (BET) and Yellowfin Tuna (YFT).

In the behavioral assumption where all vessels utilize the maximum number of active FADs allowed, the increases in catch and effort between 75 and 12.5% of the current FAD limit become more pronounced. This understanding provides managers with insight into the potential worst-case scenario. To mitigate the shift in set types and prevent the increase in catch and effort within this range, newly implemented regulations should encompass all three set types.

Additionally, this transition in set types, coupled with the initial rise in effort in object sets, modifies the species catch composition (Figure S6). Consequently, the proportion of skipjack tuna caught from FAD sets declines slightly, while the proportion of Yellowfin tuna caught from Dolphin and Unassociated sets rises. However, the most substantial impact is on Bigeye tuna effort (OBJ sets) and catch, which increases as the model predicts that fishers move their OBJ effort to areas with higher density of Bigeye tuna in response to the FAD limits (Figure S8). The fishers in POSEIDON follow a pathfinding algorithm that is driven by a behavior algorithm, which posits that fishers target ocean tiles with the highest value per FAD present in the tile. This algorithm was the best of five algorithms to match fishers behavior for the EPO tropical tuna fishery. Moreover, the catchability of bigeye tuna was calibrated to be the highest among the three species followed by yellowfin tuna to match 2022 species specific tuna catch data. When there is less FADs in the water, there is less attraction competition between FADs which means that ocean tiles with high densities of bigeye and yellowfin will aggregate more biomass faster. As the number of FADs in the ocean decreases, the FAD value spatial distribution becomes less uniform, making the FADs in bigeye and yellowfin tuna-prone areas, particularly in the South, more appealing to fishers. This results in a concentration of fishing effort in these high-value areas. This relates to the ecological hypothesis of school fragmentation.

However, it's worth noting that the model tends to slightly overestimate total catch in the southern region, suggesting that the observed increase in catch may be overestimated. Nevertheless, according to the model mitigating impacts on Bigeye tuna would require managers to limit the number of active FADs per vessel to 12.5% of the current FAD limit or combine a smaller reduction in individual vessel FAD limit combine with spatial regulations or effort regulations. Moreover, while discrepancies arise in the precise definition of active FADs between the Inter-American Tropical Tuna Commission (IATTC) Resolution and the parameters set within the POSEIDON model, the definition remain comparable. According to IATTC definition, a FAD is considered active when it is both deployed and transmitting its location via satellite. In contrast, the POSEIDON model defines an active FAD more inclusively, considering any FAD deployed at sea as active under the assumption that a deployed FAD is always transmitting geolocation data to their respective vessel. Daily active FADs from IATTC datasets and the POSEIDON model reveal seasonal similarities but also discrepancies. Most of vessels in both data sources own under 90 active FADs per vessel. However, beyond this limit, the IATTC dataset shows less vessels with 100 to 200 active FADs and a greater number of vessels reaching 300 to 400 active FADs per vessel compared to the POSEIDON model (Figure 1). These variations emerge from the POSEIDON model slightly underestimating the number of deployments (Figure S2). Class 6.a and class 6.b represent distinct categories within the fishery, each with its own characteristics and operational dynamics.

While this report has primarily focused on ecological implications, it's important to note that additional figures pertaining to economic impacts and global harvest rates are available in the supplemental materials. By integrating both ecological and economic considerations, policymakers and stakeholders can gain a comprehensive understanding of the projected implications of various management scenarios on both environmental sustainability and economic viability. This holistic approach is useful for crafting wellrounded management strategies that promote the long-term health of marine ecosystems while also supporting the livelihoods of fishing communities and ensuring the resilience of the Eastern Pacific Tropical tuna fishery in the face of evolving environmental dynamics.

5. ASSUMPTIONS AND NEXT STEPS

The scenario presented here represents only one possible outcome according to current model specifications and configuration. POSEIDON can provide additional sensitivity analysis to model assumptions that can help map out the array of potential outcomes for a specific management strategy given the unknowns relating to FAD ecology and fishing behaviors. Two key assumptions would benefit from further testing within the model.

First, is the high bigeye and yellowfin aggregation rates. While the true aggregations rates of each species are unknown, the model calibrates this rate to match total catch and fishing behavior. To achieve the provided catch, deployment numbers, and given the numbers from the stock assessment, the simulated FADs must attract high levels of BET and YFT. These high aggregations rates cause high concentrations of BET and YFT which in turn drive up catch. While this is a very plausible effect of lower FAD densities, the magnitude of those aggregations could represent an upper bound of BET aggregation. Future work should understand why the calibration tends to attract BET at a very high rate given the data inputs and sensitivity test the model outcomes at different aggregation rates which will better characterize uncertainty in the model predictions.

Second, this model configuration uses a trip planning algorithm where fishers target ocean tiles with the highest average value per FAD present in the tile. In the situation where we have high aggregation of BET, and very low numbers of FADs in a tile (at low FAD limits) this may concentrate many fish on very few FADs. This may cause an over-targeting areas of BET rich FADs as fishers could, in theory, choose to fish a square with only one BET rich FAD as the average will be higher than a square with many medium BET biomass FADs. Additional sensitivity testing on the aggregations, understanding the magnitude of BET targeting in the model, and further behavioral testing can disentangle this effect.

Last the POSEIDON-EPO tuna model researchers and IATTC staff have identified the following tasks to occur for the next management cycle:

- Update the model using 2023-2024 data
- Run spatial management scenarios.
- Economic model - integrate supply chain module and dynamic ex-vessel port prices.

6. ACKNOWLEDGEMENT

In addition to the authors listed, we are grateful for the contributions of the following individuals who supported the development of the POSEIDON-EPO tuna model. We thank the fishers and the following companies for contributing their knowledge: Ugavi, Nirsa, Atunera Dullarra, Delipesca and Albacora. From ISSF, Victor Estrepo; from AZTI, Jefferson Murua; from the FAD Advisory Group: Laurent Dagorn, Manuela Capello, Joe Scutt Phillips, Laurianne Escalle, Josu Santiago; and from the Economic Advisory Group: Patrice Guillotreau, Elizabeth Havice, Liam Campling, Santiago Buccaram; and from ATUNA, Giacinto Bottone. This work was supported by the Gordon and Betty Moore Foundation (Grant #4850.02).

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8. SUPPLEMENTAL MATERIALS

1. Information on model configuration

POSEIDON is a coupled agent-based bio-economic model (ABM) that simulates fishery vessel behaviors and evaluates the impacts of social, biological, and economic effects on the system (*Bailey et al., 2019*). It evaluates the performance of fishery management scenarios and associated tradeoffs against desired objectives by coupling traditional policy and marine biology modeling layers with an adaptive agent-based layer of fishing vessels. The use of individual agents can depict the heterogeneous responses of fishers in the system *(Carrella et al., 2020)*.

The POSEIDON framework is being adapted to represent the EPO tropical tuna fishery to achieve the following goals 1) Assess the performance (economic and biological) of alternative management scenarios for the sustainability of tropical tuna purse seine fisheries in the Eastern Pacific Ocean (EPO). 2) Expanding tools and enhancing scientific staff efficiency by automating routine evaluation of alternative management scenarios; and 3) Expand analytical capabilities related to the management of fish aggregating devices (FADs).

The POSEIDON-EPO tuna model consists of six modules that represent different aspects of the purse seine fishery (Figure S1). The modeling domain spans the entire EPO region for the tropical tuna fisheries and represents BET, SKJ, and YFT. Fleet data were input to establish the spatial configuration of the model and information such as port location, vessel properties, time at port, operating costs, and fish prices were used to initialize the model for class 6 purse seine vessels. Additional sources of catch and mortality from class 1-5 purse seine and longline vessels were included as exogenous factors in the model and their behaviors were not modeled explicitly. Supplemental information on the different components of POSEIDON is provided in Section VI.

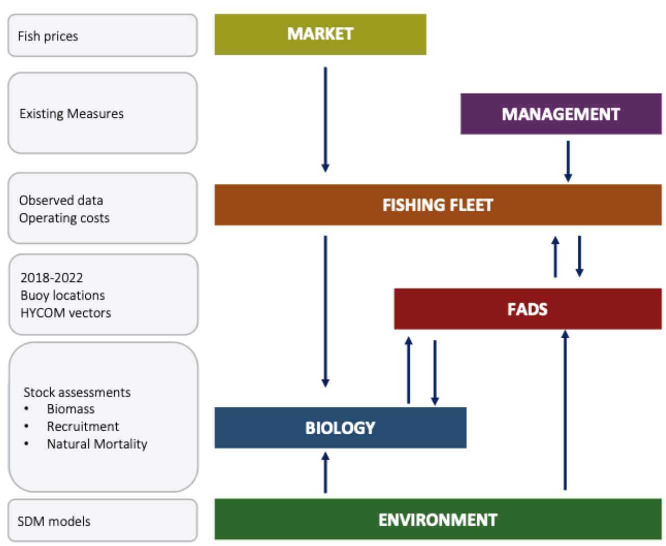

FIGURE S1. Schematic diagram of the six POSEIDON-EPO tuna modules and some examples of the data used to inform them.

<u>**Biology and Environment**</u>

An age-structured biological model for BET, SKJ, YFT was implemented using the most recent stock assessment information, which included 2022 assessments for SKJ and BET, and 2023 for YFT (Maunder, 2022; Xu, 2022; Minte-Vera, 2023). Most biological parameters were extracted directly from SS3 including selectivity, number of fish per quarterly age bin, maturity, natural mortality, and longline mortality. Fishing mortalities by quarterly age bins and by sex for each gear type (OBJ, NOA, DEL) and vessel type (class 6, all other vessels) were calculated using the size at age bins from the stock assessments, and the observed catch per length bin for each gear type provided by IATTC. Tuna biomass was spatialized using boosted regression tree species distribution models to predict relative habitability maps for adult and juvenile tuna following the methods of Lopez *et al*. (2019).

FADs

Vessels adaptively deploy FADs into 1 x 1 degree ocean cells based on historical deployment locations. A statistical FAD drift model was implemented in POSEIDON-EPO tuna which allows for a faster computation model than Langrangian methods. A 24-hour bilinear interpolation drift model was developed by comparing a series of drift models over the start and stop location of seven experimental samples of anonymized buoy data over a 30- and 90- day period (Powers *et al.*, in progress) against hourly HYCOM (Metzger *et al.*, 2017) velocity vectors estimated using an iterative interpolation.

Aggregation of fish around the FADs is a linear function of the abundance of the fish in the cell occupied by the FAD. The number of fish aggregated by the FAD is determined by age and sex selectivity, and the calibrated daily hazard rate applied randomly to each FAD. The carrying capacities of the FADs are inferred from IATTC data, using the biggest set size observed during the 2017-2023 period (456t). Aggregation rates, or the rate at which tuna are aggregated to a FAD occupying an ocean cell, for all three species are also calibrated terms.

Fisher Behavior

Fisher behavior within the model is driven by a planning strategy in which fishers try to establish which actions they intend to execute in which locations. The choice of these actions is conditioned by historical (2022) preferences of the fishers, derived from the observer database.

Several behavioral algorithms were assessed that use different perceived value metrics on where agents target their effort. The current best fitting behavioral model uses a Value Per Set (VPS) destination strategy as part of a path-planning algorithm to plan a trip. The VPS algorithm computes the average value per set in a localized area by computing the total amount of expected revenue of fish under the FADs divided by the number of FADs in that area, resulting in the average value per set of that ocean cell. The path-planning algorithm then uses the VPS algorithm to plan and revise a fishing route on regular intervals until the hold is full and the vessel returns to port.

Economics

Vessels incur daily operating costs that vary with vessel size and are inferred from Anastacio and Bucaram (2017). Annual price per ton for each of the three species is used to estimate expected revenue and profits for each FAD. A supply chain model is currently under development which will allow for testing the impacts of changes to the global supply chains and prices on the EPO tropical tuna fishery om addition to providing dynamic port-specific price estimates. Due to the global nature of the tuna market and assumptions related to imports from WCPO, the model's dynamic prices are not sensitive to overall EPO catch. The economic model uses BACI trade data (2022), international transport costs (UNCTAD 2021), tariff rates (WTO 2022), national processor capacity estimates (FAO 2008), and tuna product prices (FAO 2022).

Calibration and Diagnostics

Most simulation parameters are empirical, including those related to vessel characteristics, time at port between trips, and maximum catch under the FADs. The remaining parameters, referred to as free parameters because they are unknown, were tuned by the model. There are currently 16 FAD-related and 14 fisher behavior-related free parameters. These generally inform the FAD aggregation rate or intervene in the individual choices the fishing agents make, such as the frequency at which fishers update their fishing plan.

The following calibration process was used to estimate free parameters. First, plausible ranges for all free parameters were identified. Each parameter is given soft bounds between which initial values are randomly selected for the calibration, and hard bounds constraining the final calibrated parameter values. Bounds were informed by empirical evidence, analysis and statistical justification. Second, calibration targets using values that are known from the empirical data were identified. Lastly, a search algorithm (Streicher 2005) was used to explore the space of free parameters and identify a combination that produced values as close as possible to the calibration targets when running the simulation.

Calibration Results

The model was calibrated against 2022 observer data. This is the most recent year with a complete dataset at the start of the project. Targets used for calibration included total landings, timing and number of actions, trip durations, setting on own versus other FADs, and dolphin settings. Additionally, targets related to deviance from catch size distributions have been added in order that observed catch size distributions would emerge from the combination of species catchability, release hazard rates and other FAD related free parameters.

The resulting model was able to fit targets for the entire EPO such as the number of FAD actions (own FADs, others FADs, unassociated sets, FAD deployments, and dolphin sets), catches of all three species (own FADs, others FADs, unassociated, and dolphin sets), total catches (BET, SKJ, YFT), trip duration, and average hours out from observer data with low (<10%) error (Figure S2). Spatial fishing patterns and timing were realistic. However, FAD fishing effort north of the equator and on the western boundary of the EPO area tended to be underestimated. Additionally, the model was able to capture the patterns of deployment and FAD set regions for each of the fishing fleet clusters identified by Lennert-Cody (2018), indicating the model can capture the various fishing strategies of the fleet (Figure S3).

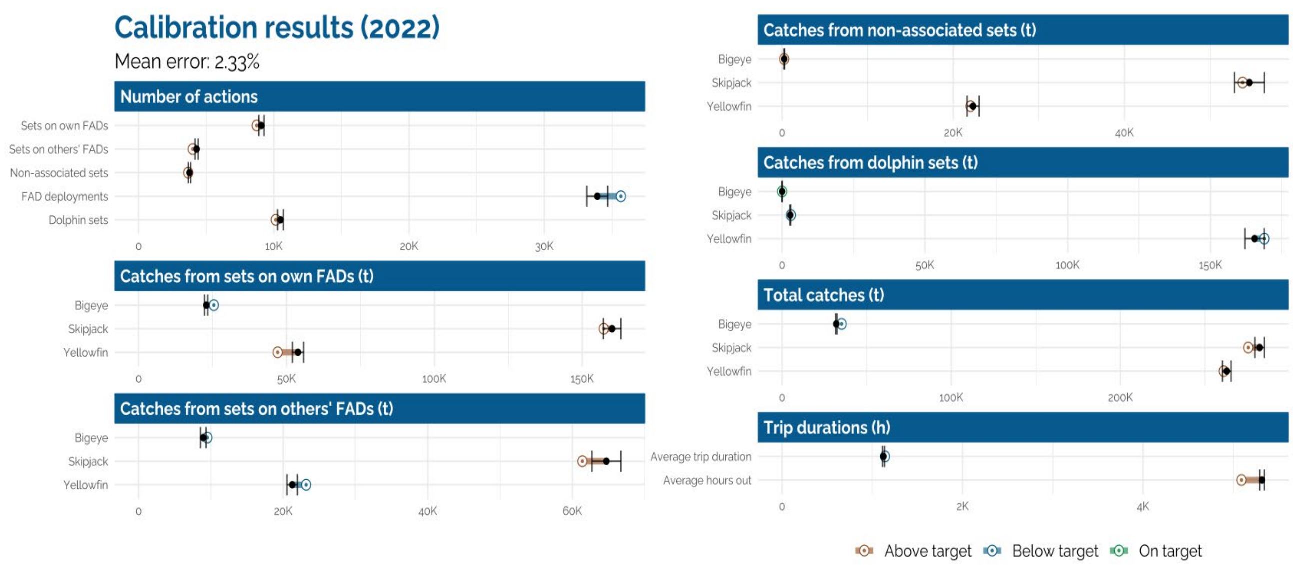

FIGURE S2. Calibration results of the most recent POSEIDON-EPO tuna model resulting in a mean calibration error of 2.33% for the core targets. For each calibration target, the bullseye represents the target value derived from observer data and the black point and range represent the calibration model outcomes.

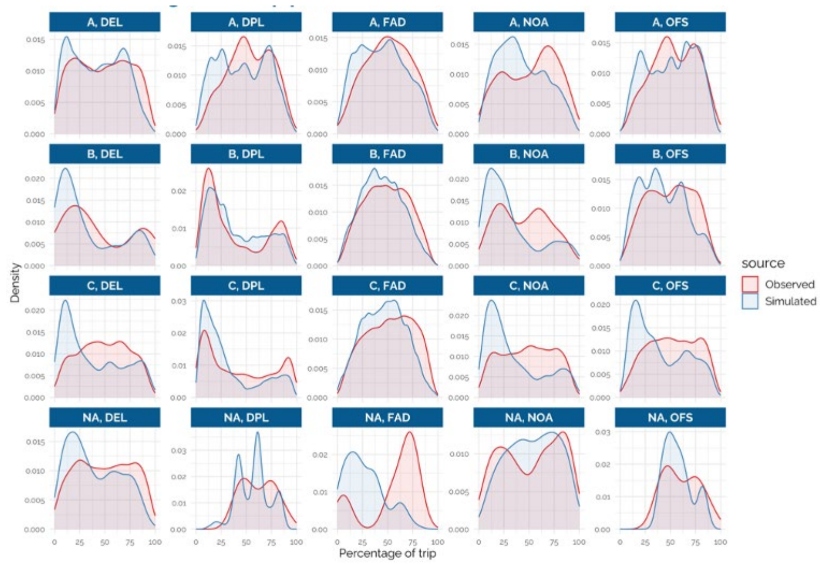

FIGURE S3. Comparison of observed and modeled timing of purse seine fishing actions (dolphin set (DEL), deployment (DPL), FAD set (FAD), unassociated set (NOA), and set on other FADs (OFS)) for each of the vessel cluster types identified by the 2022 updated analysis of Lennert-Cody (2018). Trip duration is standardized as a percentage of total trip length as individual trips will have different total durations.

2. Supplemental figures

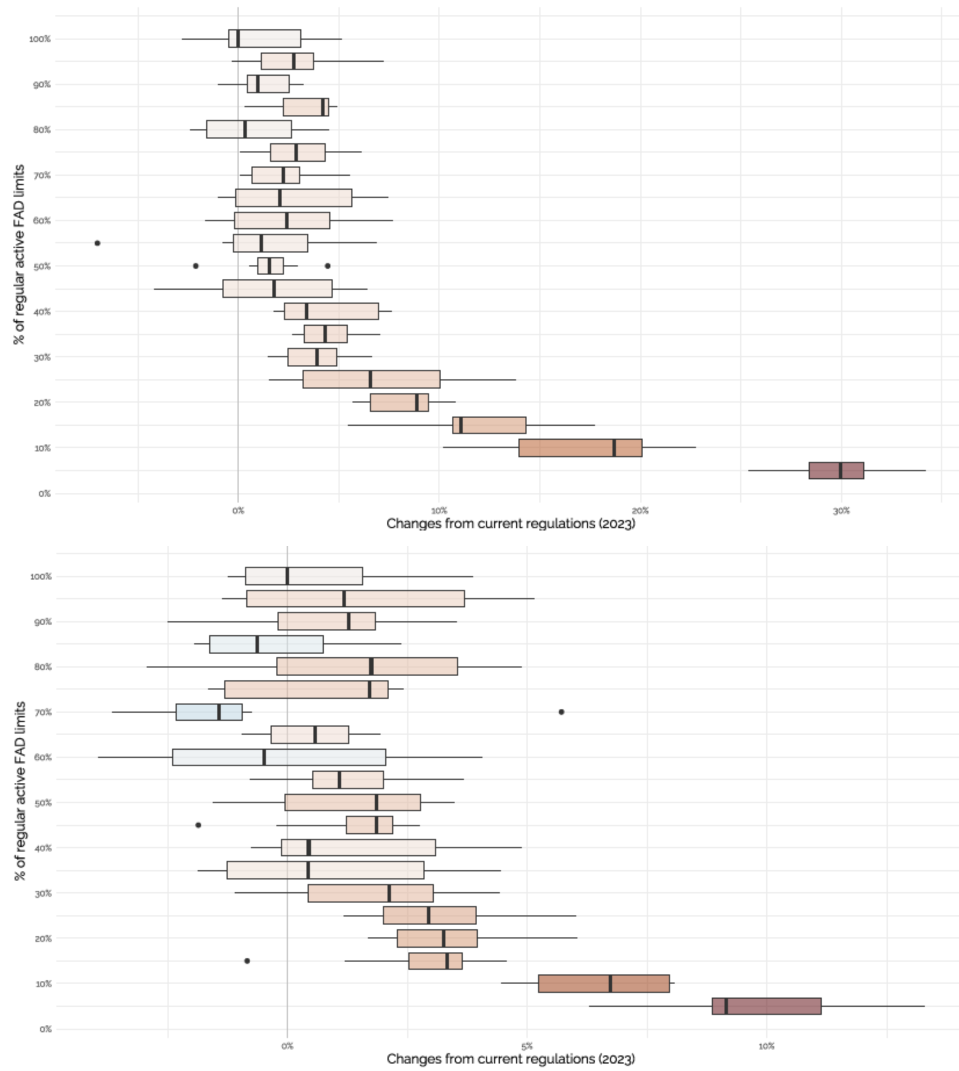

FIGURE S4. Impact of incrementally reducing the active FAD limit for Class 6 vessels (y-axis is the reduction shown as a proportion of the limit according to Resolution C-19-01) on the number of non-associated sets (top) and delfin sets (bottom) changes from current regulations in 2023.

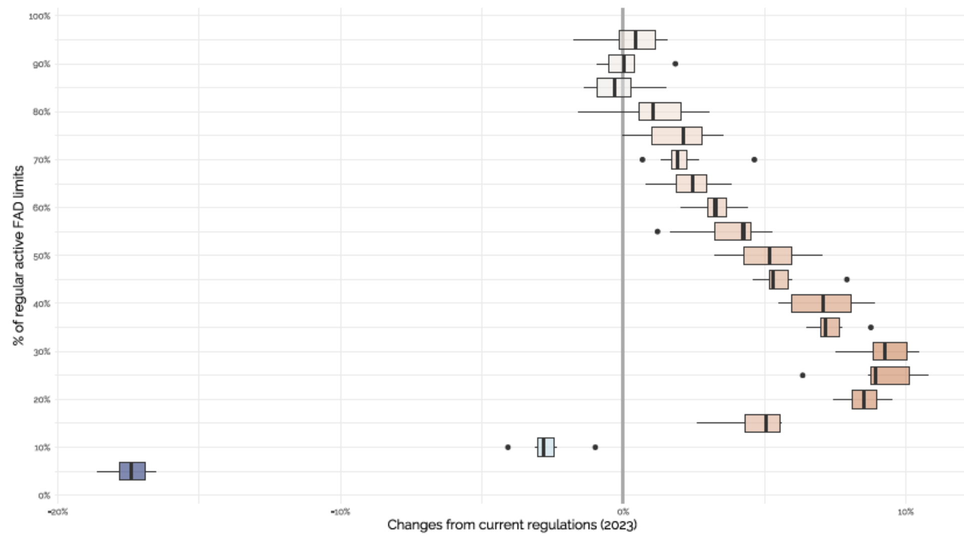

FIGURE S5. Impact of incrementally reducing the active FAD limit for Class 6 vessels (y-axis is the reduction shown as a proportion of the limit according to Resolution C-19-01) on the global harvest rates changes from current regulations in 2023.

FIGURE S6. Impact of incrementally reducing the active FAD limit for Class 6 vessels (y-axis is the reduction shown as a proportion of the limit according to Resolution C-19-01) on the harvest rate by species changes relative to 2023 for BET (left), SKJ (middle), YFT (right).

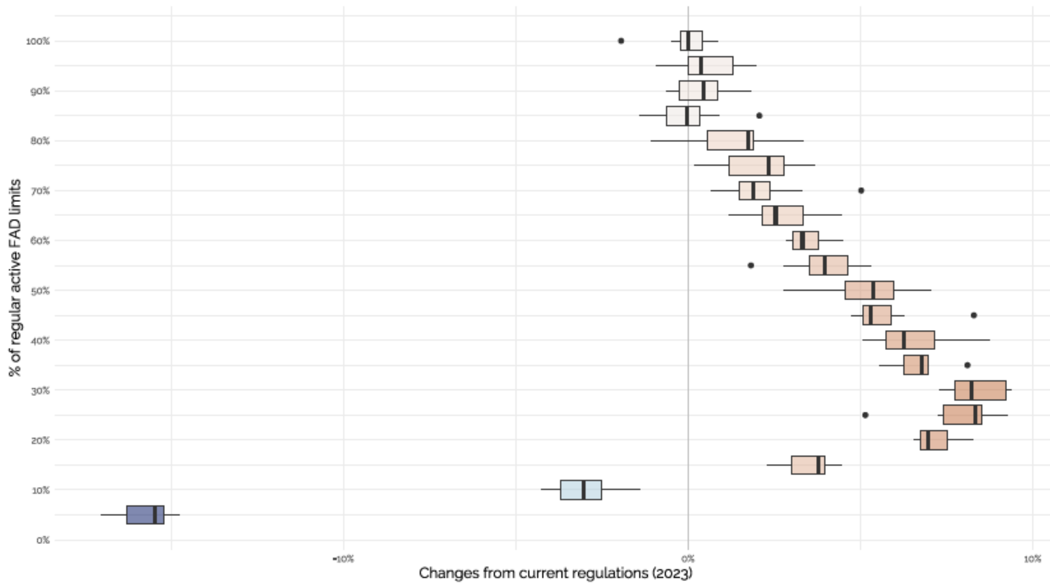

FIGURE S7. Impact of incrementally reducing the active FAD limit for Class 6 vessels (y-axis is the reduction shown as a proportion of the limit according to Resolution C-19-01) on the average earnings changes from current regulations in 2023.

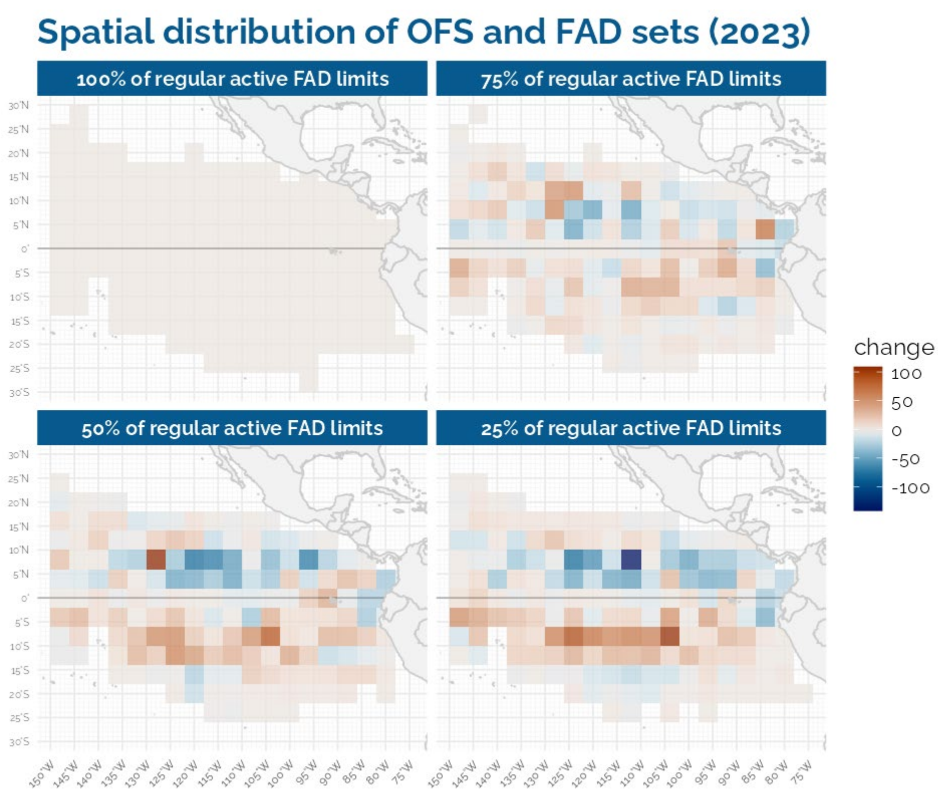

FIGURE S8. Change in spatial distribution of FAD and OFS sets compared to situation at 100% current FAD limit when reducing the active FAD limit to 100, 75, 50,25 percent of 2023 FAD limit for Class 6 vessels.

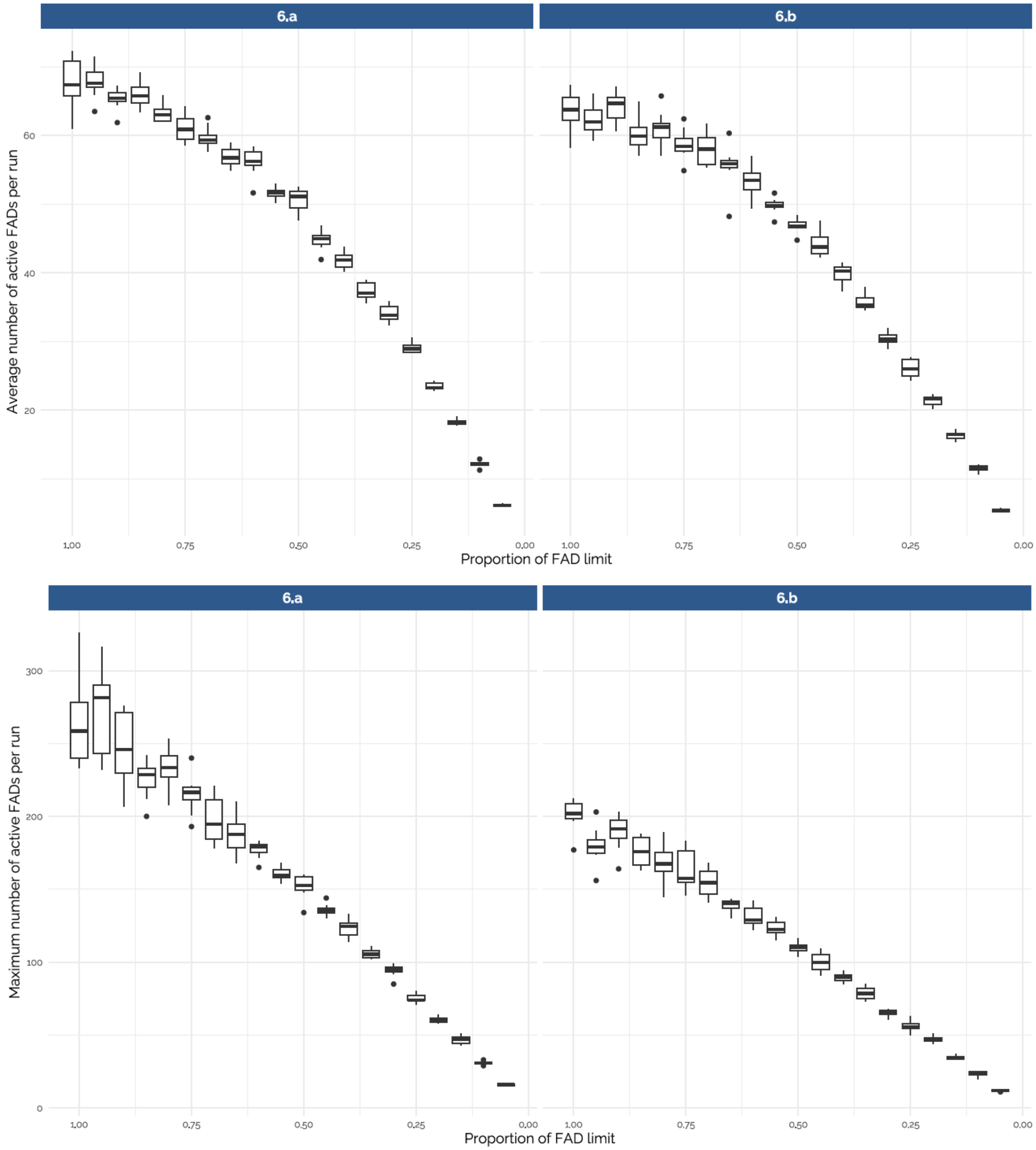

FIGURE S9. Impact of incrementally reducing the active FAD limit for Class 6a and Class 6b vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-21-04) on the percentage of the average (top) and maximum (bottom) number of active FADs outputted from the model POSEIDON, calculated for each simulation run (n=8).

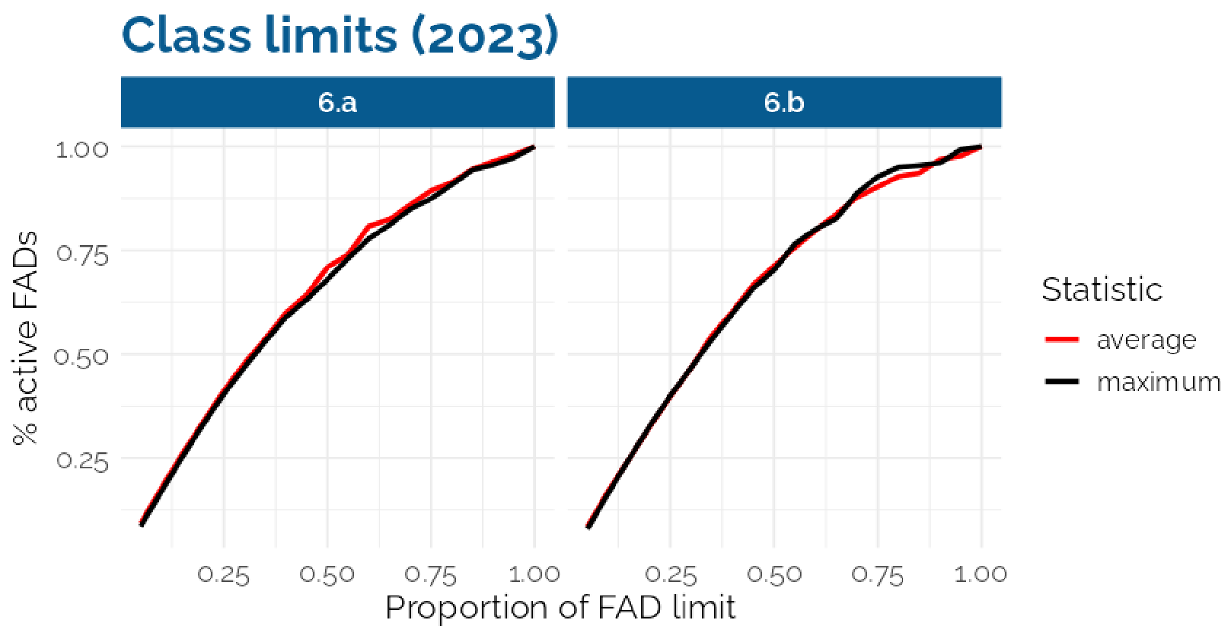

FIGURE S10. Impact of incrementally reducing the active FAD limit for Class 6.a (left) and Class 6.b (right) vessels (x-axis is the reduction shown as a proportion of the limit according to Resolution C-19-01) on the percentage of the total active FADs outputted from the model POSEIDON, calculated using the maximum (black) and average (red) number of active FADs per vessel.

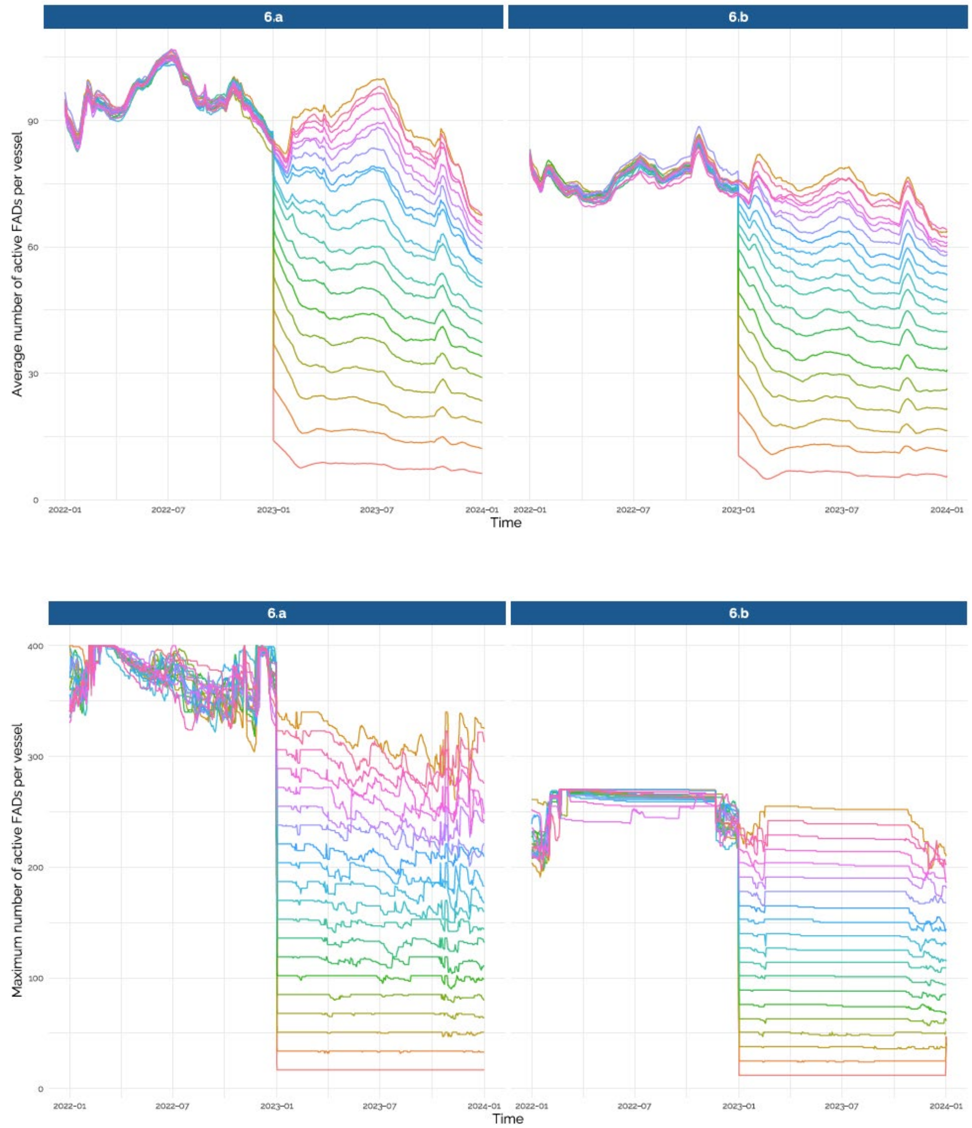

FIGURE S11. Daily average (top) and maximum (below) number of active FADs for vessel Class 6.a and Class 6.b for each FAD limit reduction in 5% increment.

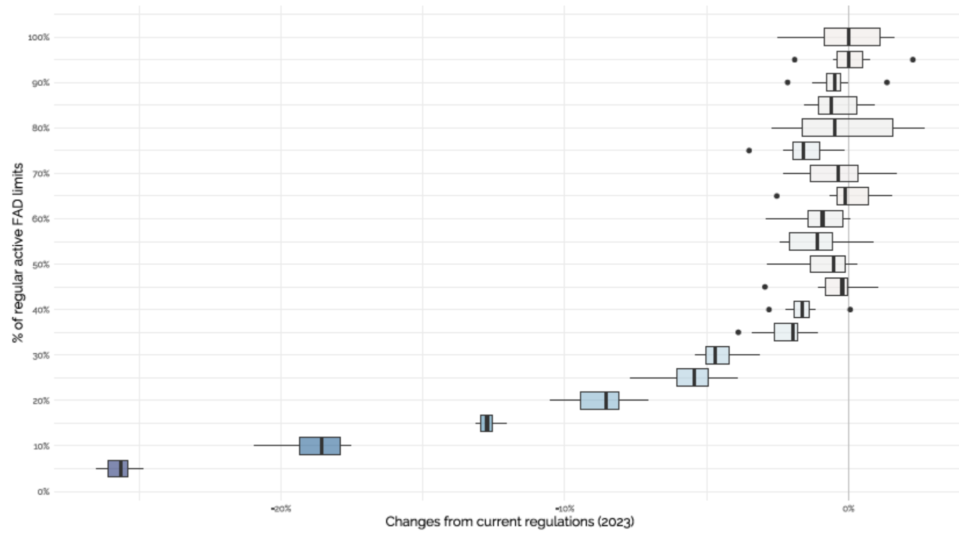

FIGURE S12. Rate of change in average FAD soak time for each FAD limit reduction in 5% increment compared to average FAD soak time at 100% of current FAD limit in 2023.

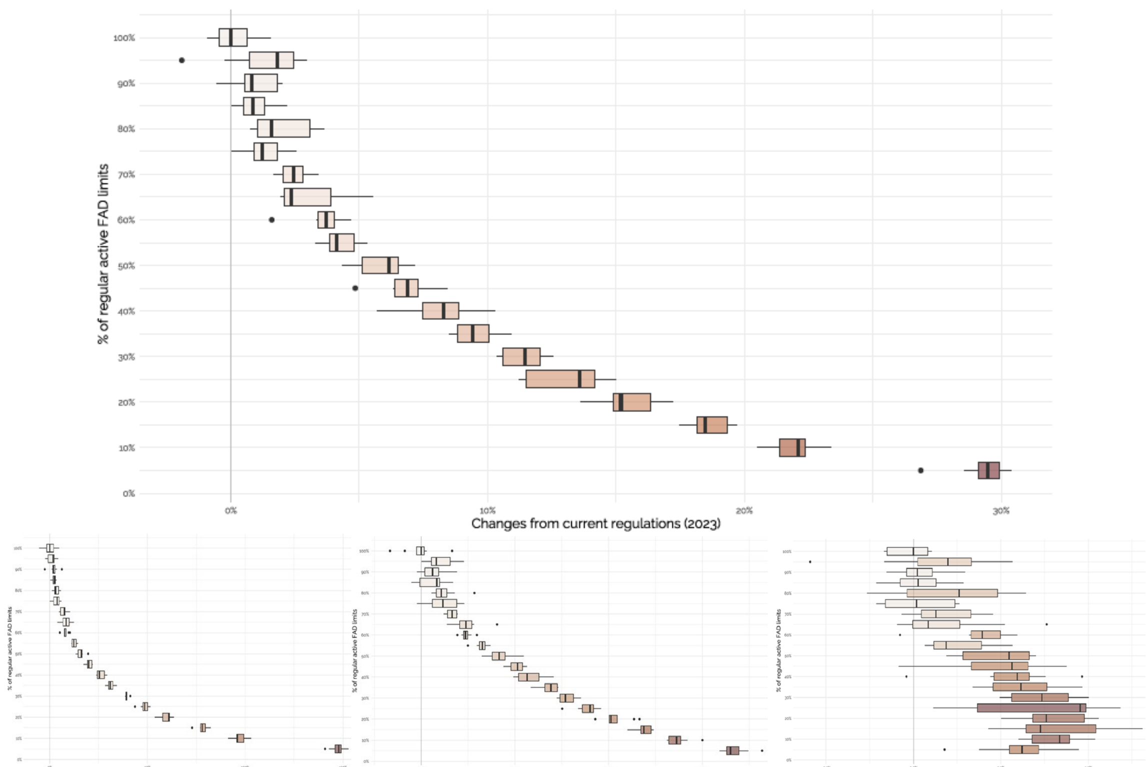

FIGURE S13. Rate of change in average catches per FAD sets for all species (top) and BET (bottom left) (, YFT (bottom center), SKJ (bottom right) for each FAD limit reduction in 5% increment compared to average catches at 100% of current FAD limit in 2023.

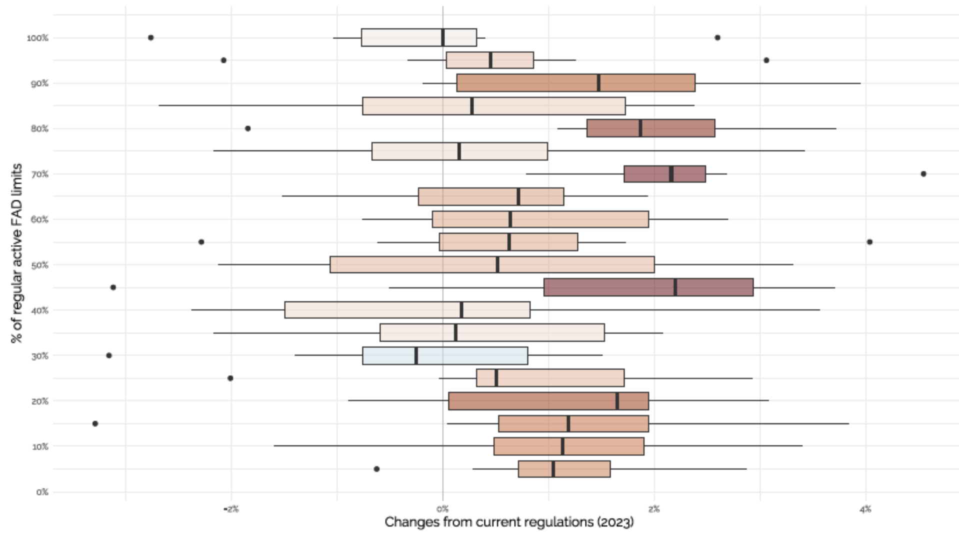

FIGURE S14. Rate of change in average catches per non-associated sets for each FAD limit reduction in 5% increment compared to average catches at 100% of current FAD limit in 2023.

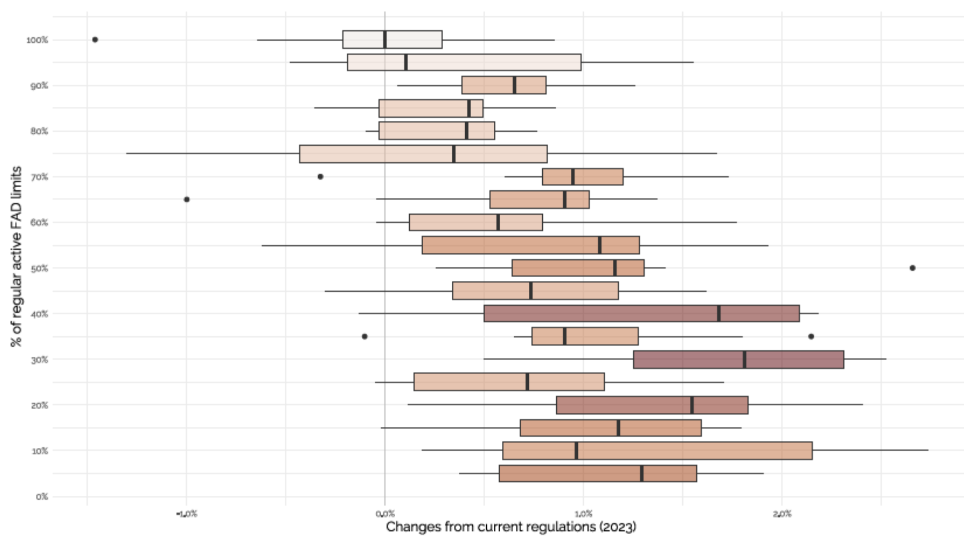

FIGURE S15. Rate of change in average catches per dolfin sets for each FAD limit reduction in 5% increment compared to average catches at 100% of current FAD limit in 2023.

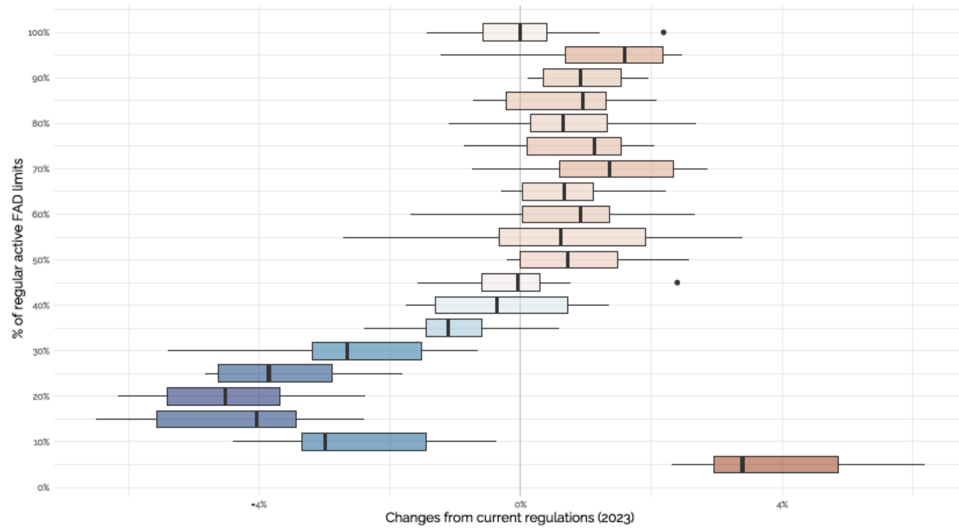

FIGURE S16. Rate of change of biomass Bigeye tuna for each FAD limit reduction in 5% increment compared to the biomass at 100% current FAD limit in 2023.

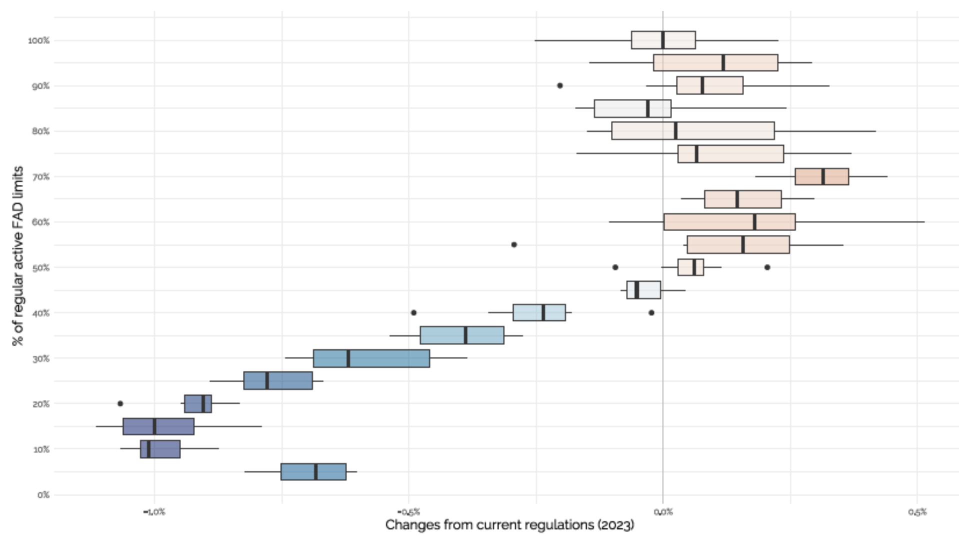

FIGURE S17. Rate of change of biomass Skipjack tuna for each FAD limit reduction in 5% increment compared to the biomass at 100% current FAD limit in 2023.

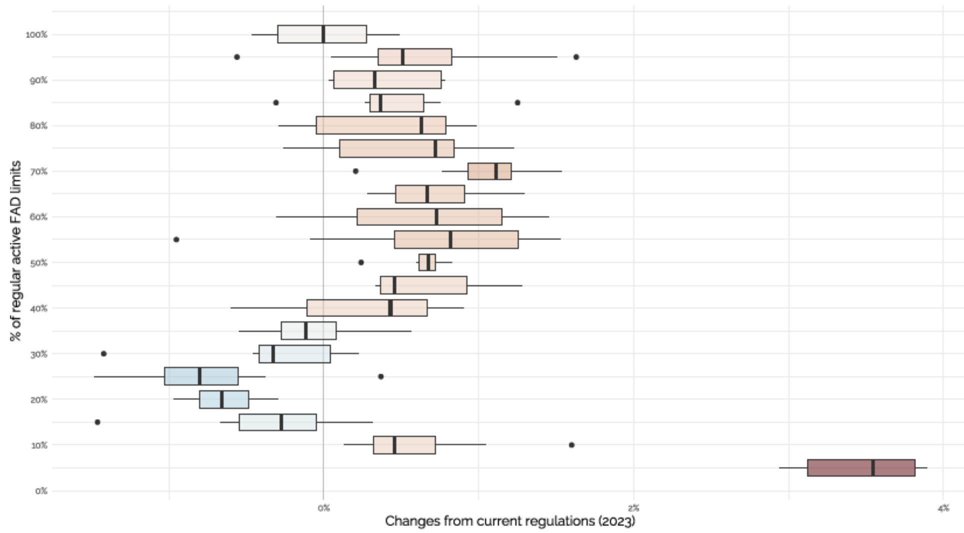

FIGURE S18. Rate of change of biomass Yellowfin tuna for each FAD limit reduction in 5% increment compared to the biomass at 100% current FAD limit in 2023.

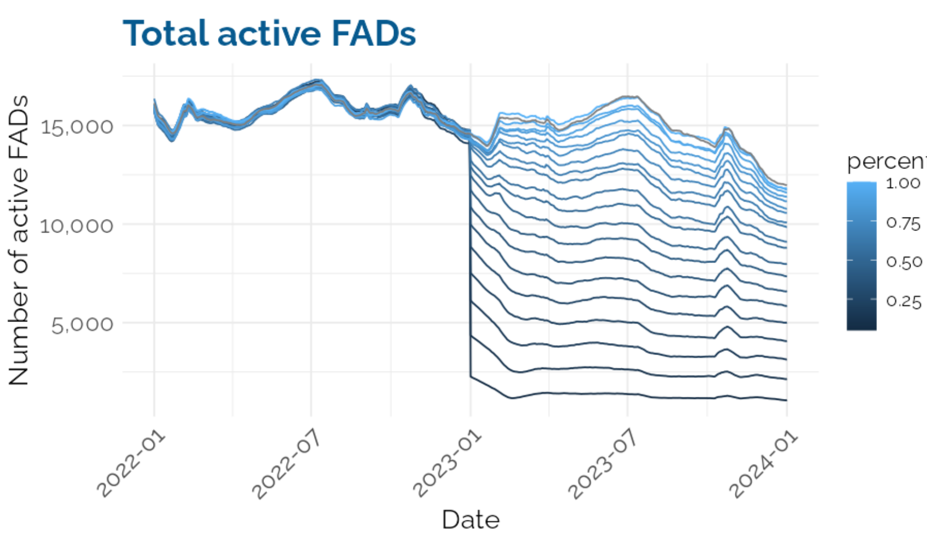

FIGURE S19. Timeseries of the total number of active FAD for 2022 – 2023 according to the FAD limit reduction in 5% increment from 100% current FAD limit.

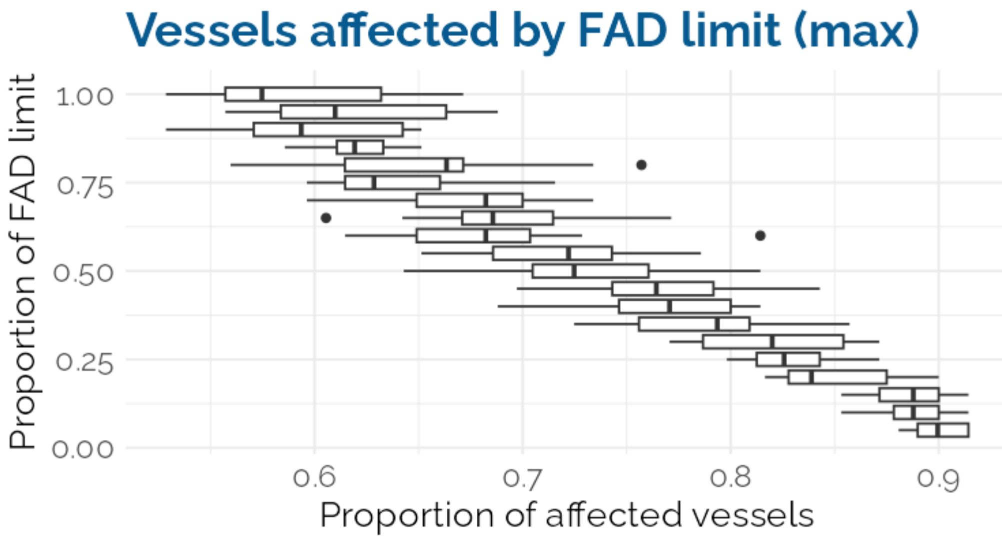

FIGURE S20. Number of vessels affected by the FAD limit reduction in 5% increment from 100% current FAD limit. A vessel is affected if the maximum number of active FADs in 2023 with the regulation is different than the 2022 baseline for that vessel.

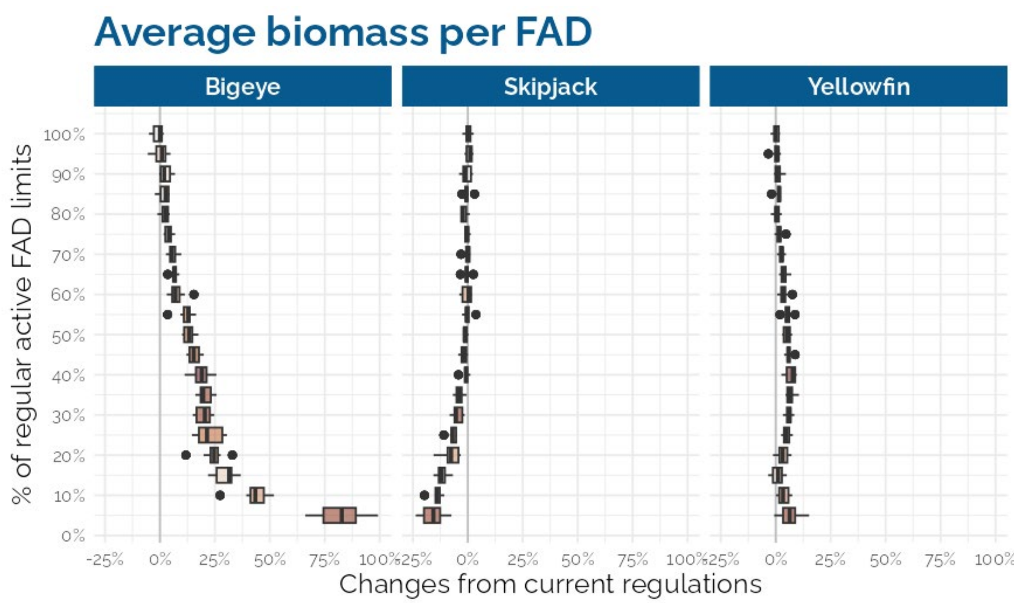

FIGURE S21. Rate of change of average biomass per FAD for all three species for each FAD limit reduction in 5% increment compared to the average biomass per FAD at 100% current FAD limit in 2023.

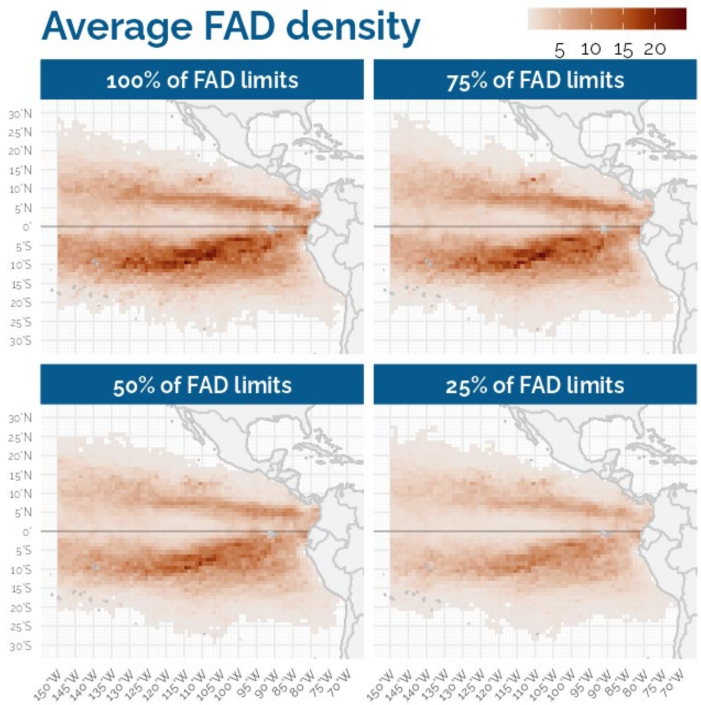

FIGURE S22. Spatial distribution of active FAD densities when reducing the active FAD limit to 100, 75, 50,25 percent of 2023 FAD limit for Class 6 vessels.

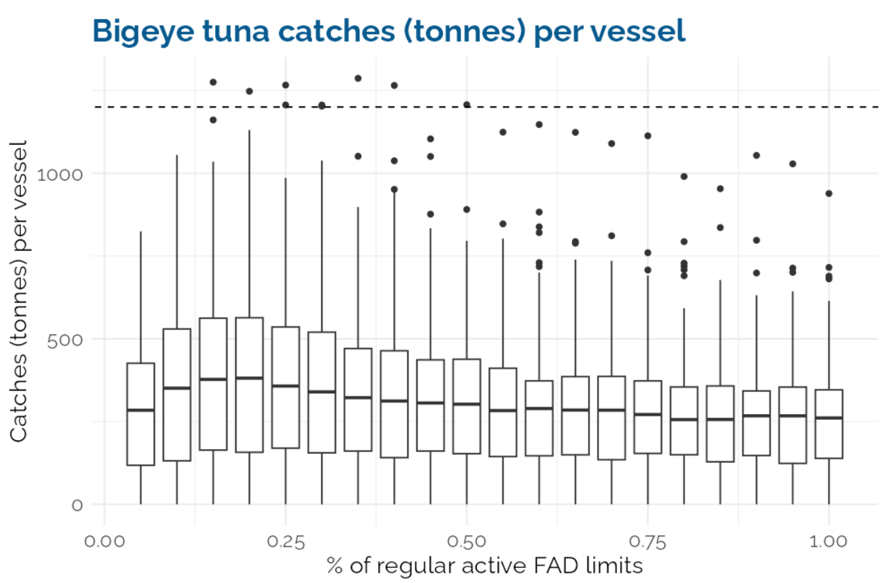

FIGURE S23. Bigeye tuna catches per vessel when applying a FAD limit reduction in 5% increment compared from 100% current 2023 FAD limit. 2023 Bigeye individual vessel limit is represented by the dash line.

TABLE S1: Potential impact of FAD limit regulation on the class 6a and class 6b fleet in 2023 compared to a 2022 baseline with maximum number of FAD.

Class A						Class B				
Limit %	Number of FADs allowed	Average FAD reduction	Standard deviation	Number of affected vessels	% vessels affected	Number of FADs Allowed	Average FAD reduction	Standard deviation	Number of affected vessels	% vessels affected
100%	340	-27	23	41	58%	255	-42	39	66	60%
95%	323	-26	23	43	62%	242	-45	42	67	62%
90%	306	-27	24	42	59%	230	-46	44	66	61%
85%	289	-29	23	43	61%	217	-49	47	69	63%
80%	272	-29	25	47	67%	204	-51	47	70	64%
75%	255	-31	25	45	64%	191	-55	50	70	65%
70%	238	-35	30	48	68%	179	-62	54	73	67%
65%	221	-36	32	49	70%	166	-65	61	74	68%
60%	204	-37	32	50	72%	153	-70	61	71	65%
55%	187	-41	33	51	73%	140	-73	65	77	71%
50%	170	-46	38	52	75%	128	-80	70	78	71%
45%	153	-49	40	56	80%	115	-88	75	81	74%
40%	136	-55	43	54	78%	102	-91	79	82	75%
35%	119	-60	46	56	80%	89	-98	85	84	77%
30%	102	-67	50	59	84%	77	-107	90	87	80%
25%	85	-74	50	59	84%	64	-116	95	88	81%
20%	68	-82	54	61	87%	51	-122	97	91	83%
15%	51	-91	58	63	90%	38	-131	101	95	88%
10%	34	-104	60	63	89%	26	-146	105	96	88%
5%	17	-111	62	64	91%	13	-157	105	97	89%

TABLE S2: Potential impact of FAD limit regulation on the combined class 6 fleet in 2023 compared to a 2022 baseline with maximum number of FAD.

Limit %	Average FAD reduction	Standard deviation	Number of affected vessels	% vessels affected
100%	-36	35	106	59%
95%	-37	37	111	62%
90%	-39	38	108	60%
85%	-41	41	111	62%
80%	-42	41	117	65%
75%	-46	44	115	64%
70%	-51	48	121	67%
65%	-53	53	123	69%
60%	-56	54	121	68%
55%	-60	57	128	72%
50%	-66	62	130	73%
45%	-72	66	136	76%
40%	-77	69	137	76%
35%	-83	74	140	78%
30%	-91	79	146	81%
25%	-99	83	148	82%
20%	-106	85	152	85%
15%	-115	89	158	88%
10%	-130	92	159	89%
5%	-139	93	161	90%