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A synthetic control approach to estimate the effect of total allowable catches in the high seas

Julia Margaret Lawson | **Conner Muir Smith**

Bren School of Environmental Science & Management, University of California, Santa Barbara, California, USA

Correspondence
Julia Margaret Lawson, Bren School of Environmental Science & Management, University of California, Santa Barbara, CA 93117, USA.
Email: jlawson@gmail.com

Abstract

Total allowable catch restrictions (hereafter referred to as catch quotas) play an important role in maintaining healthy fish stocks. While studies have identified a positive relationship between catch quota implementation and improved stock status, these methods are subject to selection bias as catch quotas are typically applied to stocks that are depleted. We address this challenge using the synthetic control method, which estimates the causal effect of catch quotas on fishing mortality and biomass by predicting a synthetic counterfactual outcome. We focus on high seas stocks (tunas, billfishes, and sharks) managed by tuna Regional Fisheries Management Organizations (tRFMOs), first providing an overview of stock status and current management measures in place. We find that implementation of catch quotas by tRFMOs has more than doubled over the past decade. Second, we predict the hypothetical fishing mortality and biomass trajectory for seven high seas quota-managed stocks in absence of a catch quota. These "synthetic non-quota stocks" are predicted using a weighted selection of high seas non-quota stocks. Credibility of the synthetic non-quota stocks is evaluated through diagnostic checks, and robustness tests assess sensitivity to study design. Five credible fishing mortality synthetic controls are predicted: three add support to the hypothesis that catch quotas successfully reduce fishing mortality, while two find that catch quotas increase fishing mortality. While our analysis is limited in scope, given that all seven quota-managed stocks are managed under a single tRFMO, we highlight the potential for the synthetic control method in fisheries management evaluation.

KEYWORDS
fisheries management, high seas fisheries, selection bias, stock status, synthetic control, tRFMO

1 | INTRODUCTION

Effective fisheries management interventions have the potential to increase fisheries resilience and generate high profits and yields (Free et al., 2020; Gaines et al., 2018). Over the past 15 years, many developed nations have improved the health of fisheries within their exclusive economic zone (EEZ) through effective management (Hilborn et al., 2020). Management is often more challenging for fisheries that move between or beyond EEZs (Liu & Molina, 2021). High seas fisheries—those that occur beyond EEZs—are open access to all nations and are therefore prone to common pool resource problems, where competitive incentives can result in overfishing (Munro et al., 2004). Encouraging cooperation among fishing nations is key to preventing overfishing in the high seas, and multilateral institutions have been formed among fishing nations to foster co-operation. Among these, five tuna Regional Fisheries Management Organizations (tRFMOs)—the International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), Inter-American Tropical Tuna Commission (IATTC), Western and Central Pacific Fisheries Commission (WCPFC), and Commission for the Conservation of Southern Bluefin Tuna (CCSBT)—generally aim to ensure the sustainability of tuna and tuna-like fishes (i.e. billfish and sharks) within their area of competence through cooperation. Economic theory suggests that fishing agreements for high-value species shared among many fishing nations are likely to have low success at inducing cooperation (Grønbæk et al., 2020), and agreement stability is diminished as the number of fishing nations increases (Pintassilgo et al., 2010). Nonetheless, the majority of tuna and billfish stocks managed by tRFMOs are healthy (Pons et al., 2017), and some of this success can likely be attributed to management actions by tRFMOs (Hilborn et al., 2021).

While there is reported evidence that prescriptive management interventions reduce fishing mortality and allow depleted stocks to recover (Hilborn et al., 2020; Juan-Jordá et al., 2022; Melnychuk et al., 2021), interventions are often endogenous to stock status. In particular, management interventions are often applied only to stocks that are depleted (self-selection bias), making it difficult to estimate a causal effect and understand the magnitude of the effect (Pons et al., 2017, 2018). Total allowable catch restrictions (TACs) show a strong positive association with recovering fish biomass and reducing fishing effort in the high seas (Pons et al., 2017). A TAC is an established annual catch limit for a given stock, often guided by scientific advice. For ease, we hereafter refer to TACs as catch quotas, although we recognize that a TAC is negotiated, adopted, and set at the stock level and a catch quota is allocated to tRFMO member states based on the recommended TAC. Placing limits on shared resources typically occurs only when a resource is severely depleted and harvests are low (Libecap, 1989). Indeed, catch quotas are typically implemented for tuna and billfish stocks that are less abundant and already overfished (Pons et al., 2017). Additionally, the health of high seas stocks is thought to be largely driven by observed and unobserved management-independent factors such as species life history, market dynamics, and the high cost of fishing (Collette et al., 2011; Hilborn, 2007; Juan-Jordá et al., 2013; Pons et al., 2017). This endogeneity can make it difficult to attribute the recovery of a depleted stock to a specific management intervention.

We address these analytical challenges by estimating the effects of catch quotas using synthetic controls. The synthetic control approach addresses the following problem: a unit is exposed to an intervention of interest, and we want to estimate the effect of the intervention. We can estimate the effect by comparing the evolution of the outcome variable of interest between the unit exposed to the intervention and a group of units that share characteristics with the exposed unit but are not affected by the intervention. Often, no single unit offers a good comparison for the unit affected by the intervention. The synthetic control uses a data-driven procedure to select a combination of unaffected units that provide a more appropriate comparison to the unit affected by the intervention (Abadie, 2021). These unaffected units serve as the predicted counterfactual. We use the synthetic control approach to estimate the causal effect of catch quotas on stock status. For example, Western Atlantic Bluefin (*Thunnus thynnus*, Scombridae) has had a catch quota in place for several decades. It is impossible to know how the fishing mortality and biomass trajectories of the Western Atlantic Bluefin stock would look if this stock had not received a catch quota. This makes it necessary to predict the counterfactual state without the catch quota using other high seas stocks that are unaffected by the Western Atlantic Bluefin catch quota. The synthetic control method is frequently used to estimate the effect of a policy intervention (Abadie et al., 2010; Abadie & Gardeazabal, 2003). Compared to propensity score matching—another method designed to estimate the effect of a policy intervention in comparative case studies where randomization is absent—the synthetic control method is especially well-suited to small sample sizes (Abadie et al., 2015). Catch quotas are non-randomized policy interventions that have been put in place for multiple tRFMO-managed high seas stocks. While the synthetic control method has been used to understand policy effects in political science, economics, and other fields (Born et al., 2019; Doudchenko & Imbens, 2016; Hope, 2016; Lepissier & Mildenberger, 2021), this approach has been rarely applied to fisheries science (although see Hilborn et al., 2021).

Previous research has shown that output controls like catch quotas are effective in preventing overexploitation and collapse of fish stocks, yet less research has focused specifically on high seas management interventions, and none have estimated causal effects. Global analyses of different output controls (such as total allowable catch limits, catch shares, individual fishing quotas, and individual transferable quotas) have reported a lower likelihood of both fishery collapse and heavy exploitation (Costello et al., 2010; Melnychuk et al., 2012), as well as improved biomass and lower fishing mortality (Melnychuk et al., 2021), relative to stocks without output controls in place. These existing studies group national and international management interventions together. However, national output controls are enforced through top-down national authorities. International fisheries management is fundamentally different as output controls are sought to be maintained through cooperative, self-enforcing agreements (Barrett, 2003). Studies that have focused specifically on high seas fisheries ascribe certain management interventions to have some positive influence on stock status (Pons et al., 2017). However, the causal effect of specific interventions is unclear given the selection effects of market dynamics, species life history, and other management-independent factors (Pons et al., 2017, 2018). Understanding the effectiveness of output controls in the high seas can help guide decision making moving forward, given the unique nature of high seas fisheries management.

We first provide an updated overview of the status and management measures in place for all tunas, billfishes, and sharks managed by tRFMOs. Next, we estimate the effect of seven catch quotas on biomass and fishing mortality using the synthetic control approach. Before predicting synthetic counterfactuals, we assess if the intention of each catch quota was to maintain or constrain fishing mortality, and if catches following implementation fell within annual quotas. Next, synthetic counterfactuals are predicted and considered credible if they can reproduce outcomes for the treated unit in the absence of the intervention for an extended pre-intervention period (Abadie, 2021). Credibility is evaluated through a series of diagnostic checks, and sensitivity of the results to changes in study design are established through robustness tests (Abadie, 2021). We conduct a panel-data event study to ensure that the 'no interference' assumption is met—that quota implementation has no spillover (leakage) effect on non-quota stocks. To evaluate the 'no anticipation' assumption, we backdate the quota implementation year using an 'in-time placebo' test to see if the predicted synthetic control closely tracks the quota treated stock prior to the intervention. Modifications were made to some synthetic controls that allowed for assumptions to be met (Abadie, 2021). Leave-one-out robustness tests check the contribution of each non-quota stock to the predicted synthetic control.

2 | METHODS

2.1 | Data sources

We provide an update of the status of tuna, billfishes, and sharks that are managed by tRFMOs. First, we gather information from the RAM Legacy Stock Assessment Database v4.496 (2021) (Ricard et al., 2011), which contains stock assessment information for commercially exploited marine populations from around the world. Second, we add or update 22 assessments from tRFMOs and provide these assessments to the RAM Legacy Database team, including new assessments for 13 shark, one tuna, and two billfish stocks (Table 1). For Western Atlantic Bluefin, biological reference points for biomass (B/B_{MSY}; current biomass, B, in relation to the biomass that produces Maximum Sustainable Yield, MSY) are not publicly available due to uncertainty in recruitment potential (ICCAT, 2021), so we only include reference points for fishing mortality (F/F_{MSY}; current fishing mortality, F, in relation to the fishing mortality that produces MSY) for this stock. Southern Bluefin Tuna, the only stock managed in the CCSBT Convention Area, was excluded given a TAC implementation year that pre-dated the Convention and due to substantial underreporting of catch data (CCSBT, 2021). We update recent stock-specific management measures that were initially reported by Pons et al. (2017) by gathering information from tRFMO websites and reports (Table S1). Because Table S1 focuses on recent management measures (mostly within the last 25 years), we also gather information on historical management measures in place before quota-managed stocks received catch quotas (Table S2).

2.2 | Hypotheses and conceptual framework

We summarize stock status using two biological reference points: B/B_{MSY} (current biomass, B, in relation to the biomass that produces Maximum Sustainable Yield, MSY) and F/F_{MSY} (current fishing mortality, F, in relation to the fishing mortality that produces MSY). We consider a stock overfished if the current biomass is less than the biomass that produces MSY ($B/B_{MSY} < 1$); and overfishing is occurring if the current level of fishing mortality is greater than the fishing

TABLE 1 List of tuna, billfish and shark stocks that are assessed by tuna Regional Fisheries Management Organizations, including stock abbreviations, biomass in relation to biomass that produces MSY (B/B_{MSY}), and fishing mortality in relation to the fishing mortality that produces MSY (F/F_{MSY}).

Species	Family	Ocean	tRFMO	Stock common name	Stock abbreviation	B/B_{MSY}	B/B_{MSY} year	F/F_{MSY}	F/F_{MSY} year
Thunnus alalunga	Scombridae	Indian	IOTC	Albacore tuna Indian Ocean	ALB-IO	1.589	2017	0.259	2017
Thunnus alalunga	Scombridae	Atlantic	ICCAT	Albacore tuna Mediterranean Sea	ALB-MED	0.57	2019	1.213	2019
Thunnus alalunga	Scombridae	Atlantic	ICCAT	Albacore tuna Northern Atlantic	ALB-N-AO	1.32	2019	0.62	2019
Thunnus alalunga	Scombridae	Pacific	IATTC	Albacore tuna North Pacific Ocean	ALB-N-PO	2.3	2018	0.6	2017
Thunnus alalunga	Scombridae	Atlantic	ICCAT	Albacore tuna South Atlantic	ALB-S-AO	1.58	2019	0.40	2019
Thunnus alalunga	Scombridae	Pacific	WCPFC	Albacore tuna South Pacific Ocean	ALB-S-PO	2.46	2019	0.27	2018
Thunnus thynnus	Scombridae	Atlantic	ICCAT	Atlantic bluefin tuna Eastern Atlantic	BFT-E-AO	1.73	2015	0.34	2016
Thunnus thynnus	Scombridae	Atlantic	ICCAT	Atlantic bluefin tuna Western Atlantic	BFT-W-AO	0.479[a]	2015	0.9[a]	2016
Thunnus obesus	Scombridae	Atlantic	ICCAT	Bigeye tuna Atlantic Ocean	BET-AO	0.94	2019	1.00	2019
Thunnus obesus	Scombridae	Pacific	WCPFC	Bigeye tuna Central Western Pacific Ocean	BET-WCPO	1.7	2018	0.74	2017
Thunnus obesus	Scombridae	Pacific	IATTC	Bigeye tuna Eastern Pacific	BET-EPO	0.34	2019	1.82	2019
Thunnus obesus	Scombridae	Indian	IOTC	Bigeye tuna Indian Ocean	BET-IO	1.29	2018	1.32	2018
Istiompax indica	Istiophoridae	Indian	IOTC	Black marlin Indian Ocean	BLM-IO	1.98	2019	0.73	2019
Prionace glauca	Carcharhinidae	Indian	IOTC	Blue shark Indian Ocean	BSH-IO	1.39	2019	0.64	2019
Prionace glauca	Carcharhinidae	Atlantic	ICCAT	Blue shark Northern Atlantic	BSH-N-AO	1.8	2015	0.2	2015
Prionace glauca	Carcharhinidae	Pacific	WCPFC	Blue shark North Pacific Ocean	BSH-N-PO	1.69	2015	0.38	2014
Prionace glauca	Carcharhinidae	Atlantic	ICCAT	Blue shark South Atlantic	BSH-S-AO	1.99	2015	0.01	2015
Makaira nigricans	Istiophoridae	Atlantic	ICCAT	Blue marlin Atlantic Ocean	BUM-AO	0.69	2016	1.03	2016
Makaira nigricans	Istiophoridae	Indian	IOTC	Indo Pacific blue marlin Indian Ocean	BUM-IO	0.82	2017	1.47	2017
Makaira nigricans	Istiophoridae	Pacific	IATTC	Blue marlin Pacific Ocean	BUM-PO	1.18	2019	0.50	2019
Istiophorus platypterus	Istiophoridae	Indian	IOTC	Indo-Pacific sailfish Indian Ocean	SFA-IO	1.14	2017	1.22	2017
Carcharhinus longimanus	Carcharhinidae	Pacific	WCPFC	Oceanic Whitetip Shark	OCS-PO	0.09	2015	3.78	2015
Thunnus orientalis	Scombridae	Pacific	IATTC	Pacific bluefin tuna Pacific Ocean	PBF	0.329[a]	2012	1.79[a]	2012
Lamna nasus	Lamnidae	Atlantic	ICCAT	Porbeagle Shark Northeastern Atlantic	POR-NEAO	0.78	2009	0.73	2009
Lamna nasus	Lamnidae	Atlantic	ICCAT	Porbeagle Shark Northwestern Atlantic	POR-NWAO	0.65	2009	0.03	2009
Lamna nasus	Lamnidae	Atlantic	ICCAT	Porbeagle Shark Southwestern Atlantic	POR-SWAO	0.48	2009	1.72	2009
Istiophorus albicans	Istiophoridae	Atlantic	ICCAT	Sailfish Eastern Atlantic	SAI-E-AO	0.46	2014	1.59	2014
Istiophorus albicans	Istiophoridae	Atlantic	ICCAT	Sailfish Western Atlantic	SAI-W-AO	0.33	2014	0.63	2014
Thunnus maccoyii	Scombridae	Southern	CCSBT	Southern bluefin tuna Southern Oceans	SBT	0.69[c]	2020	0.52[c]	2020
Isurus oxyrinchus	Lamnidae	Atlantic	ICCAT	Shortfin mako Northern Atlantic	SMA-N-AO	1.6	2015	0.54	2015
Isurus oxyrinchus	Lamnidae	Pacific	WCPFC	North Pacific Shortfin Mako Shark	SMA-N-PO	1.36	2015	0.62	2015

TABLE 1 (Continued)

Species	Family	Ocean	tRFMO	Stock common name	Stock abbreviation	B/B_{MSY}	B/B_{MSY} year	F/F_{MSY}	F/F_{MSY} year
Isurus oxyrinchus	Lamnidae	Pacific	UNKNOWN	Shortfin mako Nothwest Pacific Ocean	SMA-NWPO	NA	N/A	NA	N/A
Isurus oxyrinchus	Lamnidae	Atlantic	ICCAT	Shortfin mako South Atlantic	SMA-S-AO	1.76	2015	0.24	2015
Carcharhinus falciformis	Carcharhinidae	Pacific	WCPFC	Silky Shark Central Western Pacific Ocean	FAL-PO	1.178	2016	1.607	2016
Katsuwonus pelamis	Scombridae	Indian	IOTC	Skipjack tuna Indian Ocean	SKJ-IO	2.01	2019	0.55	2019
Katsuwonus pelamis	Scombridae	Pacific	WCPFC	Skipjack tuna Central Western Pacific Ocean	SKJ-WCPO	2.623	2017	0.461	2017
Katsuwonus pelamis	Scombridae	Atlantic	ICCAT	Skipjack tuna Eastern Atlantic	SKJ-E-AO	NA[b]	N/A	NA[b]	N/A
Katsuwonus pelamis	Scombridae	Pacific	IATTC	Skipjack tuna Eastern Pacific	SKJ-EPO	NA[b]	N/A	NA[b]	N/A
Katsuwonus pelamis	Scombridae	Atlantic	ICCAT	Skipjack tuna Western Atlantic	SKJ-W-AO	1.3	2013	0.7	2013
Kajikia audax	Istiophoridae	Indian	IOTC	Striped marlin Indian Ocean	MLS-IO	0.32	2019	2.04	2019
Kajikia audax	Istiophoridae	Pacific	IATTC	Striped marlin Northeast Pacific	MLS-EPO	1.52[a]	2009	0.075[a]	2009
Kajikia audax	Istiophoridae	Pacific	WCPFC	Striped marlin Western Pacific Ocean	MLS-SWPO	0.895	2017	1.029	2017
Kajikia audax	Istiophoridae	Pacific	IATTC	Striped marlin Western and Central North Pacific	MLS-WCPO	0.895	2017	1.029	2017
Xiphias gladius	Xiphiidae	Pacific	IATTC	Swordfish Eastern Pacific	SWO-EPAC	1.87	2012	1.11	2012
Xiphias gladius	Xiphiidae	Indian	IOTC	Swordfish Indian Ocean	SWO-IO	1.75	2018	0.60	2018
Xiphias gladius	Xiphiidae	Atlantic	ICCAT	Swordfish Mediterranean Sea	SWO-MED	0.72	2018	0.93	2018
Xiphias gladius	Xiphiidae	Atlantic	ICCAT	Swordfish Northern Atlantic	SWO-N-AO	1.04	2015	0.78	2015
Xiphias gladius	Xiphiidae	Pacific	IATTC	Swordfish North Pacific Ocean	SWO-N-PO	1.19[a]	2012	NA	N/A
Xiphias gladius	Xiphiidae	Atlantic	ICCAT	Swordfish South Atlantic	SWO-S-AO	0.72	2015	0.98	2015
Xiphias gladius	Xiphiidae	Pacific	IATTC	Swordfish South Pacific Ocean	SWO-S-PO	NA[b]	N/A	NA[b]	N/A
Xiphias gladius	Xiphiidae	Pacific	WCPFC	Swordfish Western and Central North Pacific	SWO-N-WCPO	1.87	2016	0.44	2016
Kajikia albida	Istiophoridae	Atlantic	ICCAT	White marlin Atlantic Ocean	WHM	0.58	2017	0.65	2017
Thunnus albacares	Scombridae	Atlantic	ICCAT	Yellowfin tuna Atlantic Ocean	YFT-AO	1.17	2018	0.96	2018
Thunnus albacares	Scombridae	Pacific	WCPFC	Yellowfin tuna Central Western Pacific Ocean	YFT-WCPO	2.43	2018	0.37	2017
Thunnus albacares	Scombridae	Indian	IOTC	Yellowfin tuna Indian Ocean	YFT-IO	0.78	2020	1.27	2020
Thunnus albacares	Scombridae	Pacific	IATTC	Yellowfin tuna Eastern Pacific	YFT-EPO	0.90	2019	1.08	2019

Note: All reference points were drawn either directly from stock assessments or from the RAM Legacy Database when not available in recent assessment documents. A list of references is provided in Table S6.

[a] Reference points were drawn from RAM Legacy Database as no reference points were available most recent stock assessments.

[b] Reference points were uncertain as specified in most recent stock assessment.

[c] Commission for the Conservation of Southern Bluefin Tuna (CCSBT) has measured reproductive capacity as Total Reproductive Output (TRO) rather than biomass. As such, the B/B_{MSY} ratio is TRO/TRO_{MSY}.

mortality that produces MSY ($F/F_{\mathrm{MSY}} > 1$). A healthy stock meets both requirements of $B/B_{\mathrm{MSY}} > 1$ and $F/F_{\mathrm{MSY}} < 1$. Although definitions of overfished and overfishing vary by jurisdiction (Hilborn, 2020), we choose definitions that are consistent with Pons et al. (2017) to allow for comparison across different management bodies and with previous research.

If catch quotas are effective, we expect quota-managed stocks to be in healthier condition than their predicted counterfactual synthetic non-quota stocks. In particular, we expect F/F_{MSY} of the quota-managed stock to be lower than that of the synthetic non-quota stock. We also expect B/B_{MSY} of the quota-managed stock to be higher than that of the synthetic non-quota stock. If catch quotas do not have an effect on stock status, we expect to see little difference between each quota-managed and synthetic non-quota stock pair.

2.3 | Causal identification using the synthetic control method

The synthetic control method compares the trajectory of fishing mortality or biomass for each quota-managed high seas stock with the trajectory of a weighted combination of non-quota managed high seas stocks that approximate its counterfactual state. These non-quota stocks are chosen to resemble the trajectory of the managed stock prior to quota implementation. The estimated effect of the catch quota is the difference between the weighted combination of non-quota managed high seas stocks (the synthetic control) and the quota-managed stock. The 'treated units' are the seven tRFMO-managed tuna and billfish stocks that receive treatment (catch quota) prior to 2012 (no shark stocks received a catch quota before 2012). The 'untreated units' are referred to as the 'donor pool', which consists of all tRFMO-managed tuna, billfish, and shark stocks that did not receive treatment (catch quota) prior to 2012. We chose to only examine stocks with catch quotas in place prior to 2012 as most stock assessments had biological reference points available up to 2012, and this allowed us to maximize the size of the donor pool. While some of the donor stocks receive catch quotas after 2012, these stocks are untreated throughout the duration of our time series, which runs from 1950 to 2012. Treated stocks and some donor pool stocks receive other interventions (i.e., seasonal closures, minimum size regulations, fishing capacity limits, etc.) prior to or following quota implementation. We assume that there is no systematic difference in the application of these other interventions to treated or control stocks, and effect of these other interventions will be differenced out. We use the R package *scpi* to implement the synthetic control method and generate uncertainty estimates using prediction intervals with random potential outcomes (Cattaneo et al., 2022).

We have a sample of $N+1$ units for $T_0 + T_1$ periods of time, where T_0 denotes the number of periods before treatment is implemented and T_1 the number of post-treatment periods. Units are indexed by $i = 1, 2, \ldots N, N+1$, and time periods by $t = 1, 2, \ldots, T_0, T_0 + 1, \ldots, T_0 + T_1$. The treated unit, $i = 1$, represents the seven quota-treated tuna and billfish stocks. The donor pool is denoted by $i = 2, \ldots N, N+1$. When a catch quota is assigned to a treated stock at $T_0 + 1$, the treated stock remains treated until the end of the time series. The outcome variable, Y, is either the ratio between current biomass, B, and the biomass that produces MSY (B/B_{MSY}), or fishing mortality, F, in relation to the fishing mortality that produces MSY (F/F_{MSY}). These outcome variables are examined separately.

There are two potential outcomes for each treated unit i at period t: Y_{it} (1) is the observed outcome under catch quota, and Y_{it} (0) is the outcome in absence of catch quota. The synthetic control predicts the outcome in absence of the catch quota treatment, which is referred to as the "synthetic non-quota stock" hereafter. We aim to estimate the causal impact of the catch quota treatment for the treated unit ($i = 1$). This causal quantity of interest is calculated by taking the difference between the outcome trajectory of the treated unit, and the trajectory it would have taken in absence of the treatment in the post-treatment period: $\tau_t = Y_{1t}(1) - Y_{1t}(0), t > T_0$.

The core challenge of causal inference that the synthetic control approach addresses is that the counterfactual outcome, Y_{it} (0), is always unobserved and must be predicted. The synthetic control is defined as a weighted average of a selection of units from the donor pool. It can be represented by a vector of donor pool weights $w = \left(w_2, w_3, \ldots, w_{N+1}\right)'$ using pre-quota observations from the untreated units. This set of weights allows for the prediction of the treated unit's potential outcome:

$$\hat{Y}_{1t}(0) = \sum_{i=2}^{N+1} \hat{w}_i Y_{it}(0)$$

for $t > T_0$. This weighted average, $\hat{Y}_{1t}(0)$, is the synthetic control, as it uses the untreated units to predict the counterfactual for the treated unit in the post-treatment period.

The first goal of the synthetic control method is to select weights among the donor pool such that the "synthetic non-quota stock" most closely resembles the treated stock prior to the catch quota intervention. Using the standard synthetic control constraints proposed by Abadie et al. (2010), weights are constrained to be non-negative, sum to one, and do not include an intercept, as denoted by $\hat{w}$. We select the $\hat{w}$ that minimizes the difference in the pre-treatment trajectory of the treated stock and the synthetic control:

$$\hat{w} = \underset{w \in \mathcal{W}}{\arg\min} \sum_{t=1}^{T_0} \left(Y_{1t} - Y_{2t}w_2 - \ldots - Y_{(N+1)t}w_{N+1}\right)^2$$

The second goal of the synthetic control method is to predict the "synthetic non-quota stock" in the time period following catch quota implementation for the treated stock. The post-treatment counterfactual outcome for the treated unit is predicted by: $\hat{Y}_{1t}(0) = \hat{w}, t > T_0$.

We can estimate the causal effect of catch quota implementation by taking the difference between the treated unit and the synthetic control in the post-treatment period: $\tau_t = Y_{1t}(1) - \hat{Y}_{1t}(0),\ \ t > T_0$.

We extend our analysis to assess statistical uncertainty using conditional prediction intervals. To compute prediction intervals for the treatment effect, τ_t, we consider two sources of randomness generated during the synthetic control prediction process (Cattaneo et al., 2021). The total uncertainty surrounding the prediction intervals can be expressed in the following equation and is best discussed in two parts:

$$Y_{1t}(1) - \hat{Y}_{1t}(0) = e_t - \left(X_t\left(\hat{w} - w_0\right)\right),\ \ t > T_0$$

where e_t is the out-of-sample uncertainty associated with potential misspecification and noise in the post-treatment period. We assume this out-of-sample error, e_t, is sub-Gaussian suggesting low probability for large out-of-sample prediction errors. The in-sample uncertainty, $X_t\left(\hat{w} - w_0\right)$, is generated in the pre-treatment period ($t < T_0$) using pre-treatment data and is carried over into the prediction of the synthetic control in the post-treatment period. We re-sampled the in-sample uncertainty 100 times. Further details on computing prediction intervals for synthetic controls can be found in Cattaneo et al. (2021, 2022).

2.4 | Specification

Biological reference points are available for 56 stocks from 19 species: seven stocks are treated (defined as those that received a catch quota prior to 2012; five tuna and two billfish) and 45 are donor pool stocks (17 tuna, 18 billfish, and 10 sharks). We remove truncated time series from our donor pool to maximize the length of our pretreatment and post-treatment periods (Cattaneo et al., 2021). All seven treated stocks are found within the ICCAT Convention Area (Atlantic Ocean). Donor pool stocks are found in ICCAT, IOTC (Indian Ocean), IATTC (Eastern Pacific Ocean), and WCPFC (Western and Central Pacific Ocean) Convention Areas (Table 1). The donor stocks available to predict synthetic controls for each treated unit are summarized in Table S3. Pre-treatment periods range from 7 to 22 years depending on the treated stock, while post-treatment periods range from 9 to 30 years, ending in 2012.

2.5 | Context analysis

Prior to predicting our synthetic controls, we explore if the intention of the catch quota was to maintain or constrain fishing mortality. We also examine if total annual catches are within annual quotas or if they exceed quotas, as one measure of compliance with catch quotas.

2.5.1 | Is the intention of the catch quota to maintain or constrain fishing mortality?

We categorize catch quotas as either constraining (reducing fishing mortality) or maintaining (capping fishing mortality) based on historical tRFMO report information. We obtain details on the scientific advice that prompted the recommendation to implement a catch quota from ICCAT's biennial period reports (see Table S4). We also include stock status at the time of implementation based on current stock assessments from the Ram Legacy Database.

2.5.2 | Are catches within annual quotas?

We visually compare annual total reported catches to catch quota limits to see if catches of the treated stocks are within the quota. Annual reported catches, as well as annual catch quota limits, are obtained from ICCAT Task I data (ICCAT, 2022) and ICCAT biennial reports.

2.6 | Credibility and robustness of predicted synthetic controls

A credible synthetic control is one that provides a reliable approximation of the quota-managed stock in the absence of quota implementation for an extended pre-intervention period (Abadie, 2021). A robust synthetic control is robust to changes in the study design (Abadie, 2021). We establish credibility by checking for spillover (leakage) using a panel-data event study to see if fishing pressure shifts from quota to non-quota stocks, and by backdating the intervention using an in-time placebo test to examine how well the synthetic control estimator tracks fishing mortality (or biomass) before the quota is in place. We examine how robust the synthetic control is to changes in the donor pool by iteratively removing donor stocks using leave-one-out reanalysis.

2.6.1 | Is there evidence of spillover (leakage) associated with the catch quota?

An important synthetic control method assumption is that there is ‘no interference’—no spillover (leakage) effects—on stocks that are not directly targeted by the catch quota (Abadie, 2021; Kroetz et al., 2019). We check the no interference assumption by examining shifts in reported catch volumes and composition for each vessel that fishes a mix of treated and untreated stocks using annual catch information obtained from the ICCAT Task I Database (ICCAT, 2022; see Appendix 1: Figure A1). We also conduct a leave-one-out robustness check by iteratively removing active donor units and predicting the synthetic control. This robustness check can determine if the predicted synthetic control is driven by a particular donor stock (Abadie et al., 2015).

2.6.2 | Was there evidence of anticipation ahead of the catch quota being implemented?

Another key synthetic control assumption is that treatment has no measurable effect before it is enacted. This is examined by an 'in-time placebo' test, where the intervention year is backdated by 5 and 10 years and the synthetic control is predicted. Backdating the intervention by 5 and 10 years allows us to visually assess how credible a given synthetic control is. If we find evidence of anticipation prior to exposure to treatment, the treatment time is backdated so that the full extent of the effect of the intervention can be estimated (Abadie, 2021). A credible backdated synthetic control closely tracks the outcome variable of the treated unit before the start of the actual intervention (Abadie, 2021). If a synthetic control does not track the outcome variable within that 10-year backdated period, the predicted synthetic control is considered non-credible.

3 | RESULTS

3.1 | Summary of the status of billfish, tunas, and sharks in tRFMO fisheries

We find that tunas, billfish, and sharks generally have sustainable biomass and fishing mortality rates, with roughly one quarter of stocks overfished with overfishing occurring (Figure 1). Roughly half (12 of the 22) tuna stocks and one third (6 of 20) billfish stocks are healthy (not overfished nor experiencing overfishing). While around 40% of shark stocks are assessed as healthy, these stocks show the widest range in stock status indicators and in several cases have incomplete information. ICCAT characterizes shark catches as having much greater uncertainty than tuna catches, which makes targeted management challenging (Cronin et al., 2022; ICCAT, 2019).

There are currently 18 TAC restrictions in place across 56 stocks (two of these TACs were discontinued after 1 year), and all five major tRFMOs implemented TACs for at least one stock (Table S1). The majority of these TACs are applied to tuna stocks (13), followed by billfish (5), and most recently sharks (2). We find that ICCAT has instituted the greatest number of TACs (for 14 stocks) while other tRFMOs have implemented TACs for 4 stocks. Other common management measures include seasonal closures (11 stocks), minimum size requirements (13 stocks), and fishing capacity limits (29 stocks). The latter includes resolutions that limit the number of boats, impose gear-based limitations and area closures, and limits on the use of equipment like fish aggregation devices. Some stocks have more general management measures that we categorize as "Catch restrictions other than TACs" which includes prohibition on take for certain species.

3.2 | Context analysis

3.2.1 | Intention of the catch quota to either maintain or constrain fishing mortality

All treated stocks were depleted or considered depleted at the time of quota implementation – either in historical assessments or based on our current understanding of the stock at that time (Figure 2, Table 2; Table S4). Atlantic Bigeye was considered maximally sustainably exploited (also known as 'fully fished,' meaning the stock is near or at reference points) at the time of quota implementation, and received a maintaining catch quota, although our current understanding suggests it was likely in worse condition (overfished with overfishing occurring). South Atlantic Albacore was considered healthy at the time it was appointed a maintaining quota; however, our current understanding suggests it was likely experiencing overfishing. Although North Atlantic Albacore was considered overfished with overfishing at the time of quota implementation, the initial quota aimed to maintain rather than constrain total catch.

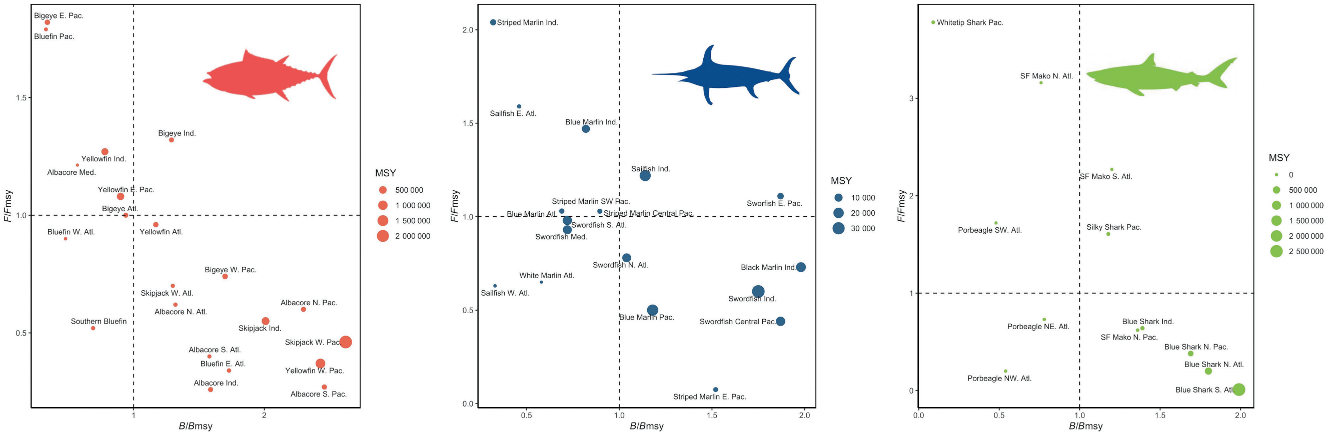

FIGURE 1 Current status of tuna, billfish, and shark stocks assessed by tuna Regional Fisheries Management Organizations. Kobe plots show the stock status relative to the target reference points (dashed lines) for fishing mortality relative to the fishing mortality that produces Maximum Sustainable Yield (F/F_{MSY}) and the ratio of biomass relative to the biomass that produces Maximum Sustainable Yield (B/B_{MSY}). The size of the circle is indicative of the relative Maximum Sustainable Yield (MSY) in metric tonnes.

3.2.2 | Evidence of annual catch within quota

Most stocks reported total catches that were at or below annual catch quotas, with the key exception of Eastern Atlantic Bluefin (Figure 3). For Eastern Atlantic Bluefin, we find that annual catches were not within annual catch quotas until almost a decade after implementation, and reported annual catches were as high as double the catch quota during this period.

3.3 | Estimating the effect of catch quotas using the synthetic control method

We predict credible fishing mortality synthetic controls for five of the seven treated stocks (Eastern Atlantic Bluefin, North Atlantic Swordfish, South Atlantic Albacore, Atlantic Bigeye, and North Atlantic Albacore; Figure 4) and credible biomass synthetic controls for one of the seven treated stocks (North Atlantic Albacore; Figure 5). Among these credible fishing mortality synthetic controls, the effect of catch quotas is heterogeneous. North Atlantic Swordfish, South Atlantic Albacore, and North Atlantic Albacore had lower fishing mortality than synthetic non-quota stocks; however Eastern Atlantic Bluefin and Atlantic Bigeye had higher levels of fishing mortality compared to their predicted synthetic non-quota stocks.

Credible synthetic controls are those that can reproduce outcomes for the treated unit over an extended pre-intervention period in absence of the intervention. First, we examine all treated stocks in our panel-data event study and find support for the no interference assumption, with little evidence of spillover (leakage) occurring (Appendix 1). Second, we find signs of anticipation in four fishing mortality (South Atlantic Albacore, Eastern Atlantic Bluefin, North Atlantic Albacore, and Atlantic Bigeye) and one biomass (North Atlantic Albacore) synthetic controls when backdated in the in-time placebo test (Figures S1 and S2). To meet the no anticipation assumption, we backdate the intervention to the year where we first observe a divergence in synthetic control and treated stock trajectories prior to the quota implementation year. Leave-one-out robustness checks show that two fishing mortality (Eastern Atlantic Bluefin, North Atlantic Swordfish) and one biomass (North Atlantic Albacore) synthetic controls are robust to changes in the donor pool, while the remaining three fishing mortality synthetic controls (South Atlantic Albacore, Atlantic Bigeye, and North Atlantic Albacore) were sensitive to changes in the donor pool (Figures S3 and S4). We include the results for all stocks prior to credibility and robustness checks in Figures S5 and S6.

3.3.1 | Evidence of spillover (leakage) associated with catch quota implementation

When we examine shifts in reported catch volumes and composition, we find little evidence of treatment spillover (leakage; Appendix 1), lending support to the 'no interference' assumption. However, leave-one-out robustness checks find evidence of some results being driven by specific heavily weighted donor stocks, which may be a potential source of bias (Table S5; Figures S3 and S4). If results rely on any one donor stock from the same region as the treated stock, this may indicate spillover (leakage) and could positively bias the results (Abadie, 2021). North Atlantic Swordfish and Eastern Atlantic Bluefin are the only two stocks for which fishing mortality is robust to changes in the donor pool, meaning that the trajectory of the synthetic control does not change upon the iterative removal of donor stocks (Figure S3).

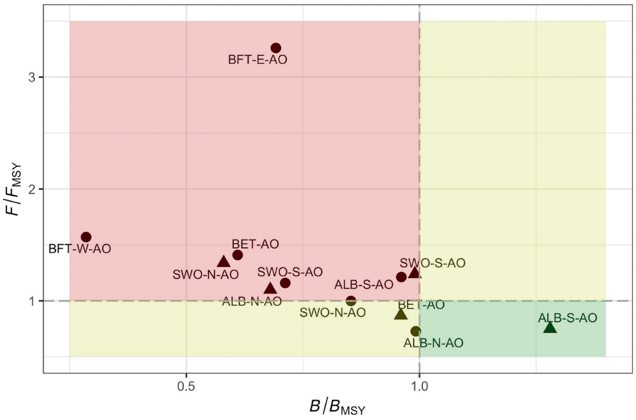

FIGURE 2 Historical stock at the time of total allowable catch implementation (▲) and our current understanding of stock status at the time of total allowable catch implementation based on the Ram Legacy Database stock assessments (•) for the seven treated stocks. This Kobe plot shows the stock status relative to the target reference points (dashed lines) for fishing mortality relative to the fishing mortality that produces Maximum Sustainable Yield (F/F_{MSY}) and the ratio of biomass relative to the biomass that produces Maximum Sustainable Yield (B/B_{MSY}). Stock abbreviations are as follows: Atlantic Swordfish (SWO-N-AO), South Atlantic Albacore Tuna (ALB-S-AO), Eastern Atlantic Bluefin Tuna (BFT-E-AO), North Atlantic Albacore Tuna (ALB-N-AO), and Atlantic Bigeye Tuna (BET-AO). No stock status estimates from historical reports were available for Western Atlantic Bluefin Tuna (BFT-W-AO) or Eastern Atlantic Bluefin Tuna (BFT-E-AO).

The results from our robustness test show that the effect of the intervention is dampened when we remove the heavily weighted donor stocks used to predict South Atlantic Albacore, North Atlantic Albacore, and Eastern Atlantic Bigeye fishing mortality synthetic controls (Figure S7). Two treated stocks show reliance on donor stocks found in the same region, which may positively bias the results: donor unit North Atlantic Shortfin Mako for treated stock South Atlantic Albacore, and donor units South Atlantic Shortfin Mako and Atlantic White Marlin for treated stock North Atlantic Albacore (Figure S3). Two other stocks show reliance on donor units found outside of their region, donor unit Oceanic Whitetip Central Western Pacific for treated stock North Atlantic Albacore, and donor unit Indian Ocean Swordfish for Atlantic Bigeye (Figure S3). Because these donor stocks are outside of the region of the treated unit, interference is less likely.

The North Atlantic Albacore biomass synthetic control is reliant on two donors from the same region: South Atlantic Shortfin Mako

TABLE 2 List of treated stocks, the year of Total Allowable Catch (TAC) implementation, and stock abbreviations.

		Stock status information from historical reports				Stock status information Ram Legacy Database		
Stock name, Stock code	TAC year	B/B_{MSY}	F/F_{MSY}	Status	Catch quota category	B/B_{MSY}	F/F_{MSY}	Status
Western Atlantic Bluefin Tuna, BFT-W-AO	1982	N/A	N/A	Depleted to low levels	Constraining	0.285	1.570	Overfished; overfishing
North Atlantic Swordfish, SWO-N-AO	1997	0.58	2.05 (1.07–3.82)	Overfished; overfishing	Constraining	0.853	0.999	Overfished; maximally sustainably exploited
South Atlantic Albacore, ALB-S-AO	1998	1.28 (0.37–4.3)	0.75 [uncertain]	Not overfished; no overfishing	Maintaining	0.961	1.213	Maximally sustainably exploited; overfishing
South Atlantic Swordfish, SWO-S-AO	1998	0.99 (0.82–1.18)	1.24 (0.94–1.93)	Maximally sustainably exploited; overfishing	Constraining	0.712	1.160	Overfished; overfishing
Eastern Atlantic Bluefin Tuna, BFT-E-AO	1999	0.19	N/A	Overfished	Constraining	0.692	3.260	Overfished; overfishing
North Atlantic Albacore, ALB-N-AO	2001	0.68 (0.52–0.86)	1.10 (0.99–1.30)	Overfished; overfishing	Maintaining	0.992	0.728	Maximally sustainably exploited
Atlantic Bigeye Tuna, BET-AO	2005	0.85–1.07	0.73–1.01	Maximally sustainably exploited	Maintaining	0.61	1.41	Overfished; overfishing

Note: Stock status information from historical reports refers to our understanding of the status of the stock at the time of quota implementation according to the relevant tuna Regional Fisheries Management Organization report (as summarized in Table S4). Stock status from the Ram Legacy Database refers to our current understanding of the status of the stock in the year of TAC implementation.

and Atlantic White Marlin (Figure S4). However, the magnitude of the estimated effect of the intervention does not change when these active donor stocks are removed.

3.3.2 | Evidence of anticipation ahead of the catch quota being implemented

For five of the seven fishing mortality synthetic controls the synthetic control closely tracks the outcome variable of the treated unit before the start of the actual intervention. Results from the in-time placebo test show that some synthetic controls closely track the treated unit for a period of time before diverging, and these can be backdated (Figure S1; South Atlantic Albacore, Eastern Atlantic Bluefin, North Atlantic Albacore, Atlantic Bigeye). Divergence for North Atlantic Swordfish occurred in the year of quota implementation, so no backdating is necessary. For Atlantic Bigeye a divergence occurred 2 years prior to quota implementation, so the intervention year is backdated by 2 years. A divergence occurred 5 years prior to quota implementation for three stocks, so these stocks are backdated by 5 years (Eastern Atlantic Bluefin, North Atlantic Albacore, and South Atlantic Albacore; Figure S1). Five of the six backdated biomass synthetic controls, and two of the seven backdated fishing mortality synthetic controls, were visually assessed to not track the outcome of the treated stock when backdated, are therefore considered non-credible. However, the North Atlantic Albacore biomass synthetic control was backdated by 5 years, as a divergence occurred 5 years prior to quota implementation (Figure S2).

3.3.3 | Estimated effect of catch quotas in the high seas

Three stocks, South Atlantic Albacore, North Atlantic Swordfish, and North Atlantic Albacore, add support to the hypothesis that catch quotas successfully reduce fishing mortality. For these three stocks, in the absence of a catch quota the stock is predicted to have a higher fishing mortality than the current quota-managed stock (Figure 4). This result is statistically significant for South Atlantic Albacore and North Atlantic Albacore, as each quota treated stock is outside of the 90% prediction intervals relative to its synthetic non-quota stock by the end of the time series. However, results for South Atlantic Albacore and North Atlantic Albacore are sensitive to changes in the donor pool, suggesting a potential positive bias in the results (Figures S3 and S7).

We also find that catch quotas increase fishing mortality for two stocks, Eastern Atlantic Bluefin and Atlantic Bigeye, where in the absence of a catch quota the stock is predicted to have a lower fishing mortality than the current quota-managed stock (Figure 4). This result is significant for Atlantic Bigeye as the treated stock falls beyond the 90% prediction intervals of the synthetic non-quota stock at the end of the time series, although this result is sensitive to changes in the donor pool (Figures S3 and S7).

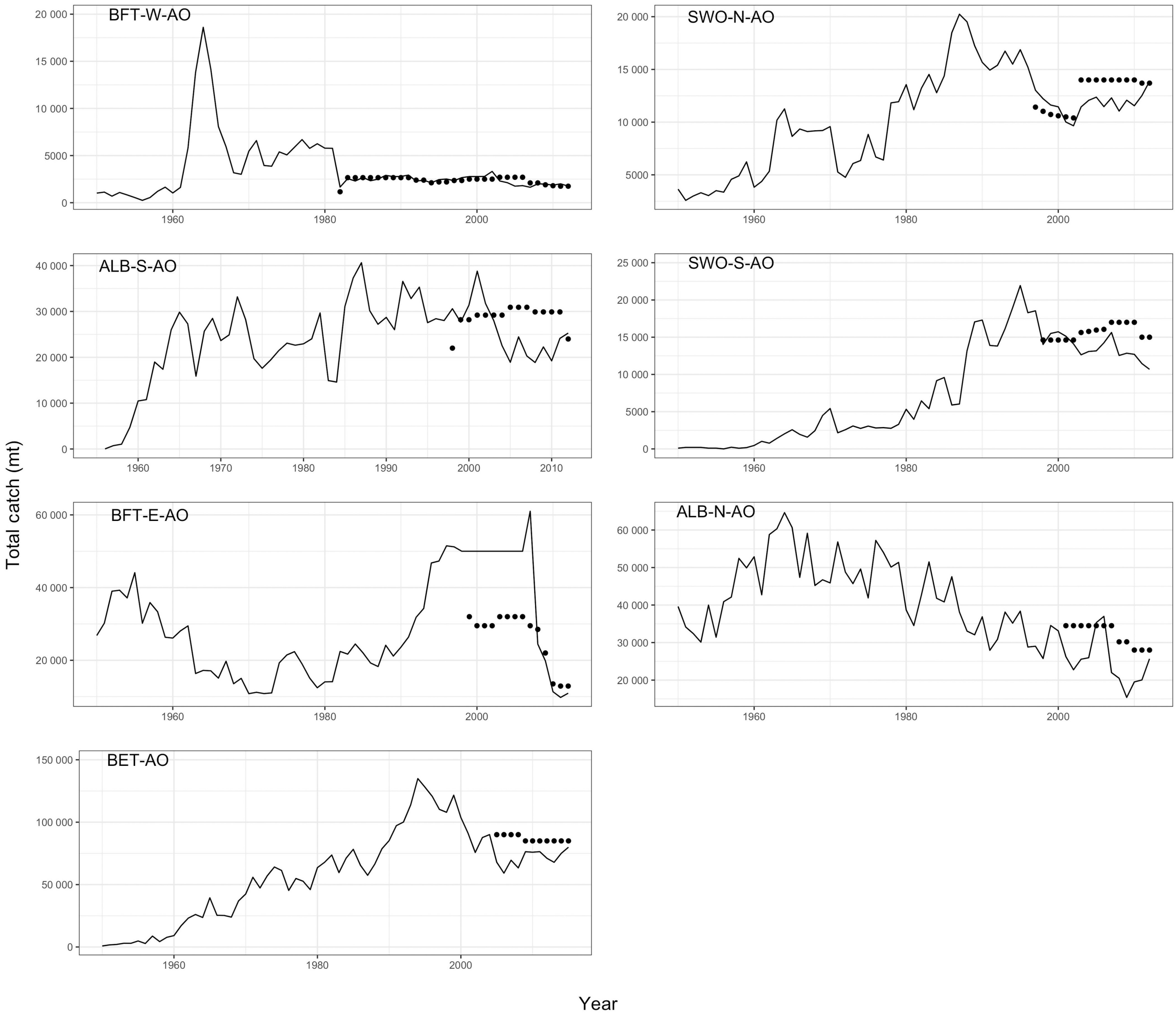

FIGURE 3 Solid lines represent total catches for the seven treated stocks (in metric tonnes), while annual total allowable catches (in metric tonnes) are represented by the black dots. Information on annual catches and total allowable catches was obtained from the International Commission for the Conservation of Atlantic Tunas. Stock abbreviations are as follows: Western Atlantic Bluefin Tuna (BFT-W-AO), North Atlantic Swordfish (SWO-N-AO), South Atlantic Albacore Tuna (ALB-S-AO), South Atlantic Swordfish (SWO-S-AO), Eastern Atlantic Bluefin Tuna (BFT-E-AO), North Atlantic Albacore Tuna (ALB-N-AO), and Atlantic Bigeye Tuna (BET-AO).

North Atlantic Albacore is the only stock where credible fishing mortality (Figure 4) and biomass (Figure 5) synthetic controls could be predicted (both backdated by 5 years). After 16 years of quota implementation the treated North Atlantic Albacore stock is healthy ($B/B_{MSY}=0.336$, $F/F_{MSY}=0.538$), whereas the predicted synthetic non-quota North Atlantic Albacore stock is fully fished ($B/B_{MSY}=0.964$) with overfishing occurring ($F/F_{MSY}=1.459$).

4 | DISCUSSION

We find that the implementation of catch quotas in the high seas has more than doubled over the past decade, and that while the effectiveness of these quotas is heterogeneous, catch quotas have successfully reduced fishing mortality for some stocks. While catch quotas were once a management tool unique to ICCAT, there are now 18 catch quotas in place and this tool is now used by all five major tRFMOs. For three treated stocks (North and South Atlantic Albacore and North Atlantic Swordfish) that were either fully fished or experiencing low levels of overfishing at the time of implementation, catch quotas reduce overfishing relative to the predicted synthetic control. However, for two treated stocks (Eastern Atlantic Bluefin and Atlantic Bigeye) that were experiencing high levels of overfishing at the time of quota implementation, we find that catch quotas worsen the status of the stock relative to the predicted synthetic control. Furthermore, catches for the most heavily overfished treated stock, Eastern

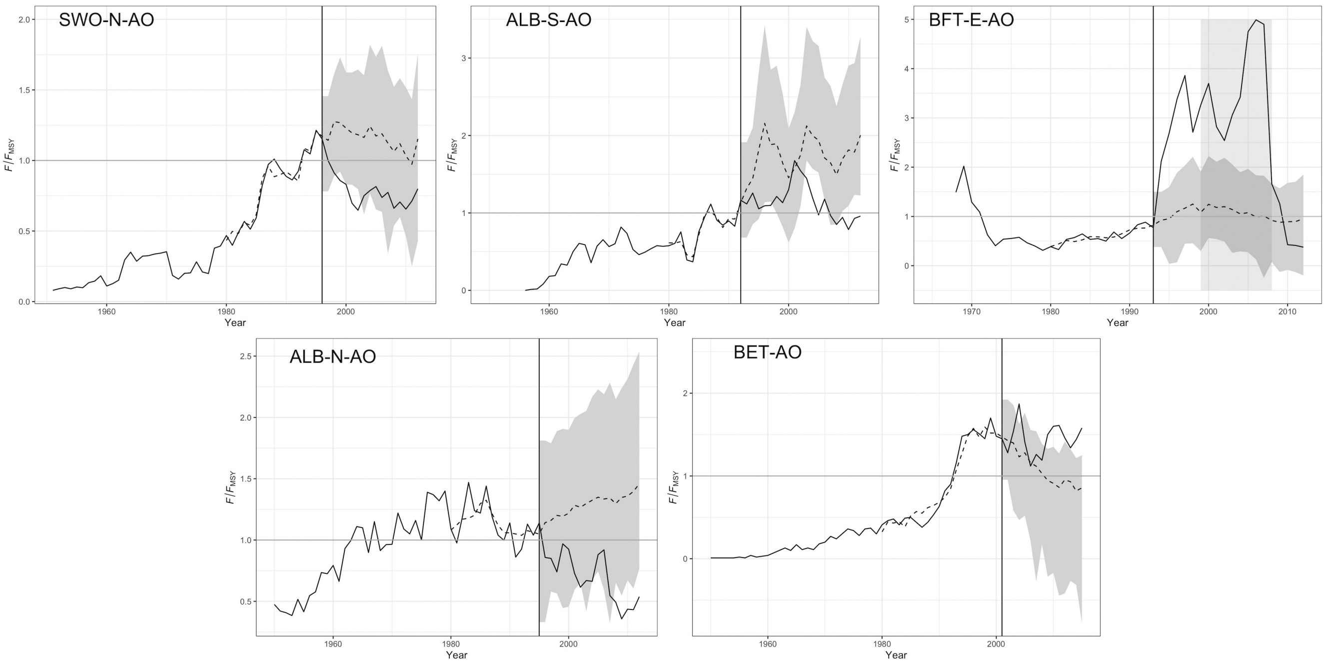

FIGURE 4 Trajectories of fishing mortality relative to the fishing mortality that produces Maximum Sustainable Yield (F/F_{MSY}). Dashed lines represent the predicted synthetic non-quota stock fishing mortality and solid lines represent the trajectory of the quota treated stock fishing mortality. Error around the synthetic control indicates 90% prediction intervals. Stock abbreviations are as follows: North Atlantic Swordfish (SWO-N-AO), South Atlantic Albacore Tuna (ALB-S-AO), Eastern Atlantic Bluefin Tuna (BFT-E-AO), North Atlantic Albacore Tuna (ALB-N-AO), and Atlantic Bigeye Tuna (BET-AO). The gray rectangle on the Eastern Atlantic Bluefin (BFT-E-AO) plot represents a period of observed non-compliance.

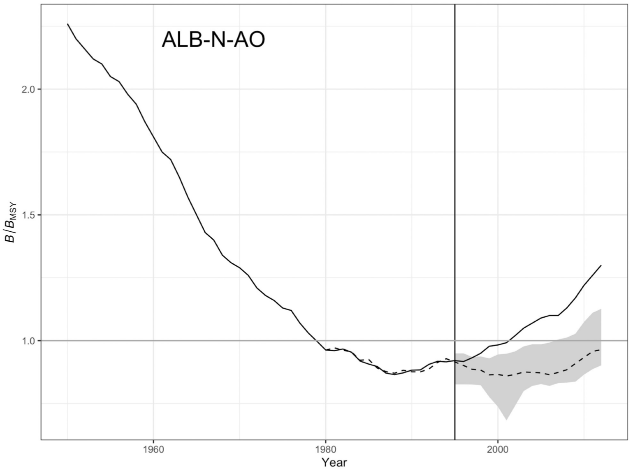

FIGURE 5 Trajectory of North Atlantic Albacore (ALB-N-AO) biomass relative to the fishing mortality that produces Maximum Sustainable Yield (B/B_{MSY}). Dashed lines represent the predicted synthetic non-quota stock biomass and solid lines represent the trajectory of the quota treated stock biomass. Error around the synthetic control indicates 90% prediction intervals.

Atlantic Bluefin, exceeded annual catch quotas for roughly a decade after implementation. Our analysis is limited in its scope, which makes it challenging to draw conclusions across all tRFMOs. By necessity, we focus on quotas implemented under ICCAT, a body which favored catch quotas as the primary harvest control tool at the time.

All but one of the treated stocks examined in our study received quotas that were implemented under ICCAT, and we consider ways in which this may bias our results. One potential concern is bias generated by other management measures applied before or after quota implementation (i.e., seasonal closures, minimum size regulations, fishing capacity limits, etc.). Previous research has found that some of these other management measures (fishing capacity limits and seasonal closures) are not influential predictors of high seas stock status while TACs, other catch restrictions, and minimum size regulations are considered influential (Pons et al., 2017). If there is no systematic difference in the application of other influential management measures between treated and donor stocks, then there is little concern for bias. However, stocks were not managed under WCPFC until the agreement entered into force in 2004 (and similarly IOTC entered into force in 1996). Therefore, some proportion of potential donor stocks had no management in place (especially those managed under WCPFC), whereas most treated stocks had at least one management intervention in place before receiving a catch quota (i.e., Atlantic Bigeye had minimum size regulations implemented in 1980). We do not see a large number of unmanaged donor stocks from newer tRFMOs: most active donor stocks were from ICCAT stocks (16 active donor stocks), followed by IOTC (10 active donor stocks), WCPFC (6 active donor stocks), and IATTC (5 active donor stocks). While focusing exclusively on ICCAT-managed stocks may bias the results due to more intensive management at the time of quota implementation, there is evidence that some of these other measures are not influential. Furthermore, when we examine donor stock composition, we do not see any concerning evidence of reliance on unmanaged donor stocks.

We find no evidence that the initial intention of a catch quota—whether to constrain or maintain fishing pressure—predicts the magnitude of the difference between the quota-managed stock and the synthetic non-quota stock. However, we do find that the extent of depletion at the time of implementation may contribute to quota effectiveness (effectiveness defined as quota-managed stocks having a lower F/F_{MSY} than synthetic non-quota stocks). Overall, our findings are consistent with the economic theory which predicts that depleted stocks are more likely to receive quotas (Libecap, 1989). Most stocks were depleted or considered depleted—either at the time of quota implementation or based on our current understanding of stock status at the time. However, the high cost of fishing in the high seas may encourage regulation prior to depletion (Costello & Ovando, 2019). Indeed, we also find that some stocks were either maximally sustainably exploited (Atlantic Bigeye) or healthy (South Atlantic Albacore) at the time of quota implementation, and the recommended South Atlantic Albacore catch quota was considered "conservative" at the time of implementation (ICCAT, 1999). In general, the stocks for which catch quotas worsen the status of the stock relative to the predicted synthetic control are typically experiencing more heavy overfishing at the time of implementation (i.e., Eastern Atlantic Bluefin Tuna $F/F_{MSY}=3.260$; Atlantic Bigeye $F/F_{MSY}=1.41$). On the other hand, the more stocks for which catch quotas reduced fishing mortality have lower levels of overfishing (or no overfishing) at the time of implementation (i.e., North Atlantic Albacore $F/F_{MSY}=0.728$; North Atlantic Swordfish $F/F_{MSY}=0.99$; South Atlantic Albacore $F/F_{MSY}=1.213$). These results suggest that it may be challenging to decrease fishing mortality if fishing pressure is very high at the time of quota implementation. While most TACs implemented since 2016 have been applied to fisheries experiencing some level of overfishing in oceans outside of the Atlantic, ICCAT has continued to apply catch quotas to healthy stocks (i.e., North and South Atlantic Blue Shark in 2019).

Once a catch quota is implemented, we find that total reported catch is typically within annual quotas, however clear evidence of non-compliance can make it challenging to assess the effectiveness of a quota. Such is the case with Eastern Atlantic Bluefin, where despite the implementation of the catch quota in 1999, illegal and unreported catch continued unabated and total catch continued to increase (Havice, 2021). It was not until over a decade later, in 2010, when fear of stock collapse had intensified, that the quota was set in alignment with scientific recommendations for the first time and enforcement tools such as sanctions were developed (Webster, 2011). Furthermore, despite the SCRS recommending a 35% reduction in total catch at the time of quota implementation (ICCAT, 2000) the initial catch quota was much higher than the scientific advice and was continuously set above scientific advice prior to 2010. To align with the stringent 2010 quota, members had to undergo significant reductions in catch allocations to meet the quota. Our analysis finds evidence of a rapid increase in fishing pressure on Eastern Atlantic Bluefin 5 years prior to catch quota implementation, relative to the predicted synthetic control. This aligns with expressions of concern from ICCAT's Standing Committee on Research and Statistics (SCRS) on the state of the stock (Garcia & Ye, 2018) and the severe overcapacity starting in the mid-1990s (Fromentin & Powers, 2005).

Our results show two types of anticipation: a ramping up of fishing mortality (an anticipatory race-for-fish) and a decrease in fishing mortality (anticipatory compliance) prior to catch quota implementation. Additional study is warranted to determine if quotas are implemented in response to a ramping up of fishing mortality, or if the ramping up of fishing mortality is in anticipation of quota implementation. However, preemptive behavior in response to an anticipated fisheries management intervention has been documented in other contexts. Following the announcement of a large-scale no-take marine reserve in the Pacific, fishing activity increased by 130% roughly 1 year prior to implementation within the forthcoming marine reserve (McDermott et al., 2019). To our knowledge, anticipatory compliance, or a decrease in fishing pressure prior to implementation has not been documented ahead of a fisheries management intervention. However, this phenomenon has been documented in other international agreements, such as the International Monetary Fund's Article VIII Commitment, where countries complied with certain account restrictions 4 years prior to formally signing the agreement (Von Stein, 2005). In this context, countries were thought to engage in anticipatory compliance as a way to prepare for compliance (Simmons & Hopkins, 2005). In tRFMO settings, discussions regarding the introduction of a total allowable catch often occur several years prior to implementation. During this period, the declining health of the stock is highlighted, and formal statements of concern are made by member states or non-governmental organizations. For example, an anticipatory response was observed for South Atlantic Albacore five years prior to catch quota implementation. In 1993 South Africa announced their intention to recommend a total allowable catch if the stock assessment continued to signal overfishing (ICCAT, 1994). By the next Commission meeting a recommendation was put forward by South Africa and adopted by the Commission to limit catches to 90% of the 1989–1993 average catches (ICCAT, 1996). The failure to successfully implement this recommendation led to the eventual 1998 catch quota (ICCAT, 1999). This aligns with the anticipation we observed 5 years prior to quota implementation for South Atlantic Albacore.

Our results bolster previous research that has found positive relationships between management interventions and stock recovery (Hilborn et al., 2020; Juan-Jordá et al., 2022), yet these studies have been unable to make causal claims because of limitations in research design (Melnychuk et al., 2013, 2021; Pons et al., 2017, 2018). Random forests have been used in previous studies examining the importance of various management measures on stock status. This approach uses regression trees to identify covariates (fisheries and life history characteristics, as well as management measures), that have a strong influence on a numerical response variable (biological reference points; Melnychuk et al., 2013; Pons et al., 2017, 2018).

More recently, Hierarchical Autoregressive Integrated Moving Average (ARIMA models), were used to project baseline trends in biomass and fishing mortality reference points given the presence or absence of rebuilding plans (Melnychuk et al., 2021). This approach allows for a counterfactual state to be projected. While this counterfactual has temporal causality (the present state of the outcome variable depends on past year states but not future year states) in the outcome variables (biomass and fishing mortality reference points), it does not account for selection bias. Overall, there has been growing recognition in fisheries science that methods which allow scientists to make causal claims are critical in advancing fisheries management (Hilborn et al., 2021).

We were unable to predict credible biomass synthetic controls, with the exception of North Atlantic Albacore; and while we were able to predict fishing mortality synthetic controls for most stocks, these results may be subject to bias from biological or modeling constraints. Management measures directly affect fishing mortality and indirectly affect stock biomass (Melnychuk et al., 2021). This suggests that a lagged response in stock biomass is expected following the implementation of catch quotas. It also may explain why we were only able to predict one credible and robust biomass ratio synthetic control (North Atlantic Albacore) out of our seven treated stocks. The limited ability of our synthetic control approach to find suitable donor units for biomass could be improved by including features or covariates that may help improve pre-treatment fit (Abadie, 2021). For example, we included covariates for stock-specific sea surface temperature (Free et al., 2020), and species-specific ex-vessel prices (Swartz et al., 2013), but neither of these covariates changed or improved the pre-treatment fit or the trajectory of the post-treatment synthetic non-quota stock.

We encourage researchers evaluating the effectiveness of fisheries management interventions to consider synthetic control methods, given recent advances in methodology (Amjad et al., 2018; Pang et al., 2022; Xu, 2017), and suitability for small sample size comparative case studies where randomization is absent (Abadie, 2021). Synthetic control methods are widely used in economics and political science to estimate the effect of various policies, ranging from the effects of right-to-carry laws to Brexit (Born et al., 2019; Donohue et al., 2019). Increasingly, synthetic controls are used to estimate the effects of different conservation interventions, such as the reducing emissions from deforestation and degradation (REDD+) policy mechanism (Roopsind et al., 2019) and other deforestation policies (Sills et al., 2015). Recently, the synthetic control method was used to examine the effect of a Great Barrier Reef Marine Park no-take closure on commercial fishery catch (Hilborn et al., 2021). Potential research directions where the synthetic control approach may successfully be applied include examining the causal effect of harvest control rules. Our study is limited in scope: examining seven catch quotas in place prior to 2012, implemented by only a single tRFMO. As longer time series become available, future research can extend our analysis and examine the effectiveness of these interventions across all tRFMOs.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data used in this study are publicly available through the Ram Legacy Database and the International Commission for the Conservation of Atlantic Tunas. Additional data used in this study are available in supplemental files.

ORCID

Julia Margaret Lawson https://orcid.org/0000-0001-6404-9434

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX 1. Spillover 'Leakage' analysis

BACKGROUND

Leakage in fisheries occurs when effort allocation shifts from one fishery to another and is measurable and attributable to a policy change. In fisheries, leakage has been shown to occur when catch shares are implemented—especially when gear similarity and market substitutability are high (Asche et al., 2007; Cunningham et al., 2014; Hsueh & Kasperski, 2018; Kroetz et al., 2019). The implementation of catch quotas may cause leakage if the restriction shifts fishing effort toward a stock that is not regulated by a quota. The primary aim of this supplemental analysis is to ensure that the 'no interference' assumption is met for the synthetic control, and that there is no treatment spillover (leakage) to other stocks in the donor pool.

All catch quotas examined in this study were adopted under ICCAT (the International Convention on the Conservation of Atlantic Tunas).

DATA

We analyze Task I catch data reported to the International Convention on the Conservation of Atlantic Tunas (ICCAT) from 1950 to 2012 (ICCAT, 2022) using a standard event setup (Schmidheiny & Siegloch, 2019). Catch data are available for 20 stocks, including seven treated (quota-managed) stocks and 12 control stocks (those within ICCAT's area of competence that did not receive a catch quota prior to 2012).

Our aim is to understand how the presence of at least one catch quota stock in the total catch affects the quantity of non-quota treated stocks. The dependent variable y is total catch quantity (in tonnes) of a given control stock (i), within a given fleet (j), in a given year (t). We estimate the effect of our binary treatment (the presence of a quota treated stock) on our dependent variable y over time periods $t = t, \dots, t$. Our aim is to look at the treatment effect over time ranging from $j < 0$ periods prior to the treatment to $j > 0$ periods after the treatment. This is the effect window. The standard event specification for all time periods, $t = t, \dots, t$ is given by

$$y_{ijt} = \sum_{k=\underline{k}}^{\bar{k}} \beta_k b_{ijt}^{k} + \mu_{ij} + \sigma_{jt} + \epsilon_{it}$$

The treatment indicator, b_{itj}^{k}, is a binary variable that indicates the presence of at least one quota managed control stock at the fleet level. This treatment is happening $k \in \left[\underline{k}, \overline{k}\right]$ periods away from t. We include two fixed effects: μ_{ij} is the unit fixed effect (stock-fleet) and σ_{jt} is the time fixed effect (fleet-time), and standard errors, ε, are clustered by stock-year. If leakage is occurring we expect β to be positive. This would suggest that within vessels that are catching at least one catch quota regulated species, control stocks are increasing in quantity caught.

RESULTS

The results indicate that leakage is not occurring as our estimated β is negative. The presence of at least one catch quota stock in the total catch slightly decreases the quantity of non-quota treated stocks in the total catch ($\beta = -100.247$, SE $= 78.99$) and this result was not statistically significant (p-value $= 0.20486$). Figure S1 summarizes the change in quantity of control stocks caught after at least one quota stock was present in total catch (the intervention).

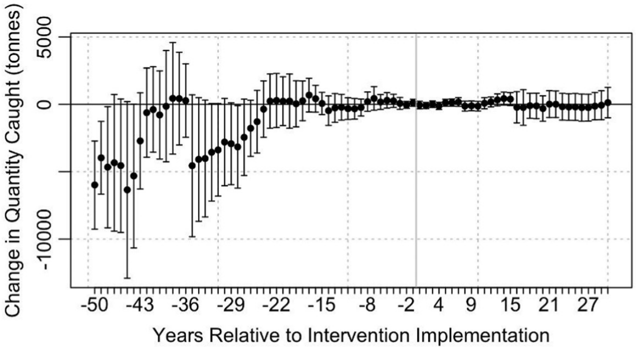

FIGURE A1 Change in quantity (tonnes) of non-quota stocks caught among fleets that caught at least one quota-managed stock.