Regulating Biological Resources: Lessons from Marine Fisheries in the United States*

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7/12/2022

Abstract

In 1996, with United States (US) fish stocks in decline, Congress overhauled fishing laws with a strict, science-based management regime. In the years since, the Magnuson-Stevens Fishery Conservation and Management Act (MSA) has come to be regarded internationally as a gold standard in sustainable fishery management. Yet as the law awaits a long-overdue and likely controversial reauthorization, its impact on US fish populations and fisheries remains poorly understood. A major challenge to measuring the efficacy of biological resource management policies is that data are noisy and policy treatments are not randomly assigned. As a result, causally interpretable empirical studies of such policies' impacts are rare, and in the case of MSA there has been none until now. Compiling the largest dataset to date on US, Canadian, and European Union fishery status and management, we carefully construct sets of stocks to approximate the counterfactual biomass that they would have experienced without the treatment. We find that treated stocks increased by almost half their size in biomass relative to these counterfactuals following the establishment of rebuilding provisions in the MSA's 1996 reauthorization.

*We are grateful for helpful comments from Amir Jina, Kailin Kroetz, Kyle Meng, James Rising, and Jeffrey Shrader. We would like to thank Jesse Adelman, Sushant Banjara, Jennifer Boughton, David Foote, Alessandra Guerrero, Stephanie Klunk, Chong An Ong, Pete Rodrigue, Ruby Roty, Daniel Tropper, and Vanessa Zemke, for excellent research assistance. We would also like to thank participants at University of Illinois Urbana-Champaign, UC Davis, The World Bank, Resources for the Future, Midwest Energy Fest, the Ostrom Workshop, and the AERE Sessions at the AEA for their helpful comments. We also thank the staff members at the different Fishery Management Councils and the National Oceanic and Atmospheric Administration, especially Karen Greene, for their assistance in accessing, validating, and interpreting the data.

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1 Introduction

Global resource extraction has seen a threefold increase since 1970, and many renewable resources are in decline (UNEP 2020). Water scarcity is increasing, deforestation is outpacing regrowth, species face higher rates of extinction, and many historic fisheries have collapsed (Arrow et al. 2004). Despite the growing calls for sustainable management (Scheffer et al. 2001; Heal and Schlenker 2008; Polasky et al. 2019; Lubchenco et al. 2020; Slough et al. 2021; Burke et al. 2021), we lack well-identified evidence on the impact of biological resource use policies, in contrast to the large literature that has evaluated other environmental policies.[1] Unlike pollution or non-renewable resources, renewable resources have uncertain replenishment rates that can undergo regime shifts (Pindyck 1984; Conrad and Clark 1987; Hanski et al. 1996; Nøstbakken 2006; Estes et al. 2011; Zeeuw 2014; Wagener 2015). Evaluating policies that govern renewable resources is challenging because it is difficult to disentangle the treatment effect of the policy from natural system dynamics (Daily et al. 2000; Ferraro et al. 2019; Greenstone and Gayer 2009; Polasky et al. 2019).

Previous work on renewable resource management often assumed complete information regarding a resource's behavior and simple functional forms for its growth (Gordon 1954; Clark et al. 1979; Beltratti et al. 1998; Brander and Taylor 1998). However, recent studies have emphasized the stochasticity of biological systems and the resulting difficulties of managing them (Pindyck 1984; Nøstbakken 2006; Sethi et al. 2005; Carson et al. 2009; Brozović and Schlenker 2011; Memarzadeh et al. 2019). An additional complicating feature of biological resources is that they can undergo regime shifts that involve long-term alterations in the replenishment rate or even an irrevocable collapse of the resource (Conrad and Clark 1987; Estes et al. 2011; Zeeuw 2014; Wagener 2015). For instance, a rainforest, once logged beyond a certain point, may regrow as savanna (Boulton et al. 2022), or a species whose population declines below a given level may lose habitat to another species (Estes et al. 2011). Many environmental policies rely on thresholds to trigger regulatory interventions in order to simplify management or enforcement, even when the marginal costs and marginal benefits around the threshold are continuous (Weitzman 1974). But renewable resource theory justifies using threshold-based policies to avoid tipping points that could lead to resource collapse (Conrad and Clark 1987; Hanski et al. 1996; Brander and Taylor

[1] See for example existing work that studied US policies such as: Clean Water Act (Keiser and Shapiro 2019; Jerch 2021), Clean Air Act (Greenstone 2002; Auffhammer and Kellogg 2011; Walker 2013; Isen et al. 2017; Gibson 2018), Superfund sites (Greenstone and Gallagher 2008; Currie et al. 2011), Corporate Average Fuel Efficiency standards (Austin and Dinan 2005; Jacobsen 2013; Jacobsen and Benthem 2015).

1998; Kremer and Morcom 2000).

This article's primary contribution is to provide large-scale evidence for a threshold-based policy's success in recovering a depleted renewable resource. We are the first, to the best of our knowledge, to accomplish this without relying on strong structural assumptions regarding the replenishment rates or growth dynamics of the resource. We do this by studying the requirement to rebuild overfished stocks under the 1996 reauthorization of the Magnuson-Stevens Act (MSA) (*Sustainable Fisheries Act: Amendments to the Magnuson Fishery Conservation and Management Act, Magnuson-Stevens Act* 1996), which regulates all marine fisheries in the United States (US).[2] Under the MSA, a predetermined scientific population threshold for each fish stock triggers the reduction of catch until the stock population is considered rebuilt to a sustainable level, often necessitating a doubling or more of the stock size.[3] Using data from the US, Canada, and the European Union (EU) on the staggered depletion of stocks below their population threshold, we leverage the fact that the requirement to rebuild stocks was adopted in the US two decades before Canada and the EU. Across multiple comparisons, we find evidence that the rebuilding provisions led to significant recoveries. On average, stock populations that trigger rebuilding provisions in the US increase by 47.7% compared to counterfactual trajectories in Canada and the EU.

The MSA enjoys a reputation internationally as a gold standard in sustainable fishery management, and it has become a model for countries around the world ((Testimony of Eric Brazer) 2018; (Testimony of Janet Coit) 2021). As of 2018, wild capture marine fisheries provide 84.4 million tonnes of fish, an important source of protein and food security, and 39 million jobs and livelihoods worldwide (FAO 2020). Sustainably managing them is among the UN's Sustainable Development Goals (SDGs) (UN General Assembly 2015). Canada and the EU have already adopted similar laws (Canada 2019; EU 2013), and 193 countries have signed on to the commitment to integrate similar language under the SDGs into their national laws (UN General Assembly 2015).

Despite its increasing adoption internationally, this traditionally bipartisan act is highly controversial among the fishing industry and fisher communities. The debate around MSA's reauthorization, which has been held up in Congress for ten years, centers on how successful these rebuilding provisions have been, as well as their impacts on fishing communities. Many fishers believe populations will rebound without such prescriptive regulation, because they have seen generations of natural boom and bust cycles in fish populations (*Sacred Cod: The*

[2] The same requirement is in the 2018 Modern Fish Act, which governs US recreational fisheries.

[3] A biological fish stock is a group of fish of the same species that live in the same geographic area and mix enough to breed with each other when mature.

Fight for a New England Tradition 2016). This notion of fishery recovery in the absence of policy accords with the theory that as the marginal costs of extraction increase with a declining resource, fishing pressure will decrease, and the stock will recover (Clark 1976; Burgess et al. 2017). Competing reauthorization bills have differed on whether the rebuilding provisions should be weakened.[4] Changes to the strength of these rebuilding provisions will have direct repercussions for US commercial fisheries that employ 1.2 million people and generate over $165 billion dollars annually (National Marine Fisheries Service 2022).

Early analyses and case studies suggested that the MSA's rebuilding plans were not working, with very few stocks considered rebuilt (Rosenberg et al. 2006). Subsequent studies found results trending in a positive direction (Milazzo 2012; Sewell et al. 2013; Oremus et al. 2014; NRC 2014; Hilborn et al. 2020). These studies either lacked enough data for program evaluation (Rosenberg et al. 2006) or did not include a control group (Milazzo 2012; Sewell et al. 2013; Oremus et al. 2014; NRC 2014; Hilborn et al. 2020), precluding causal interpretation. Two papers examine population trends. Oremus et al. (2014) analyzes US stock data and find evidence for positive trend breaks for 19 out of the 34 stocks that entered a rebuilding plan. Hilborn et al. (2020) uses a global dataset, and find that 36 of 47 potentially overfished stocks experience population increases after 2006, but not to healthy levels. Both studies do not include a comparison group. A few studies use simulations to evaluate rebuilding provisions versus other fishery management options (Benson et al. 2016), or to consider other timelines instead of the ten-year maximum (Patrick and Cope 2014; Carruthers and Agnew 2016), or to examine the role of uncertainty in rebuilding success (Memarzadeh et al. 2019). However, none of these simulation-based studies are aimed at empirically measuring the policy's efficacy.

In order to identify the treatment effects of rebuilding plans and reject alternative explanations, we need to approximate the counterfactual population dynamics of stocks that meet the condition for a rebuilding plan. To facilitate this, we collect and harmonize data on US, Canadian, and EU fishery status and management, resulting in the largest dataset of its kind. This allows us to construct both contemporaneous and historic comparison groups that leverage the timing of when the biological reference thresholds were developed and when

[4] In July 2021, Congressman Huffman introduced H.R. 4690 to the House after engaging in a year-long, cross-country listening tour. Congressman Young, one of the authors of the original 1976 MSA, introduced an alternative bill, H.R. 59, that has its roots in a 2018 failed bill. In 2018, the House of Representatives passed a bill, the Strengthening Fishing Communities and Increasing Flexibility in Fisheries Management Act, that would reauthorize MSA and redirect rebuilding objectives toward the needs of fishing communities. However, this bill never passed the Senate and thus expired at the end of the 115th Congress. Opponents of the Act have derided it as the "Empty Oceans Act."

they became binding. Specifically, our empirical design exploits data in countries that did and did not implement the policy, as well as data on the same US fish stocks from before and after the policy's implementation, to compare how stocks rebounded from population declines with and without the rebuilding requirements.

We use data from Canada, which enacted a rebuilding framework only in 2019, and the EU, which passed the policy in 2013 with full enactment by 2020. Using a difference-in-differences design, we compare US stocks that went into rebuilding with Canadian and EU stocks that met the conditions for rebuilding but did not receive the treatment. Populations are measured by their biomass, the aggregated weight of all fish in a stock. We find that by the tenth year after dropping below the biomass threshold, stock biomass was 53% higher in the treated group relative to the control group. The magnitude of this effect is in keeping with the goals of the policy, which for many stocks aims to double the biomass from the threshold.

We also compare the same US stocks to themselves prior to 1996. We find that stocks that fell below their threshold did not consistently recover prior to 1996, but did consistently recover once the requirement for rebuilding plans was put in place. We refine the historic comparison further by restricting the sample to stocks that met the conditions for a rebuilding plan in both time periods, before and after the 1996-regime, which allows us to hold the stock composition constant. We then use a paired-differences estimator and find that stock biomass more than doubles relative to their historic counterfactual. Similar to our contemporaneous comparisons, stock biomass was higher in the treatment group relative to the control group.

These approaches leave open the possibility that changes over time or space in environmental conditions, market demand, and fishing technology could account for some of the observed effects, confounding the results. Using a proxy for environmental conditions, we do not detect differences in the growth rate of the stocks between the comparison and treatment groups. When comparing catch levels between the comparison and treatment groups, we do not find evidence consistent with a decline in demand driving the recovery of the stocks.

These comparisons support the conclusion of the analysis: stock biomass increases, on average, for the stocks that enter a rebuilding plan, but it does not recover in the absence of such management actions. We interpret these results as evidence for the efficacy of the rebuilding provisions. We find indirect evidence that other plausible mechanisms are not consistent with what we observe in the data. Our findings have direct policy implications for domestic and global fishery management, and provide support for the role of scientifically informed thresholds in renewable resource management.

In what follows, we introduce fishery management in the US; review the conceptual framework around threshold-based renewable resource management; summarize our data sources; describe the empirical strategy; present the main findings; discuss potential spillovers; and briefly conclude.

2 Rebuilding Provisions Under The Magnuson-Stevens Act

The first federal law to regulate fishing in US waters was the original Fishery Conservation and Management Act, which passed in 1976. The act defined the US's national jurisdiction, or Exclusive Economic Zone (EEZ), created regional councils, and restricted fishing in US waters to domestic vessels. The act later became known as the Magnuson-Stevens Act (MSA), after the two senators who sponsored it. The MSA is the primary law governing marine fisheries in the US and lays the groundwork for all regional and state management.

Increased fishing by US commercial fleets depleted stocks, and the MSA was reauthorized in 1996 as the Sustainable Fisheries Act (SFA) with more conservation measures, including the crucial requirement to rebuild overfished stocks. The SFA required regional fishery management councils to develop and implement rebuilding plans whenever a given stock is deemed overfished. The plans are "expected" to bring the stock back to sustainable population levels in a time period not to exceed 10 years, unless that is biologically impossible (*Sustainable Fisheries Act: Amendments to the Magnuson Fishery Conservation and Management Act, Magnuson-Stevens Act* 1996). National Marine Fisheries Service further defines "expected" to mean that rebuilding plans have at least a 50 percent probability of attaining healthy populations under their National Standard 1 Guidelines. A second MSA reauthorization in 2006 required that the rebuilding plan be implemented within two years of the stock being declared overfished.

The MSA uses three thresholds to determine a stock's health. The first defines "overfishing" as an unsustainable harvest rate. The second defines "overfished" as a population that has dropped too low. The third defines "rebuilt" as the population level at which the stock is considered healthy. The policy's goal is to both conserve the population and maximize long-term catch by identifying stocks that are overfished and bringing them back to healthy levels. As an example, we plot the trajectory of one stock, spiny dogfish that experienced the full policy cycle from becoming overfished to rebuilt in Figure A1.

All three of these thresholds are based on a concept known as maximum sustainable yield (MSY). MSY is defined as the largest average catch that can be taken from a stock over the long term – that is, without depleting the stock. The population level that produces this optimal catch rate for a given stock is known as its biomass at maximum sustainable yield, or BMSY. Under MSA, the population at which the stock is considered rebuilt is typically set at BMSY. The stock is considered overfished when its population is below a certain fraction of BMSY, known as the minimum stock size threshold (MSST). In many cases, that fraction is 50%. Overfishing occurs when the rate of mortality due to fishing, known as F, exceeds the rate that produces MSY, known as FMSY.[5] As of the end of 2020, 47 stocks have been rebuilt since 2000 (NOAA Fisheries, 1997-2020).

Under this framework, fishery management councils develop MSY targets for each stock and thresholds at which it is considered overfishing, overfished, and rebuilt. Management councils set annual catch quotas, known as total allowable catch, designed to maintain stocks at healthy levels. These quotas are set according to what is known as a harvest control rule (HCR), when a stock goes below BMSY. The HCR starts when B<BMSY and before a stock reaches MSST. When a stock falls below its MSST and is designated overfished, this harvest control rule changes discontinuously as catch limits are dramatically reduced. The council must then develop a rebuilding plan. The discontinuity in the harvest control rule is meant to act as an automatic stabilizer until the rebuilding plan is implemented.

However, management is not the only variable that influences a stock's status. The stock's environment, ecology, and biology, as well as the economics of the fishery impact stock status. Uncertainties in these systems can alter the threshold that triggers the policy intervention (Sethi et al. 2005; Carson et al. 2009; Brozović and Schlenker 2011; Memarzadeh et al. 2019). They can also affect the trajectory of rebuilding, as stocks recover more slowly or quickly than would be expected from the management interventions alone.

3 Conceptual Framework for the Impacts of Uncertainty & Noise on Renewable Resource Management

Managing renewable resources using predetermined thresholds presents two challenges: estimating the appropriate threshold, and accurately assessing a stock's status so you know when it has been crossed (Brozović and Schlenker 2011). In the case of fish, both are subject to significant measurement uncertainty, which can impact the policy's effectiveness (Costello et al. 2016; Memarzadeh et al. 2019; Sethi et al. 2005). Set the threshold too high, and it will trigger the policy unnecessarily, imposing costly restrictions on a resource that would have replenished anyway, albeit more slowly (Hilborn 2019; McQuaw and Hilborn 2020). Set

[5] In general, fishing mortality F is expressed as $F = \frac{Catch}{Biomass}$, such that at the target levels it is $FMSY = \frac{MSY}{BMSY}$.

the threshold too low, and the stock will be depleted before the policy intervention, making rebuilding unnecessarily difficult, if not impossible (Duarte et al. 2020; Worm et al. 2009). Likewise, an error in measurement of the stock's status in either direction could lead to the policy triggering unnecessarily or failing to trigger when needed.

We illustrate these two distinct problems in Figure 1 in order to demonstrate the challenge of evaluating the causal treatment effect of the policy. Our discussion here focuses on fisheries, but these points apply to renewable resources more generally. In Figure 1a, the level of the resource, in this case fish population, is on the y-axis, and time is on the x-axis. With complete information about the stock's population dynamics, we can set the threshold that triggers the policy exactly at the tipping point that avoids resource collapse (denoted by the horizontal dotted red line labeled MSST). While we make the simplifying assumption that there is no measurement error, we still allow the population to fluctuate over time due to natural cyclicality.[6] Unexpectedly, the population experiences an abrupt negative shock and drops below its MSST. At this point, the policy kicks in, placing restrictions on extraction, and we observe a recovery of the stock, as shown by the dashed dark blue line labeled "Rebuilding."

The question is: What is the counterfactual stock trend in the absence of the policy? Would the stock have rebounded on its own (dashed light blue line) or collapsed (dashed orange line)?

If the MSST line is set too high (Figure 1b), then the regulators underestimated the range of the natural cyclicality in the population. Fishers sometimes argue that this is the case with MSA, leading to the unnecessary imposition of rebuilding plans on stocks that were simply at a low point in the cycle. If so, then what looks like a successful rebuilding plan was an accelerated version of the rebound that could have been achieved without the costs imposed by the policy.

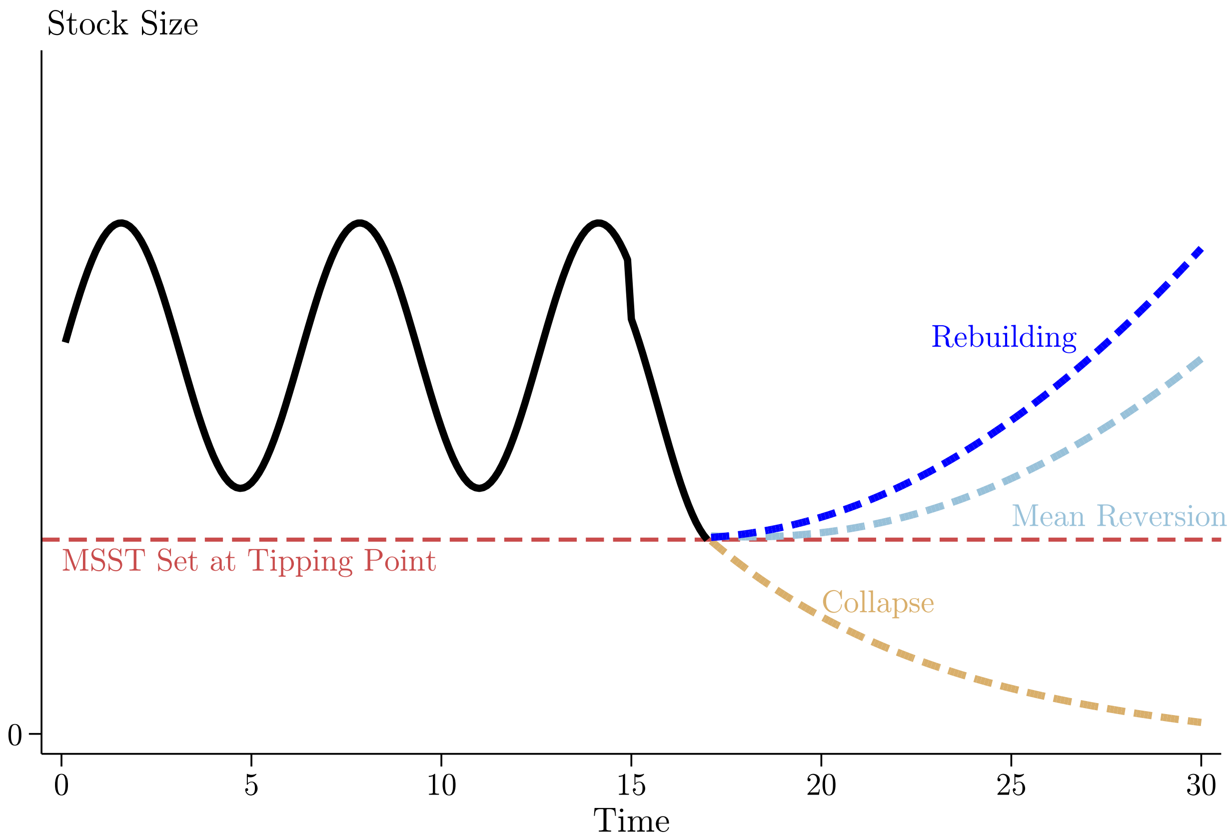
On the other hand, if the MSST is set too low, then the policy will not trigger until the stock has crossed a tipping point, such that even an aggressive rebuilding plan may not be able to rehabilitate it (1c). Even if the stock does not experience a full collapse, it could converge towards a new equilibrium that is lower in size or higher in volatility.

Our discussion above assumes that the stock level was known and focuses on the complexities around the choice of the threshold. We now turn our attention toward uncertainty and error in population estimates. If the estimated population is below the threshold, but the true population level is above the threshold, then the policy will trigger unnecessarily.

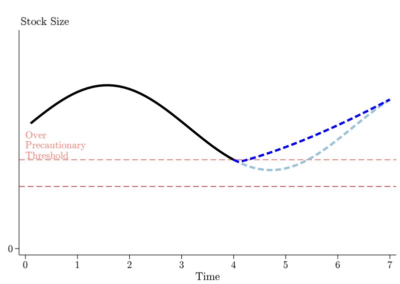
[6] Many variables contribute to cyclicality in population dynamics, including food availability, environmental conditions, and markets that influence the extraction rate.

Figure 1: Conceptual Framework for Resource Policy Design & Evaluation

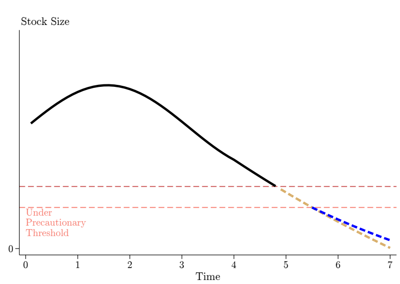
(a) Counterfactuals of Collapse or Mean Reversion Following Depletion Below Threshold



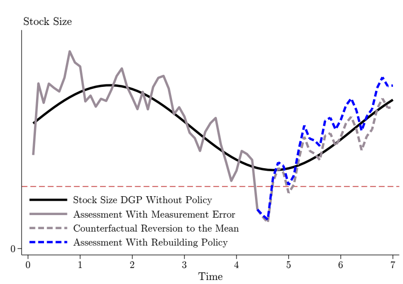
(b) Threshold Too High



(c) Threshold Too Low



(d) Measurement Error



Notes: Summarizing possible scenarios for a stock that drops below a tipping point, resulting in a regime shift and potential collapse in the absence of recovery action (yellow line), experiences gradual reversion to its previous dynamics (light blue line), or undergoes a rebuilding phase that rehabilitates it.

Note that this can occur with minimal natural cyclicality, even when the threshold is correctly determined.[7] This presents a challenge for policy evaluation, because the population outcomes after receiving policy treatment could be very similar to outcomes in absence of treatment (1d).

Due to uncertainty in the tipping point and population level, policy makers are more likely to set the MSST higher than the estimated tipping point (Nichols et al. 2018). This creates a buffer between the tipping point and policy trigger. Stocks with larger variability or higher uncertainty are more likely to need a larger buffer, making the counterfactual more likely to look like panel b. Stocks with more predictable population dynamics could withstand a smaller buffer, albeit still biasing the counterfactual towards panel b. Finally, changes in environmental conditions could change the tipping point or lead to higher uncertainty in stock dynamics (Lam et al. 2016), increasing the size of the buffer.

The key to empirically evaluating the policy, then, is approximating the counterfactual in which a given stock does not receive a rebuilding policy. Because the policy mandates rebuilding any stock that meets the condition for treatment, simply observing the population trajectory following rebuilding does not allow us to measure the policy's effect. Our approach in this analysis is to find stocks that would have met the criteria for treatment, but were not in fact treated, whether due to jurisdiction or timing. We can then use them to approximate the counterfactual trajectories for the stocks in the US that did receive treatment under rebuilding plans. This will allow us to answer the question of whether stocks rebounded due to the policy or due to natural cyclicality.

4 Data

In order to evaluate the effectiveness of rebuilding provisions under the MSA, we gather panel data on catch, population, and the timing of policy implementation, as well as management thresholds by fish stock. A biological fish stock is a group of fish of the same species that live in the same geographic area and mix enough to breed with each other when mature.

Yearly US catch, biomass, and productivity for each stock were obtained from the National Oceanic and Atmospheric Administration's (NOAA's) StockSMART System, a database of stock assessments (NOAA 2022). Management thresholds for each stock are always obtained from the same source and the same assessment year. The management thresh-

[7] Consider a stock with no natural cyclicality, maintaining a constant stock size over time. A sufficiently large enough assessment error could determine the stock has crossed the threshold. If assessment errors are serially correlated, then this pattern could persist in the assessment data for several periods, giving higher confidence in the determination.

olds include MSST for the "overfished" designation, FMSY for the "overfishing" designation, BMSY for the "rebuilt" designation, annual total allowable catch (TAC), and MSY. These are also known as reference points. If data from StockSMART were incomplete, missing data were digitized from the stock assessment or directly obtained from the stock assessor.[8] When a unit mismatch occurred between a stock's time series data and its reference points, we converted the reference point value to match the units of the time series data (see Data Appendix for full documentation).

Fish stock assessment reports are developed by NOAA fish scientists. They use peer-reviewed models to estimate fish populations and reference points. The models are calibrated using observed data from fisher catch and fish abundance surveys. Catch data include landings that are sold at the dock, discards at sea, and bycatch, which is accidental catch of a species that fishers weren't targeting. A network of monitoring programs are used to enforce quality control of this data, including third-party dockside and boat observers, log books, and recreational sampling. Abundance surveys employ fishing methods, but they are statistically designed, run by NOAA, and use standardized sampling methods (same boat, gear, ocean sampling grid, and time of year). NOAA's website describes stock assessments as conceptually similar to their National Weather Service dynamic atmospheric models: "Even though fish stock assessments operate on much longer time scales than weather models—months and years rather than hours and days—they similarly combine and incorporate many different complex observations into a holistic picture of the situation."

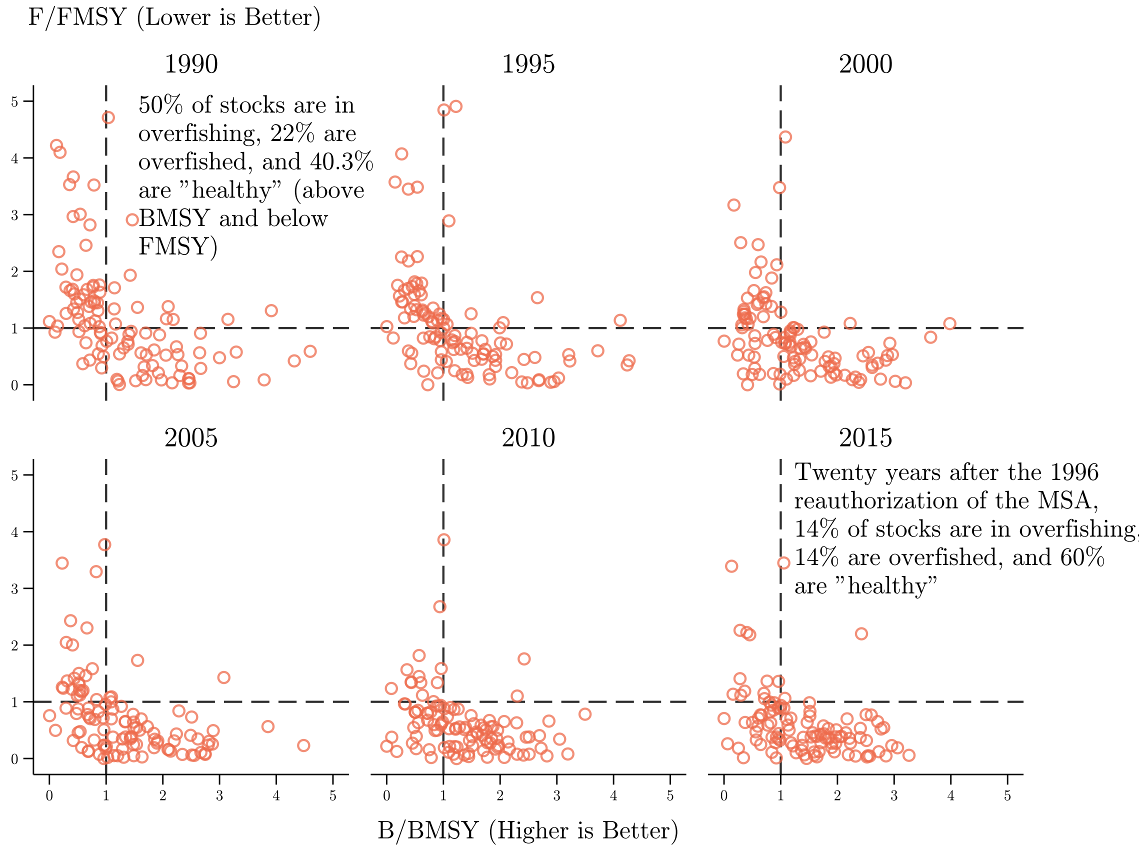
We went through each of NOAA's yearly Status of Stocks reports (NOAA Fisheries, 1997-2020) to record the years that fishery management councils designated a stock as "in overfishing," near overfished, overfished, in rebuilding, and rebuilt. We validated these years with the information stored at NOAA's Office of Sustainable Fisheries.[9] Fifty-six of the 189 non-migratory and non-anadromous US stocks in our dataset entered rebuilding after the re-authorization of the MSA in 1996. To date, this is the largest harmonized panel dataset of US fish stock populations and management.

Our dataset is limited to stocks that can be found in federal waters and excludes non-migratory stocks to ensure we are studying stocks that are only affected by US fishing pressure and regulations. We also exclude anadromous stocks, such as salmon, as they

[8] Incomplete data includes missing time series, missing reference points, or mismatched units between a stock's time series and its reference points.

[9] This validation is especially important during the earlier years of the post-1996 reauthorization of the MSA, because several stocks were incorrectly classified due to confusion about the new determinations. These errors were not corrected in the public records, and the true regulatory history is only available in non-public records managed by NOAA. See the Data Appendix for additional details.

Figure 2: Stocks' Statuses Relative to Biological Reference Points



Notes: Summarizing the status of stocks relative to their target reference points in five-year intervals, for stocks that have data reported in each time period (n=114). The y-axis shows the fishing mortality (catch over biomass) relative to the target level, while the x-axis shows the biomass relative to the biomass target level. Stocks with F/FMSY above one are experiencing overfishing. Stocks with low B/BMSY values, generally below half of their BMSY value (below 0.5 on the x-axis), are considered overfished. We truncate the axes at 5 to allow for easier visual insepction of the data.

spend part of their life cycle in fresh waters that are subjected to different local and federal regulations, making it difficult to account for the full regulatory treatment they experience. Finally, we omit crab species, as their assessment process and management is very different relative to the other species.

We also gather data on the quantity and revenue of fish sold, which are tallied by region and species, a higher taxonomic level than fish stock.[10] When possible, we match species-region landings to their equivalent Stock SMART stock. In some cases, landings data combines landings from multiple stocks of the same species in a given region. (E.g., New England Atlantic cod landings come from two stocks, one in the Gulf of Maine and one in Georges Bank.) For these situations, annual revenue and landings data are distributed to each stock according to its proportion of the total annual catch for the stocks of that species in that region.

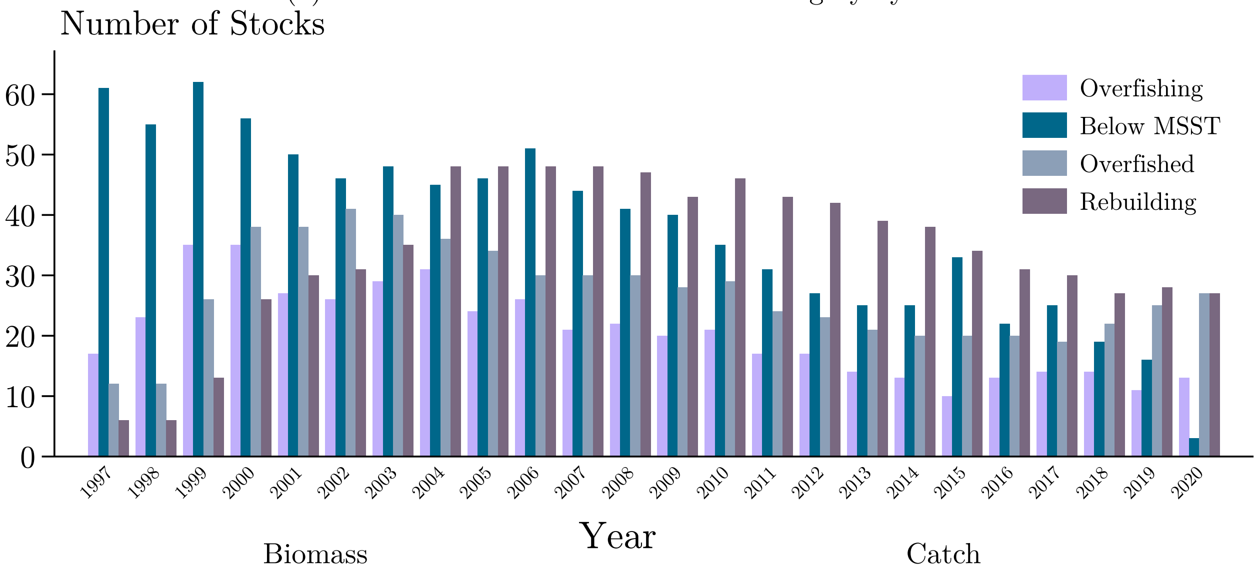
We complement our US data with data from Canadian and EU marine fisheries, which have comparable fish species, technology, access to similar global markets, a fishery management body and government agency, and scientists who assess stocks (Halliday and Pinhorn 1996). Canada's Fisheries and Oceans department (DFO) does not centralize its stock assessments. Catch, biomass, and productivity time series were obtained from the RAM Legacy Stock Assessment Database (re3data.org 2021), a voluntary compilation of stock assessment results for commercially exploited marine populations from around the world. This database is missing many management reference points. Missing reference points were obtained from the 2020 Oceana Audit (Oceana Canada 2020) on Canadian fish stocks and rebuilding progress. Oceana collected this data directly from stock assessments. We quality-checked the data to make sure that reference points came from the same assessment year as time series data and that units matched between datasets. Stocks which had reference points from the Oceana Audit but were not listed in RAM were manually added from stock assessment reports. For stocks with missing reference points, we follow DFO guidelines and set its BMSY equal to half of the stock's maximum historical biomass, and define a pseudo MSST equal to half of this BMSY proxy.[11] There are a total of 103 Canadian stocks in our dataset, of which 96 have biomass that dropped below the MSST. Canadian landings and revenue data were collected from DFO's Seafisheries Landings database (DFO 2022). We merged the species-region landings and revenue with the stock data in the same manner as we merged the US data.

[10] Data was obtained from NOAA Fisheries One Stop Shop (NOAA FOSS 2021).

[11] See https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm for additional details about the DFO fishery management framework. Accessed: 2/5/2022.

Figure 3: MSA Determinations & Changes in Key Outcomes Around Those Events

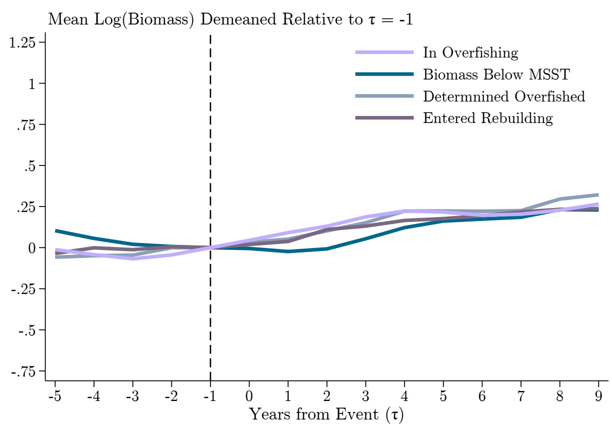
(a) Number of Stocks in Each MSA Category by Year



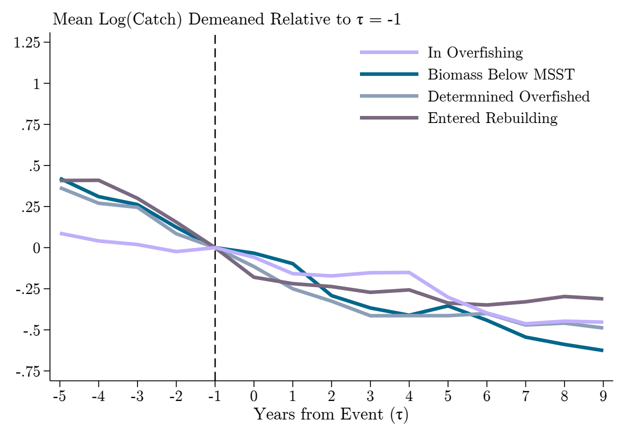
Biomass

Catch

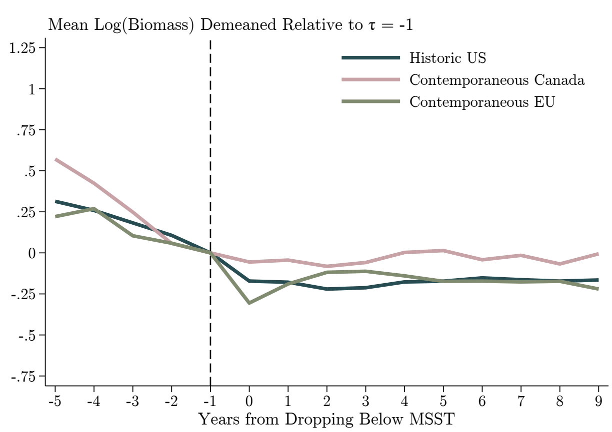
(b) Stocks With Rebuilding Plans



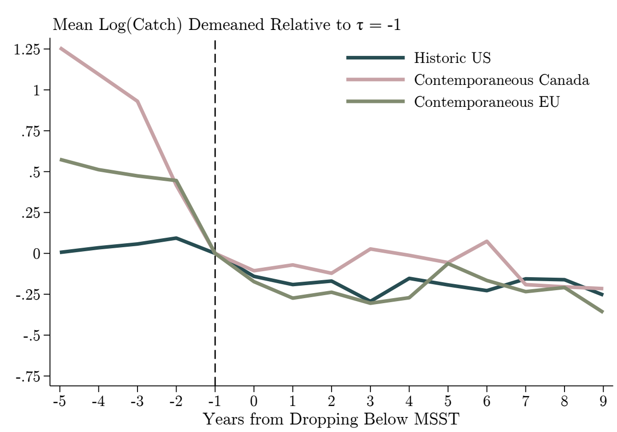
(c) Stocks With Rebuilding Plans



(d) Stocks Without Rebuilding Plans



(e) Stocks Without Rebuilding Plans



Notes: Summary of the number of US stocks with MSA events in each year (a), and changes in biomass and catch around events of interest for stocks with (b-c) or without (d-e) rebuilding plans (b-c).

EU catch, biomass, and productivity time series data, as well as management reference points, are obtained from a 2020 European Commission report monitoring the Common Fisheries Policy, the primary EU fisheries law (EU 2013). Catch data came from three sources: the ICES Stock Assessment Database (ICES 2022) for Northeast Atlantic stocks and to two databases — the EU's Scientific, Technical and Economic Committee for Fisheries database (STECF 2022) and FAO's Validated stock assessment forms (FAO GFCM 2022) — for Mediterranean stocks. Unfortunately, landing and revenue data had too short a time series to be collected. There are a total of 293 EU stocks in our dataset, of which 150 have biomass that dropped below the MSST.

5 Estimating the Treatment Effect of The Magnuson-Stevens Act

Under an ideal experiment, we would have been able to randomly assign rebuilding plans to stocks that have been depleted below their MSST. In practice, the assignment of rebuilding plans follows the statutory requirement of the Act to develop and implement a rebuilding plan for stocks that have been determined as overfished, after their biomass falls below their MSST. We consider each one of these three events — a stock's biomass falling below its MSST, a stock being declared overfished, and a stock entering a rebuilding plan — as a potential MSA event of interest. Our focus in the main analysis is on stocks that enter rebuilding. To avoid anticipatory effects, we define the first treatment year as the year the stock's biomass dropped below its MSST. However, we report results for the other MSA events in the main text and Appendix.

US stocks that receive rebuilding plans are systematically different than US stocks that do not because they are following systematically different trajectories. Rebuilding plans can also affect stocks that are not in a rebuilding plan, causing a violation of the stable unit treatment value assumption (SUTVA). Stocks in the same region could have an effect on one another through the food web (Estes et al. 2011).[12] Restrictions on species in rebuilding could benefit other species if they are typically caught together, or if the stock in rebuilding serves as a food source for the stock that is not in rebuilding. There could also be economic spillovers. Stocks in rebuilding that undergo changes in fishing effort, such as changes to catch limits, allowed days at sea, or the timing and length of the fishing season, might result in fishers substituting their efforts toward other species in the region (Kroetz et al. 2019). Finally, declines in catch could affect relative prices, increasing the demand for fish from

[12] This is known as trophic cascade effects.

other regions.

The lack of a readily available comparison group is the key empirical challenge we face in estimating the causal treatment effect of the MSA on the health of marine fishery stocks. A valid comparison group needs to approximate the population dynamics of a stock that is depleted below the MSST, but does not enter a rebuilding plan. We overcome this inference problem using two comparison groups: (i) a contemporaneous comparison group that relies on updates to the scientific and management frameworks in Canada and the European Union (EU), and (ii) a historic comparison group of stocks in the US that have data going back to 1984 or longer, when rebuilding was not required by law.

Recognizing the potential limits of comparing stocks within US waters after the 1996 passage of MSA, we leverage the recent adoptions of the requirement to rebuild overfished stocks in Canada and the EU that are similar to the MSA. In 2019, Canada modernized their Fisheries Act (FA) by introducing a rebuilding requirement for depleted fish stocks. Similar to the MSA, FA uses biological reference points based on MSY to sustainably manage fish stocks. Since 2017, Fisheries and Oceans Canada (DFO), the equivalent agency to NOAA Fisheries, has been developing the scientific assessments that define the Limit Reference Point (LRP). When a stock's biomass falls below the LRP, a rebuilding plan needs to be developed and implemented to bring the stock back to its Target Reference Point (TRP), often the stock's Upper Stock Reference (USR) point.

The EU adopted a similar policy when they amended the Common Fisheries Policy (CFP) in 2013. The policy calls for rebuilding all commercially used fish stocks above levels that are capable of of producing MSY. They set a goal of reducing fishing mortality, F, below FMSY by 2015, latest by 2020. The EU defines for each stock the Safe Biological Limit (SBL), equivalent to the MSST under the MSA.

Our main empirical strategy is a staggered difference-in-differences that uses the different timing of stocks dropping below their MSST. This research design relies on the set of stocks in Canada and the EU that exhibit the same depletion dynamics after dropping below their MSST equivalent thresholds, but do not receive treatment in the form of a mandatory rebuilding plan during the time period of study. The recent adoptions of the FA and CFP management frameworks provide us with a contemporaneous comparison group that is less likely to be affected by rebuilding plans taking place in the US. We use biomass data on Canadian stocks and their LRPs to define the first year a stock drops below their LRP, similar to the first year US a stock drops below its MSST. We repeat this approach using biomass data and SBL values for the stocks managed under the EU's CFP.

In the historic comparison, we compare stocks that meet the conditions to receive treatment – a rebuilding plan – in two time periods: before and after the 1996 reauthorization of the MSA. Before 1996, the MSST was not yet established, and if the biomass of a stock went below it, it would not trigger any regulatory action. We examine both stocks that had their biomass below their MSST in at least one year during the time before 1989, or after 1996, as well as stocks that were below the MSST in both time periods.

Explicitly, we require stocks to be below their MSST before 1989, or after 1996. This means that stocks could have either dropped below MSST only after 1996; dropped below MSST before 1989 and remained below MSST after 1996; or dropped below MSST before 1989, recovered, and dropped below MSST again after 1996. In each time period, we define the first year the stock's biomass is below its MSST as the event year. We reserve the 1989 to 1996 period as the post-treatment period for the pre-authorization period.

The historic comparison between stocks that were below the MSST in both time periods has the advantage of focusing on the same stocks, holding their biology and potentially their stock assessment methodologies constant. However, comparing stocks in the 1970s and 1980s to stocks in the 2000s and 2010s, raises concerns that other factors might be driving their recovery. Over these decades, there could be changes to the market demand for these stocks; the technology used for fishing could become less harmful to fish habitat; and changing environmental conditions could increase the growth rate of fish stocks. A valid contemporaneous comparison group would alleviate these concerns.

The key identifying assumption of the DD design is that the stocks that entered rebuilding would have had their counterfactual outcomes develop along parallel trends to the control stocks in the absence of the actions taken under the MSA to recover and rebuild the stock.

5.1 Cohort-Weighted Difference-In-Differences Specification

We estimate the dynamic treatment effects around the MSA event of interest relative to the contemporaneous comparison group by estimating the cohort-weighted regression specification developed in Sun and Abraham (2020). This DD estimator allows us to estimate the staggered DD research design while avoiding the estimation issues with two-way fixed effects (TWFE) estimators. The key intuition about the undesired properties of using TWFE estimators for a staggered DD design is that the TWFE estimator would use stocks that receive early treatment as controls for stocks that receive treatment later, potentially violating the parallel trends assumption. This could give rise to negative weights in the weighted estimate for the average treatment effects on the treated (ATT), distorting and potentially even flipping the sign of the effect. These problems are more pronounced when there are dynamic treatment effects, and/or heterogeneous treatment effects – both of which are likely present in our empirical setting (see Chaisemartin and D'Haultfoeuille (2020) and Goodman-Bacon (2021) for additional details and discussion of these issues).

We follow the formulation of the cohort-weighted DD estimator and define the set of treatment cohorts that entered rebuilding as E, and the set of non-US stocks that dropped below their MSST as C. The estimator developed by Sun and Abraham (2020) simply estimates a separate set of leads and lags around the event of interest by interacting those leads and lags with a cohort dummy. Those specific cohort ATT (CATT) estimates are then weighted for each event time to obtain an estimate for the coefficient of interest on each lead and lag. This process results in a minor modification to the canonical TWFE specification by simply adding an interaction term for each cohort that undergoes treatment:

$$y_{st} = \sum_{e \neq C} \sum_{\tau \neq -1} \beta_{e,\tau} \mu_{e,\tau} \mathbb{1}\{E_s = e\} + \lambda_s + \delta_t + \varepsilon_{st} \tag{1}$$

Where y_{st} is the outcome of interest, in log points, for fishery stock s, in year t.[13] We include leads and lags, $\mu_{e,\tau}$, that are equal to one when the stock in cohort e is τ years away to the event of interest: dropping below its MSST, receiving an overfished determination, or entering a rebuilding plan. Our focus is on the time window of five years leading up to the MSA-event and ten years after the MSA-event. As a result, we bottom and top code the leads and lags, and exclude the bottom and top coded coefficients when reporting the estimation results. The set of coefficients, $\beta_{e,\tau}$, recovers the dynamic path around the time of the event for each cohort, relative to one year prior to the event. The final estimation step is calculating a simple mean of the coefficients for each event time coefficient.[14]

We include stock fixed effects, λ_s, to account for time-invariant characteristics of each stock, such as the fishing gear used to catch it, long-term demand and market size, and the biological factors that determine its growth dynamics. The stock fixed effects also nest fishery management council fixed effects that account for cross-sectional variation across jurisdictions. To flexibly account for pooled time shocks, we include year fixed effects, δ_t, that absorb large macroeconomic cycles as well as large-scale changes to environmental

[13] Explicitly, we use the inverse-hyperbolic-sine: $\log(x + \sqrt{1 + x^2})$.

[14] Because we focus on the sets of leads and lags where the composition of stocks is the same (five years before and ten years after the event) the weighted average simplifies to a simple average where each cohort receives the same weight.

conditions. Any unobserved heterogeneity is captured by the error term, ε_{st}, which we cluster at the stock level.

5.2 Event-Study Regression Specification

In addition to the cohort-weighted estimator described above, we also estimate a simpler event study specification in which we focus our attention on one group of stocks, in either treatment or control status. Specifically, we estimate the following regression specification:

$$y_{st} = \sum_{\tau \neq -1} \beta_\tau \mu_\tau + \lambda_s + \boldsymbol{X_{st}} \boldsymbol{\theta} + \varepsilon_{st} \tag{2}$$

The specification in Equation (2) is identical to the one in Equation (1) except for the year fixed effects, which we replace with less flexible time trends. We avoid including year fixed effects when we subset the sample to either treated or control stocks because we cannot separately estimate the event time coefficients and the year fixed effects (Borusyak et al. 2021). In the main results, we include quadratic time-trends as part of the set of controls, $\boldsymbol{X_{st}}$. Quadratic time-trends allow us to control for changes in fishing technology, changes in input prices, and oscillations in environmental conditions. In the Appendix, we report a set of results that excludes the quadratic time-trends, as well as results that include diesel prices on the east and west coasts, along with annual climatic indices that are relevant for the habitat range of each stock.

This simple event-study design relies on the unexpected timing of MSA events: the drop below MSST, overfished determination, or subsequent implementation of a rebuilding plan. While this estimation lacks a comparison group, we find this parsimonious specification provides an important summary of stock dynamics around key MSA events. For the sample we used in the main analysis, we balance stocks such that we observe both biomass and catch for the entire 15-year time window.

6 The Effects of Rebuilding Plans on Fishery Stocks

This section reports the results from two comparison groups that meet the conditions for treatment, but do not receive rebuilding policies: a contemporaneous group from Canada and the EU, and a historic group from the US before the policy was adopted. Our analysis recovers large gains in biomass, above 40% in the contemporaneous group, and up to a doubling in stock size relative to the historic US set of stocks.

6.1 Comparisons to Depleted & Untreated Contemporaneous Stocks

We evaluate changes in stock biomass after dropping below the minimum stock size threshold (MSST), for stocks that received the treatment of interest – a rebuilding plan. Our comparison group includes stocks in Canada and the EU that also depleted below their MSST thresholds, but did not enter rebuilding because policy did not yet require such fishery management action.

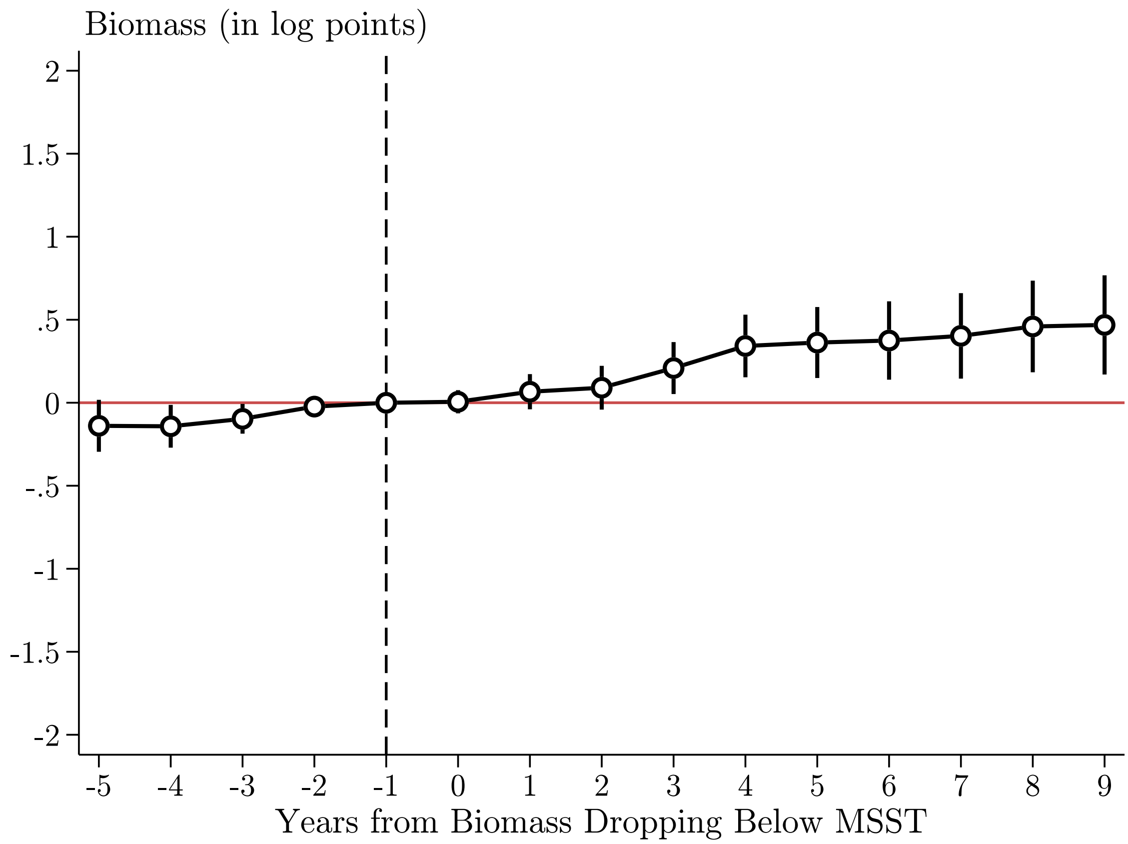
We estimate that rebuilding plans led to large gains in stock biomass, up to 53% by the tenth year after dropping below the MSST. In Figure 4, we report the results from the DD specification in Equation (1), as well as separate event studies that decompose the changes around the event of dropping below the MSST using the specification in Equation (2). Prior to dropping below the MSST, US stocks that eventually entered rebuilding were not systematically different, on average, than stocks that also dropped below their threshold in Canada and the EU (Figure 4a). We start to see a precisely estimated divergence between the US stocks and the control stocks five years after dropping below the MSST. On average, during the six to ten years after the event, US stocks have biomass levels that are 47.7% higher relative to the control stocks (Table 1, column 1).

Our focus around the drop below the MSST allows us to observe the dynamics separately for each group of stocks, treatment and control. This is of particular interest as one of the key challenges in the empirical exercise here is disentangling the treatment effect from the underlying dynamics (see Section 3 for more details). We observe two different responses for biomass dynamics following the depletion below the threshold. Stocks in the US begin to recover quickly, and stabilize at biomass levels 64% higher six to ten years after they drop below the MSST (4b). In contrast, Canadian and EU stocks do not recover after they deplete below the biomass threshold. Stocks in Canada decline in biomass until they cross the threshold, and on average, remain effectively at the same level even ten years after. Stocks in the EU also exhibit a downward trend, albeit smaller than the Canadian stocks, prior to going below the MSST, continue to decline even after crossing the threshold. Though there is recovery to this threshold that often defines an "overfished" stock, they do not climb above it.

Neither of the control groups indicates that natural cyclicality alone is capable of bringing stocks back to a healthy population (often defined as double MSST). The two groups of control stocks provide empirical evidence that is more consistent with the theoretical prediction

Figure 4: The Effect of Rebuilding Plans on Stock Biomass

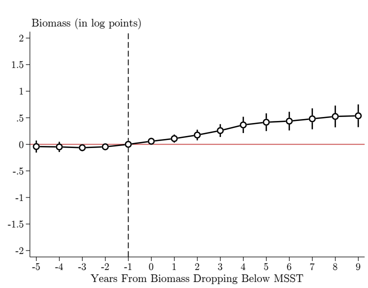
(a) Comparing US Stocks that Enter Rebuilding to Canadian and EU Stocks



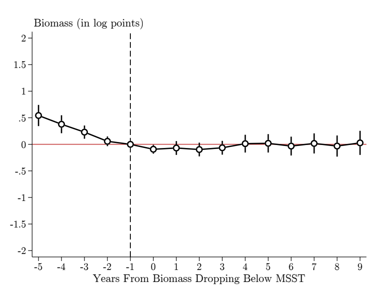
Treated Stocks

Untreated Stocks

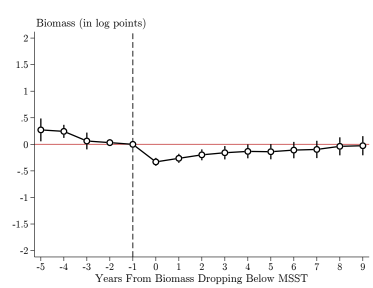
(b) United States



(c) Canada



(d) European Union



Notes: Estimation results showing coefficients and 95% CIs for the DD specification in Equation (1) (a) comparing US stocks that entered rebuilding to stocks in Canada or the EU that have depleted below their threshold but have not entered rebuilding. Panels (b-d) decompose the DD estimation by treated (US) and control (Canada and EU) stocks using the specification in Equation (2) that estimates the change in biomass around the time of crossing the minimum stock size threshold for each group of stocks. The regression in (a) includes stock and year fixed effects, while the regressions in (b-d) include stock fixed effects and quadratic time trends. Standard errors are clustered at the stock level.

of no recovery shown in Figure 1a, yet they do not display trends of collapse.

Table 1.
Summary of Difference-In-Differences Estimation Results

	Logged Biomass			Logged Catch		
	(1)	(2)	(3)	(4)	(5)	(6)
Event Time 1-5	0.16	0.25	0.19	-0.14	-0.04	0.03
	(0.05)	(0.05)	(0.06)	(0.12)	(0.13)	(0.15)
Event Time 6-10	0.39	0.42	0.29	0.03	0.40	0.37
	(0.11)	(0.10)	(0.11)	(0.21)	(0.25)	(0.25)
Within R^2	0.120	0.136	0.101	0.035	0.019	0.024
N	2,997	2,916	2,700	2,997	2,916	2,700
Clusters	111	108	100	111	108	100
Centered On:						
Biomass Below MSST	X			X		
Determined Overfished		X			X	
Entered Rebuilding			X			X

Notes: Estimation results from the DD specification in Equation (1). We report the linear combinations for the event time dummies after the stock drops below the MSST (columns 1 and 4), is determined to be overfished (columns 2 and 5), and enters rebuilding (columns 3 and 6), for the average of the first to fifth lags, and the sixth to tenth lags, excluding the top-coded lag coefficient. Columns 1-3 report results using the set of US stocks across all fishery management councils, while columns 4-6 report results using the set of stocks not managed by the New England fishery management council (see text for more details). All regressions include stock and year fixed effects. Standard errors are clustered at the stock level.

The delay in stock recovery relative to the control group reflects two mechanisms. The first is the delay between a stock dropping below the MSST and going into a rebuilding plan. There is a one to two year delay between surveying the stock and estimating the population in order to designate it as “overfished.” MSA requires stocks enter rebuilding within two-years of the overfished designation, causing a second delay. Consequently, the results in Figure 4a potentially underestimate the magnitude of the rebuilding plan effect because treatment onset occurs a few years *after* the stock drops below its MSST. Though US stocks experience full treatment after entering a rebuilding plan, management responds to declining biomass levels before entering rebuilding. This is done through a harvest control rule, which does not allow overfishing when the population declines below a healthy level, BMSY. This places a cap on the annual total allowable catch (TAC), often reducing the TAC as biomass declines.

The second mechanism, is the time it takes a fish to reach reproductive maturity, which can vary widely depending on the species. Shrimp can reproduce in less than a year and some Pacific groundfish will not reach reproductive maturity until age 20. It may also take more than one generation to see increases in biomass.

We report results where we re-center the event study around the timing of the overfished determination, or the implementation of a rebuilding plan in Figures A3a and A3b, and summarize them in Table 1. Centering around these two events recovers estimates that show positive biomass gains. For both overfished and rebuilding events, stock biomass begins to increase during the pre-event years; in accord with the harvest control rule working as an automatic stabilizer, reducing catch in those years. Because management action begins before the first year following the overfished determination or rebuilding plan implementation, we should expect to see some of the biomass gain to already be occurring during those pre-periods. On average, stocks increase in biomass between 15-20% in those years leading to the event, and gain an additional 37-50% in the six to ten years after the event (Table 1, columns 2 and 3).

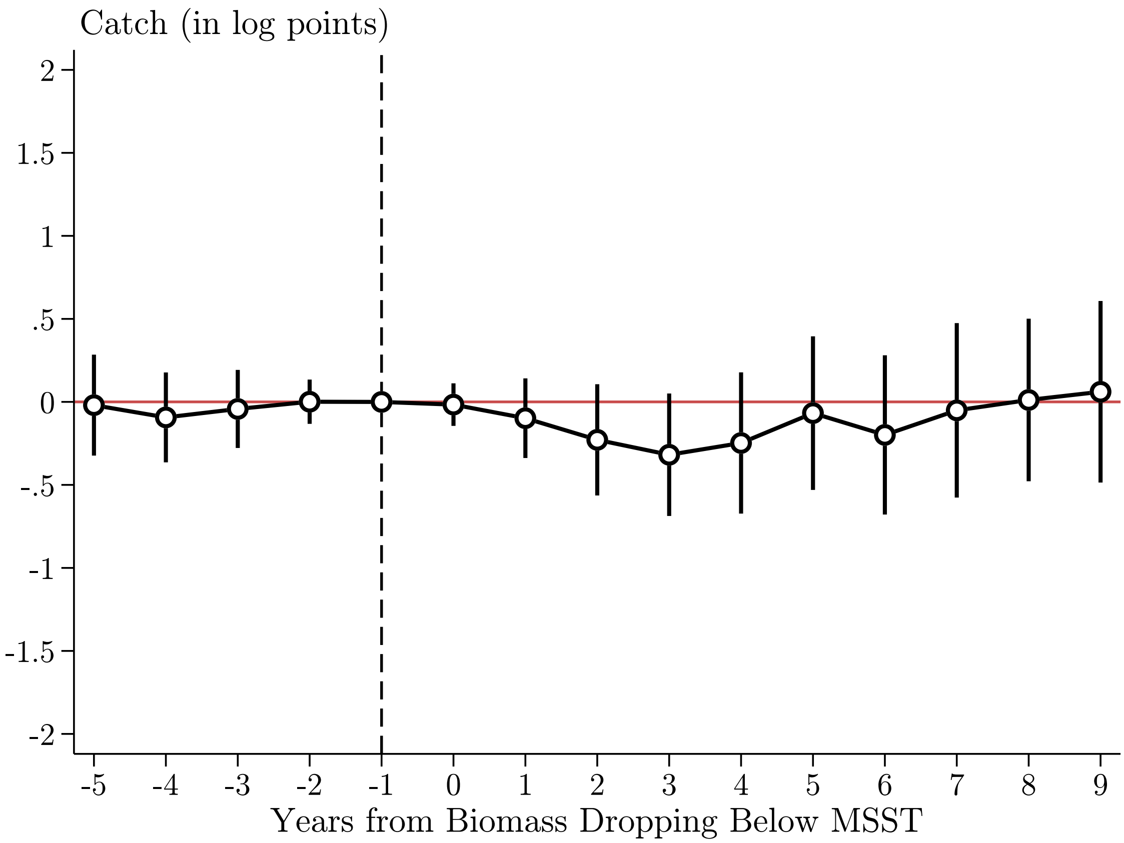
In order to rehabilitate stocks' biomass the policy aims to reduce fishing effort, namely catch levels (see Section 2 for more details). We repeat the DD estimation for catch and report the results in Figure 5a. We find an imprecisely estimated drop of 13% in the first five years, and a return to baseline levels in another subsequent five years relative to catch in Canada and the EU. The imprecision in the catch estimates could be masking large heterogeneity between stocks, which we report on in more detail in a later section.

The drop in catch levels, while imprecise, suggests potentially large revenue losses for fishers during rebuilding if prices do not offset quantity losses. In Figures 5b-5g, we report results from the simple event study specification in Equation (2) for catch, price per-ton, and revenue for US stocks that entered rebuilding, with and without quadratic time trends. We limit our attention to treated US stocks because a sufficiently long panel on revenue does not exist for EU stocks (see Section 4).

All three outcomes, catch, price-per-ton, and revenue, decline relative to a quadratic time trend for US stocks after they drop below the MSST. Catch begins to drop prior to treatment, which potentially reflects the lower population levels and higher search costs (Figure 5e). While we see price-per-ton increase in Figure 5c, including quadratic trends shows a decline in price after the stocks drop below the MSST (Figure 5f). Finally, the combination of lower catch and lower prices result in meaningful revenue losses. Excluding time trends, revenues are about 30% lower in the years after the stock declines below the

Figure 5: The Effects of Rebuilding Plans on Catch, Prices & Revenue

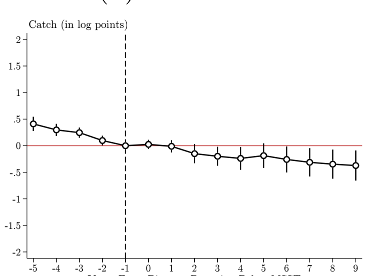
(a) Comparing US Stocks that Enter Rebuilding to Canadian and EU Stocks



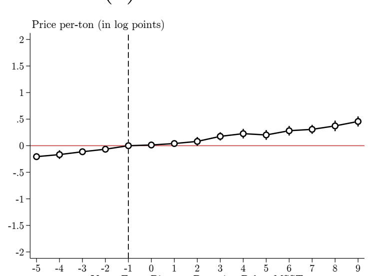
Event Studies Using Data for US Stocks Only

Catch	Price per-ton	Revenue

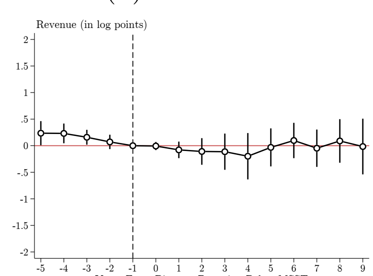
(b) No Trends



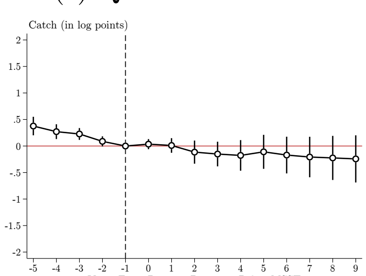
(c) No Trends



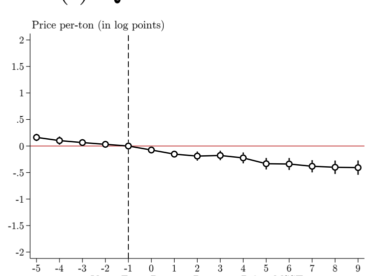
(d) No Trends



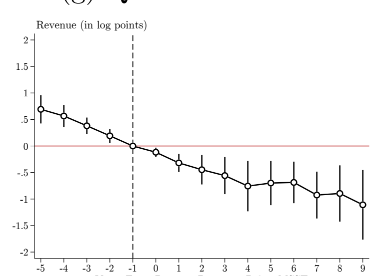
(e) Quadratic Trends



(f) Quadratic Trends



(g) Quadratic Trends



Notes: See Figure 4.

MSST relative the years before (Figure 5d). However, when we include quadratic time trends (Figure 5g), revenue declines as the stock biomass approaches the MSST and continues to decline by almost 50% more by the fifth year after dropping below the MSST (Figure 5g).

Price could be dropping for three main reasons. First, lowering the annual quota could create a "race to fish" before the total allowable catch for the fishery is reached, compressing the fishing season (Huang and Smith 2014; Birkenbach et al. 2017). The compression of the fishing season could increase short-term supply, lowering prices, even if overall supply throughout the year declines. Second, average fish-size declines with overfishing as the largest and oldest fish are targeted, leaving only young and small fish that fetch lower prices (Diekert 2012). Similar price and revenue effects have been documented in the case of apple production and extreme weather that lower prices more than they lower yields (Dalhaus et al. 2020). Third, the lower supply, and potential higher volatility in supply, might shift demand by wholesalers towards other species as substitutes resulting in the observed declines in prices.

6.2 Comparisons to Historic US Stock Data Pre-1996 Policy Regime

In our historic comparison, we compare stocks that meet the threshold for rebuilding after 1996 to stocks that would have met the threshold for a rebuilding plan before 1989, when the policy was not yet in place. This historical comparison group serves as another potential set of stocks that can approximate the counterfactual of a rebuilding plan.

We run two separate event studies for each time period using the specification in Equation (2). First, we estimate this "double-event-study" looking at stocks that experienced the *same condition*: having biomass below its MSST in a 15-year time window. Second, we narrow this comparison group down to the set of stocks that entered rebuilding after 1996, but also met the conditions for a rebuilding plan before 1989. In this more restrictive empirical exercise, we are comparing the *same stocks* during two different time periods.

We find that stocks increase in biomass after falling below their MSST only in the post-1996 period. During the pre-1989 period, their biomass continues to decline after going below the MSST. In Figures 6a and 6c, we plot the double-event-study results showing a gain of over 60% in biomass during the post-1996 period (as in Figure 4b), relative to a drop of close to 40% during the pre-1989 period. These effects remain similar in magnitude when controlling for fuel prices and climate indices.

By comparing the same stocks during two different time periods (Figure 6c), we can construct paired-differences for each stock in each event time period relative to the event year. For each stock, we take the difference in logged biomass in each event time period. We use this stock-specific difference in logged biomass as our outcome variable in equation (2). In Figure 6e, we plot the results of estimating the event-study specification on the paired-differences. We recover estimates that reflect an average difference of +113% in biomass between treated and control stocks. This difference appears six to ten years after they drop below their MSST and is relative to the difference in biomass between treated and control stocks, one year before this event.

The historic comparison provides additional evidence that rebuilding provisions meaningfully increased biomass. These gains are consistent with the rebuilding goal of achieving BMSY, a level of biomass that is often double the MSST (most MSSTs are defined as 50% BMSY). Under the alternative explanation that cyclical population dynamics increased biomass, stocks would have recovered in absence of actions aimed at rebuilding the stock. Here, we observe that stocks did not recover during a time period when rebuilding actions were not taken.

An important difference between this historic control group and the contemporaneous control groups from Canada and the EU, is the untreated set of stocks continues to see its biomass decline in the years after biomass dropped below MSST. In addition to not showing signs of recovery, the historic comparison stocks exhibit trends consistent with the collapse path in Figure 1a. One potential reason for this difference is that Canada and the EU have other sustainable policies in place that are not necessarily triggered by MSST. Another possibility is that Canadian and EU fishers are more easily able to switch their efforts from an overfished stock to stocks with healthier biomass levels. A third reason could be that stocks had higher biomass historically, and have not managed to recover to those levels since. This would result in a larger baseline level of biomass compared to stocks in Canada and the EU today.

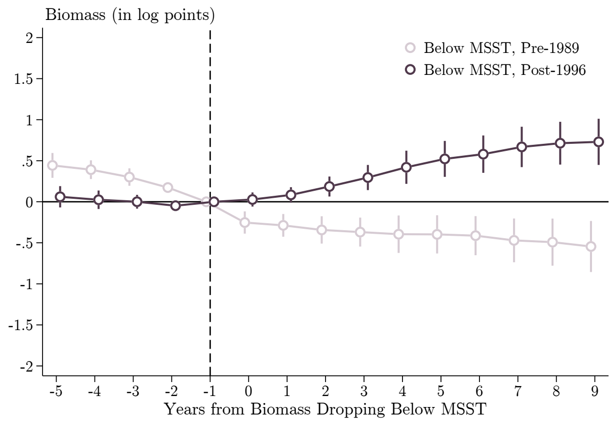
We repeat the historic comparison for catch and find that catch levels decline after the event of interest (biomass dropping below the MSST) during both time periods (Figures 6b, 6d, and 6f). While catch decreases more during the pre-1989 period, the differences are not statistically significant. The fact that catch is imprecisely higher during the post-1996 period suggests that the increase in biomass is not driven by lower demand for the stocks in the post-1996 period.

The results in the historic analysis are in the same direction as the contemporaneous analysis. We observe higher levels of biomass for stocks that eventually entered rebuilding, but only observe noisy changes in catch. The limitation of the historic comparison is that

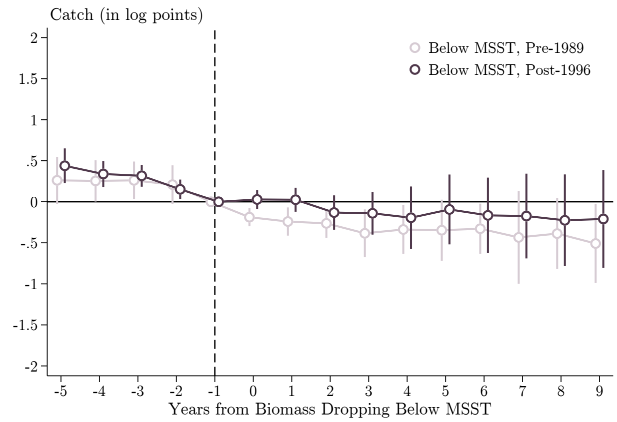
Figure 6: Estimation Results for the Historic Comparison Group

All Stocks That Were Below Their MSST Either Pre-1989 or Post-1996

(a) Biomass: Double-Event-Study

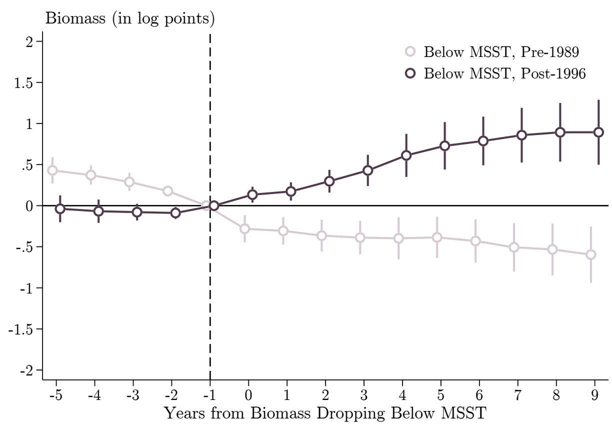


(b) Catch: Double-Event-Study

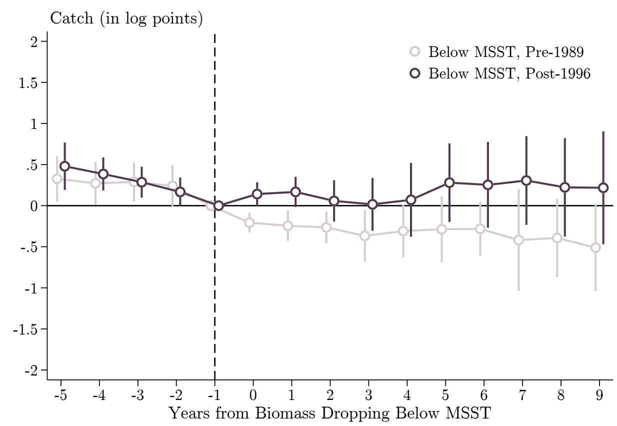


Holding Stock Composition Constant: Stocks Below MSST Pre-1989 and Post-1996

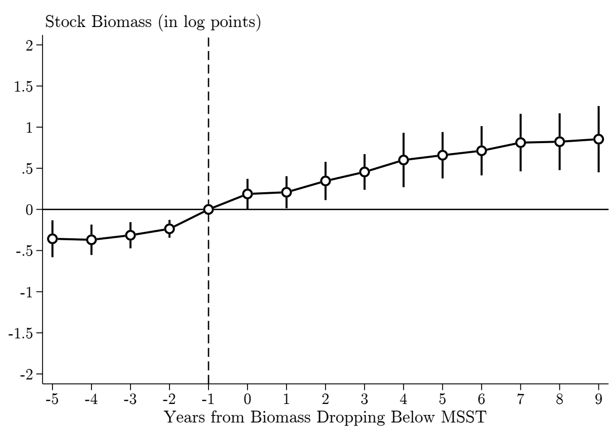
(c) Biomass: Double-Event-Study



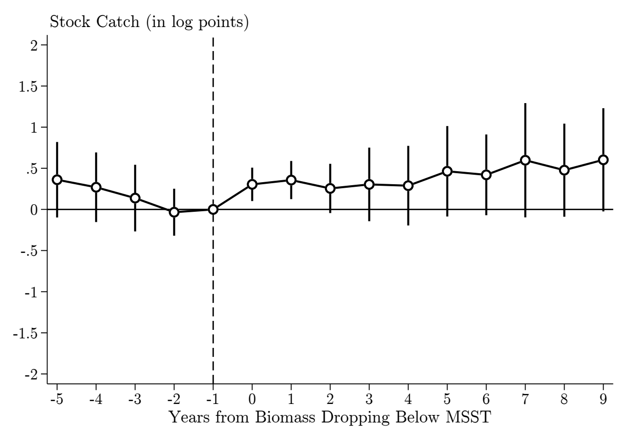
(d) Catch: Double-Event-Study



(e) Biomass: Paired-Differences



(f) Catch: Paired-Differences



Notes: Estimation results showing coefficients and 95% for the specification in Equation (2). Standard errors are clustered at the stock level.

several other factors could be changing on the multi-decadal time-scale of our study period (see Section 5). Between the two sets of comparison groups we trade off using data from contemporaneous time periods, but different global regions, stocks, and management agencies, with using data from the same assessment agency (NOAA) and same stocks. In both cases, the fundamental conclusion holds: Stocks recover towards their biomass target levels, on average, after they drop below their MSST *only* if they entered a rebuilding plan.

6.3 Heterogeneous Treatment Effects when Excluding New England Stocks

A somewhat surprising result is that catch does not fall for treated stocks in the post-1996 period compared to the pre-1989 stocks that meet the conditions for treatment (see Figure 5e). Heterogeneity analysis reveals that the higher catch levels post-1996 are driven by the New England Fishery Management Council (NEFMC). NEFMC has historically struggled with management action and fisher compliance (Layzer 2006) (we report suggestive evidence for compliance in Figure A10), as well as rapidly warming waters (Pershing et al. 2015), and stock assessments that were deemed inaccurate (Schrope 2010). Because stocks managed by the NEFMC might exhibit different responses than stocks managed by the other fishery management councils, we report a set of results excluding NEFMC stocks.[15]

First, we report the DD estimates for biomass and catch in Figure 7. The increase in biomass is more pronounced. Treated stocks show a 68.6% increase in biomass relative to the control stocks six to ten years after their biomass declines below the MSST. The decline in catch is also stronger five to eight years after entering treatment for treated US stocks, followed by a return to higher catch levels as biomass recovers.

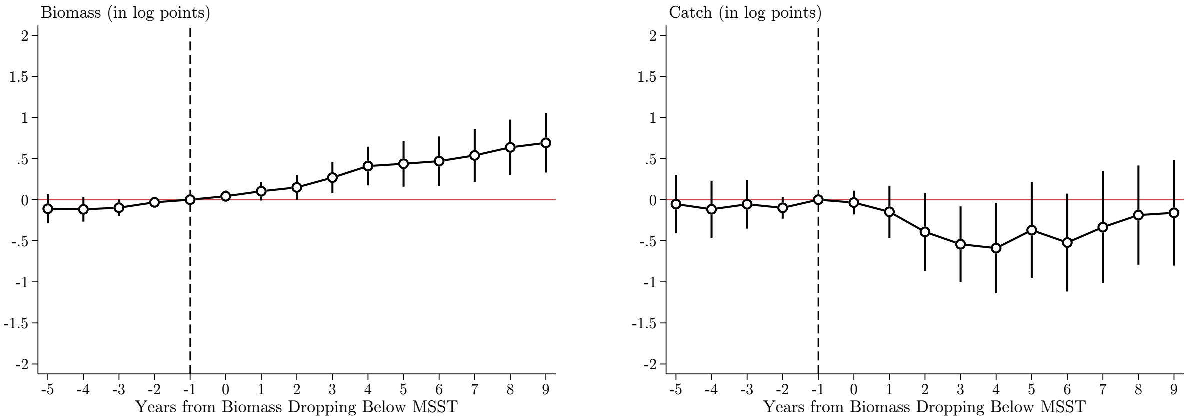
In order to evaluate whether these larger treatment effects are also present when using the historic US comparison group, we report results excluding NEFMC stocks in Figures 6a and 6b. The key difference is that catch in the stocks that receive treatment (post-1996) is lower relative to catch that did not receive treatment (pre-1989). The point estimates are not statistically significant from one another, but the effect of non-treated versus treated stocks flips direction and sign. Finally, the increase in biomass is of similar magnitude, but begins a year or two earlier.

In Table 2, we summarize the heterogeneous DD effects from the contemporaneous analysis with Canadian and EU stocks. Our main result using all treated US stocks are repeated in column 1. Columns 2 and 3 show results using control stocks in Canada and the EU

[15] This reduces the number of treated stocks in the balanced sample from 44 to 25.

Figure 7: Excluding the New England Region from the Contemporaneous Comparison

(a) DD Results for Biomass (b) DD Results for Catch

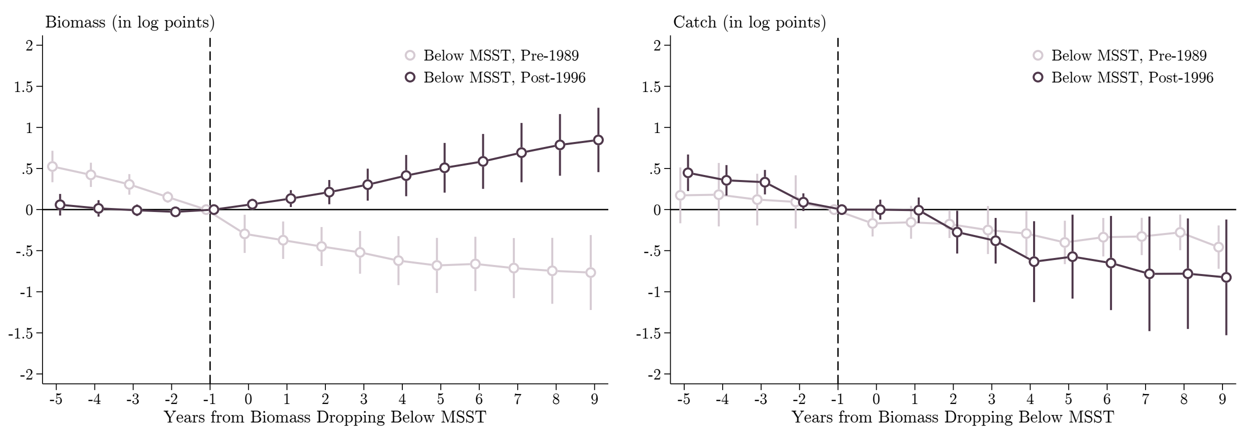


Notes: Estimation results showing coefficients and 95% for the specification in Equation (1). Standard errors are clustered at the stock level.

Figure 8: Excluding the New England Region from the Historic Comparison

All Stocks That Were Below Their MSST Either Pre-1989 or Post-1996

(a) Biomass: Double-Event-Study (b) Catch: Double-Event-Study



Notes: Estimation results showing coefficients and 95% for the specification in Equation (2). Standard errors are clustered at the stock level.

separately. In columns 4-6, we repeat columns 1-3, excluding treated US stocks managed by NEFMC. Overall, gains in biomass are larger when excluding NEFMC stocks six to ten years after the event of interest (panel A, columns 4-6). Most of these gains are driven by EU control group (Panel A, column 6). However, we cannot reject that these effects are equal to our main results (Panel A, columns 1-3) at the 95% confidence level. Excluding NEFMC stocks, increases the reduction in catch across all comparisons, yet they remain imprecisely estimated (Panel B, columns 4-6).

In order to fully examine the distribution of treatment effects, we estimate a separate regression by stock. Explicitly, we report the coefficient six to ten years after the event relative to five years before the event. We define the event as biomass falling below the MSST and run this for treated US stocks that experience this event pre-1989 and post-1996. We report the results for biomass and catch in Figure A9 for each stock, as well as a summary of their distribution. The distribution has shifted to larger positive effects on biomass and larger negative effects on catch in the post-1996 period relative to the pre-1989 period.

6.4 Evidence for Beneficial Spillovers & Leakage

There are several channels through which rebuilding plans can generate violations of the stable unit treatment value assumption (SUTVA), either in the form of co-benefits for stocks in the US, or in the form of leakage to either US or non-US stocks. We use sub-samples and modifications to the our specifications in order to examine the scope to which either one of these potential spillovers is occurring in our empirical setting. We are interested in quantifying these spillovers because they might present threats to the identification strategy, but also because they are interesting regardless of the efficacy of rebuilding plans.

Beneficial spillovers (co-benefits) can occur because in most cases it is difficult for fishers to target only one specific stock. Fishing vessels end up catching non-target stocks (known as bycatch) because many species share the same habitat and get caught by the same fishing gear. Consequently, when a stock enters rebuilding, restrictions are placed on both the direct catch levels of the stock as well as incidental catch of this stock from other fisheries. Some concurrently caught species will have their season closed early because the bycatch quotas of a stock in rebuilding have been met. This could lead to biomass gains for stocks in the absence of treatment.

Our main analysis focuses on stocks that had their MSST defined well before 2007, however, for some US stocks the biological reference points needed for their management were only developed more recently. This is due to a combination of these stocks having lower

Table 2.
Heterogeneity in Difference-In-Differences Estimation Results

	All FMCs			Excluding NEFMC		
Panel A. Logged Stock Biomass						
	(1)	(2)	(3)	(4)	(5)	(6)
Event Time 1-5	0.16	0.13	0.18	0.19	0.16	0.22
	(0.05)	(0.06)	(0.06)	(0.06)	(0.07)	(0.07)
Event Time 6-10	0.39	0.34	0.43	0.48	0.41	0.53
	(0.11)	(0.13)	(0.13)	(0.14)	(0.16)	(0.15)
Within R^2	0.120	0.182	0.124	0.152	0.281	0.170
N	2,997	1,890	2,403	2,457	1,350	1,863
Clusters	111	70	89	91	50	69
Panel B. Logged Stock Catch						
	(1)	(2)	(3)	(4)	(5)	(6)
Event Time 1-5	-0.14	-0.11	-0.13	-0.25	-0.25	-0.23
	(0.12)	(0.15)	(0.14)	(0.13)	(0.17)	(0.16)
Event Time 6-10	0.03	0.09	0.01	-0.18	-0.16	-0.16
	(0.21)	(0.34)	(0.23)	(0.25)	(0.38)	(0.26)
Within R^2	0.035	0.089	0.059	0.033	0.088	0.064
N	2,997	1,890	2,403	2,457	1,350	1,863
Clusters	111	70	89	91	50	69
Control Stocks:						
Canada	X	X		X	X	
European Union	X		X	X		X

Notes: Estimation results from the DD specification in Equation (1). We report the linear combinations for the event time dummies after the stock drops below the MSST for the average of the first to fifth lags, and the sixth to tenth lags, excluding the top-coded lag coefficient. Columns 1-3 report results using the set of US stocks across all fishery management councils, while columns 4-6 report results using the set of stocks not managed by the New England fishery management council (see text for more details). All regressions include stock and year fixed effects. Standard errors are clustered at the stock level.

commercial value and not being prioritized for developing reference points, or challenges in the modeling their population dynamics. We use recently developed MSST values to identify stocks that we now know in hindsight had their biomass drop below the MSST and should have gone into treatment, but did not. These "would-have-should-have" stocks would have entered rebuilding, however, the information was not available to determine if they should have been classified as overfished. These stocks represent yet another group of stocks that experience biomass declining to overfished levels, similar to those in our main analysis, without receiving treatment.

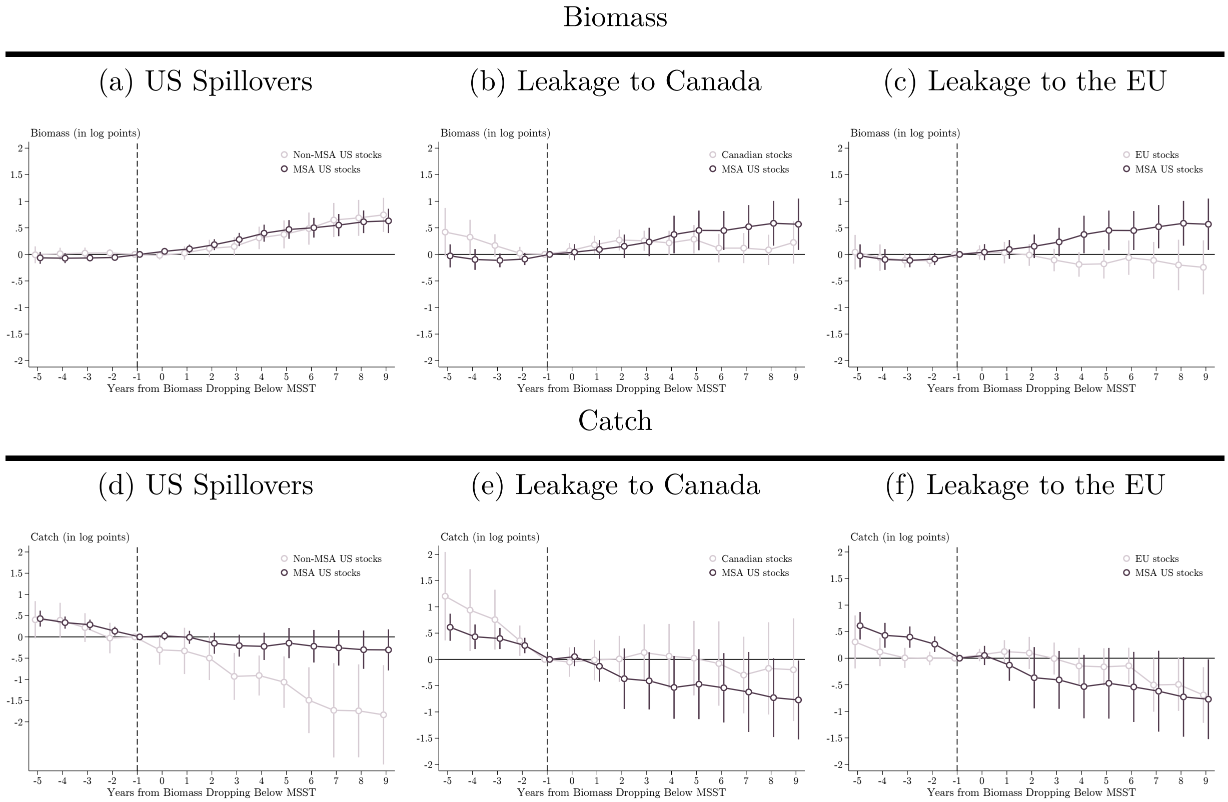
We verify that out of 20 of these "would-have-should-have" stocks, 14 (70%) of them are either of low commercial value or are caught with other stocks that entered rebuilding. We estimate an event study using the specification in Equation (2), and compare their dynamics after dropping below the MSST to that of the US stocks that entered rebuilding in Figure 9a. Stocks that we only now know should have entered a rebuilding plan exhibit biomass gains as large as the stocks that eventually entered rebuilding. Benefits across the marine ecosystem are often not accounted for in the evaluation of the MSA, yet this result shows that the magnitude of these beneficial spillovers is large and meaningful. In fact, we see that the catch levels for these stocks drop sharply, despite not entering rebuilding or being determined overfished after declining below their MSST (9d). This result also validates that contemporaneous US stocks are not a suitable comparison group as they are affected by the treatment status of the stocks that have overlapping habitats with.

One other form of a SUTVA violation is leakage. Within the US, leakage could occur if fishers shift their efforts from overfished stocks in rebuilding to healthier stocks. However, in the context of the US, this type of substitution of effort across stocks is often restricted. In many fisheries, especially those with high commercial value, fishers need a permit, and most fisheries are under moratorium (no longer issuing new permits). Since permits are often tied to the quota, boat, and gear, if a fishing operation wishes to switch to a different stock, they would need to buy the permit, vessel, and gear from a current permit holder.[16]

Another potential channel for leakage is through consumer demand shifting to other, more readily available fish, either through a direct response by the consumers or by the fish bought and offered at restaurants and grocery stores. This shift could lead to higher levels of catch, especially of other fish that could act as substitutes for the fish that are in rebuilding. While both of these effects might be taking place in our sample, they are not of great concern

[16] Prices vary across fisheries. Sea Scallops permits one of the most commercially valuable stocks can fetch high prices. The sale of the "Codfather's" 11 sea scallop vessels and their associated permits for $46 million made the news when he was required to sell off all his vessels and permits for fish laundering.

Figure 9: Summarizing Evidence for the Scope of Beneficial Spillovers & Leakage



Notes: We examine potential spillovers within and outside the US. We estimate the specification in Equation (2) with several changes to the samples and modifications to the treatment onset definition. See the main text for details.

because we do not use contemporaneous US stocks as a control group in our analysis.

A more concerning type of leakage is through global market prices for fish. If supply in the US goes down, but demand stays at similar levels, then fishers in other countries might respond to the higher prices by increasing their catch levels. This response would lower biomass for those stocks, leading us to double count the gain in biomass in the US and the decline in biomass outside of the US. To examine the scope of this type of spillover on our results, we perform the following test: We subset to the same species of fish – where spillovers are most likely to occur – and estimate how catch changes for the non-US species after the equivalent US species drop below the MSST. In other words, for the Canadian and EU stocks, we compare stocks in the US matching the same species in either Canada or the EU, where those stocks have also dropped below their MSST. However, to check for whether those non-US stocks are responding to US fishery management, we center the treatment of the non-US stocks around the time that the US stocks drop below their MSST. This recentering allows us to test whether stocks in Canada or the EU change, on average, in their biomass or catch levels after their most direct US counterpart – same species – drops below its MSST.

In Figure 9b, we observe the opposite of a market spillover. Instead, there is an increase in *Canadian* stock biomass after the *US* species drop below the MSST. These gains are likely the result of the transboundary range of several of the stocks. Many commercial fish species in the US have habitat ranges that extend into Canada. Stocks that are managed under a rebuilding plan in the US regain their biomass, positively affecting Canadian stocks of the same species across the border. This likely attenuates our biomass comparison that uses Canada as a control group, which is reflected in the comparison to the EU stocks recovering a larger effect (Table 2, columns 3 and 6). More importantly, we do not observe an increase in catch for the same species in Canada, which would have raised concerns that our biomass estimates are biased upwards. For the same evaluation that uses the EU stocks of the same species, we do not find evidence of spillovers on biomass or any leakage in the form of larger catch (Figures 9c and 9f).

6.5 Addressing Changes in Environmental Conditions

Environmental conditions are in constant flux in both the Pacific and Atlantic oceans due to known climatic oscillations, as well as stochastic perturbations (Chavez et al. 2003; Vert-pre et al. 2013; Overland et al. 2010).[17] A key concern for our study is that more beneficial environmental conditions could be increasing fish populations. If the main reason stocks declined below their MSST was poor environmental conditions, caused by either long-term cycles or short-term shocks, then a reversal of the cycle or return to baseline would lead to higher levels of biomass. If these conditions are more common today, and more common in the US than in Canada or the EU, then these variables could be driving our results.

The full interaction of environmental conditions with each stock is a complex function, however, we can observe an important proxy of stocks' recovery: productivity of the stock, also referred to as recruitment.[18] Explicitly, we can calculate the recruitment per-unit of fish biomass (hereafter, recruitment per-biomass). If recruitment per-biomass is increasing over time, especially after 1996, then it could be the main mechanism responsible for the observed improvement in biomass.

We do not observe an increase in recruitment per-biomass over time. Instead, we observe

[17] Examples for known oceanic oscillations in the northern hemisphere are El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO).

[18] Changes to habitat, upwelling, primary productivity, food availability, predators and temperature can all impact recruitment.

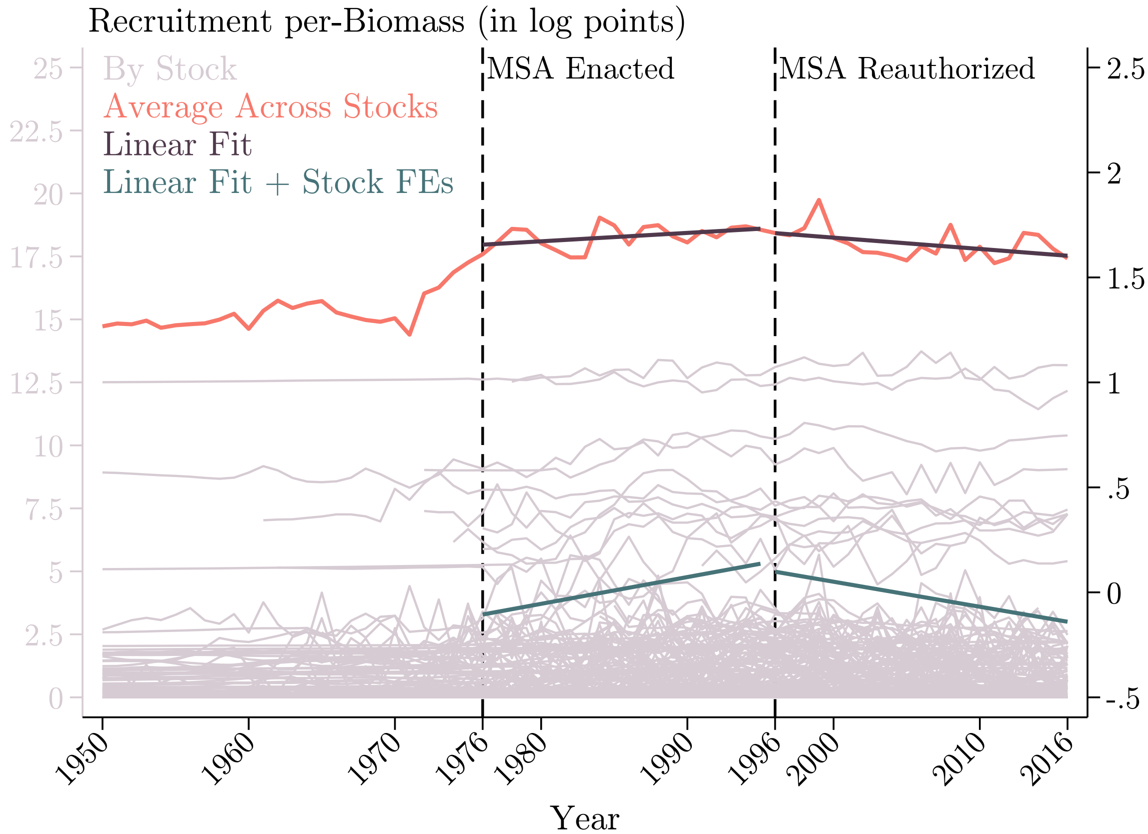
the opposite — recruitment is declining on average. Lower recruitment per-biomass in recent years suggests it should be harder for stocks to recover after being overfished. In Figure 10a, we plot the recruitment per-biomass over time for each of the 133 stocks for which we have both recruitment and biomass data. We include the average across stocks in each year (orange line), as well as linear fits before MSA reauthorization (1976-1996) and after reauthorization (after 1996), with or without residualizing on stock fixed effects (green and dark purple line, respectively).

We repeat the contemporaneous and historic analysis with recruitment-per-biomass as our outcome variable. In both cases, we find that the recruitment-per-biomass ratio remains stable around the event of interest until biomass begins to recover, overtaking any growth in total recruitment (Figures 10b and 10c). In other words, more beneficial environmental conditions are not driving increases in biomass because recruitment-per-biomass it not differentially higher for stocks in the US relative to the non-US stocks or historic US stocks.

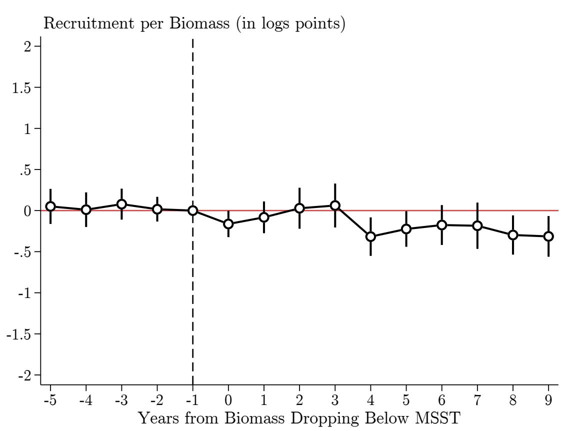
Potential explanations to the finding that recruitment declines for treated stocks are outside the scope of this paper to evaluate. One explanation could be due to a permanent decline in productivity due to changing environmental conditions (Free et al. 2019), especially for US stocks on opposite sides of the Gulf Stream from Canadian stocks. Another explanation could be due to fishers' behavioral responses that lower stock productivity. When a stock goes into rebuilding, the annual quota is reduced, potentially creating a "race to fish" before the total allowable catch (TAC) for the fishery is reached, compressing the fishing season. This short-term compression of fishing effort has been empirically documented in US fisheries, and "the race to fish" is linked to detrimental fishing practices that destroy habitat and increase bycatch (Birkenbach et al. 2017; Costello et al. 2008; Essington 2010; Gordon 1954; Huang and Smith 2014).

Figure 10: Assessing Changes in Stock Growth Dynamics

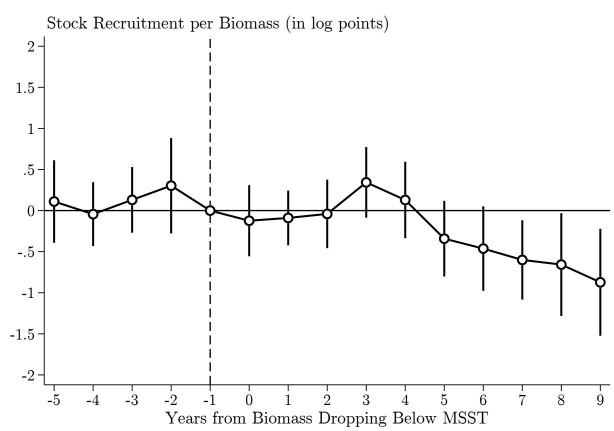
(a) Trends in Recruitment Dynamics



(b) Contemporaneous Comparison: DD



(c) Historic Comparison: Paired Differences



Notes: In panel (a), each gray line (left y-axis) corresponds to recruitment per-biomass of one stock over time. The coral line (right y-axis) is the average across stocks in each year. The linear fit lines (right y-axis), in dark purple and dark teal, are estimating a simple linear trend model either between 1976 and 1996, and post-1996. The dark teal line fits the recruitment per-spawning biomass after residualizing them on stock fixed effects. Panel (b) repeats the contemporaneous DD estimation as in Figure 4a, and panel (c) repeats the paired differences between the same stocks in the historic comparison group as in Figure 6e.

7 Conclusions

Regulating renewable resources, as well as setting conservation policies, is challenging due to the complex dynamics that govern these processes, the inherent incomplete information about the state of the stocks, and the parameters that govern their growth. We study the Magnuson-Stevens Act's rebuilding provisions, the key policy for the sustainable management of fish stocks in the United States. Departing from previous studies, we place little structure on how the prescribed rebuilding provisions affect biomass and catch outcomes, and we consider that stocks can become treated either after the rebuilding plan is implemented or even sooner when they cross the scientific-threshold that defines them as overfished. Our findings confirm that while there is considerable heterogeneity, stocks managed under the MSA see improvements, on average, to their biomass, and experience large declines in catch during rebuilding years. The MSA is an example of a policy that attempts to use scientifically-informed decision rules. These science-based thresholds that determine when a policy intervention is needed and when the stock can be considered stable and sustainable might be helpful in regulating other renewable resources.

References

(Testimony of Eric Brazer). 2018. *H.R.200: Strengthening Fishing Communities and Increasing Flexibility in Fisheries Management Act: Hearings before the House of Representatives, 115th Congress.*

(Testimony of Janet Coit). 2021. *H.R. 59, H.R. 4690, and H.R. 5770: Legislative Hearing before the House Subcommittee on Waters, Oceans, and Wildlife, 116th Congress.*

Arrow, Kenneth, Partha Dasgupta, Lawrence Goulder, Gretchen Daily, Paul Ehrlich, Geoffrey Heal, Simon Levin, et al. 2004. "Are We Consuming Too Much?" *The Journal of Economic Perspectives* 18 (3): 147–172.

Auffhammer, Maximilian, and Ryan Kellogg. 2011. "Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality." *The American Economic Review* 101 (6): 2687–2722.

Austin, David, and Terry Dinan. 2005. "Clearing the air: The costs and consequences of higher CAFE standards and increased gasoline taxes." *Journal of Environmental Economics and Management* 50 (3): 562–582.

Beltratti, Andrea, Graciela Chichilnisky, and Geoffrey Heal. 1998. "Sustainable Use of Renewable Resources." In *Sustainability: Dynamics and Uncertainty,* edited by Graciela Chichilnisky, Geoffrey Heal, and Alessandro Vercelli, 49–76. Dordrecht: Springer Netherlands.

Benson, Ashleen Julia, Andrew B Cooper, and Thomas R Carruthers. 2016. "An Evaluation of Rebuilding Policies for U.S. Fisheries." *PLoS One* 11 (1): e0146278.

Birkenbach, Anna M, David J Kaczan, and Martin D Smith. 2017. "Catch shares slow the race to fish." *Nature* 544 (7649): 223–226.

Borusyak, Kirill, Xavier Jaravel, and Jann Spiess Ucl. 2021. "Revisiting Event Study Designs: Robust and Efficient Estimation." *Working Paper.*

Boulton, Chris A, Timothy M Lenton, and Niklas Boers. 2022. "Pronounced loss of Amazon rainforest resilience since the early 2000s." *Nat. Clim. Chang.* 12 (3): 271–278.

Brander, James A, and M Scott Taylor. 1998. "The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use." *Am. Econ. Rev.* 88 (1): 119–138.

Brozović, Nicholas, and Wolfram Schlenker. 2011. "Optimal management of an ecosystem with an unknown threshold." *Ecological Economics* 70 (4): 627–640.

Burgess, Matthew G, Christopher Costello, Alexa Fredston-Hermann, Malin L Pinsky, Steven D Gaines, David Tilman, and Stephen Polasky. 2017. "Range contraction enables harvesting to extinction." *Proceedings of the National Academy of Sciences of the United States of America* 114 (15): 3945–3950.

Burke, Marshall, Anne Driscoll, David B Lobell, and Stefano Ermon. 2021. "Using satellite imagery to understand and promote sustainable development." *Science* 371 (6535).

Canada, Parliament of. 2019. *Fisheries Act: An Act to amend the Fisheries Act and other Acts in consequence, S.C. c. 14.*

Carruthers, Thomas R., and David J. Agnew. 2016. "Using simulation to determine standard requirements for recovery rates of fish stocks." *Marine Policy* 73:146–153. ISSN: 0308-597X.

Carson, Richard T, Clive Granger, Jeremy Jackson, and Wolfram Schlenker. 2009. "Fisheries Management Under Cyclical Population Dynamics." *Environmental & Resource Economics* 42 (3): 379–410.

Chaisemartin, Clément de, and Xavier D'Haultfoeuille. 2020. "Two-Way Fixed Effects Estimators with Heterogeneous Treatment Effects." *American Economic Review* 110 (9): 2964–2996.

Chavez, Francisco P., John Ryan, Salvador E. Lluch-Cota, and Miguel Niquen C. 2003. "From Anchovies to Sardines and Back: Multidecadal Change in the Pacific Ocean." *Science* 299 (5604): 217–221. doi:10.1126/science.1075880.

Clark, C. 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* Wiley, New York.

Clark, Colin W, Frank H Clarke, and Gordon R Munro. 1979. "The Optimal Exploitation of Renewable Resource Stocks: Problems of Irreversible Investment." *Econometrica: journal of the Econometric Society* 47 (1): 25–47.

Conrad, Jon M, and Colin Whitcomb Clark. 1987. *Natural Resource Economics: Notes and Problems.* Cambridge University Press.

Costello, Christopher, Steven D Gaines, and John Lynham. 2008. "Can catch shares prevent fisheries collapse?" *Science* 321 (5896): 1678–1681.

Costello, Christopher, Daniel Ovando, Tyler Clavelle, C Kent Strauss, Ray Hilborn, Michael C Melnychuk, Trevor A Branch, et al. 2016. "Global fishery prospects under contrasting management regimes." *Proc. Natl. Acad. Sci. U. S. A.* 113 (18): 5125–5129.

Currie, Janet, Michael Greenstone, and Enrico Moretti. 2011. "Superfund Cleanups and Infant Health." *The American Economic Review* 101 (3): 435–441.

Daily, Gretchen C, Tore Söderqvist, Sara Aniyar, Kenneth Arrow, Partha Dasgupta, Paul R Ehrlich, Carl Folke, et al. 2000. "The Value of Nature and the Nature of Value." *Science* 289 (5478): 395–396.

Dalhaus, Tobias, Wolfram Schlenker, Michael M Blanke, Esther Bravin, and Robert Finger. 2020. "The Effects of Extreme Weather on Apple Quality." *Scientific Reports* 10 (1): 7919.

DFO. 2022. *Seafisheries Landings.* https://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm.

Diekert, Florian K. 2012. "Growth Overfishing: The Race to Fish Extends to the Dimension of Size." *Environ. Resour. Econ.* 52 (4): 549–572.

Duarte, Carlos M, Susana Agusti, Edward Barbier, Gregory L Britten, Juan Carlos Castilla, Jean-Pierre Gattuso, Robinson W Fulweiler, et al. 2020. "Rebuilding marine life." *Nature* 580 (7801): 39–51.

Essington, Timothy E. 2010. "Ecological indicators display reduced variation in North American catch share fisheries." *Proceedings of the National Academy of Sciences of the United States of America* 107 (2): 754–759.

Estes, James A, John Terborgh, Justin S Brashares, Mary E Power, Joel Berger, William J Bond, Stephen R Carpenter, et al. 2011. "Trophic downgrading of planet Earth." *Science* 333 (6040): 301–306.

EU, Parliament of. 2013. *regulation (EU) No. 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the common fisheries policy.* Technical report.

FAO. 2020. *The State of World Fisheries and Aquaculture.*

FAO GFCM. 2022. *Validated stock assessment forms.* https://www.fao.org/gfcm/data/safs/en.

Ferraro, Paul J, James N Sanchirico, and Martin D Smith. 2019. "Causal inference in coupled human and natural systems." *Proceedings of the National Academy of Sciences of the United States of America* 116 (12): 5311–5318.

Free, Christopher M, James T Thorson, Malin L Pinsky, Kiva L Oken, John Wiedenmann, and Olaf P Jensen. 2019. "Impacts of historical warming on marine fisheries production." *Science* 363 (6430): 979–983.

Gibson, Matthew. 2018. "Regulation-induced pollution substitution." *The Review of Economics and Statistics.*

Goodman-Bacon, Andrew. 2021. "Difference-in-differences with variation in treatment timing." *Journal of Econometrics.*

Gordon, H Scott. 1954. "The Economic Theory of a Common-Property Resource: The Fishery." *The journal of political economy* 62 (2): 124–142.

Greenstone, Michael. 2002. "The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures." *The Journal of Political Economy* 110 (6): 1175–1219.

Greenstone, Michael, and Justin Gallagher. 2008. "Does Hazardous Waste Matter? Evidence from the Housing Market and the Superfund Program." *The Quarterly Journal of Economics* 123 (3): 951–1003.

Greenstone, Michael, and Ted Gayer. 2009. "Quasi-experimental and experimental approaches to environmental economics." *Journal of environmental economics and management* 57 (1): 21–44.

Halliday, R G, and A T Pinhorn. 1996. "Special Issue: North Atlantic Fishery Management Systems: A Comparison of Management Methods and Resource Trends." *Journal of Northwest Atlantic Fishery Science; Halifax* (Halifax, Canada, Halifax) 20.

Hanski, Ilkka, Atte Moilanen, and Mats Gyllenberg. 1996. "Minimum Viable Metapopulation Size." *The American Naturalist* 147 (4): 527–541.

Heal, Geoffrey, and Wolfram Schlenker. 2008. "Sustainable fisheries." *Nature* 455 (23): 1044–1045.

Hilborn, Ray. 2019. "Measuring fisheries performance using the "Goldilocks plot"." *ICES journal of marine science: journal du conseil* 76 (1): 45–49.

Hilborn, Ray, Ricardo Oscar Amoroso, Christopher M Anderson, Julia K Baum, Trevor A Branch, Christopher Costello, Carryn L de Moor, et al. 2020. "Effective fisheries management instrumental in improving fish stock status." *Proc. Natl. Acad. Sci. U. S. A.* 117 (4): 2218–2224.

Huang, Ling, and Martin D Smith. 2014. "The Dynamic Efficiency Costs of Common-Pool Resource Exploitation." *The American Economic Review* 104 (12): 4071–4103.

ICES. 2022. *ICES Stock Assessment Database.* Copenhagen, Denmark. https://standardgraphs.ices.dk.

Isen, Adam, Maya Rossin-Slater, and W Reed Walker. 2017. "Every Breath You Take—Every Dollar You'll Make: The Long-Term Consequences of the Clean Air Act of 1970." *The journal of political economy.*

Jacobsen, Mark R. 2013. "Fuel Economy and Safety: The Influences of Vehicle Class and Driver Behavior." *American Economic Journal. Applied Economics* 5 (3): 1–26.

Jacobsen, Mark R, and Arthur A van Benthem. 2015. "Vehicle Scrappage and Gasoline Policy." *The American Economic Review* 105 (3): 1312–1338.

Jerch, Rhiannon. 2021. "The local benefits of federal mandates: Evidence from the Clean Water Act." *Working Paper.*

Keiser, David A, and Joseph S Shapiro. 2019. "Consequences of the Clean Water Act and the Demand for Water Quality." *Quarterly Journal of Economics:* 349–396.

Kremer, Michael, and Charles Morcom. 2000. "Elephants." *The American Economic Review* 90 (1): 212–234.

Kroetz, Kailin, Matthew N Reimer, James N Sanchirico, Daniel K Lew, and Justine Huetteman. 2019. "Defining the economic scope for ecosystem-based fishery management." *Proceedings of the National Academy of Sciences of the United States of America:* 201816545.

Lam, Vicky W Y, William W L Cheung, Gabriel Reygondeau, and U Rashid Sumaila. 2016. "Projected change in global fisheries revenues under climate change." *Scientific reports* 6:32607.

Layzer, Judith. 2006. "Fish stories: Science, advocacy, and policy change in New England fishery management." *Policy Stud. J.* 34 (1): 59–80.

Lubchenco, Jane, Peter M Haugan, and Mari Elka Pangestu. 2020. "Five priorities for a sustainable ocean economy." *Nature* 588 (7836): 30–32.

McQuaw, Kristin, and Ray Hilborn. 2020. "Why are catches in mixed fisheries well below TAC?" *Marine Policy* 117:103931.

Memarzadeh, Milad, Gregory L Britten, Boris Worm, and Carl Boettiger. 2019. "Rebuilding global fisheries under uncertainty." *Proc. Natl. Acad. Sci. U. S. A.* 116 (32): 15985–15990.

Milazzo, Matteo J. 2012. "Progress and problems in U.S. marine fisheries rebuilding plans." *Rev. Fish Biol. Fish.* 22 (1): 273–296.

National Marine Fisheries Service. 2022. *Fisheries Economics of the United States, 2019.* U.S. Department of Commerce, NOAA Tech. Memo.

Nichols, Rachel, Satoshi Yamazaki, and Sarah Jennings. 2018. "The Role of Precaution in Stock Recovery Plans in a Fishery with Habitat Effect." *Ecological Economics* 146:359–369.

NOAA. 2022. *Stock SMART data records.*

NOAA Fisheries. 1997-2020. *Report to Congress on the Status of U.S. Fisheries.* https://www.fisheries.noaa.gov/national/status-stocks-reports.

NOAA FOSS. 2021. *NOAA Fisheries One Stop Shop.* https://www.fisheries.noaa.gov/foss/f?p=215:200:13359200179404:Mail:NO:::.

Nøstbakken, Linda. 2006. "Regime switching in a fishery with stochastic stock and price." *Journal of environmental economics and management* 51 (2): 231–241.

NRC. 2014. *Evaluating the Effectiveness of Fish Stock Rebuilding Plans in the United States.* Washington, DC.

Oceana Canada. 2020. *Fishery Audit 2020.* https://docs.google.com/spreadsheets/d/1Io4hCCPvOTn0ZcL8w7PchzqyvuExrPVqZdeU21pvmZI/edit#gid=2062614875.

Oremus, Kimberly Lai, Lisa Suatoni, and Brad Sewell. 2014. "The requirement to rebuild US fish stocks: Is it working?" *Marine Policy* 47 (0): 71–75. ISSN: 0308-597X.

Overland, James E, Juergen Alheit, Andrew Bakun, James W Hurrell, David L Mackas, and Arthur J Miller. 2010. "Climate controls on marine ecosystems and fish populations." *J. Mar. Syst.* 79 (3): 305–315.

Patrick, Wesley S, and Jason Cope. 2014. "Examining the 10-year rebuilding dilemma for U.S. fish stocks." *PLoS One* 9 (11): e112232.

Pershing, Andrew J., Michael A. Alexander, Christina M. Hernandez, Lisa A. Kerr, Arnault Le Bris, Katherine E. Mills, Janet A. Nye, et al. 2015. "Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery." *Science* 350 (6262): 809–812.

Pindyck, Robert S. 1984. "Uncertainty in the Theory of Renewable Resource Markets." *The Review of economic studies* 51 (2): 289–303.

Polasky, Stephen, Catherine L Kling, Simon A Levin, Stephen R Carpenter, Gretchen C Daily, Paul R Ehrlich, Geoffrey M Heal, and Jane Lubchenco. 2019. "Role of economics in analyzing the environment and sustainable development." *Proceedings of the National Academy of Sciences of the United States of America* 116 (12): 5233–5238.

re3data.org. 2021. *RAM Legacy Stock Assessment Database.* February 15, 2021.

Rosenberg, Andrew A, Jill H Swasey, and Margaret Bowman. 2006. "Rebuilding US fisheries: progress and problems." *Frontiers in Ecology and the Environment* 4 (6): 303–308. ISSN: 1540-9295.

Sacred Cod: The Fight for a New England Tradition. 2016.

Scheffer, M, S Carpenter, J A Foley, C Folke, and B Walker. 2001. "Catastrophic shifts in ecosystems." *Nature* 413 (6856): 591–596.

Schrope, Mark. 2010. "Fisheries: What's the catch?" *Nature* 465:540–542.

Sethi, Gautam, Christopher Costello, Anthony Fisher, Michael Hanemann, and Larry Karp. 2005. "Fishery management under multiple uncertainty." *Journal of environmental economics and management* 50 (2): 300–318.

Sewell, Brad, Seth Atkinson, David Newman, and Lisa Suatoni. 2013. *Bringing back the fish: an evaluation of U.S. fisheries rebuilding under the Magnuson-Stevens Fishery Conservation and Management Act.*

Slough, Tara, Jacob Kopas, and Johannes Urpelainen. 2021. "Satellite-based deforestation alerts with training and incentives for patrolling facilitate community monitoring in the Peruvian Amazon." *Proceedings of the National Academy of Sciences of the United States of America* 118 (29).

STECF. 2022. *Mediterranean & Black Sea Stock Assessments.* https://stecf.jrc.ec.europa.eu/reports/medbs.

Sun, Liyang, and Sarah Abraham. 2020. "Estimating dynamic treatment effects in event studies with heterogeneous treatment effects." *Journal of Econometrics.*

Sustainable Fisheries Act: Amendments to the Magnuson Fishery Conservation and Management Act, Magnuson-Stevens Act. 1996. Technical report.

UN General Assembly. 2015. *Transforming our world : the 2030 Agenda for Sustainable Development.* Technical report.
https://www.refworld.org/docid/57b6e3e44.html.

UNEP. 2020. *Global resources outlook 2019: Natural resources for the future we want.* UN.

Vert-pre, Katyana A., Ricardo O. Amoroso, Olaf P. Jensen, and Ray Hilborn. 2013. "Frequency and intensity of productivity regime shifts in marine fish stocks." *Proceedings of the National Academy of Sciences* 110 (5): 1779–1784. doi:10.1073/pnas.1214879110.

Wagener, Florian. 2015. "Economics of Environmental Regime Shifts." In *The Oxford Handbook of the Macroeconomics of Global Warming,* edited by Lucas Bernard And Semmler. Oxford University Press.

Walker, W Reed. 2013. "The Transitional Costs of Sectoral Reallocation: Evidence From the Clean Air Act and the Workforce." *The Quarterly Journal of Economics* 128 (4): 1787–1835.

Weitzman, Martin L. 1974. "Prices vs. Quantities." *Rev. Econ. Stud.* October, 41 (4).

Worm, Boris, Ray Hilborn, Julia K Baum, Trevor A Branch, Jeremy S Collie, Christopher Costello, Michael J Fogarty, et al. 2009. "Rebuilding global fisheries." *Science* 325 (5940): 578–585.

Zeeuw, Aart de. 2014. "Regime Shifts in Resource Management." *Annu. Rev. Resour. Econ.* 6 (1): 85–104.

Appendix

A.1 The Rebuilding of the Atlantic Spiny Dogfish

To better clarify the terms and how they interact, we plot the regulatory and stock health history of the Atlantic spiny dogfish in Figure A1. While the stock was doing well in the early 90s, it saw increases in fishing mortality and reductions in biomass until is was designated as overfished in 1999. The rebuilding plan was implemented in 2002, which reversed the trend in declining biomass and led to reduced fishing mortality. The stock was declared rebuilt in 2010. At face value, this appears to be a successful case study for the policy. A stock started to perform below its target levels, crossed the regulatory threshold (MSST), and received changes to its management that lowered catch and successfully rebuilt the stock to sustainable levels. However, interpreting the changes to the stock as a causal treatment effect of the rebuilding plan assumes that in the absence of rebuilding plans, the stock would have either continued to decline or stagnate around its MSST.

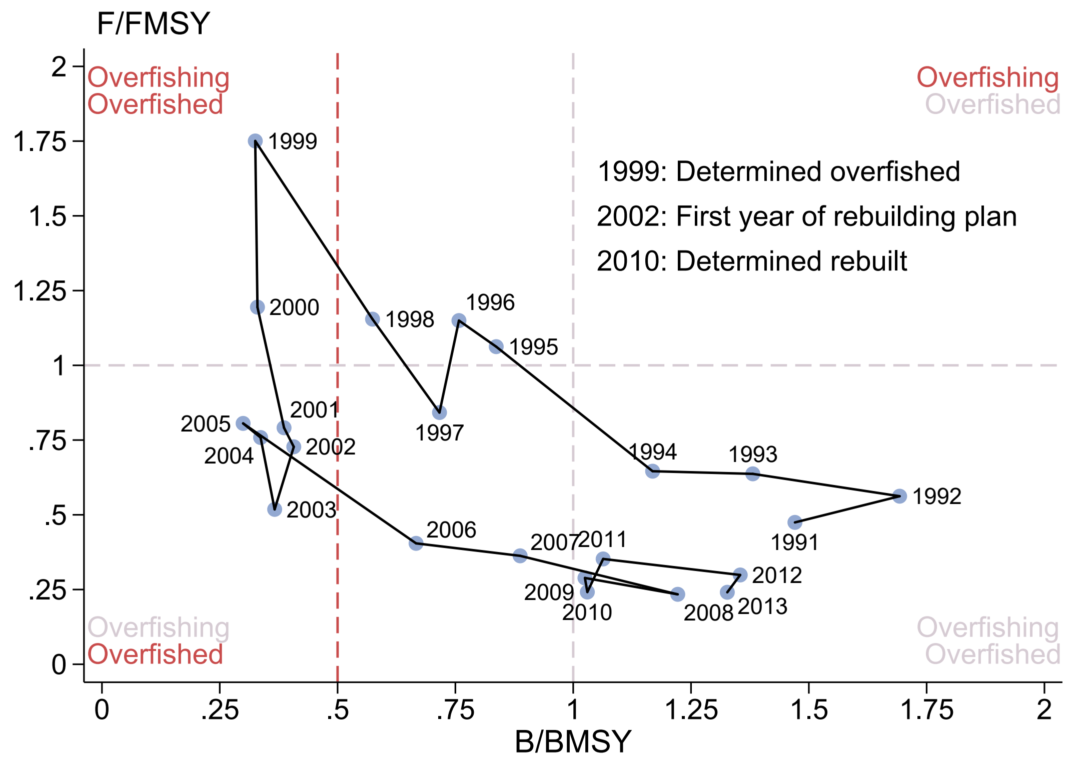
We cannot rule out other explanations such as natural, cyclical population dynamics in the stock. Causal inference can be especially challenging when oscillations are combined with measurement error in the assessment of the size of the stock. As the stock approaches a low value in its cycle, even small measurement error could end up determining that the stock is below its MSST. It will be hard to disentangle how much of the observed increase is due to the rebuilding plan and how much is simply driven by natural variability.

A.2 Delay Between Overfished Determination & Rebuilding Plan

An overfished determination requires, under the MSA, to develop an implement a rebuilding plan. The 2006 reauthorization of the MSA requires that the rebuilding plans be implemented within two years following the overfished determination. Historically, many stocks experienced long delays between the overfished determination and the onset of a rebuilding plan.

We summarize the delays in Figure A2. Stocks that have not yet received a rebuilding plan have either rebuilt prior to the implementation of a rebuilding plan, do not have sufficient data to design a rebuilding plan, or are listed under, and have their recovery plan governed by, the Endangered Species Act.

Figure A1: MSA Management Example: Atlantic Spiny Dogfish

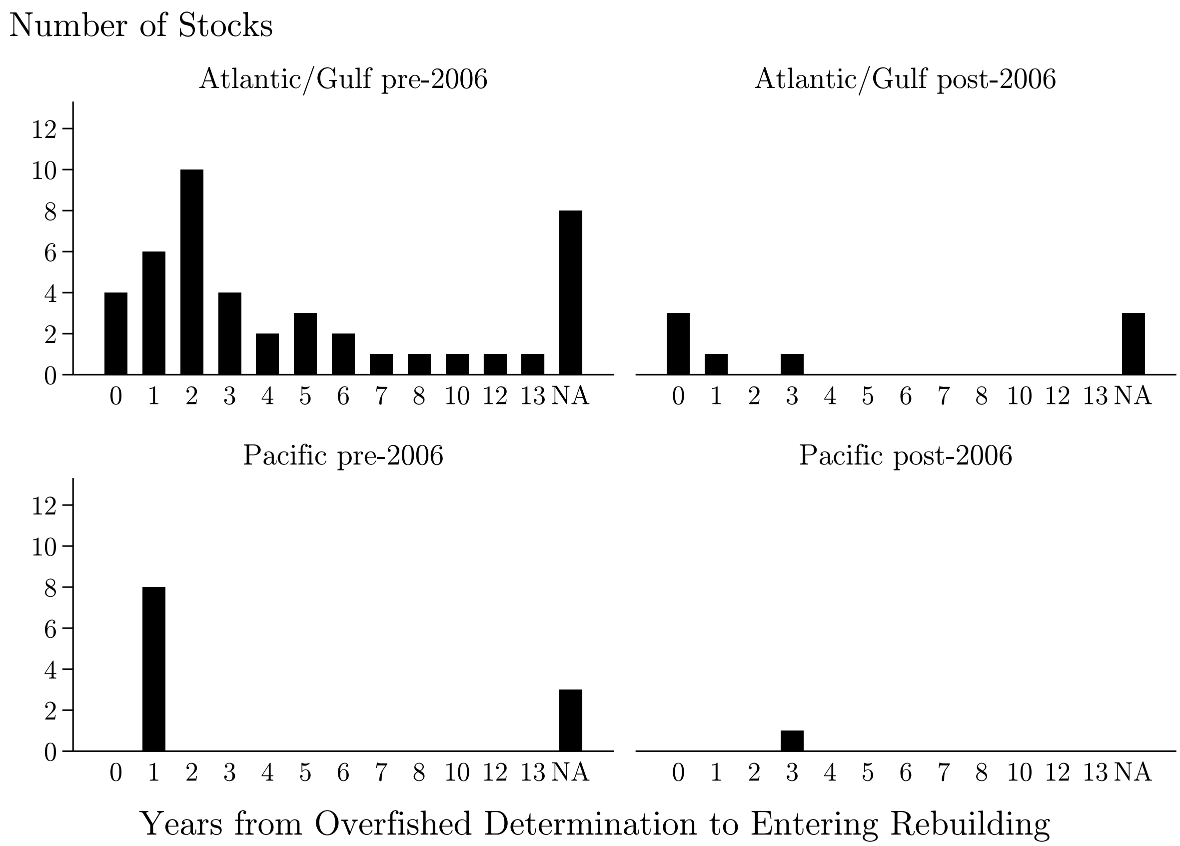


Notes: The x-axis show the biomass relative to the target biomass, and the y-axis shows the fishing mortality relative to the target fishing mortality. Each blue dot represent a specific year of data for the Atlantic spiny dogfish. When the stock is meeting both its targets, for biomass and fishing mortality, the values of B/BMSY and F/FMSY should be centered around the point (1,1) on the plot. When biomass drops below the Minimum Stock Size Threshold (50% of its BMSY target), the Atlantic spiny dogfish is considered to be overfished (left of the vertical red dashed line). When the fishing mortality is above FMSY, the stock is considered to be experiencing overfishing (above the horizontal gray line).

A.3 DD Results Centered Around Overfished Determination & Rebuilding Plan Implementation

In Figure A3, we report results for the same specification in Equation (1), only we center around the overfished determination or the entry to rebuilding. Overall, we recover qualitatively similar results to those we report in the main text. However, as treatment under the MSA starts even before the implementation of a rebuilding, we observe stocks increase in biomass even before the event (see the main text for more details).

Figure A2: Years From Overfished To Rebuilding Plan



Notes: Summarizing the time, in years, between the overfished determination and the first year, if any, of a rebuilding plan.

A.4 Results Without Quadratic Time Trends

In Figures A4-A6, we repeat the estimation reported in the main text, which includes quadratic time trends, and only include unit fixed effects. Overall, we recover similar trajectories for the outcomes after stocks enter rebuilding.

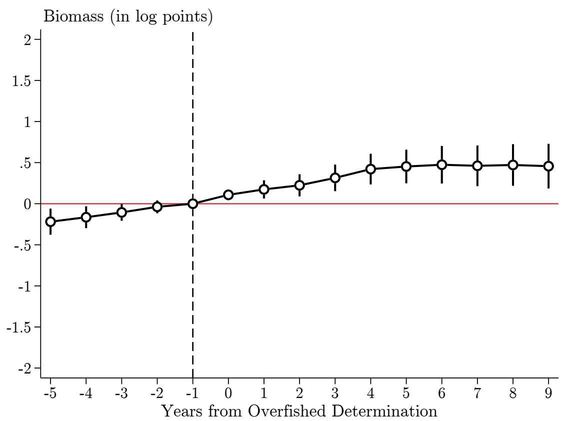
A.5 Event-Study Results Relative to Overfished Determination

In the main text, Figure A4, we report the results for biomass, catch, and revenue, around the time the stocks enter their rebuilding plan. Because regulations under the MSA already place restrictions on catch following an overfished determination, we repeat the analysis here and re-center around the timing of the overfished determination.

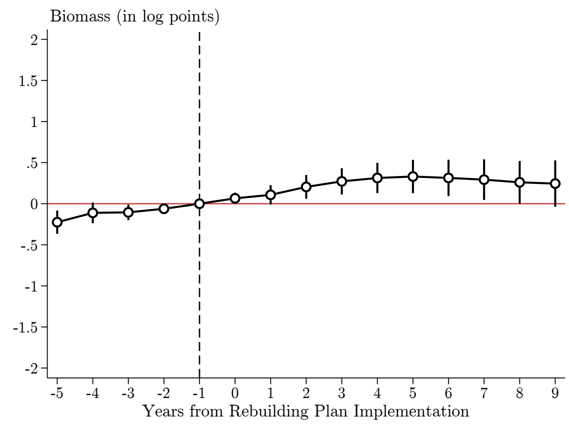
The results in Figure A7 are similar to those in Figure A4. Following an overfished determination, stock biomass increases, catch declines, and revenue falls but recovers to

Figure A3: The Effect of Rebuilding Plans on Stock Biomass Using Different Treatment Onsets

(a) Centered Around Overfished



(b) Centered Around Rebuilding



Notes: See Figure 4.

baseline levels, albeit, imprecisely. The effects, especially for biomass and catch, are stronger in the Pacific than in the Atlantic. The increase in biomass is smaller, and less precisely estimated, which is consistent with the delays between the overfished determination and entering rebuilding.

Catch levels begin to fall even before the overfished determination. One reason for this could be the lower density and higher search costs involved with finding the stocks. The second reason is that the Harvest Control Rule already scales down the catch and effort limits relative to the declining biomass.

We compare the results from the event study specification to a linear trend-break specification. In Figure A8, we report more descriptive results that estimate a linear trend separately for the years before and after the implementation of a rebuilding plan, or dropping below the MSST . In Figure A9, we include a more detailed breakdown of the event study results. We estimate a model per-stock in each time period, for the effect of being six to ten years after the stock drops below MSST.

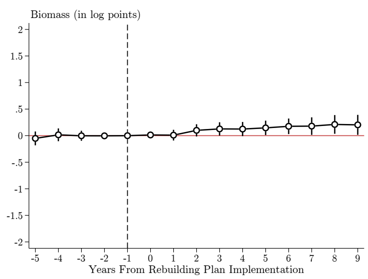
A.6 Suggestive Evidence for Compliance

In Figure A10, we plot the mean change in stock biomass during the first ten years after entering a rebuilding plan relative to two measures of interest. First, the mean deviation of the realized catch from the total allowable catch (TAC) during the ten years after entering rebuilding. This acts as a proxy for how fishers are complying with management decisions regarding the utilization of the stocks. We observe a negative correlation between biomass change and compliance, meaning the higher the catch is from the TAC, the lower the gain in biomass is. This pattern is reversed when we compare the change in biomass to the change in the management buffer, which we measure as the difference between the MSY and TAC. We observe a positive correlation between the change in biomass and the management buffer. This suggests that when managers place larger restrictions on catch, stocks are better able to recover.

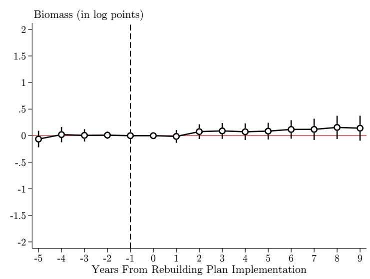
Figure A4: Effect on Stock Biomass, Catch & Revenue Following Rebuilding With Unit FEs Only

Atlantic/Gulf & Pacific	*Atlantic/Gulf*	*Pacific*

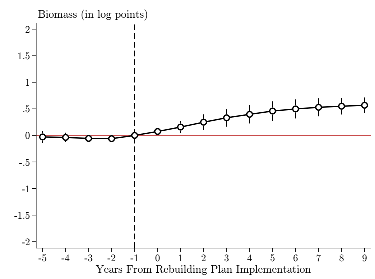
(a) Biomass



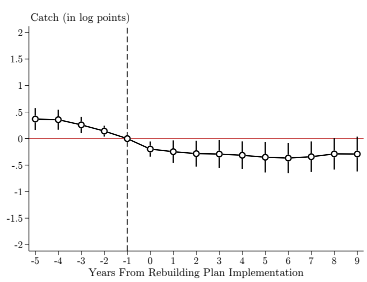
(b) Biomass



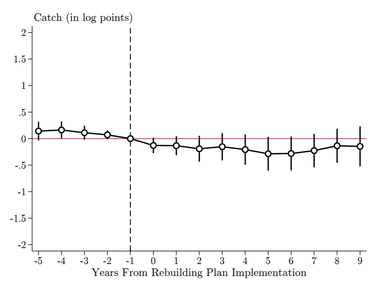
(c) Biomass



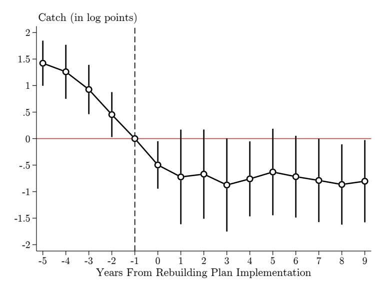
(d) Catch



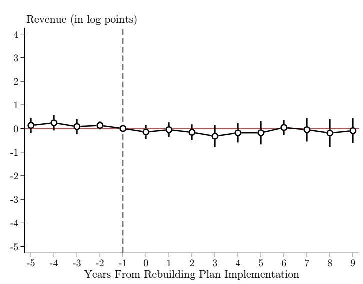
(e) Catch



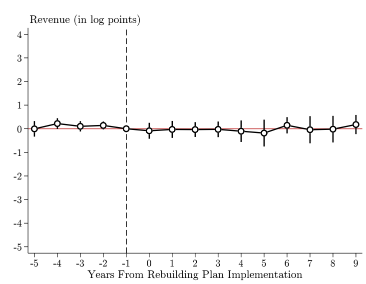
(f) Catch



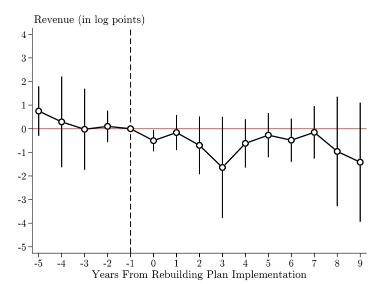
(g) Revenue



(h) Revenue



(i) Revenue

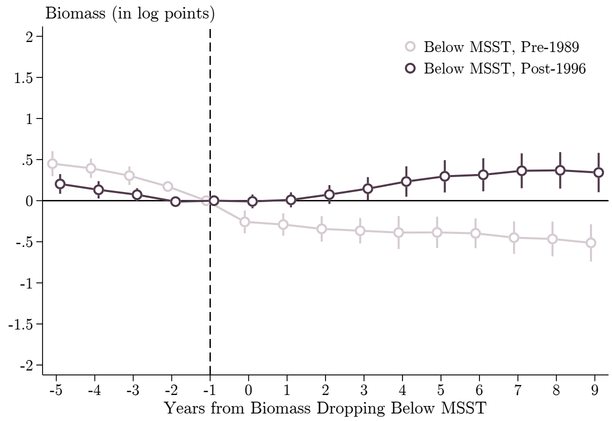


Notes: Estimation results showing coefficients and 95% CIs for the specification in Equation (2). Standard errors are clustered at the stock level.

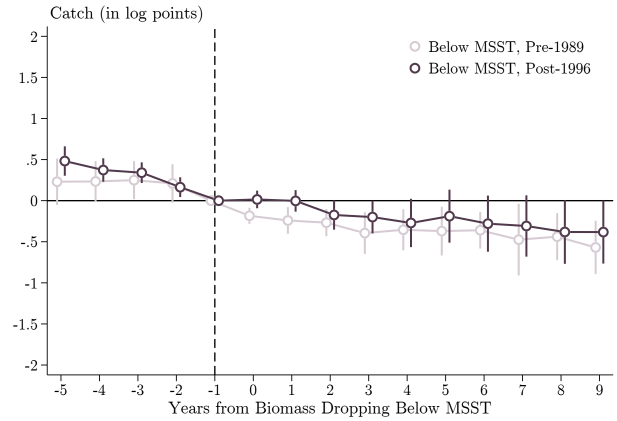
Figure A5: Estimation Results for the Historic Comparison Group With Unit FEs Only

All Stocks That Were Below Their MSST Either Pre- or Post-SFA

(a) Biomass: Double-Event-Study

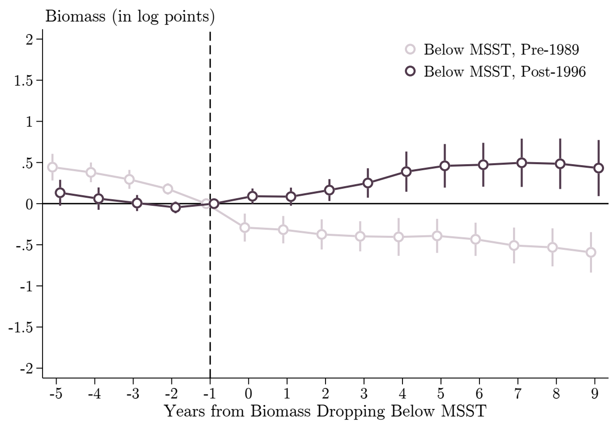


(b) Catch: Double-Event-Study

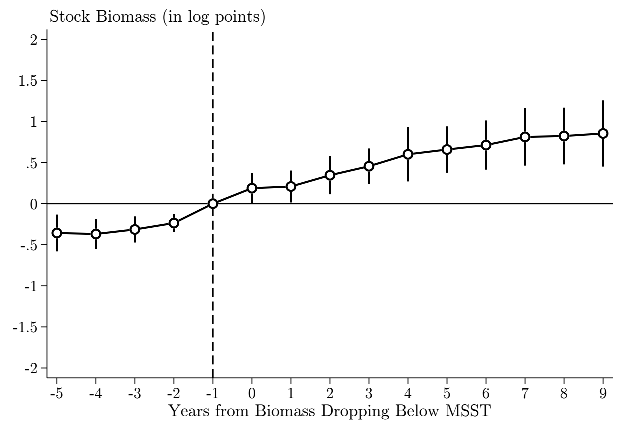


Holding Stock Composition Constant

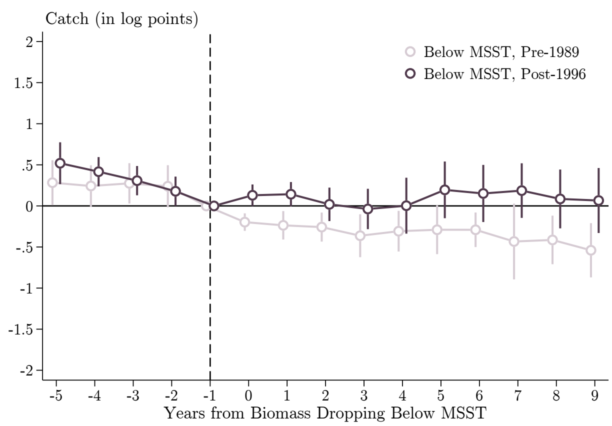
(c) Biomass: Double-Event-Study



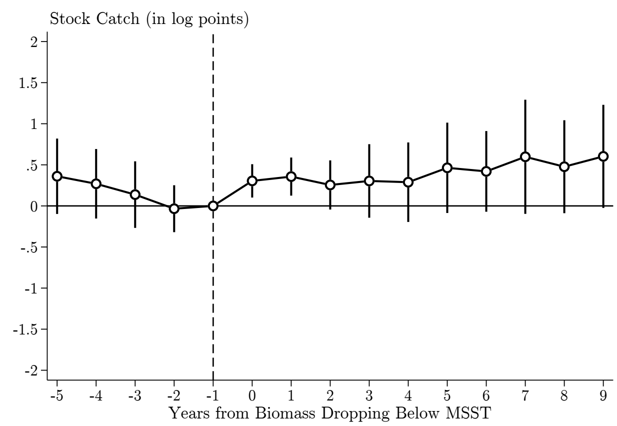
(d) Biomass: Paired-Differences



(e) Catch: Double-Event-Study



(f) Catch: Paired-Differences

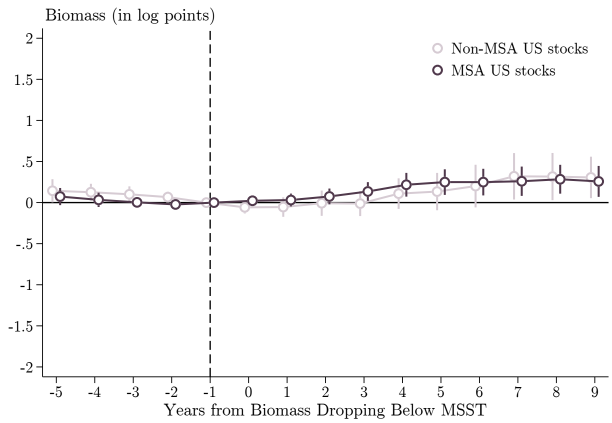


Notes: Estimation results showing coefficients and 95% for the specification in Equation (2). Standard errors are clustered at the stock level.

Figure A6: Estimation Results for the Contemporaneous Comparison Groups With Unit FEs Only

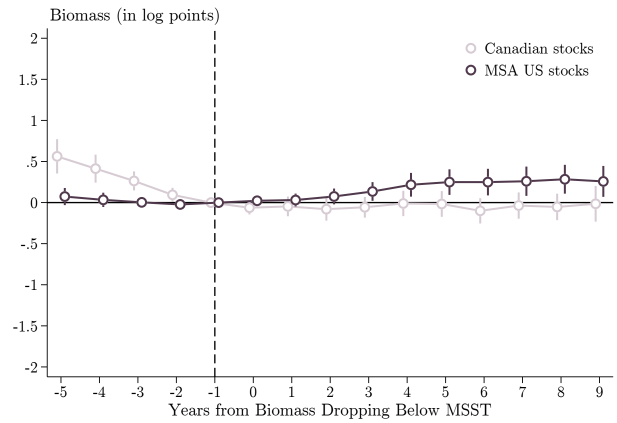
USA: High Susceptibility to Spillovers

(a) Biomass

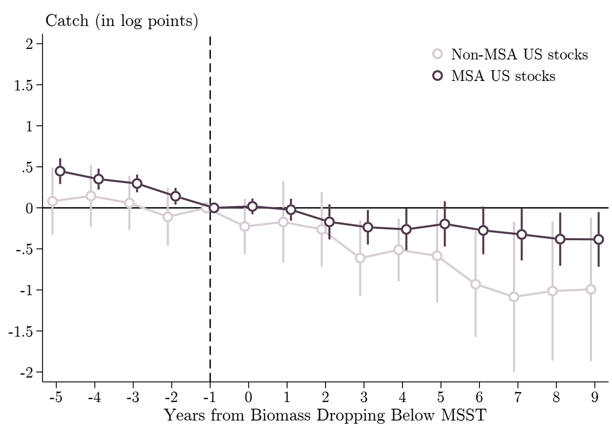


CAN: Low Susceptibility to Spillovers

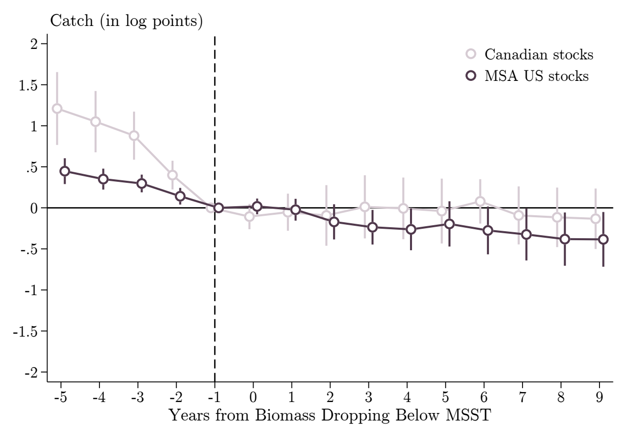
(b) Biomass



(c) Catch

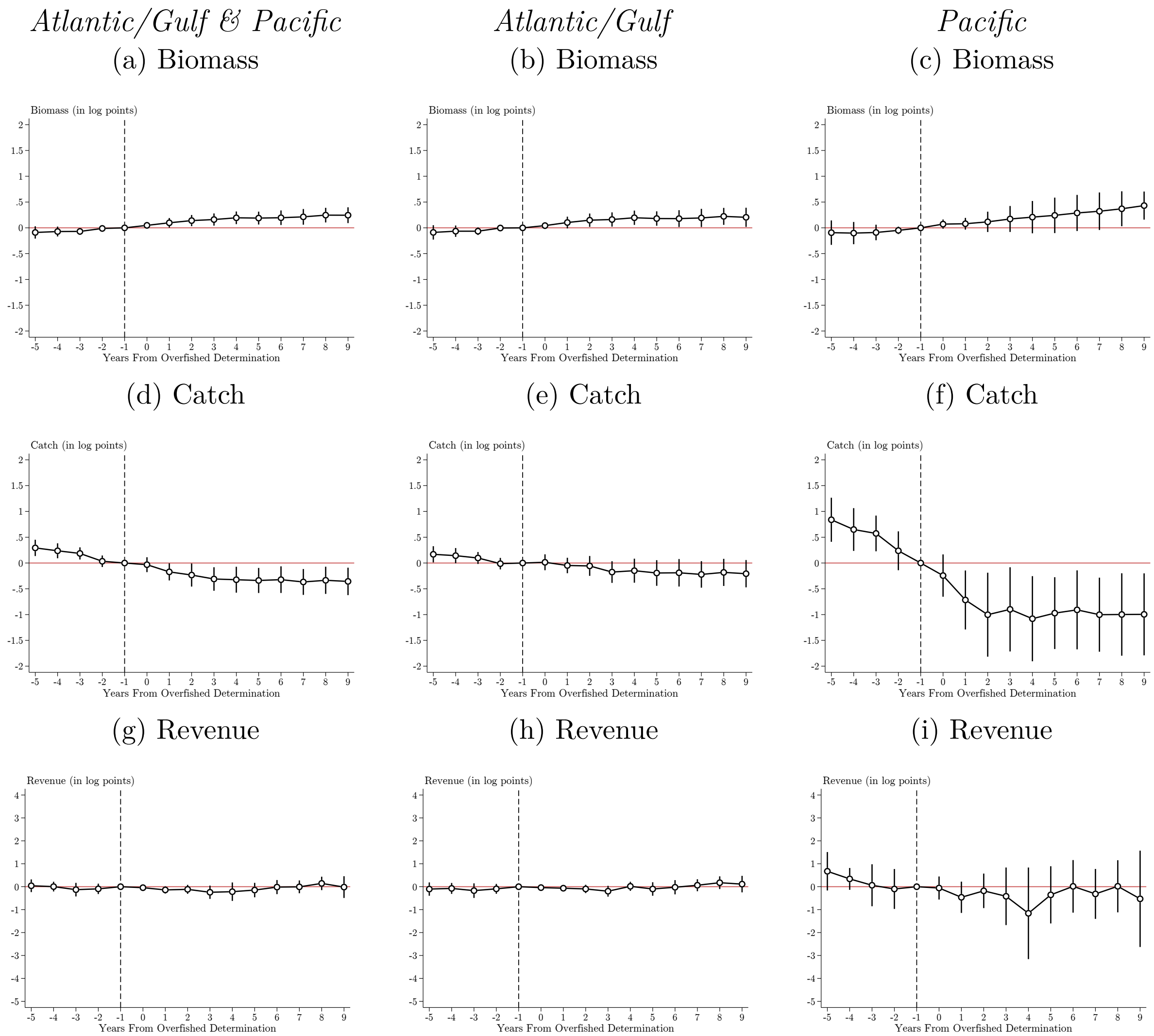


(d) Catch



Notes: Estimation results showing coefficients and 95% CIs for the specification in Equation (2). Standard errors are clustered at the stock level.

Figure A7: Effect on Stock Biomass, Catch & Revenue Following Overfished Determination

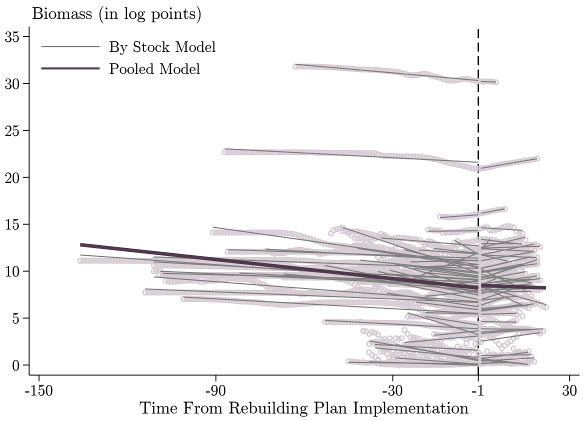


Notes: Estimation results showing coefficients and 95% CIs for the specification in Equation (2). Standard errors are clustered at the stock level.

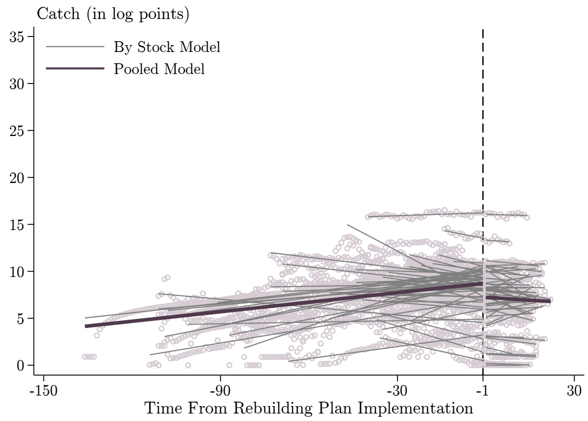
Figure A8: Trend-Break Models

Centered Around Entering A Rebuilding Plan

(a) Biomass

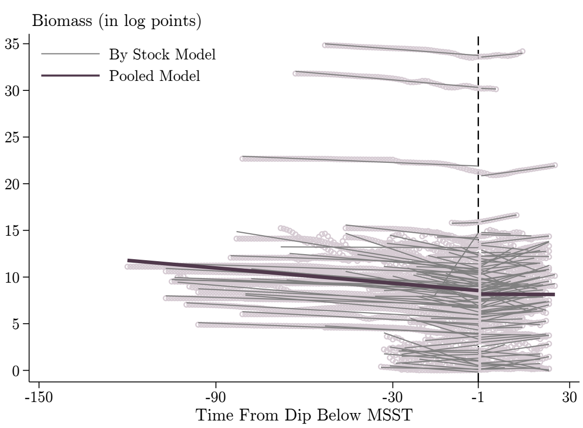


(b) Catch

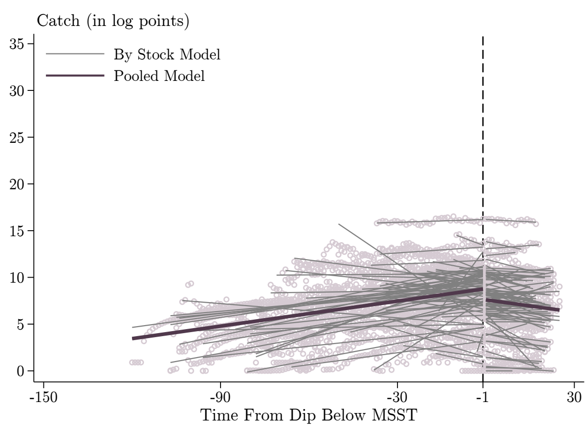


Centered Around Dropping Below the MSST

(c) Biomass

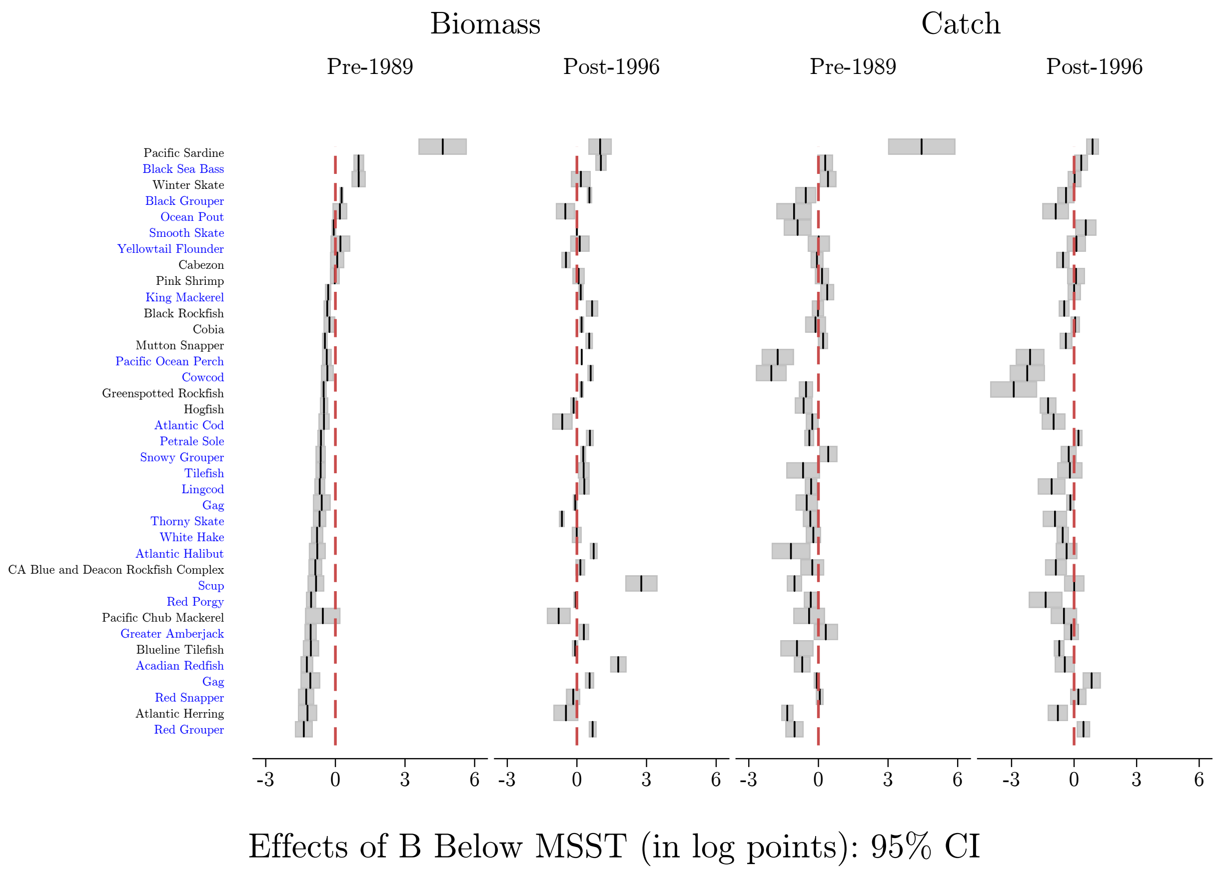


(d) Catch



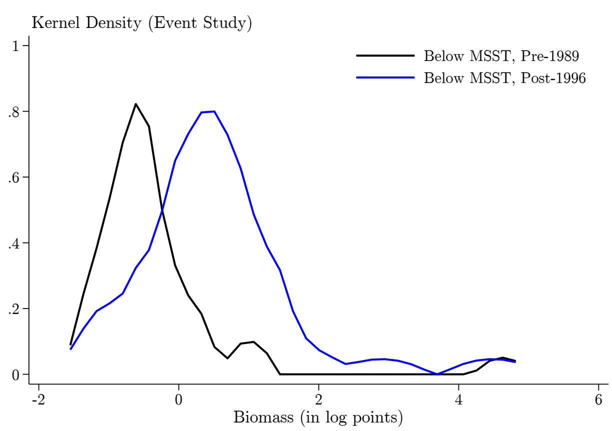
Notes: We run linear time trend models by stock, or by pooling all stocks together, centered around the implementation of a rebuilding plan, or the first observed drop below the MSST.

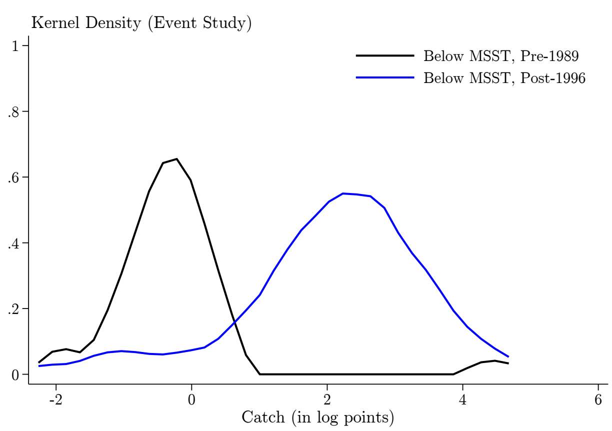
Figure A9: Changes in Biomass & Catch Following Decline Below MSST, by Stock



(a) Biomass

(b) Catch



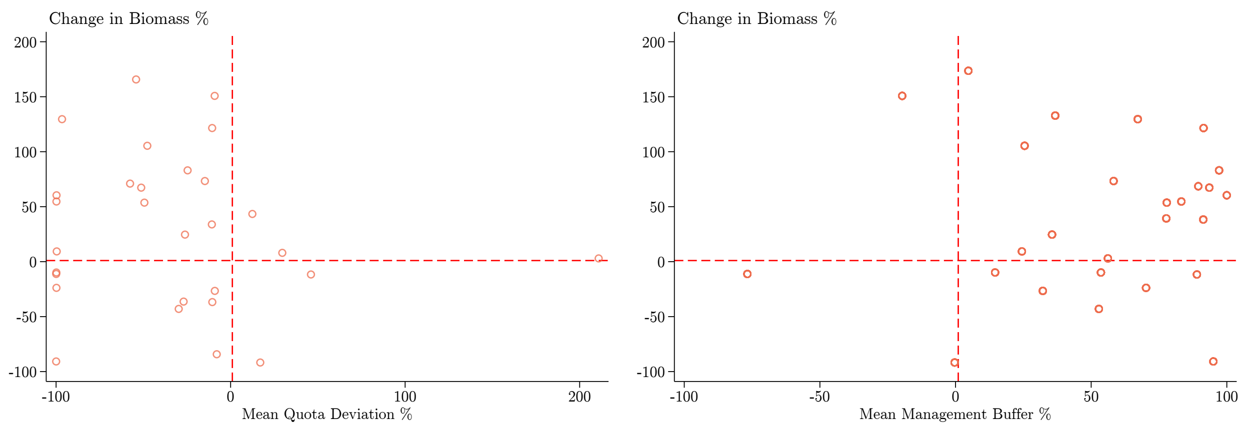


Notes: We report the estimates from a stock-by-stock regression, where we report the coefficient on a dummy variable for being six to ten years after the event of dropping below the MSST. We repeat the estimation in pre-1989 and post-1996 periods, capturing the historic comparison when holding the composition of stocks constant (see Figure 6). Stock that are highlighted in blue are those that also entered a rebuilding plan post-1996. In Panels (b) and (c), we summarize the distribution of the coefficients by the time period for each outcome.

Figure A10: Mean Change in Biomass for Stocks that Entered Rebuilding

(a) Relative to Deviations from Quotas

(b) Relative to Management Buffer



Notes: For each stocks, we calculate the mean change in biomass during the first ten years after entering rebuilding, and compare it to the mean difference between the realized catch and the total allowable catch (a), or the difference between the MSY value and the total allowable catch (b). The first suggests how closely do fishers follow the prescribed quotas, and the second suggests how strongly fishery managers limit fishing during rebuilding.