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

Eyal Frank† Kimberly Oremus‡

12/30/2019

Preliminary and incomplete - Please do not cite or circulate

Abstract

Managing renewable resources requires making decisions based on noisy data. Despite the uncertainty of resource management, it is still important to assess the efficacy of such policies. In this paper, we examine the Magnuson-Stevens Fisheries Conservation and Management Act (MSA), which is internationally regarded as a gold standard in sustainable fishery management. In event-study designs, we find that implementing the conservation requirement to rebuild stocks, biomass increases by over 25%, and catch decreases by about 45%. We document large heterogeneity across stocks, and compare it with commonly used trend-break models in the literature. We proceed to use the thresholds that necessitate rebuilding plans to investigate whether these effects can be interpreted as causal treatment effects of the MSA. Comparing the same stocks that meet the condition for a rebuilding plan in two time periods, before and after these plans were required, allows us to construct plausible approximations for the counterfactual biomass that stocks would have experienced in the absence of the rebuilding policy. We find that stocks more than double in their biomass relative to these counterfactuals, following the establishment of the rebuilding requirements in the MSA. Even as we explore alternative confounders to these effects, such as changes in demand, environmental conditions, and technology, our interpretation of the results holds.

*We would like to thank 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, and the Ostrom Workshop for their helpful comments. We also thank the staff members at the different Fishery Management Councils and the National Oceanic and Atmospheric Administration for their assistance in accessing and interpreting the data.

†Harris Public Policy and Energy Policy Institute (EPIC), University of Chicago. Office 2057, 1307 E. 60th Street, Chicago, IL 60637, USA. Email: eyalfrank@uchicago.edu

‡School of Marine Science and Policy and Department of Economics, University of Delaware. Robinson 308, 261 S College Avenue, Newark, DE 19716, USA. Email: oremus@udel.edu

1 Introduction

Global extraction of resources, both renewable and non-renewable, is on the rise. A 2017 report estimated global resource use at approximately 90 billion tons, a three-fold increase relative to 1970. It is further expected to double by 2050 relative to 2015 levels (UNEP 2017). When managing renewable resources, the emphasis lies on balancing flows and stocks. This raises the question of what are the optimal harvest rates subject to the growth rate of the stock. Previous work that analyzed optimal extraction problems, as in the seminal work by Hotelling (1931), Gordon (1954), Dasgupta and Heal (1974), Stiglitz (1974), and Clark et al. (1979), often relies on complete information regarding the behavior of the stock and simple functional forms for its growth. Further studies in the literature have emphasized the stochastic nature of such biological systems and the difficulties that arise as a result with respect to management (Pindyck 1978; 1984; Nøstbakken 2006; Sethi et al. 2005; Carson et al. 2009; Brozović and Schlenker 2011; Memarzadeh et al. 2019). Marine fisheries are an example of such a stock. They are an important source of protein, food security, jobs and livelihoods worldwide as well as part of a global market (FAO 2014). However, their populations are declining worldwide. Various management regimes can theoretically yield different outcomes (Costello et al. 2016). As the global demand for fish continues to rise, countries have agreed to manage fisheries sustainably as part of the Sustainable Development Goals (SDGs) (UN General Assembly 2015). Whether current management practices are able to sustain stocks such that they follow their optimal harvest paths remains an open question (Arrow et al. 2004; Kroetz et al. 2019; Memarzadeh et al. 2019).

In this paper, we study the primary policy instrument countries have adopted to sustainably manage stocks (under SDG Target 14.4). We examine this instrument, the requirement to rebuild overfished stocks, in the United States, which has used this scientifically-driven management regime since 1996. From this point in the text, we refer to this as the "1996 regime." Under the management plan, each stock, defined as a subpopulation of a particular species of fish, has assigned target levels for its population and harvest levels (both often expressed in biomass or an equivalent measure). These targets also define key thresholds that the stock managers use to determine whether the stock is in a state of over-fishing, is overfished, or both.[1] When stocks are assessed to be below their specific thresholds a rebuilding plan is developed and implemented that aims to restore the stock back to its target levels. We examine how stocks perform during their time in a rebuilding plan in order to

[1] The distinction is between the rate of extraction, and the level of the stock.

estimate if they are making progress towards their target levels. Because rebuilding plans are not assigned randomly, we rely on pre- and post-comparisons that also leverage data on the stocks from before the enactment of this management regime. On average, we find evidence that stocks increase in their biomass by approximately 25% after ten years spent in rebuilding status. The increase in biomass after declining below a specific threshold level only appears once the threshold becomes binding, that is, after the 1996 management regime is applied. The impact on biomass more than quadruples when we compare the same stocks both before and after policy's enactment. In the years prior to the enactment, stocks that met the condition for a rebuilding plan continued to decline, but in the years after enactment, they exhibited an increase in their biomass. Holding the composition of stocks constant, we use a paired-difference estimator and find that stocks more than double in biomass relative to their historic counterfactual.

The Magnuson-Stevens Fisheries Conservation and Management Act (MSA) is internationally regarded as a gold standard in sustainable fishery management. This is mostly due to its 1996 reauthorization as the Sustainable Fisheries Act (SFA), which established a requirement to rebuild overfished stocks based on the best available science. The rebuilding provisions require that each fishery management council develops a fishery management plan. Each plan includes stock-specific, population targets and sustainable levels of harvest conditional on that target. These plans also include Minimum Stock Size Thresholds (MSST). When these thresholds are crossed, managers are required to develop and implement a rebuilding plan. Such plans often place strong restrictions on harvest, referred to as catch in fisheries management, until the population is rebuilt to the target amount. These restrictions range from limits on total allowable catch, the number of fishing permits, closures of specific regions, reductions in the length of the fishing season, time spent at sea, or changes to permitted fishing gear.

While this traditionally bipartisan Act is internationally renowned as a highly effective policy tool that uses pre-determined decision rules, it is highly controversial among the fishing industry and fisher communities. The debate around the Act's reauthorization, which has been held up in Congress for six years, centers on how successful these rebuilding provisions have been, as well as their impacts on fishing communities.[2] Recently the Chair of the Water, Oceans, and Wildlife subcommittee, Representative Huffman, embarked on a listening tour

[2] In 2018, the House of Representatives passed a bill, 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."

in an attempt to restore the bipartisan nature of the Act before introducing a bill next spring. Changes to the strength of these rebuilding provisions will have direct repercussions for U.S. commercial fisheries that employ 166,952 people and generate over $14 billion dollars (National Marine Fisheries Service 2018).

Early studies found rebuilding plans did not stop overfishing, 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). 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). Without a valid comparison group to act as a control, any observed changes in biomass can be attributed to changes in environmental conditions, market shifts in demand, or other confounding factors that could systematically occur around the same time as the implementation of rebuilding plans. A few studies use simulations to evaluate rebuilding provisions versus other fishery management options (Benson et al. 2016), or consider other timelines instead of the 10-year maximum (Patrick and Cope 2014; Carruthers and Agnew 2016) or examine the role of uncertainty in rebuilding success (Memarzadeh et al. 2019). However, none of these studies are aimed at empirically measuring the efficacy of the policy.

A key challenge in coupled natural and human systems is to learn about the causal effect of policy interventions in those systems (Daily et al. 2000; Ferraro et al. 2019; Greenstone and Gayer 2009; Polasky et al. 2019). We study how the main outcome of interest, the fishery stock biomass, changes following the implementation of a rebuilding plan. We also compare this outcome with the use of the policy's main tool, reducing catch. Using data on the years before and after the implementation of a rebuilding plan, we observe increases in biomass and large declines in catch. If we change the event of interest from the time of rebuilding plan implementation to the determination of the stock as overfished, the condition which necessitates the development of a rebuilding plan, we find similar effects.

Despite observing effects that suggests the policy is effective, we cannot rule out other explanations such as noisy stock assessments or natural cyclicality. We exploit the fact that the biomass threshold that triggers the required policy was only developed and became binding after the 1996-reauthorization. Using data on the stocks before the rebuilding requirement (1996), we estimate how biomass develops in the years after a stock's biomass declines below the threshold that would have necessitated rebuilding under 1996 laws. We only find an average increase in biomass for the years after the rebuilding provisions are required. While other confounders such as market demand, environmental conditions and fishing technology could be changing over the two periods, this exercise allows us to hold the biology of the stocks constant. We interpret these results as evidence for the efficacy of the program and find indirect evidence that other plausible mechanisms are not consistent with what we observe in the data.

2 Rebuilding Provisions Under The Magnuson-Stevens Act

The first federal Act to regulate fishing in U.S. waters was the original Fishery Conservation and Management Act which passed in 1976. The scope of the original legislation defined the U.S.'s national jurisdiction or Exclusive Economic Zone (EEZ), created regional councils and restricted fishing in U.S. waters to U.S. vessels only. The name of the Act was later changed to reflect the contributions of the two congress members that played a pivotal role in its formulation: Magnuson-Stevens Act (MSA). The MSA is the primary law governing marine fisheries in the U.S. and lays the groundwork for all regional and state management.

Increased overcapitalization of US commercial fishing fleets led to overfished stocks and the need to reauthorize MSA in 1996 with more conservation measures, specifically the requirement to rebuild overfished stocks. Regional fishery management councils are required to develop and implement rebuilding plans when a fish stock is considered overfished. The plans must bring a stock back to sustainable population levels in as short as time possible, not to exceed 10 years unless it is not biologically possible (*Sustainable Fisheries Act: Amendments to the Magnuson Fishery Conservation and Management Act, Magnuson-Stevens Act* 1996). When MSA was reauthorized in 2006, the rebuilding plan was required to be implemented within two years of the stock being declared overfished. The language in its rebuilding provisions is even echoed in Section 104 of the recently enacted Modern Fish Act governing all U.S. recreational fisheries (Wicker 2018). Countries around the world recently adopted similar rebuilding provisions through the EU Common Fisheries Policy (European Parliament and Council 2013) and the Sustainable Development Goal 14, Target 14.4 (UN General Assembly 2015).

The MSA uses two thresholds to determine the status of that stock's health: one that defines overfishing or when the fishery is catching too much and one that defines when the stock is overfished or if the biomass of a given stock is too low. However, management is not the only variable that influences the status of the stock. The environment, ecology and biology of the stock, as well as the economics of the fishery impact stock status. Large 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). The key concept that governs the management under the MSA is that of Maximum Sustainable Yield (MSY). The definition, as clarified by the National Standard Guidelines as "the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions" while maintaining a sustainable population (*Sustainable Fisheries Act: Amendments to the Magnuson Fishery Conservation and Management Act, Magnuson-Stevens Act* 1996).

The goal is to have the stock close to the level of biomass which produces the maximum amount of growth. Theoretically, this enables harvesting of that growth while maintaining the population over time. This means that over time, as long as the stock is at the biomass level which produces the maximum amount of growth (referred to as BMSY), then the managers can allow the harvest of MSY while sustaining the population. This also defines the target level of catch, formally denoted as fishing mortality which is the ratio between the catch level relative to current biomass.[3]

Assessed biomass for each stock is evaluated relative to the target biomass, and catch levels are evaluated relative to the target fishing mortality ratio. Each stock has a threshold for its biomass level, defined as the Minimum Stock Size Threshold (MSST). It is often 50% of its BMSY value[4]. When the stock is below its MSST it is determined to be overfished.

An overfished designation has an immediate effect on the management of the stock as well a longer-term impact. First, many management councils set allowable catch targets as a proportion of the assessed stock biomass. This Harvest Control Rule (HCR) changes discontinuously when a stock crosses its MSST. This means that catch is set to a lower level following an overfished designation. While this could lead to some degree of recovery, the key intervention that is meant to restore the stock back to its target biomass level is the rebuilding plan. A stock is considered rebuilt when its biomass reaches BMSY. As of 2018, 45 stocks have been rebuilt since 2000 (NOAA Fisheries). However, uncertainty in this threshold requires frequent re-evaluation and alterations in the threshold over time.

Another important classification is when fishing mortality is above FMSY. In this instance, the stock is determined to be experiencing overfishing. Overfishing and overfished are determinations regarding the status of the harvesting rate, and the stock, respectively. To better clarify the terms and how they interact, we plot the regulatory and stock health history of the Atlantic spiny dogfish in Figure 1. 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

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

[4] Although it can be at lower ranges of 10-20% of its BMSY.

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.

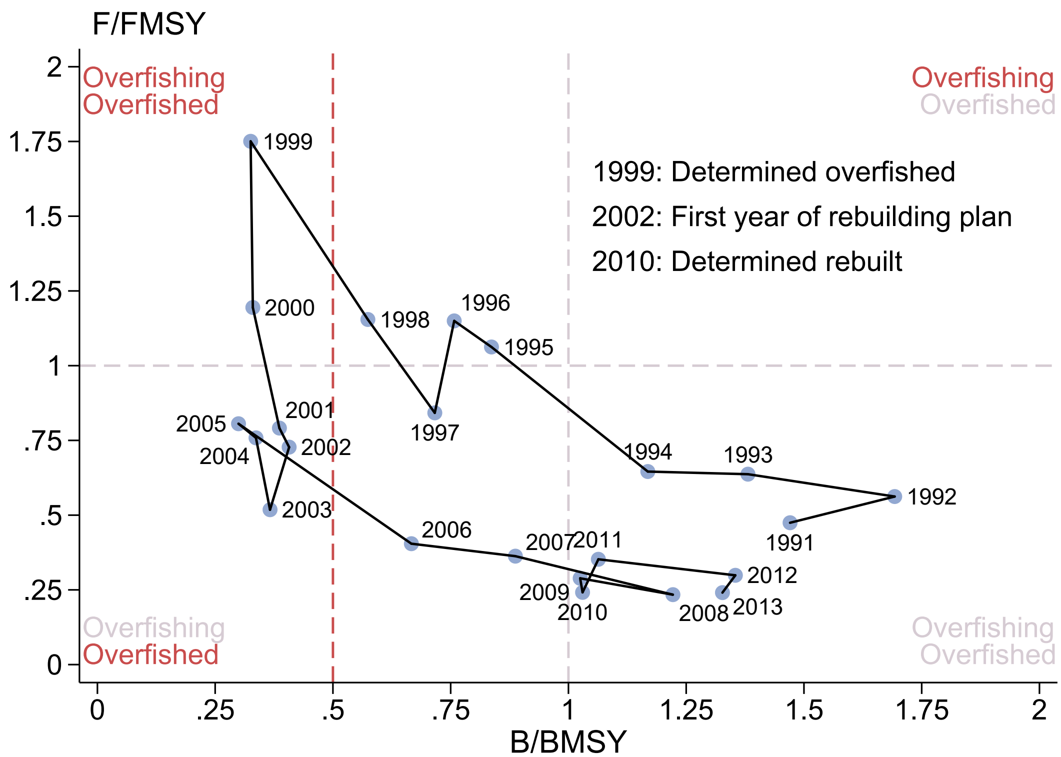


Figure 1: MSA Management Example: Atlantic Spiny Dogfish

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).

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.

3 Data

Our work puts together a centralized U.S. database on fishery management. We compile data on the biomass and catch of different stocks using data from stock assessment summaries provided by The National Oceanic and Atmospheric Administration's (NOAA's) Species Information System (SIS) (Office of Science and Technology 2016).[5] We compiled the regulatory history of stocks using the yearly Status of Stocks reports from NOAA. We then add data we manually collected from stock assessments, fishery management plans, and other regulatory documents on the history of the biological reference points: MSY, BMSY, FMSY, and MSST.

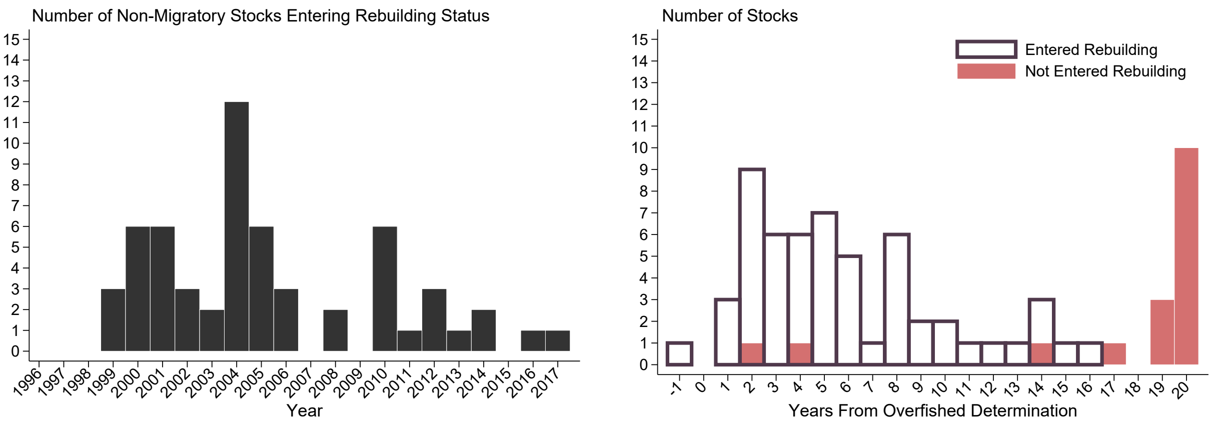
NOAA obtains data on catch from log books of fishing vessels, which are verified using detailed receipts produced by fish wholesale dealers. NOAA also has observers aboard fishing vessels. Some stocks are required to have an observer 100% of the time, as well as observers at the docks to monitor the landings process (when fish are unloaded from the vessel). The catch data are combined with data on the abundance of each stock from surveys that NOAA conducts. The different data elements are incorporated into a model which leverages the biological knowledge of the species. The model output provides population biomass estimates which are consistent with the observed catch, abundance surveys, and the traits of the species.

There are rebuilding plans for 57 non-migratory and non-anadromous stocks that entered rebuilding under the MSA since the approval of the SFA in 1996.[6] See Figures 2a and 2b for the number of stocks that went into rebuilding each year, and the years it took to implement a rebuilding plan after being declared overfished. Figure 2b shows it can take several years for a rebuilding plan to be implemented. 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

[5] The data were previously publicly available but have since been removed. NOAA plans to release a new public portal in the near future that will enable access to the data.

[6] We focus on non-migratory stocks to ensure we are studying stocks that are only affected by U.S. fishing pressure and regulations. We also exclude anadromous stocks, such as salmon, as they spend part of their life cycle crossing waters that are subjected to different local regulations in addition to the federal regulations, making it difficult to account for the full regulatory treatment they experience. We also omit crab species as their assessment process and management is very different relative to the other species.

by, the Endangered Species Act.



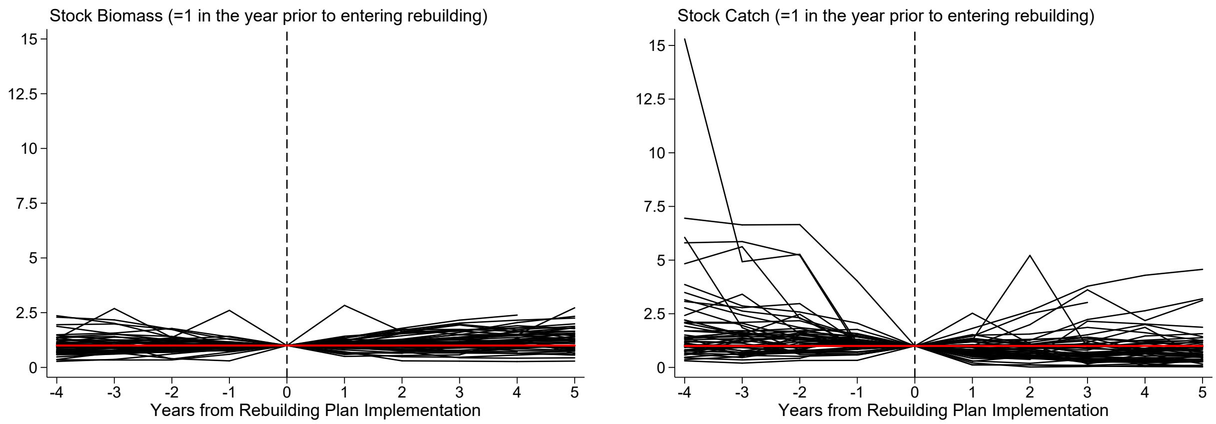
(a) Stocks That Entered Rebuilding

(b) Years From Overfished To Rebuilding Plan

Figure 2: Descriptive Data On Rebuilding Plans

Source: Data from NOAA's Status of Stocks Reports.

In Figure 3, we plot the raw data on biomass and catch for stocks that enter rebuilding, in the years before and after rebuilding. For comparison of stocks, we normalize the biomass and catch to equal 1 in the year prior to rebuilding (year 0). Many stocks are declining with respect to their biomass and catch in the years prior to rebuilding. However, some stocks' biomass increase in years before the implementation of a rebuilding plan. This is likely a result of the Harvest Control Rule (HCR) that fishery councils enact for each stock. The rule ties total allowable catch to the estimated biomass of the stock. This can lead to small increases in biomass prior to implementing a rebuilding plan, especially for stocks with a long delay before entering rebuilding (see Figure 2b).



(a) Biomass

(b) Catch

Figure 3: Raw Data Scaled Relative to One Year Prior Rebuilding
Notes: Data from NOAA's Status of Stocks Reports and the stock assessment summaries from NOAA's SIS.

4 Estimating Changes in Biomass and Catch Relative to Rebuilding Plan Implementation

In order to measure the effectiveness of the rebuilding policy, we need to compare the biomass of an overfished stock in two worlds: One where the policy is implemented and one where the policy is not implemented. In an ideal experiment, we would randomly assign rebuilding plans to some of the stocks that are depleted below their MSST, and leave the rest as controls. Under the post-1996 regime, we only get to observe stocks that are depleted below their MSST and then receive a rebuilding plan.[7]

We first exploit the different timing of rebuilding plans to summarize the average impact they have on all treated stocks, as well as the impact they have on each individual stock. In these specifications, the treated stocks in the non-treated periods serve as the control group. In a subsequent section, we examine how biomass responds for stocks that approach their MSST in different time periods, pre- and post-1996 MSA reauthorization (which established the rebuilding provisions). Hereafter, we refer to the post-reauthorization period as the "post-1996 regime".

We study the change in biomass and catch using a simple event-study design. There are

[7] If they did not receive a rebuilding plan due to insufficient scientific knowledge or existing Endangered Species Act protections, then they are systematically different than the stocks that do receive such plans, and are an inadequate control group. Stocks that do not dip below their MSST are unlikely to be on a similar downward trend with respect to their biomass and might have very different counterfactual outcomes than those that are, making them a poor comparison group.

several ways to measure how biomass and catch change over time. First, in levels, but this is problematic given the different scales and measurement units, where some stocks are in thousands or millions of metric tons, and some stocks are measured by their adult biomass and others by their count of eggs spawned. Using a log transformation allows us to focus on the relative changes within a stock over time. We can also use the target levels, either BMSY or MSST to normalize the levels. However, these targets change over time. In order to not introduce variation in the targets to the metric we use to evaluate the policy, we focus on the logged values of biomass and catch as our preferred metric. When we do normalize by one of the reference points, we choose the one determined in the most recent assessment, which mostly corresponds to the biomass time-series we use.

In this setting, we are interested in the changes following the implementation of a rebuilding plan. For each stock, we define the year of entering a rebuilding plan as the event of interest. We measure leads and lags from that year in event time for a balanced set of stocks. Using the natural logarithm of either biomass or catch, y_{st}, for stock, s in period t, we test for the mean change in the years before and after the event with the following specification:

$$y_{st} = \sum_{\substack{\tau \in \{\underline{T}, \dots, \overline{T}\} \\ \tau \neq 0}} \mu_\tau + \theta_s + \varepsilon_{st} \tag{1}$$

Each μ_τ is a dummy variable that is equal to one when a stock is τ years away from the year of treatment.[8] The estimated value of each μ_τ coefficient is the mean value of either the biomass or catch in the years before and after the plan, relative to the omitted category of one year before treatment. In addition, we include stock fixed effects to account for time-invariant stock characteristics such as differences in magnitudes, location, fishing seasons, and fishing gear. Finally, any unobserved heterogeneity is captured by the error-term, ε_{st}. We cluster the standard errors at the stock level to address serial correlation in the data.

The advantage of this specification is that it allows us to recover different patterns in the data, without placing many restrictive assumptions. For example, it is common in the fishery management literature to use trend break models (Costello et al. 2008; Oremus et al. 2014). This requires assuming whether the structure of the trend is linear, quadratic, or some higher degree polynomial. We run the specification with five years before rebuilding to establish a baseline, and five or ten years after rebuilding to measure the impact of the policy. Extending the time window around rebuilding means there are fewer stocks in the

[8] Formally, $\mu_\tau = \mathbb{1}\{\text{Year - Rebuilding Year} = \tau\}$.

analysis due to data limitations.[9]

To focus on the overall average change in the years after the rebuilding plan implementation, we focus on the average of y_{st} in the post-rebuilding period:

$$y_{st} = \beta(\text{Post Rebuilding})_{st} + \theta_s + \varepsilon_{st} \tag{2}$$

Where $(\text{Post Rebuilding})_{st}$ is a dummy variable that is equal to one in the years, t, after a rebuilding plan is implemented for stock s. All the other variables are the same as in Equation (1). In this specification, the coefficient β is capturing the average effect on the outcome in the years after entering rebuilding, relative to the years before rebuilding. An alternative approach will be to divide the post rebuilding period to just two coefficients of interest, the first and last five years after rebuilding, when considering ten years of data after rebuilding.

$$y_{st} = \beta_1(\text{Post Rebuilding, 1-5})_{st} + \beta_2(\text{Post Rebuilding, 6-10})_{st} + \theta_s + \varepsilon_{st} \tag{3}$$

This specification estimates the average effect on the outcome in years post rebuilding, focusing on later periods when the stock should be exhibiting improvements in biomass. However, when considering the effects on catch, we should be concerned more with the impact of the policy while the stock is still in rebuilding. Once the stock is considered rebuilt, we could see an increase in catch, which is a desired outcome of the policy. In order to focus on the effect of rebuilding plans while the stock is in rebuilding, we will also estimate the following specification:

$$y_{st} = \phi_1(\text{In Rebuilding})_{st} + \phi_2(\text{Rebuilt})_{st} + \theta_s + \varepsilon_{st} \tag{4}$$

This equation is similar to Equation (3), but ϕ_1 captures the average effect during the years of rebuilding, and ϕ_2 captures the effect in the years after a stock is rebuilt.

5 Results Under The Post-1996 Regime

We present the main results for the event-study as well as pre- and post-treatment estimation. As treatment can be considered as either the implementation of a rebuilding plan, or as the

[9] This is due to placing a condition on the data used in each analysis that each stock is balanced within the event window. Stocks that do not have data for recent years or have only recently entered rebuilding will not meet this condition. This is important because otherwise each coefficient, μ_τ, will be estimated using a different group of stocks. It will be unclear whether the results are driven by actual changes in the outcome, or in the composition of the sample.

determination that the stock is overfished, we present results for both cases. For both treatment onset definitions, we find evidence for an increase in biomass and sharp declines in catch. The gains in biomass appear several years after the designation as overfished or the implementation of a rebuilding plan. The decline in catch is concentrated during the time the stock is not yet considered to be rebuilt. However, following a rebuilt declaration, catch levels do not necessarily bounce back to their baseline levels prior to the overfished determination.

5.1 Impacts Relative to Rebuilding Plan Implementation

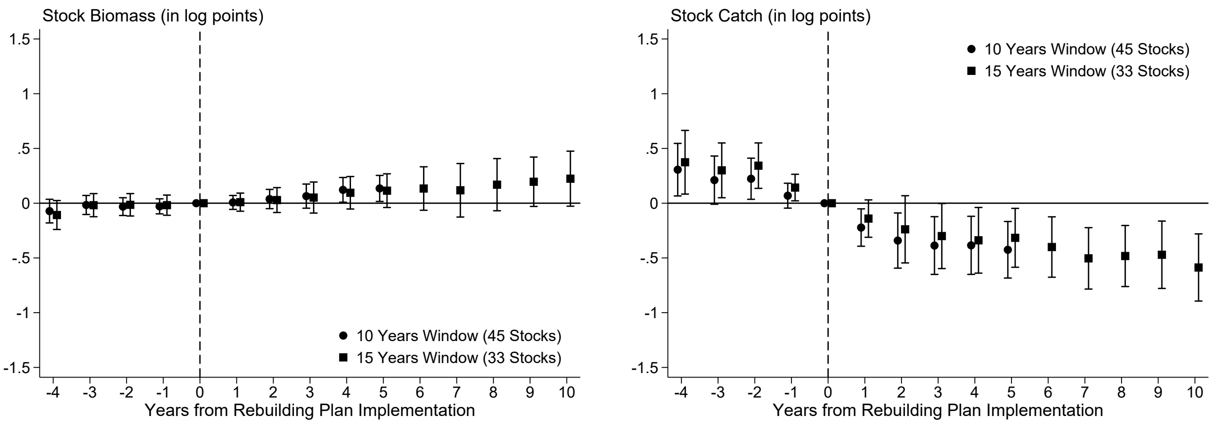
First, we will define "treatment" as the implementation of a rebuilding plan. We summarize the results from Equation (1) in Figure 4. We find that, on average, a stock's biomass imprecisely increases by about 25.1% at the end of the ten-year rebuilding horizon relative to the year prior to treatment. Catch drops sharply throughout the rebuilding program, and can drop by 44.9% during the rebuilding period, relative to the period prior to rebuilding.[10]

The pre-trend in Figure 4b shows that a decline in catch emerges even before the implementation of the rebuilding plan. In the years prior to entering rebuilding, the stock receives an overfished determination. When a stock is determined as overfished the Harvest Control Rule (HCR), which sets the allowable catch target as a function of biomass, changes discontinuously. This sharp drop in catch targets acts as an automatic stabilizer which reduces catch and is meant to stabilize the stock even before a full rebuilding plan is developed and put in place. Such a decline in catch even prior to a rebuilding plan is also evident in the example of the Atlantic spiny dogfish where catch dropped by more than half between 1999 and 2002 (see Figure 1).

The existence of automatic stabilizers such as the HCR mean that treatment onset might be earlier than the implementation of a rebuilding plan. Solely focusing on the timing around rebuilding could mean we are not accounting for gains in biomass that occur between the overfished determination and the implementation of a rebuilding plan. In the following section, we formally test this by defining treatment as the year in which the stock is determined to be in overfished status.

The results from Equations (2), (3), and (4) are summarized in Table 1. The increase in biomass is only meaningfully positive when considering the ten-year rebuilding horizon, but is imprecisely estimated (column 2). The positive effect is mostly driven by gains made between the sixth and tenth year following the implementation of a rebuilding plan, averaging

[10] Using the $e^{\beta} - 1$ correction to get the effect size in percents.



(a) Biomass (b) Catch

Figure 4: Event-Study Regression Results: Rebuilding

Notes: Regression results for the specification in Equation (1). The results show average changes to biomass and catch, in log points, relative to an implementation of a rebuilding plan. Standard errors are clustered at the stock level.

Source: Data on stock status from NOAA's Status of Stock Reports, and data on biomass and catch from NOAA's SIS (Office of Science and Technology 2016).

at an imprecise increase of 22.1% (column 3). We find that catch levels drop considerably, and precisely, following rebuilding plan implementations. Catch declines between 39.9-44.6% during rebuilding (columns 4 to 6), and remains 40.6% lower even after the stock is declared rebuilt (column 6).

We compare the results from the event study specification to a linear trend-break specification. In Figure 5, we report more descriptive results that estimate a linear trend separately for the years before and after the implementation of a rebuilding plan. In Figure A3, we include a more detailed breakdown of the trend-break results. Using all the years of data for all 53 stocks in our rebuilding sample, we estimate both a pooled trend-break regressions, as well as a model per-stock. In the pooled model, for both the log of biomass, and biomass normalized by MSST, we estimate a negative trend which changes to a positive trend following the implementation of a rebuilding plan.

In both the event study results and in the trend-break results, there is evidence of large heterogeneity. In Figure 4, the wide confidence intervals around the point estimates suggest there is either substantial noise in the data or there is large heterogeneity across stocks. This heterogeneity also appears in Figure 5, where not all stocks follow the same trend, in either direction or magnitude, around the timing of rebuilding.

To further study the heterogeneity in stocks' response, we estimate a version of (3) for each stock. In Figure 6, we plot the effect of rebuilding plans on biomass (bar) and catch

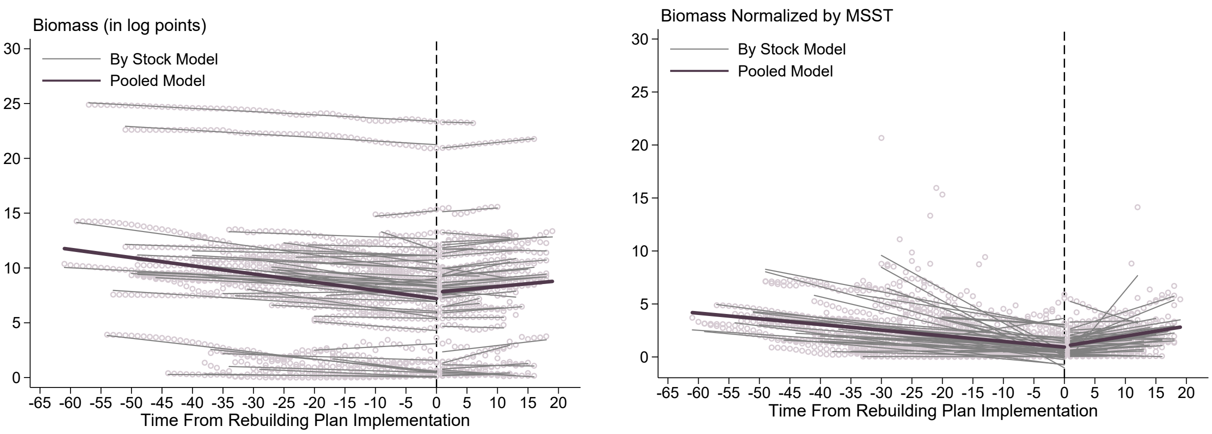
Table 1
Rebuilding Plan Implementation: Average Effects For Biomass & Catch

	Biomass (Log Points)			Catch (Log Points)		
	(1)	(2)	(3)	(4)	(5)	(6)
Post-Rebuilding (5-Years)	0.10			-0.51		
	(0.06)			(0.14)		
Post-Rebuilding (10-Years)		0.15			-0.61	
		(0.08)			(0.16)	
Post-Rebuilding (Years 1-5)			0.09			
			(0.07)			
Post-Rebuilding (Years 6-10)			0.20			
			(0.10)			
In-Rebuilding						-0.59
						(0.16)
Post-Rebuilt						-0.52
						(0.19)
R^2	0.998	0.995	0.995	0.937	0.946	0.946
N	450	495	495	450	495	495
Clusters	45	33	33	45	33	33

Notes: Regression results for the specifications in Equations (2), (3), and (4). Standard errors are clustered at the stock level.
Source: Data from NOAA's Status of Stocks Reports and NOAA's SIS (2016).

(capped line) by stock. The results are from individual regressions we ran for each stock and each bar and capped line are the 95% confidence intervals for the change in biomass or catch. Figure 6a shows the average change in biomass for the five first years after the implementation of a rebuilding plan, and the average change in catch for up to five years in rebuilding. Figure 6b repeats this but focuses on the sixth to tenth year in the rebuilding period for biomass, allowing the stock more time to rebuild. Extending the length of the time window results in fewer stocks for which we have data for the span of 15 years. As a results, there are some stocks that appear in Figure 6a but not in Figure 6b.

The results, especially in Figure 6b, show that many stocks exhibit large gains in biomass, sometimes doubling relative to pre-treatment years. This doubling is not entirely unreasonable given the policy is designed to double the biomass in ideal circumstances. The goal of rebuilding plans is to build a stock to sustainable levels, defined as biomass at Maximum Sustainable Yield (BMSY). For most stocks, managers define the MSST as 1/2 of BMSY. Rebuilding plans are designed to build stocks back up to BMSY within a specific time period



(a) Log(Biomass) (b) $\frac{\text{Biomass}}{\text{MSST}}$

Figure 5: Trend-Break Models

Notes: We run linear time trend models by stock, or by pooling all stocks together, centered around the implementation of a rebuilding plan.
Source: See Figure 4

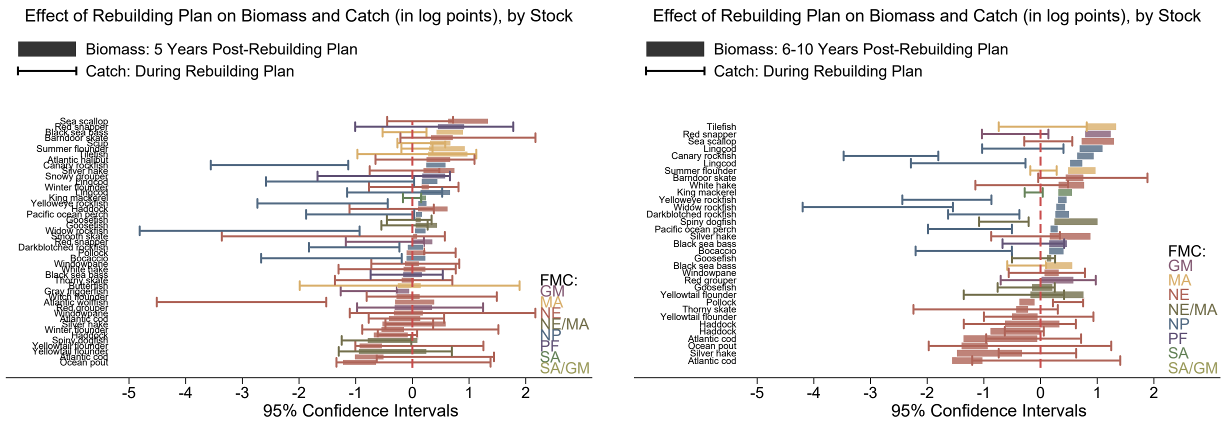
with a 50% probability.

For some stocks, the biomass does not change after receiving the rebuilding plan. In absence of a control group, we do not know if this means the policy was ineffective or if the policy stabilized a stock that would have otherwise declined in absence of a rebuilding plan. However, there are stocks that are clearly still experiencing large declines. Also evident from Figure 6b, is that not all stocks that experienced increases in biomass experienced reductions in catch. This could suggest that catch was already brought down between the overfished designation and the implementation of a rebuilding plan. Alternatively, this could reflect that the Fishery Management Council chose to use policy instruments other than restrictions on allowable catch.

5.2 Impacts Relative to Overfished Determination

Previous studies measured the impacts that rebuilding plans had on biomass and catch. However, the policy already plays a role in placing the stock back on a path towards recovery once the stock is declared overfished. Overfished is defined as when the stock's biomass declines below its Minimal Stock Size Threshold (MSST). Similar to how there are delays with rebuilding plan implementations, stocks can also experience delay in overfished determinations even after they decline below their MSST.

We will redefine the "treatment" as when a stock is declared overfished. The Harvest Control Rule further reduces allowable catch for stocks that are considered overfished. Low-



(a) 10 years window

(b) 15 years window

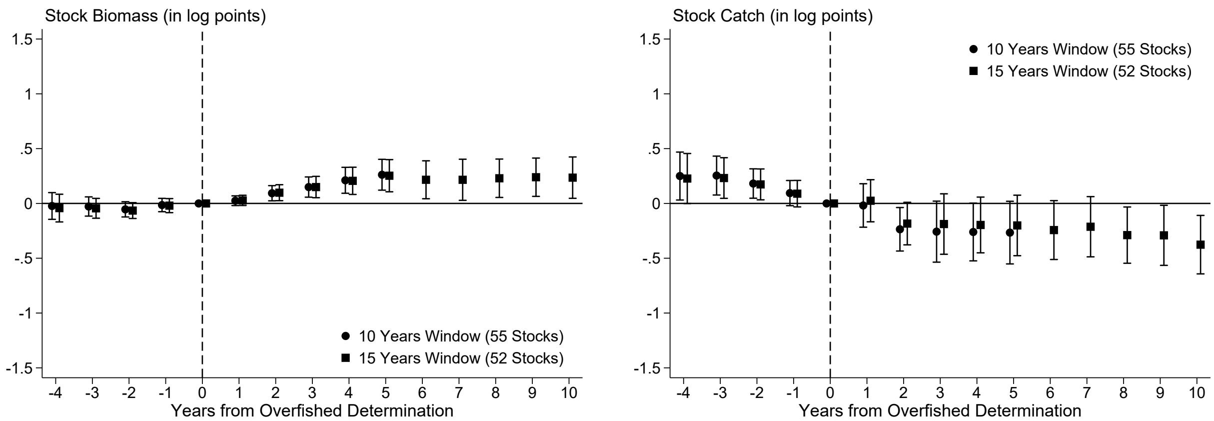
Figure 6: Effects of rebuilding plan on biomass and catch by stock

Notes: Each bar and line show the 95% CI from Equations (3) and (4), respectively. Each color represents a different Fishery Management Council. Source: NOAA (2016).

ering catch levels can help stabilize the population of the fish stock and place it back on a growth trajectory. For some stocks, there are long delays between overfished determination and rebuilding plan implementation, as is evident from Figure 2b. This could lead to gains in stock biomass even prior to an implementation of a rebuilding plan. In such cases, any improvements in biomass will not be accounted for if the event of interest is solely the implementation of a rebuilding plan.

We test for the impacts of overfished determination both independently from the implementation of a rebuilding plan, and for the combination of the two. This simply changes the event of interest in Equation (1) to the timing of overfished determination. First, we report the results, in Figure 7, for the set of stocks that are balanced within ten and fifteen years of their overfished status. The increases in biomass are similar, yet slightly larger and more precise, to those estimated relative to rebuilding plan implementation in Figure 4. Following the overfished status, catch drops considerably, by about 20% in the first few years after the determination, and by 30% ten years post-overfished designation.

Estimating the average effects in the post-overfished determination period, we find positive and precise effects for biomass, as well as large, negative, and precise effects for catch. In Table 2, we report increases in biomass following an overfished determination of 18.5-29.7% (columns 1 to 3). For catch, we find that during the first five or ten years following the overfished designation, catch drops by about 30% (columns 4 and 5). When focusing on the time periods in which the stock is post-overfished determination and potentially also under a rebuilding plan, the effect increases to an average decline of 45.1% in catch (column 6).



(a) Biomass (b) Catch

Figure 7: Event-Study Regression Results: Overfished

Notes: Regression results for the specification in Equation (1). The results show average changes to biomass and catch, in log points, relative to overfished determination. Standard errors are clustered at the stock level.
Source: Data on stock status from NOAA's Status of Stock Reports, and data on biomass and catch from NOAA's SIS (2016).

Once a stock is out of rebuilding, catch reamins lower by about 30%, on average, relative to the years prior to the overfished assessment (column 6). The effects on catch, except for the one regarding post-rebuilding, are all precisely estimated.

When shifting the focus to overfished stocks, we are also changing the composition of the sample. There are 52 stocks, relative to only 33 stocks, in the fifteen years overfished sample relative to the rebuilding sample, respectively. To verify that the observed effects are not completely driven by changes in the composition of the sample, we re-estimate the results for a fully balanced sample with respect to overfished and rebuilding events. In Figure A1, we report the results for biomass and catch relative to either an overfished or a rebuilding event. The results for biomass are similar to the previous ones. However, the impacts on catch are even greater, reflecting declines above 57.7%, yet are much less precise than before. Relative to either event, the gains in biomass are still evident, and the decline in catch originating earlier than the implementation of a rebuilding plan is also still evident.

Finally, heterogeneous effects from classification as overfished shows a similar pattern to heterogeneous effects from entering rebuilding plans (Figure A2). Again, in absence of a control group, we do not know if this means the policy was ineffective or if the policy stabilized a stock that would have otherwise declined in absence of a rebuilding plan. The use of Difference-In-Differences and Synthetic Controls methods could enable such a comparison. However, given the non-random assignment of treatment, it is not clear the non-treated

Table 2
Overfished Determination: Average Effects For Biomass & Catch

	Biomass (Log Points)			Catch (Log Points)		
	(1)	(2)	(3)	(4)	(5)	(6)
Post-Overfished (5-Years)	0.17			-0.36		
	(0.05)			(0.14)		
Post-Overfished (10 Years)		0.22			-0.36	
		(0.07)			(0.14)	
Post-Overfished (Years 1-5)			0.18			
			(0.06)			
Post-Overfished (Years 6-10)			0.26			
			(0.09)			
In-Rebuilding						-0.60
						(0.19)
Post-Rebuilt						-0.37
						(0.35)
R^2	0.998	0.996	0.996	0.945	0.950	0.952
N	550	780	780	550	780	780
Clusters	55	52	52	55	52	52

Notes: Regression results for the specifications in Equations (2), (3), and (4). Standard errors are clustered at the stock level.
Source: Data from NOAA's Status of Stocks Reports and NOAA's SIS (2016).

stocks offer a valid comparison group. For completeness, we include and discuss these results in the Appendix (see Figures A6-A8). In the following section, we use historic assessment data on stocks in periods in which they declined below their MSST to approximate such counterfactuals.

6 Minimum Stock-Size Thresholds as Natural Experiments

To measure the causal impact of a policy, the ideal experiment would compare a group that was randomly selected to receive the policy to a group that was randomly selected to not receive the policy. We attempt to approximate this ideal experiment by focusing on the stocks that meet the conditions for rebuilding in two distinct time periods, before and after the 1996 reauthorization of the MSA.

The event of interest in this case is when the biomass of a stock declines below its MSST. We will call this the "below-MSST event". This designates the stock as overfished and triggers the rebuilding requirement. However, the "treatment" or rebuilding requirement only occurs in the time period after 1996. When the biomass declines below the MSST before 1996, a rebuilding plan would not have been required, nor the stabilization of catch levels. This means that for stocks that experience a below-MSST event both before and after the 1996 rebuilding provision, we can hold other characteristics of the stock unrelated to the 1996 regime constant and test how their biomass responds following the below-MSST event. For example, if the observed gains in biomass following a rebuilding plan are mostly driven by natural cyclicality or measurement error, then we should expect the biomass to increase even in the absence of overfished determinations and rebuilding plans. However, if the treatment effect of the rebuilding plan is what is causing the biomass gains, then we should only observe them under the post-1996 MSA requirement.

We provide a graphical schematic of this type of comparison in Figure 8. For some hypothetical stock, we define the first below-MSST event as the time when the biomass drops below its MSST value before 1989. We define the second below-MSST event as the first year after 1996 in which the stock is below its MSST. The period between 1989 and 1996 acts as a buffer to reduce the overlap between the post-period after the first below-MSST event, and the pre-period before the second below-MSST event. We are using the change in biomass after the first below-MSST event as an approximation for the counterfactual biomass levels in the absence of a rebuilding plan. The second below-MSST event will include both the treatment effect of the rebuilding plan, and any cyclicality the stock might be experiencing. The first below-MSST event will only provide information regarding the cyclicality without the treatment effect.

6.1 Results That Exploit Treatment Assignment Threshold

In Figure 9, we use Equation (1) where the "event" is defined as a stock's biomass being below MSST. We repeat the estimation for the same event, but in two different time periods. After 1996, when a stock either declined or was already below their MSST, fishery managers were required to implement a rebuilding plan to rebuild stocks back to sustainable biomass levels. In light purple, we estimate the effect before and after a below-MSST event when rebuilding was not required. In dark purple, we estimate the effect before and after a below-MSST event when rebuilding was required.

We stack all the event windows of the stocks both five years before and 10 years after they decline below their MSST. The dark purple point estimates show precisely estimated, positive increases in biomass after a below-MSST event, when rebuilding the stock was required. The

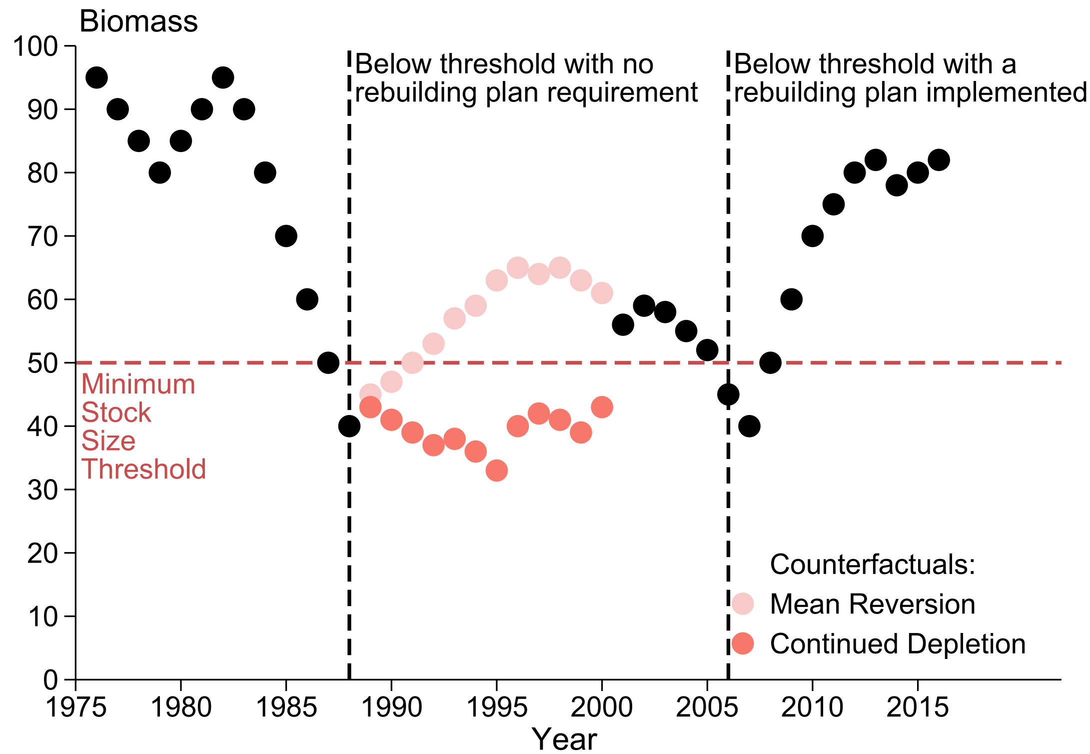


Figure 8: Exploiting Declines Below MSST Before & After the 1996 Regime
Notes: Schematic design of how we use stocks that decline below their MSST both in periods when rebuilding plans are required and not required.

increase in biomass peaks at 60%. In contrast, when rebuilding was not required, the light purple point estimates show a continuing decline in biomass after the a below-MSST event. In these results, biomass continues to decline by 52%. We find these results do not change, when our data is constrained to stocks that have ever been declared overfished or placed in rebuilding plans (Appendix Figure A4-A5).

These results have a causal interpretation because they are identifying the effect of changes within the same group of 37 stocks. These 37 stocks meet the condition for the implementation of a rebuilding plan, or a reduction in total allowable catch following an overfished determination in two time periods, but are only assigned such treatment in one of those times. The remaining caveat to this approach is that other variables, such as changes to the market, physical environment or technology between the two event times could potentially confound our results.

For example, if market demand declined for reasons unrelated to rebuilding provisions, the stocks that went into rebuilding may have rebounded due to a decline in fishing effort and not necessarily the implementation of rebuilding provisions. If environmental conditions increased fecundity in the stock or reduced the number of predators, the biomass could have rebounded. Finally, improved technology could have enabled harvesting in a manner that is less harmful to the structure of fish population.

To date, overall market demand for fish has increased during this time period (FAO 2018). Environmental conditions are warming and becoming more polluted driving global populations down (Free et al. 2019; Shahidul Islam and Tanaka 2004). Technology has enabled higher levels of catch with less fishing effort (Squires and Vestergaard 2018). Regardless of these global trends, we cannot rule out the possibility that these variables may be confounding our results on a regional scale. In subsequent parts of the paper, we augment our analysis with additional data to test whether these alternative explanations are consistent with the data.

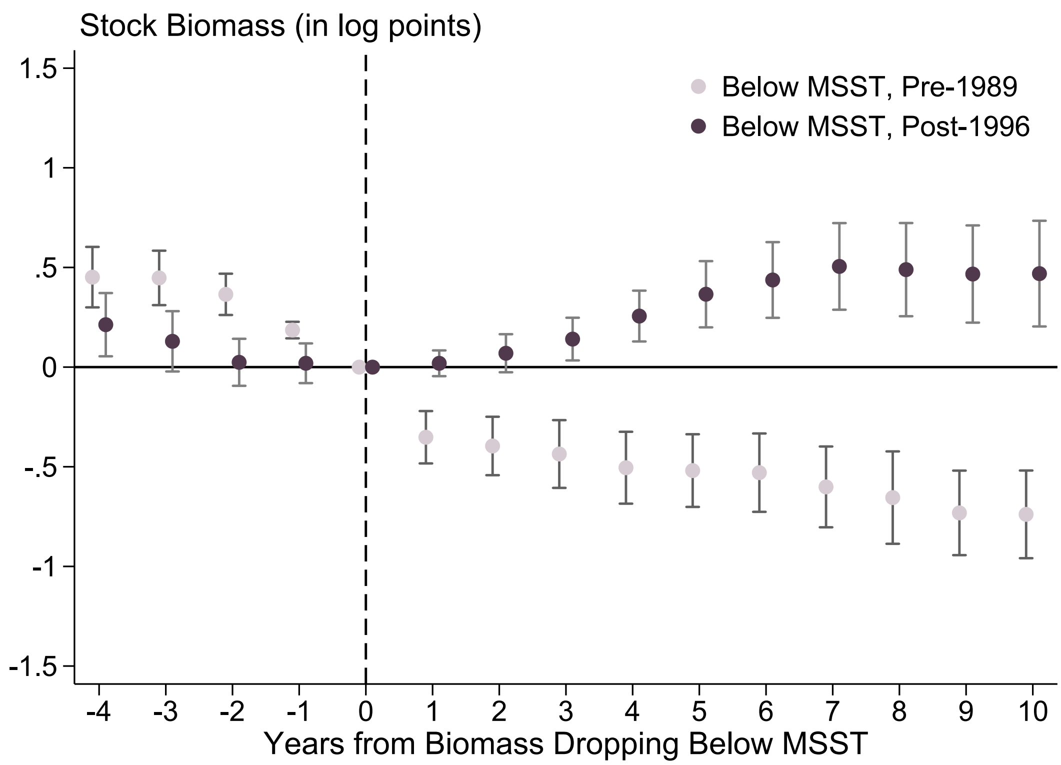


Figure 9: Changes in Biomass After Crossing the MSST

Notes: Regression results from the specification in Equation (1) for MSST events before 1996 (light purple) and after 1996 (dark purple). Standard errors are clustered at the stock level.
Source: See 4.

6.2 Paired-Difference Comparison for Stocks that are Below their Threshold in Both Periods

To check if confounders may be plausible, we can observe the difference in biomass across the two time periods, the pre-1996 regime and post-1996 regime. First, we record the biomass (in logs) when it declines below the MSST for each stock in each time period: The biomass when it declines below the MSST in the pre-1996 time period and the biomass when it declines below the MSST in the post-1996 time period. Both of these events will define event time, τ=0. Second, we subtract these values from each other and call this difference Δ_τ.[11] Third, we measure the biomass τ years later for each stock in each time period and take the same difference. We call these pairwise differences and now have a time series of these pairwise differences from τ=-4 to τ=5. Fourth, we then estimate Equation (1) for the paired-difference sample. In order to avoid cases where the post-period after the first below-MSST event is also counted as the pre-period following the second below-MSST event, we focus on five years before and after instead of the previous five years before and ten years after.

We find that stocks see large increases in their biomass after a below-MSST event, in the post-1996 regime period, relative to the pre-1996 regime. Five years after a decline below the MSST, stocks gain 124% in their biomass in the post-1996 regime period relative to the pre-1996 regime, as can be seen in Figure 10. The large effects we estimate in the paired-difference specification do not mean that stocks more than double in biomass, in the post-1996 regime, just five years after declining below their MSST. From the results in Figure 9 we see that they increase by about 60% by the time they are seven to ten years after their below-MSST event. The larger results we report in Figure 10, tell us more about the increase in biomass relative to a counterfactual of continued depletion. The negative point estimates, in Figure 10, prior to the below-MSST event mean that stocks start off at a lower baseline prior to their below-MSST event in the post-1996 regime. This may be due to the fact that some stocks never returned to their historic levels prior to the first below-MSST event even though they rebuilt to their MSST levels. This also means we cannot rule out confounders such as changing environmental conditions that may be driving our results.

[11] This means we calculate $\log(\frac{biomass_\tau^{Post-1996}}{biomass_\tau^{Pre-1996}})$ where τ=0 for each event time period. We take the log of the ratio of biomass in each event time period, relative to the event of being below the MSST either before 1989 or after 1996.

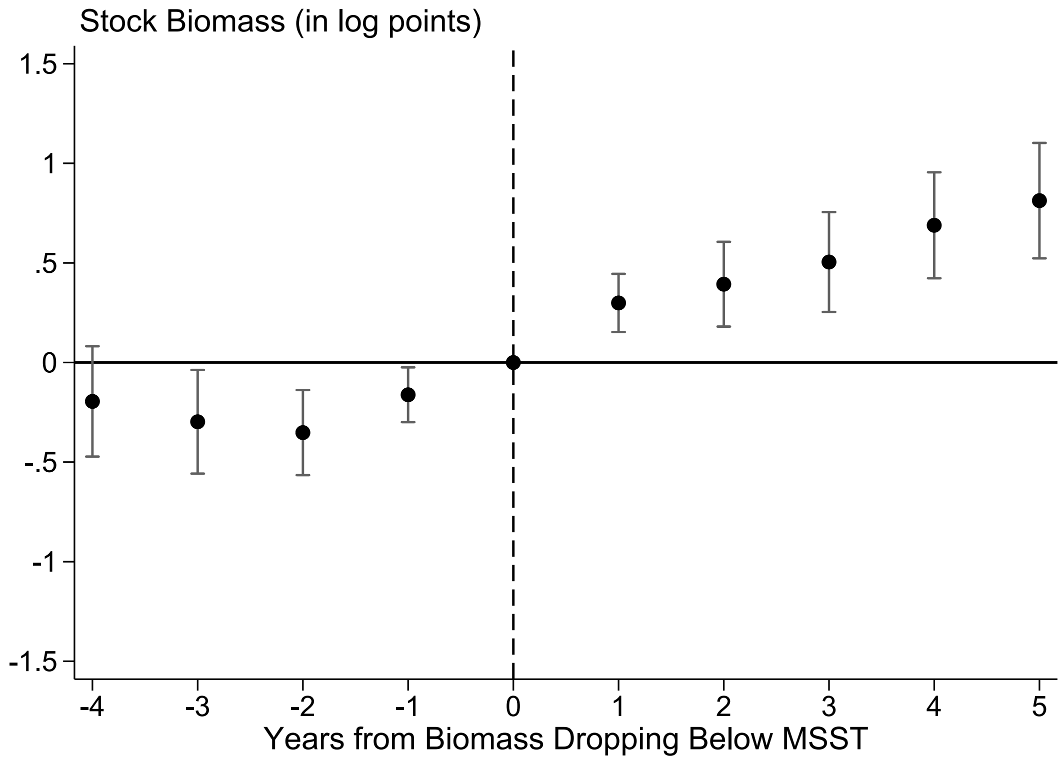


Figure 10: Paired Biomass Difference Results for Stocks that Drop Below their MSST
Notes: Estimates for the specification in Equation (1) using the paired-differences time-series for stocks the have below-MSST event pre-1989 and post-1996. Standard erros are clustered at the stock level.
Source: See Figure 4.

7 Examining the Impacts of Changes in Demand, Environmental Conditions & Technological Innovations

Comparing stocks that meet the conditions for rebuilding over time allows us to hold stock composition constant. However, because we are comparing the same stocks between two different time periods there are multiple factors that could also be different. For example, if environmental conditions are better, on average, for the stocks that enter rebuilding post-1996, then our below-MSST comparison will pick up the improved conditions and we will mistakenly interpret it as the effect of the post-1996 regime. The same holds if consumer preferences change systematically with a decline in biomass post-1996, or if technological innovation or recent restrictions on fishing gear allow stocks to recover more quickly. We offer indirect evidence that these plausible mechanisms are not consistent with what we observe in the data.

7.1 Addressing Changes in Demand for Fish

To address confounders such as changes to market demand, we run the same analysis for catch (Figure 11). In time periods before the event, $\tau<0$, the difference in catch is zero. This provides some preliminary evidence that market conditions did not alter demand significantly between the two time periods, prior to the event of the biomass dropping below the MSST. This is supported by FAO data showing global marine capture catch has not increased since 1985, but aquaculture has substantially grown to meet the increasing global demand for fish (FAO 2018).

However, catch is also not significantly different from zero between the two time periods after the event, from $\tau = 0$ to $\tau = 5$. This is contrary to what we expected to find. Some plausible explanations are that the post-1996 policy regime did not succeed in reducing catch. Alternatively, the catch in the pre-1996 regime was so high that it collapsed the stock, dramatically reducing the catch and biomass after the MSST event in the pre-1996 regime. This decline may have been so dramatic that any changes to catch in the post-1996 regime would be small in comparison.

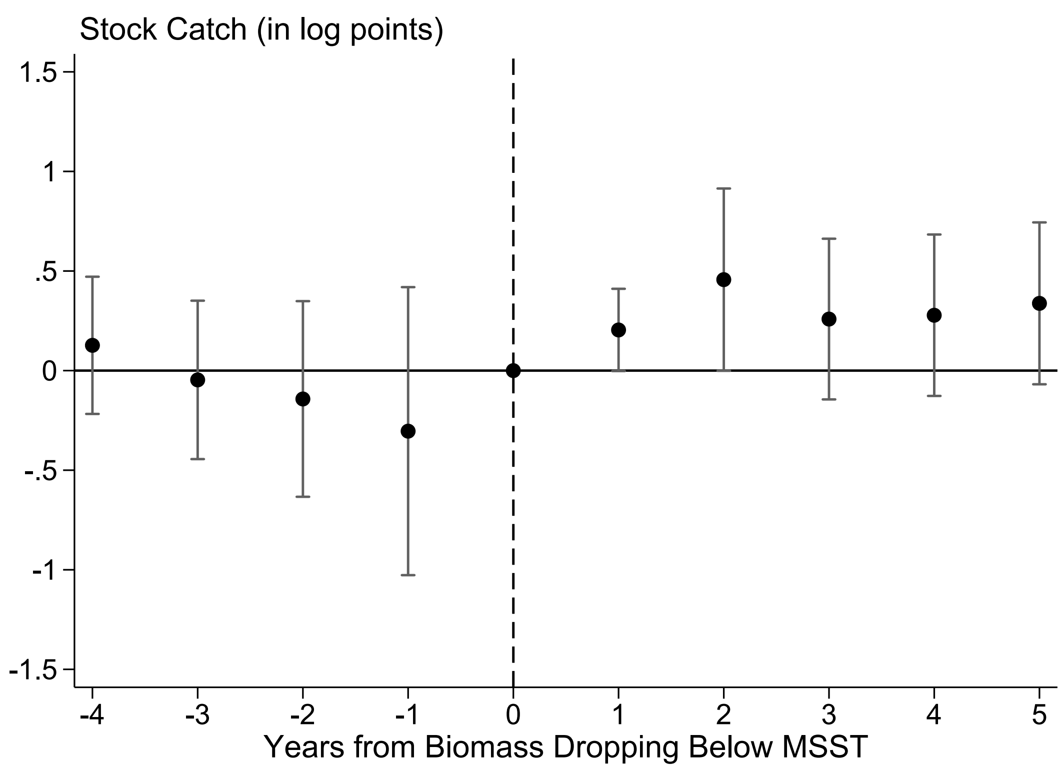


Figure 11: Paired Catch Difference Results for Stocks that Drop Below their MSST
Notes & Source: See Figure 10.

7.2 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).[12] A key concern for our interpretation of the results in Figures 9 and 10 as causal evidence for the positive impact of the post-1996 regime is that over time, the conditions in the oceans could be improving. If the main reason stocks decline below their MSST was due to poor 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.

While the full interaction of environmental conditions with each stock is a complex function, we can observe an important proxy of stocks' recovery: productivity of the stock, also referred to as recruitment. Explicitly, we can calculate the recruitment per-unit of spawning fish biomass (hereafter, recruitment per-spawning biomass). If recruitment per-spawning 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-spawning biomass over time. On the contrary, on average, it is declining which suggests it should be harder for stocks to recover after exploitation brings them below their MSST. In Figure 12, we plot the recruitment per-spawning biomass over time for each of the 98 stocks for which we have both recruitment and spawning biomass data for. We include the average in each year, as well as linear fits after 1976 to 1996, and after 1996, with or without residualizing on stock fixed effects.

In Figure 13, we find that recruitment declines for stocks that either enter rebuilding or are determined to be overfished. This could be due to a permanent decline in productivity due to changing environmental conditions (Free et al. 2019). Alternatively, behavioral responses by fishers that lower stock productivity. Because the main policy instrument used after either event is reducing the total allowable catch (TAC), this could also be suggestive of negative impacts of setting more stringent TAC targets. The mechanism that could explain why lower TAC targets lead to lower recruitment levels is a "race to fish." In the absence of Individual Transferable Quotas (ITQs) which assign property rights, fishers might respond to lower TAC levels by attempting to fish early in the season before the catch target is met and managers proceed to close the fishery for the year. This compression of fishing effort has been empirically documented in U.S. fisheries, and it is widely accepted that such compression can

[12] Examples for known oceanic oscillations are El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), etc.

be detrimental to recovery efforts (Birkenbach et al. 2017; Costello et al. 2008; Essington 2010; Gordon 1954; Huang and Smith 2014).

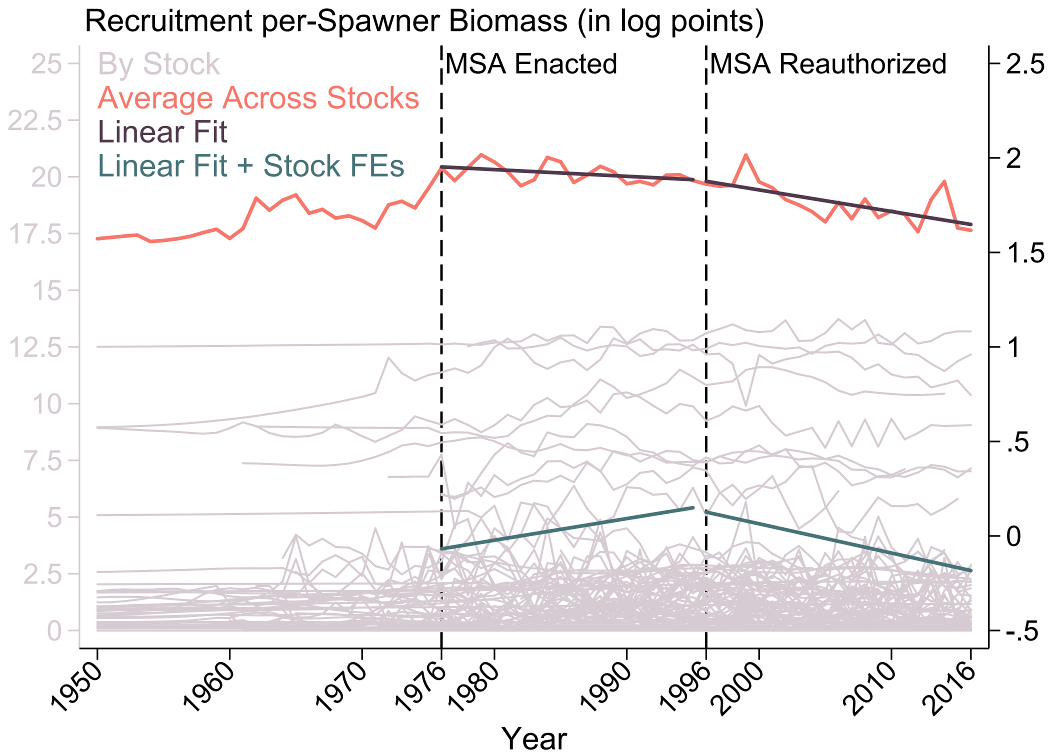
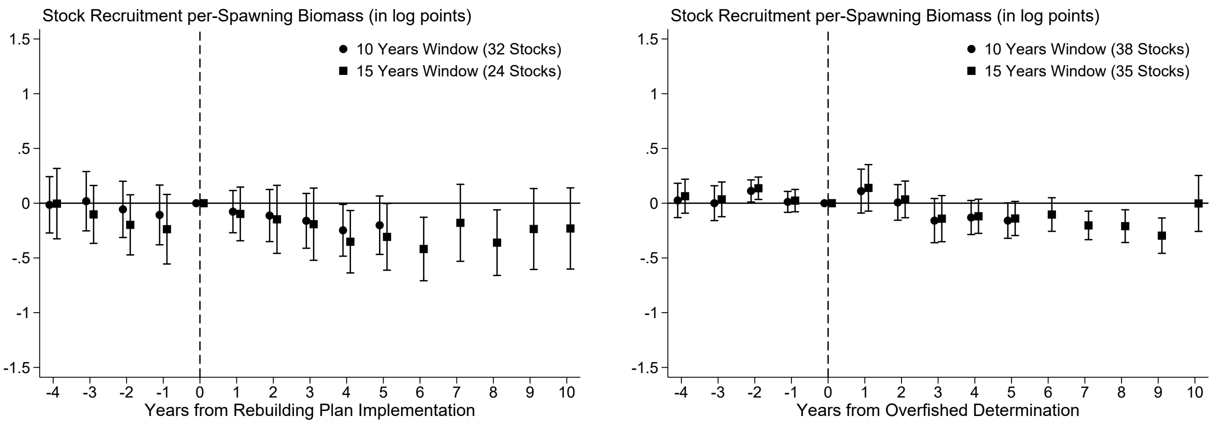


Figure 12: Recruitment per-Spawning Biomass Over Time

Notes: Each gray line (left y-axis) corresponds to recruitment per-spawning 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.

Source: See Figure 4

If environmental conditions were improving for the stocks after rebuilding or overfished events, we would expect to see an increase in recruitment per-spawning biomass, yet we see the opposite. In Figure 14, we repeat the below-MSST analysis for the recruitment outcome. We find that for the same set of stocks, recruitment increases for the below-MSST events prior to 1989. This is what population-density growth models would predict. Recruitment should increase as the density of the stock declines because there is less competition for resources. We see the relationship reverse its sign for the below-MSST events following the post-1996 regime. The negative impact on recruitment per-spawning biomass is perhaps consistent with an unintended consequence of fishing season compression or permanent shifts in environmental conditions such as warming waters, but is not consistent with a higher stock

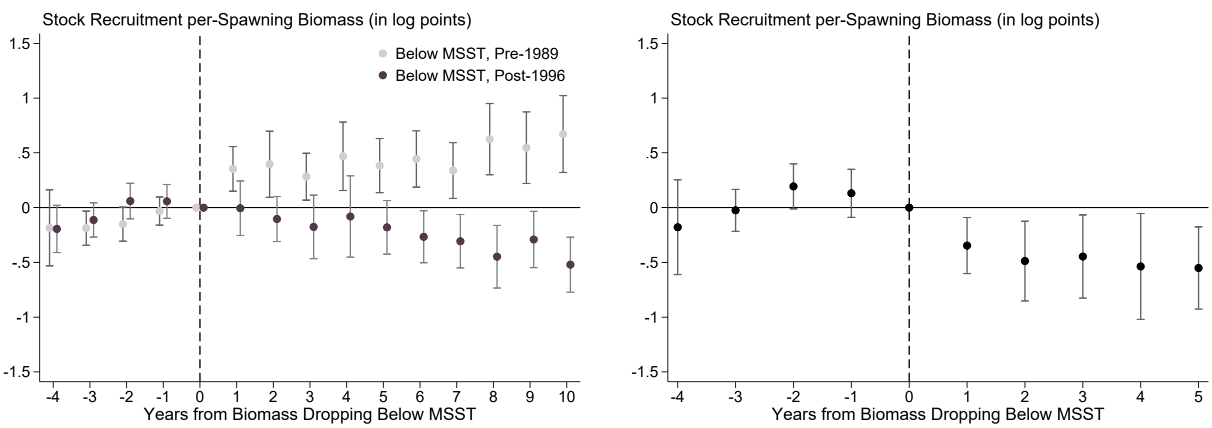


(a) (b)

Figure 13: Recruitment Event-Study Regression Results: Rebuilding & Overfished

Notes & Source: See Figure 4.

productivity driving the observed recovery.



(a) (b)

Figure 14: Impacts on Recruitment per-Spawning Biomass Exploiting Below-MSST Events

Notes & Source: See Figures 9 and 10.

7.3 Addressing Changes in Fishing Technology

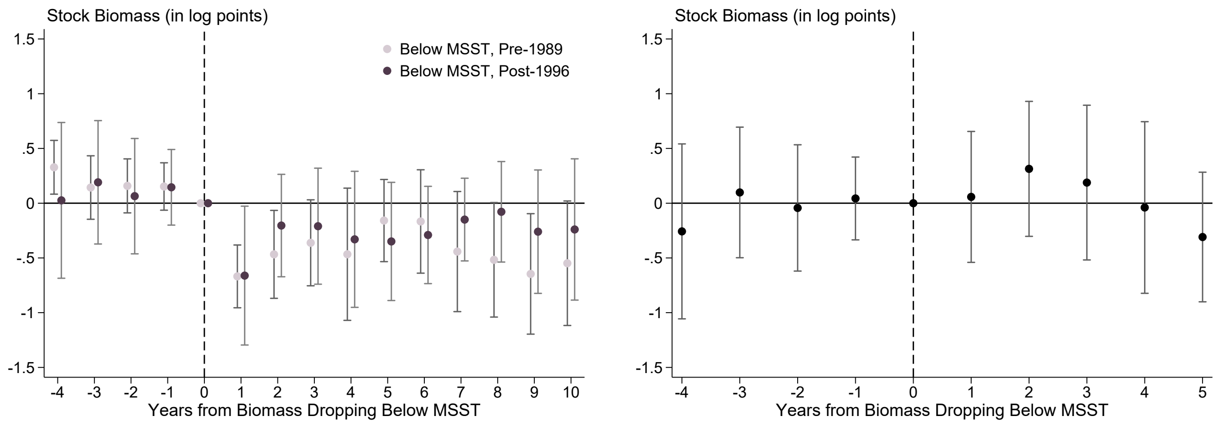
Technological innovation can operate in different directions on stock biomass recovery. Depth finders, temperature sensing devices, ultrasound technologies and GPS allow fishermen to see where the stocks are concentrated in real-time. This lowers the search costs of fishing vessels and can result in larger rates of harvest, over shorter periods of time. With the use of TAC quotas, technology can contribute to an even faster "race to fish." However, these same innovations along with innovations in gear and monitoring allow improved targeting, reducing bycatch and habitat destruction. This could preserve the surrounding ecosystem and result in faster growth of the stock. Complicating things further are restrictions on fishing gear that change over time and with the status of the stock. For these reasons, it is hard to conclude whether technology in the post-1996 regime is more beneficial to fisheries than it was in previous decades.

To test whether modern fishing technology has a positive effect on biomass recovery we use data on Canadian marine fisheries. Canadian fishing vessels use similar technology to that used in the U.S. (Squires and Vestergaard 2018), but they do not face the same regulatory regime. Canada is still in the process of developing a similar framework that uses reference points to define when to implement rebuilding plans. We use data from the RAM database on stock assessments that have Canada as the management authority, and exclude stocks that are subject to multinational agreements. Following the guidelines in the Canadian framework document we calculate a proxy for the biomass target for each stock by taking 50% of the highest recorded biomass.[13,14] Similar to how MSST is 50% of the biomass target, we define a pseudo-MSST for the Canadian stocks at 50% of the proxy biomass target we construct (25% of the highest recorded biomass). Data availability limits us to only 19 stocks with below-MSST events pre-1989 and post-1996, that can be compared to the same event definition used for U.S. fisheries.

Using the constructed pseudo-MSST values, we repeat the below-MSST events analysis for the Canadian stocks. If technology is sufficiently similar between the two fishing fleets, and on net, better technology is responsible for the faster recovery we observe in the U.S., then we should expect to see a similar pattern for the Canadian fisheries. In Figure 15, we observe no difference in biomass recovery in the post-1996 regime which exists in the U.S. but not in Canada. Because we only have 19 stocks to run this comparison, the point estimates are very imprecise. However, the emphasis here is that the points estimates are not reversing in the post-1996 period for Canadian fisheries as they do in the U.S. analysis.

[13] The framework, "A fishery decision-making framework incorporating the precautionary approach," is available at http://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm.

[14] BMSY values are chosen such that they maximize growth. Under simple population-density-dependent growth models, the BMSY value is half of the maximum biomass. At the maximum biomass growth reaches zero, and is negative above that level.



(a) (b)

Figure 15: Changes in Biomass for Canadian Fisheries After Crossing the Pseudo-MSST

Notes & Source: See Figures 9 and 10.

8 Conclusions

Regulating renewable resources, as well as setting conservation policies, is challenging due to the complex functional forms 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. This is an example of a policy that attempts to use scientifically-informed decision rules regarding when a policy intervention is needed and when the stock can be considered stable and sustainable. 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 are assessed to be 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.

References

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: a journal of the American Economic Association* 18 (3): 147–172.

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.

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

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.

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, 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.

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.

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.

Dasgupta, Partha, and Geoffrey Heal. 1974. "The Optimal Depletion of Exhaustible Resources." *The Review of economic studies* 41:3–28.

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.

European Parliament and Council. 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. 2014. *The State of World Fisheries and Aquaculture.*

———. 2018. *The State of World Fisheries and Aquaculture.*

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.

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

Hotelling, Harold. 1931. “The Economics of Exhaustible Resources.” *The journal of political economy* 39 (2): 137–175.

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

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.

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. 2018. *Fisheries Economics of the United States, 2016.* U.S. Department of Commerice, NOAA Tech. Memo.

NOAA Fisheries. *2018 Report to Congress on the Status of U.S. Fisheries.* https://www.fisheries.noaa.gov/national/2018-report-congress-status-us-fisheries. Accessed: 2019-12-30.

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.

Office of Science and Technology. 2016. *Species Information System Public Portal.* NOAA Fisheries. https://www.st.nmfs.noaa.gov/sisPortal/sisPortalMain.jsp.

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.

Pindyck, Robert S. 1978. “The Optimal Exploration and Production of Nonrenewable Resources.” *The journal of political economy* 86 (5): 841–861.

———. 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.

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.

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.*

Shahidul Islam, Md, and Masaru Tanaka. 2004. "Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis." *Mar. Pollut. Bull.* 48 (7-8): 624–649.

Squires, Dale, and Niels Vestergaard. 2018. "Rethinking the commons problem: Technical change, knowledge spillovers, and social learning." *J. Environ. Econ. Manage.* 91:1–25.

Stiglitz, Joseph. 1974. "Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths." *The Review of Economic Studies* 41:123–137.

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. 2017. *The Executive Director's Report: Towards a Pollution-Free Planet.* Technical report. UNEP.

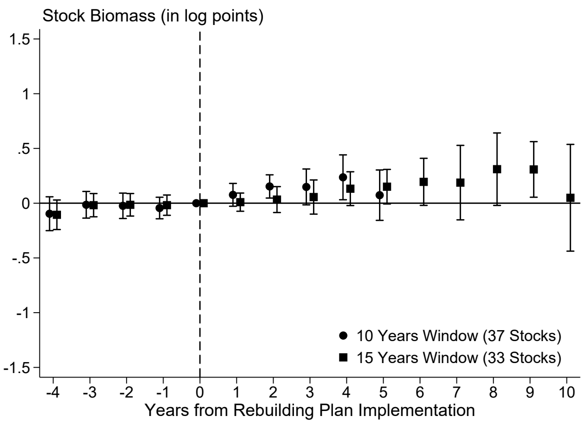
Vert-pre, Katyana A., Ricardo O. Amoroso, Olaf P. Jensen, and Ray Hilborn. 2013. "Frequency and intensity of productivity regime shifts in marine fish stocks." *Proceedings of the National Academy of Sciences* 110 (5): 1779–1784. doi:10.1073/pnas.1214879110.

Wicker, Roger F. 2018. *Modernizing Recreational Fisheries Management Act of 2018.*

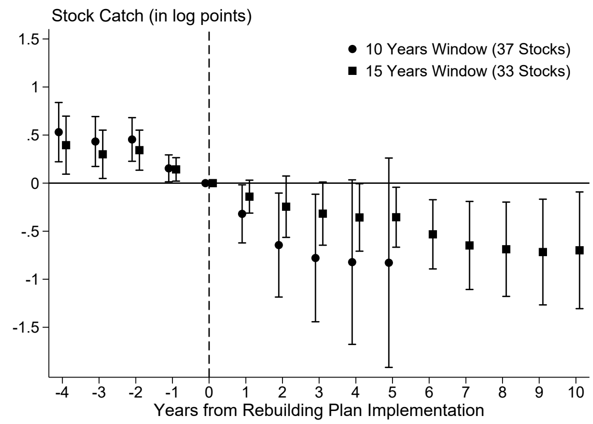
Appendix

A.1 Additional Figures

Relative to Rebuiliding Plan Implementation

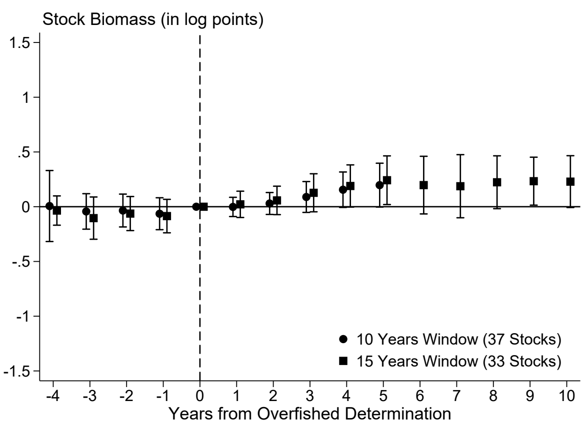


(a) Biomass

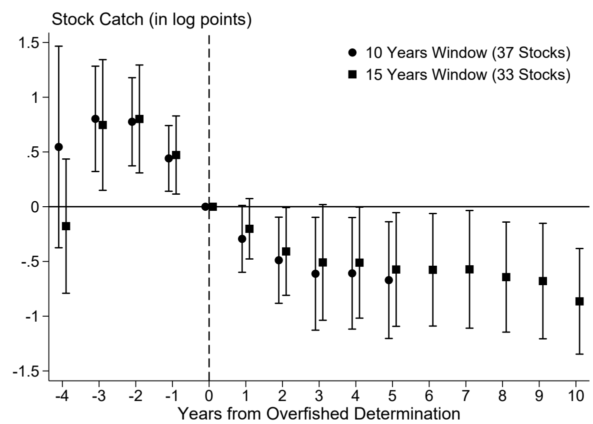


(b) Catch

Relative to Overfished Determination



(c) Biomass



(d) Catch

Figure A1: Event-Study Regression Results: Rebuilding & Overfished

Notes: Regression results for the specification in Equation (1). The results show average changes to biomass and catch, in log points, relative to an overfished determination. Sample composition is held constant across all the estimation results. Standard errors are clustered at the stock level. Source: Data on stock status from NOAA's Status of Stock Reports, and data on biomass and catch from NOAA's SIS (Office of Science and Technology 2016).

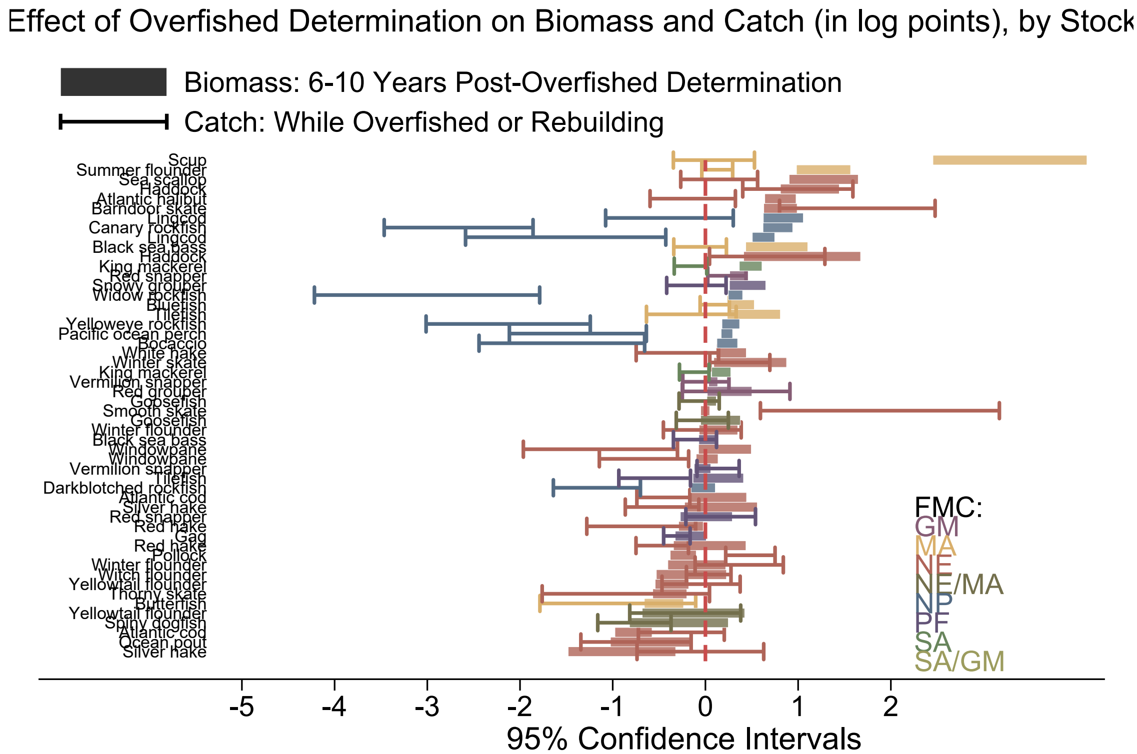


Figure A2: Effects of Overfished Determination on Biomass and Catch
Notes: Each bar and line show the 95% CI from Equations (3) and (4), respectively. Each color represents a different Fishery Management Council. Source: NOAA (2016).

A.2 Using Non-Overfished Stocks as a Comparison Group

In the main text we focus our attention to stocks that at some point in time get determined to be overfished, or enter a rebuilding plan. Here we consider using the stocks that never receive an overfished determination or a rebuilding plan as a comparison group for the stocks that do.

The assignment of treatment, overfished determination or rebuilding plan, is not random and there are likely large systematic differences between the stocks that ever meet those conditions and those that never do. However, under the assumption that the only meaningful difference is in the size of the stock relative to its MSST, then comparing these two groups can enable us to account for changes in environmental conditions and technological innovation.

We use the non-treated stocks, those that do not designated as overfished or enter rebuilding plan, in three ways. First, we run pooled Difference-In-Differences (DD) for all the treated and non-treated stocks. Second, we run a DD for each treated stock separately, choosing non-treated stocks that reside in a different region in order to reduce potential

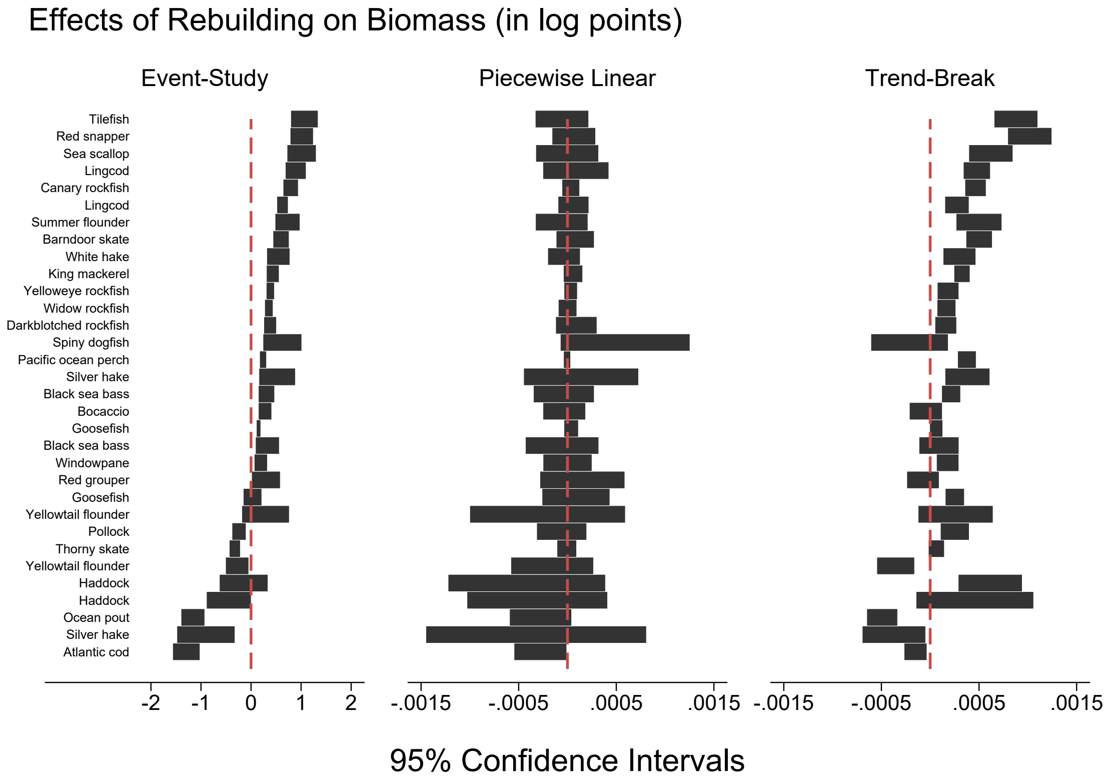


Figure A3: Comparison of the Event-Study & Trend-Break Results

Notes: Each bar represents the 95% CI from a separate regression for biomass after the implementation of a rebuilding plan. The first set of results (most-left column), is for the results from the event-study specification in Equation (3), for the 6th to 10th year after rebuilding plant implementation. The results in the center-column take the same event window of five years pre- and ten years post-rebuilding plan implementation, and estimate a linear trend break model. The coefficient is for the interaction of the time trend with the dummy for a being in the 6th to 10th year in a rebuilding plan. The right-most column of results estimates a single break and uses all years of available data from before and after entering rebuilding.
Source: See 4

SUTVA violation. Third, we run a Synthethic Control Method separately for each treated stock, using the non-treated stocks from outside its region as the potential donors for the synthetic control.

For the pooled DD model, we define the treatment group as all the stocks that entered rebuilding and have a at least five years of biomass and catch data before and ten years after entering rebuilding. This comparison helps to account for other time-variant confounding factors such ocean dynamics and oscillations, changes to market dynamics due to increasing imports or exports, changes in fishing technology, or other regulatory changes that apply to all fishing stock in U.S. economic waters.

We define the control group as all the stocks that are fully balanced between 1990 and

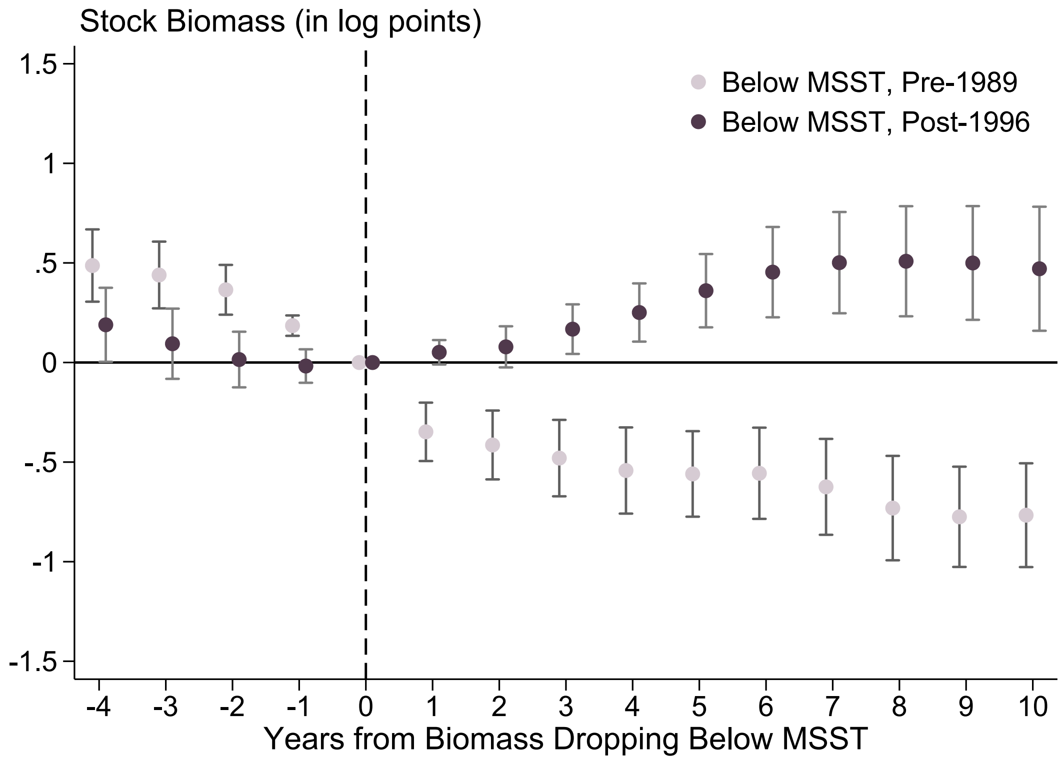


Figure A4: Differential Effects of MSST before and after 1996 for Overfished Stocks
Notes: Regression results from the specification in Equation (1) for MSST events before 1996 (light purple) and after 1996 (dark purple). Standard errors are clustered at the stock level. Source: See A7d.

2016 and have never entered a rebuilding plan. This results in 41 treated stocks, and 43 non-treated stocks. We repeat this classification using overfished determination as the event of interest, which results in 58 treated stocks, and 38 non-treated stocks. To account for the different composition across the rebuilding and overfished samples, we estimate the DD model using overfished determination as the event of interest, but using the stocks in the rebuilding sample. We estimate the following specification:

$$y_{st} = \sum_{\substack{\tau \in \{\underline{T}, \ldots, \overline{T}\} \\ \tau \neq 0}} \mu_\tau + \underline{\lambda}_{st} + \overline{\lambda}_{st} + \theta_s + \delta_t + \varepsilon_{st} \tag{5}$$

Where the specification is the same as in Equation (1), with the different of including year fixed effects, δ_t. We account for stocks that have more than ten years after or more than five years before an event by bottom and top coding, captured by the $\underline{\lambda}_{st}$ and $\overline{\lambda}_{st}$ dummies.[15]

[15] Explicitly, $\underline{\lambda}_{st}$ is equal to one when the stock is six or more years before the event of interest, and $\overline{\lambda}_{st}$ is equal to one when the stock is eleven or more years after the event of interest. We report this co-

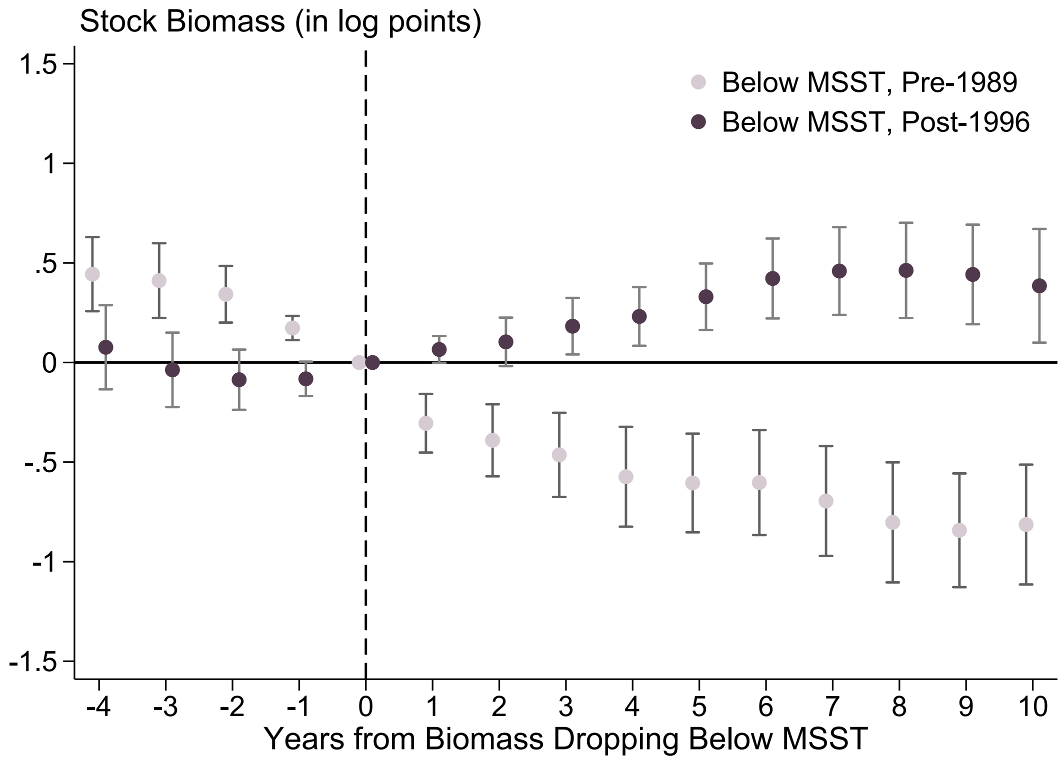


Figure A5: Differential Effects of MSST before and after 1996 for Stocks in Rebuilding Plans

Notes: Regression results from the specification in Equation (1) for MSST events before 1996 (light purple) and after 1996 (dark purple). Standard errors are clustered at the stock level. Source: See A7d.

We report the results from the DD model across the different treatment onset and sample definitions in Figure A6. Overall, biomass increases and catch decreases for the stocks that either enter rebuilding or are determined to be overfished, relative to the stock that do not.

The main difference across the results are that the declines in catch are only precisely estimated for stocks that enter rebuilding. Conversely, the increases in biomass are precisely estimated following an overfished determination. This is in line with previous results in the main text, and echoes that there could be substantial gains in biomass even before a rebuilding plan is implemented due to management changes that follow an overfished determination.

While there are appear to be no pre-trends for biomass across the different results, there is a strong declining trend in catch. We further investigate whether pre-trends are an issue by

efficients in the figures, but do not interpret them as they include different composition of treatment length.

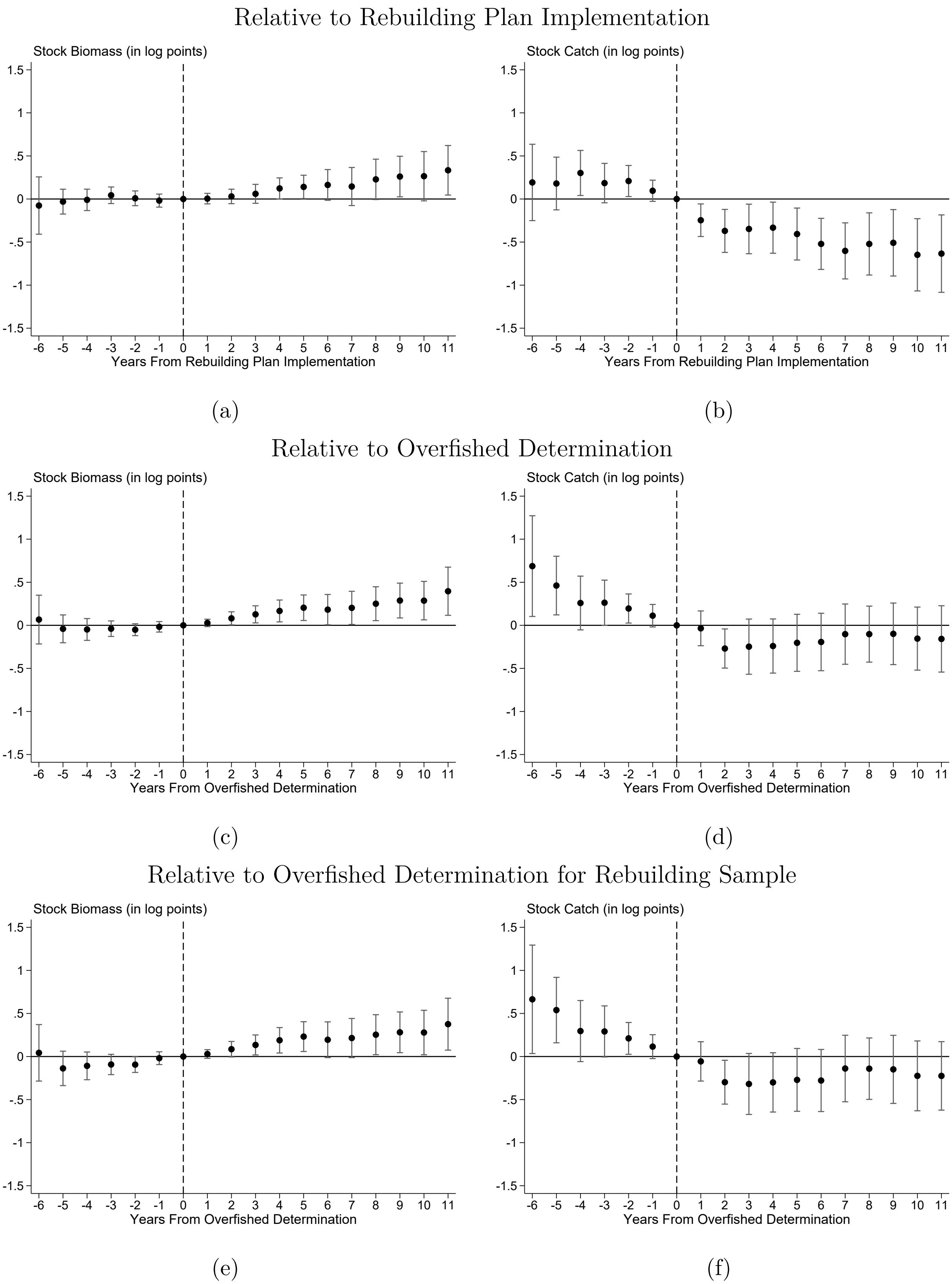


Figure A6: Pooled Difference-In-Differences Regressions Results

Notes: Regression results for the specification in Equation (5). Standard errors are clustered at the stock level.

Source: See 4.

running multiple DD models to each treated stock. In this regressions, we limit the control group to be stocks that reside outside the management region of the stock that is entering rebuilding.

We restrict the control group this way to account for potential channels for SUTVA violations. This restriction helps to limit potential leakage that could occur from substituting effort within a region, if fishers hold permits for multiple stocks. This also reduces concerns that other stocks in the region are affected by the reduction in catch of the treated stock. If the treated stock is a predator of other stocks, those stocks could see a decline in their biomass, and vice-versa for stocks that prey on the treated stock. Such spillovers at the ecosystem level will either upward or downward bias our results.

From the results in Figure A7 we conclude that there is very large heterogeneity between stocks in the DD results. We plot lines that connect the point estimates for each stock, and omit confidence intervals for the sake of legibility. As is evident by the event study results in the main text, there are pre-trends in both biomass and catch. Some stocks are seeing increases in their biomass or declines prior to rebuilding. More importantly, the lack of parallel trends in the pre-treatment period raises the concern that the necessary assumption of parallel trends on the counterfactual outcomes does not hold. This suggests that because assignment of treatment status in this case is not random, that there are large and meaningful systematic differences between stocks, invalidating the non-treated stocks as a comparison group.

We use the same constructed control groups used for the results in Figure A7 to run a Synthetic Control Method. The control stocks are now the potential donors for each treated stock. For conciseness, we only plot the results for biomass, where each line is a separate estimated treatment effect comparing a treated stock to its synthetic control. We fail to obtain close to zero effects in the year prior to rebuilding (Figure A7d). In some cases the differences prior to treatment are so large, preventing any sensible interpretation of the results.

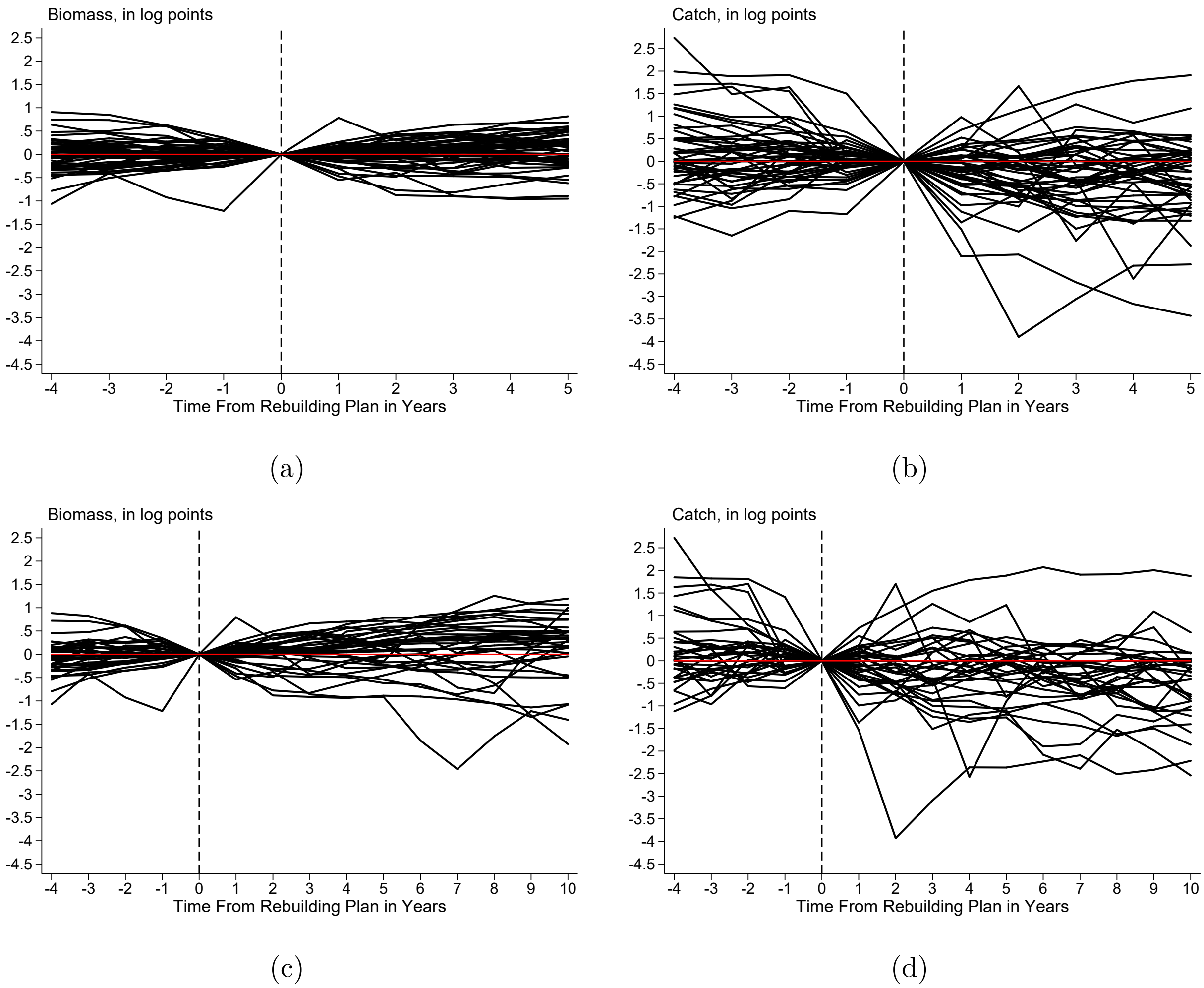


Figure A7: Separate Difference-In-Difference Regression Results

Notes: Regression results for the specification in Equation (5) run separately for each treated stock relative to a control group of stocks that reside outside the treated stock's management region. Standard errors are clustered at the stock level.
Source: See 4.

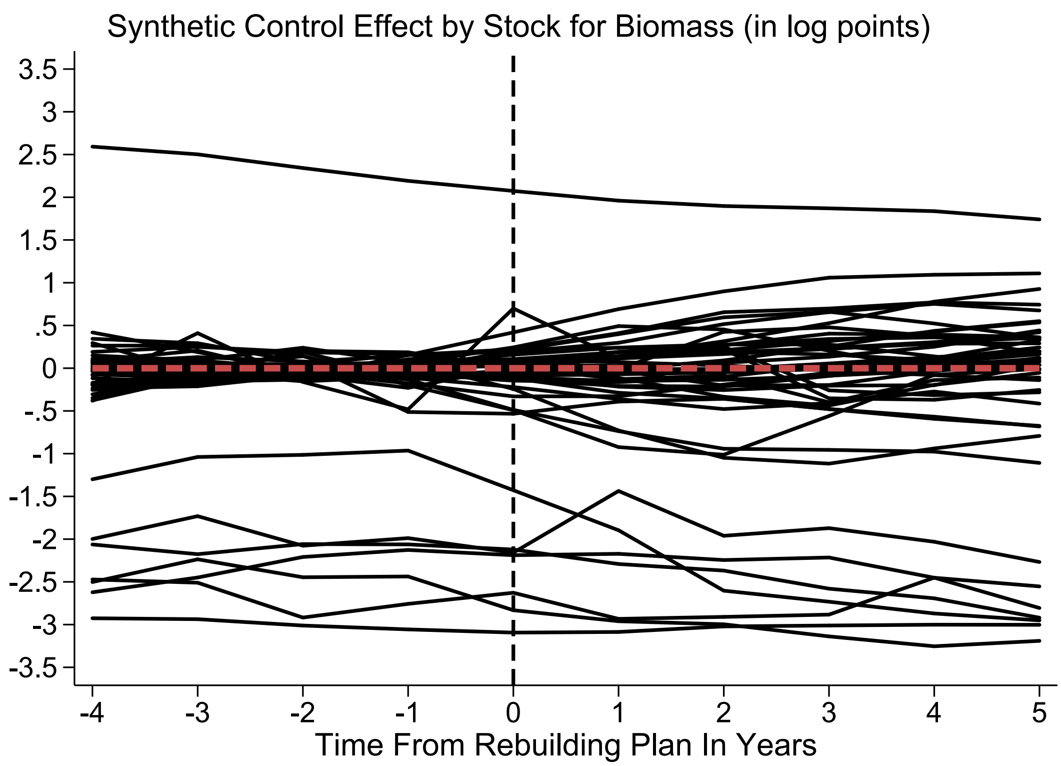


Figure A8: Synthetic Control Method Results for Biomass

Notes: SCM results for comparing each stock that entered a rebuilding plan to a syntehtic control group constructed using donor stocks that reside outside the treated stock's management region, and remained untreated during the event window.

Source: See 4.