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

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Abstract

Can policy sustainably manage economically valuable biological resources? We find evidence it can, with the use of science-based decision rules. In 1996, with United States fish populations in decline, Congress overhauled fishing laws with scientific thresholds for rebuilding overfished stocks. The law's impact is contested, and lawmakers have spent a decade debating its reauthorization. We develop the first causally interpretable evaluation of this law, exploiting the fact that the European Union has comparable fisheries but only recently developed similar laws. Compiling the largest dataset to date on US and EU fishery status and management, we examine fish populations that decline to unhealthy levels and measure the effect of a policy that aims to rebuild them to health. We find that treated stocks increase by 50% relative to these counterfactuals. Though the policy constrains catch, we find both catch and revenue ultimately rebound and stabilize at or above baseline levels.

Keywords: natural resources, resource management, common-pool resources, fisheries.

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1 Introduction

Biological resources are fundamental in supporting human well-being (Daily et al. 2000; Cardinale et al. 2012; Dasgupta 2021), yet we are rapidly depleting them (Clark 1973; Arrow et al. 2004; Polasky et al. 2019). Our global use of resources—which has increased threefold since 1970 (UNEP 2020)—has led to increasing wetland degradation, deforestation outpacing regrowth, accelerating biodiversity losses, and fisheries collapsing (Hansen et al. 2013; Ceballos et al. 2015; Costello et al. 2016; Fluet-Chouinard et al. 2023). 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 policies regulating biological resources, in contrast to the large economics literature that has evaluated pollution reduction, energy efficiency policies, and oil and gas extraction.¹

Marine fisheries are a canonical common-pool resource problem and a primary example of the tension between utilizing and jeopardizing a biological resource. 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). In the US alone, commercial fisheries employ 1.2 million people and generate over 165 billion USD annually (NMFS 2022). In addition to their direct use benefits, fish play a vital role in the biogeochemical cycle that can trap carbon in the ocean for thousands of years (Wilson et al. 2009; Siegel et al. 2023). A recent study estimated that modern levels of harvest in the oceans have reduced the rate of this cycle by half (Bianchi et al. 2021). Sustainably managing fisheries is among the UN’s Sustainable Development Goals (SDGs), and 193 countries have committed to integrate it into their national laws.

This article provides the first large-scale evidence for a policy’s effectiveness in recovering a depleted biological resource—fish stocks. We collect the largest dataset of its kind to study the requirement to rebuild overfished stocks under the 1996 reauthorization of the Magnuson-Stevens Act (MSA), which has a reputation internationally as a gold standard in sustainable fishery management (Brazer 2018; Coit 2021). The MSA regulates all commercial marine fisheries in United States (US) federal waters, the world’s second-largest exclusive

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), bond requirements for oil and gas drilling (Davis 2015; Boomhower 2019), and how lease expiration clauses distort drilling decisions (Herrnstadt et al. 2020).

economic zone (EEZ).² Under the MSA, when a fish population falls below a predetermined scientific population threshold, total catch must be reduced until the population is rebuilt to a sustainable level, often necessitating a *doubling or more* of the stock size.³ Since the MSA’s reauthorization, other countries have adopted sustainable fishing policies with comparable provisions. Using two research designs, we find evidence that the rebuilding provisions led to significant population recoveries. Our first research design leverages the fact that the requirement to rebuild stocks was implemented in the US two decades before the European Union (EU). Examining data from the two jurisdictions on the staggered depletion of stocks below their population thresholds, we find that on average, stock populations under rebuilding plans in the US increased by 52.2% compared to their counterfactual in the EU. In the second research design, we recover a similar pattern in which depleted US stocks since the 1996 MSA more than double in size compared to depleted US stocks prior to the law. These recoveries are not consistent with alternative explanations of mean reversion or measurement error. We find that while catch and revenue drop after stocks enter rebuilding, they recover, albeit imprecisely, to baseline levels or higher after stocks are rebuilt.

Even as countries around the world increasingly adopt sustainable fishing policies, they remain controversial politically, and often face opposition from the fishing industry and fisher communities. In the US, the MSA’s latest reauthorization has been held up in Congress since 2013. Competing reauthorization bills have differed on whether the rebuilding provisions should be weakened.⁴ The debate centers on how successful these rebuilding provisions have been, and whether to strengthen or loosen them. Many fishers believe populations will rebound without such prescriptive regulation, because they have seen generations of natural boom-and-bust cycles in fish populations (Abel et al. 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 will decrease, and the stock will recover (Clark 1976; Burgess et al. 2017).

To identify the treatment effects of rebuilding plans, it is not enough to simply compare the stocks that received the treatment with those that did not. A stock’s growth rate depends on its population, and only stocks with depleted populations go into rebuilding plans.

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.

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 failed 2018 bill. The 2018 bill loosened rebuilding provisions in favor of short-term needs of fishing communities. Opponents of the Act have derided it as the “Empty Oceans Act.”

A plausible control group would consist of depleted stocks that do not receive rebuilding plans. However, since the MSA’s 1996 reauthorization, all depleted US stocks must receive rebuilding plans. To overcome this, we employ two research designs: one comparing US stocks since 1996 contemporaneously to those in jurisdictions that had yet to implement similar rebuilding policies, and a second comparing US stocks since 1996 to US stocks prior to 1996. These groups of stocks allow us to compare how depleted populations recover (or not) with and without the rebuilding requirements.

In our contemporaneous research design, we use 1990-2016 data from the EU, whose updated fishery management policy was adopted in 2013 and took full effect by 2020 (EU 2013). Using a difference-in-differences design, we compare US stocks that went into rebuilding with EU stocks that met the conditions for rebuilding but did not receive the treatment. A rebuilding plan aims to recover the fish population, measured by its 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 52.2% 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 relative to the threshold.

In our historical research design, we compare US stocks after 1996 to US stocks 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 rebuilding requirement took effect. We refine the historical comparison by restricting the sample to the same stocks before and after the 1996 regime. This allows us to hold the species composition and fisheries constant. We then use a paired-differences estimator and find that stocks’ biomass more than doubled relative to their historical counterfactual. Similar to our contemporaneous comparisons, stock biomass was higher in the treatment group relative to the control group.

Our approach offers an alternative to bioeconomic models, whose accuracy relies on their fidelity to real-world population dynamics. Instead of imposing assumptions on the resource’s biology, we approximate its counterfactual population with data on untreated stocks that experience similar depletion dynamics. Both approaches require assumptions for causal interpretation; ours requires a parallel trend assumption, for which we provide evidence to support its validity.

In additional analysis, we address potential confounders, such as the possibility that some of the observed effects could be due to changes in environmental conditions, market demand, or potential spillover effects (Hilborn et al. 2021; Kroetz et al. 2022). Using fisheries’ growth rate as a proxy for environmental conditions (Szuwalski et al. 2015), we

do not detect differences between the comparison and treatment groups. Using catch data, we examine changes in supply before stocks receive treatment and do not find evidence consistent with a decline in demand driving the recovery of the stocks. Finally, we do not find evidence of market spillovers. Our analysis already limits the scope for spillovers as we purposefully omit highly migratory stocks that could travel between the US and EU. We further test, and fail to find evidence for leakage between the US and the EU, as fishing intensity does not increase in the EU after the same fish species receives policy treatment in the US.

We conclude that the MSA substantially increased biomass for stocks that entered a rebuilding plan. Our findings have direct policy implications for domestic and global fishery management and provide support for the role of predetermined, scientific thresholds in biological resource management. For example, forest management could utilize tree-density or forest area thresholds; wetland areas could be preserved to buffer against various rain intensity thresholds; and conservation policies could predetermine viable population levels or habitat sizes. Such predetermined thresholds may have the added benefit of mitigating regulatory capture, a problem in natural resource management with weak property rights (Costello and Grainger 2018).

Related Literature: Early analyses found stock biomass trending in a positive direction after the introduction of the MSA or similar policies (Milazzo 2012; Sewell et al. 2013; Oremus et al. 2014; NRC 2014; Hilborn et al. 2020; Britten et al. 2021). None of these studies included a control group, precluding causal interpretation. Other studies have used simulations to explore specific aspects of the MSA or its implementation, such as rebuilding timelines (Patrick and Cope 2014; Carruthers and Agnew 2016), the role of uncertainty (Memarzadeh et al. 2019), or the harvest control rule (Benson et al. 2016); or to evaluate the potential of sustainable fishing policies globally (Costello et al. 2016). None of these simulation-based studies empirically measured the MSA’s efficacy. Previous economic literature on fisheries management has examined the use of individual tradable quotas (ITQs) (Grafton et al. 2000; Homans and Wilen 2005; Costello et al. 2008; Birkenbach et al. 2017), essentially cap-and-trade with fish catch shares. But ITQs have proven politically unpopular, and few US fisheries are managed with them (Costello and Grainger 2018; Ben-Hasan et al. 2021). There has also been recent causal work on aspects of fisheries management other than rebuilding provisions, including Kroetz et al. (2015) and Birkenbach et al. (2017) on catch shares; McDermott et al. (2019) on how fishers preemptively increase effort before marine areas become protected; Englander (2019) on how EEZs deter

foreign fishing; Shin et al. (2020) on fishing moratoriums; Shrader (2020) on how fishers adapt to climate change; Noack and Costello (2022) on the role of credit markets and property rights in fishery utilization; Medoff et al. (2022) and Burgess et al. (2023) on marine protected areas (MPAs); and Englander et al. (2023) on how fuel subsidies affect fishing effort.

In what follows, we introduce fishery management in the US; review the conceptual framework around biological 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 (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 B_{MSY} . Under MSA, the population at which the stock is considered rebuilt is typically set at B_{MSY} . The stock is considered overfished when its population is below a certain fraction of B_{MSY} , known as the minimum stock size threshold (MSST). In many cases, that fraction is 50% (see Figure A2). Overfishing occurs when the rate of mortality due to fishing, known as F , exceeds the rate that produces MSY, known as F_{MSY} .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 to be experiencing 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 B_{MSY} . The HCR starts when $B < B_{MSY}$ 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. Free et al. (2022) offer a detailed review of different functional forms for harvest control rules.

New England Fishery Management Council (NEFMC) has historically struggled with management action and fisher compliance (Layzer 2006) (we report suggestive evidence for compliance in Figure A15), 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.

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.

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

3 Conceptual Framework for Biological Resource Management

The justification for management interventions in the form of rebuilding plans is grounded in theoretical work on biological resources. Here, we summarize the dynamics that could result in the collapse of a fish stock, and the relevant underlying ecological theory. Our discussion focuses on fisheries, but these points apply to biological resources more generally.

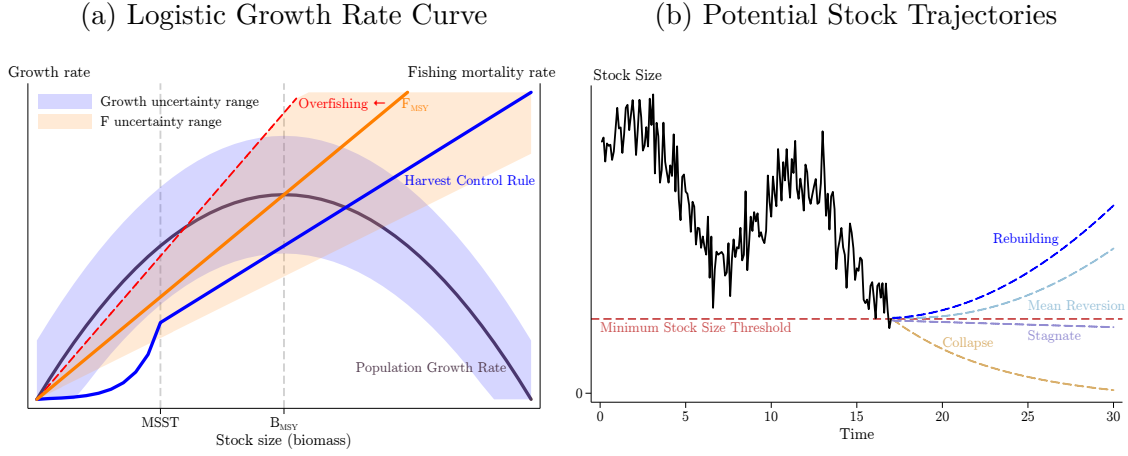
Recent theoretical work emphasized the stochasticity and uncertainty of biological systems (Pindyck 1984; Nøstbakken 2006; Sethi et al. 2005; Carson et al. 2009; Brozović and Schlenker 2011; Memarzadeh et al. 2019), in contrast to previous work that assumed complete information and simple functional forms for its growth (Gordon 1954; Clark et al. 1979; Beltratti et al. 1998; Brander and Taylor 1998). Managing biological resources using predetermined thresholds presents three challenges: estimating the stock’s level or status, the stock’s recharge rate, and the sustainable extraction rate (Brozović and Schlenker 2011; Szuwalski et al. 2015). In the case of fish, all three metrics are subject to significant measurement uncertainty, which can impact the policy’s effectiveness (Roughgarden and Smith 1996; Sethi et al. 2005; Costello et al. 2016; Memarzadeh et al. 2019; Kroetz et al. 2022). During the fishing season, stock assessors and managers have incomplete information on stocks’ real-time biomass and utilization. Resource management decisions must be made before better information on the status of the stock is available.

Population biology theory commonly uses a logistic growth model, shown in Figure 1a. In this model, growth is a function of the population size, intrinsic growth rate, r , and the carrying capacity, K . In steady state, the stock’s growth rate (y-axis) depends on its population size (x-axis), represented by the dark purple line in Figure 1a.⁶ Changes to the environment or predator-prey dynamics create uncertainty in the intrinsic growth rate, r , so the growth rate curve could lie anywhere within the light shaded purple region (Roughgarden and Smith 1996). The largest growth occurs at $\frac{K}{2}$ or B_{MSY} , the stock size that produces MSY. Uncertainty in the growth rate can also lead to uncertainty in B_{MSY} , MSY, and MSST. Most US fisheries are still managed by catch quotas and/or effort controls on harvesting. The law allows managers to set $F = F_{MSY}$, where the orange line intercepts the growth rate curve at B_{MSY} . However, changes in catchability of fish with season, year, technology, gear, and prices can create uncertainty in F (Roughgarden and Smith 1996). If the true fishing mortality is greater than F_{MSY} , then F would have a steeper slope than F_{MSY} and overfishing would be occurring (anywhere between orange line and dashed red line). A lower

⁶ Formally, in the logistic growth model, the change in the size of the stock N is determined by: $\frac{\partial N}{\partial t} = rN(1 - \frac{N}{K})$.

fishing mortality would have flatter slope.

Figure 1: Conceptual Framework for Resource Policy Design & Evaluation



Notes: Summarizing fishery management under uncertain growth and harvest rates. Panel (a) shows uncertainty in the growth rate (light purple region) and fishing mortality rate (peach region). The harvest control rule, which kinks at the Minimum Stock Size Threshold (MSST), is in blue. Panel (b) shows year-to-year variability in stock size over time (black line). When the stock size declines to the MSST (dashed red line), fishing is restricted and the stock rebuilds (dark blue line). The counterfactual population in absence of the requirement to rebuild the overfished stock could naturally revert to its previous levels (light blue dashed line), collapse (yellow dashed line), or stagnate somewhere in the middle (lavender dashed line).

Consider the red-dashed line that represents an overfishing rate in Figure 1a. If the population growth curve (light purple region) is below this line, then this fishing rate can cause the population to collapse. This dynamic could happen whenever F is above the population growth rate curve—anywhere in the shaded orange region, including when $F = F_{MSY}$.

Harvest control rules (HCR) were created to buffer against these uncertainties (Free et al. 2022). The blue line depicts the HCR used in the Mid-Atlantic. It is set at 75% F_{MSY} when $B > MSST$. When $B < MSST$, the HCR declines precipitously to allow the depleted stock to rebuild. In the absence of full information, we do not know if F is safely below the growth rate curve or dangerously above it. In other words, we do not know if the precipitous drop in the HCR at MSST is necessary to rebuild a stock or not. The HCR can be seen as precautionary. However, it also reflects the large uncertainty of population dynamics once they are depleted below the MSST. With fewer observations, stock assessors often need to reevaluate whether previous stock dynamics are still relevant under these conditions.

These uncertainties also apply outside of a steady-state framework. In Figure 1b, the stock size is on the y-axis and time is on the x-axis. Assuming no measurement error, we observe variability in the population due to environmental variability. If a negative shock

caused the population to drop below MSST, the HCR would lower F and rebuild the stock (dashed dark blue line labeled “Rebuilding” in Figure 1b). The question is: What is the counterfactual stock trend in the absence of the policy and full information? Would the stock have rebounded on its own (dashed light blue line) or collapsed (dashed yellow line) or stagnate somewhere in the middle (dashed lavender line)?

These counterfactual uncertainties complicate choosing the correct level for the MSST. Set the MSST too high, and the policy will impose unnecessary and costly restrictions on a resource that would have replenished anyway, albeit more slowly (Hilborn 2019; McQuaw and Hilborn 2020). Set 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).

The key to empirically evaluating the policy is approximating the counterfactual in which a given stock does not receive a rebuilding policy. Because the policy mandates rebuilding all overfished stocks, we collected data on stocks that would have met the criteria for treatment, but were not treated. This could be because they were in another country that did not have the requirement, or because they were overfished before the law took effect. We use these stocks to approximate the counterfactual trajectory for the stock if it had never gone into a rebuilding plan, so we can measure the effect of the policy.

4 Data

In order to evaluate the effectiveness of rebuilding provisions under the MSA, we gather fish stock panel data on catch, biomass, as well as management thresholds that are used to determine the status of a 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. For the fish stocks in the US, we also build a complete timeline of policy implementation.

4.1 Data from the United States

We obtain yearly US catch, biomass, and productivity for each stock from the National Oceanic and Atmospheric Administration’s (NOAA’s) Stock SMART 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 thresholds include the MSST for the “overfished” designation, F_{MSY} for the “overfishing” designation, B_{MSY} for the “rebuild” designation, annual total allowable catch (TAC), and MSY. These are also

known as reference points. We plot the stock mortality (F) relative to its reference point (F_{MSY}), versus its biomass (B) relative to its reference point (B_{MSY}) in Figure 2 for six different snapshots spanning 1990 to 2015.

To ensure we are studying stocks that are only affected by US fishing pressure and regulations, we narrow the main sample to stocks that can be found in federal waters, and we exclude highly migratory stocks whose habitat include international waters. We also exclude anadromous stocks, such as salmon, as they 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 than other species.

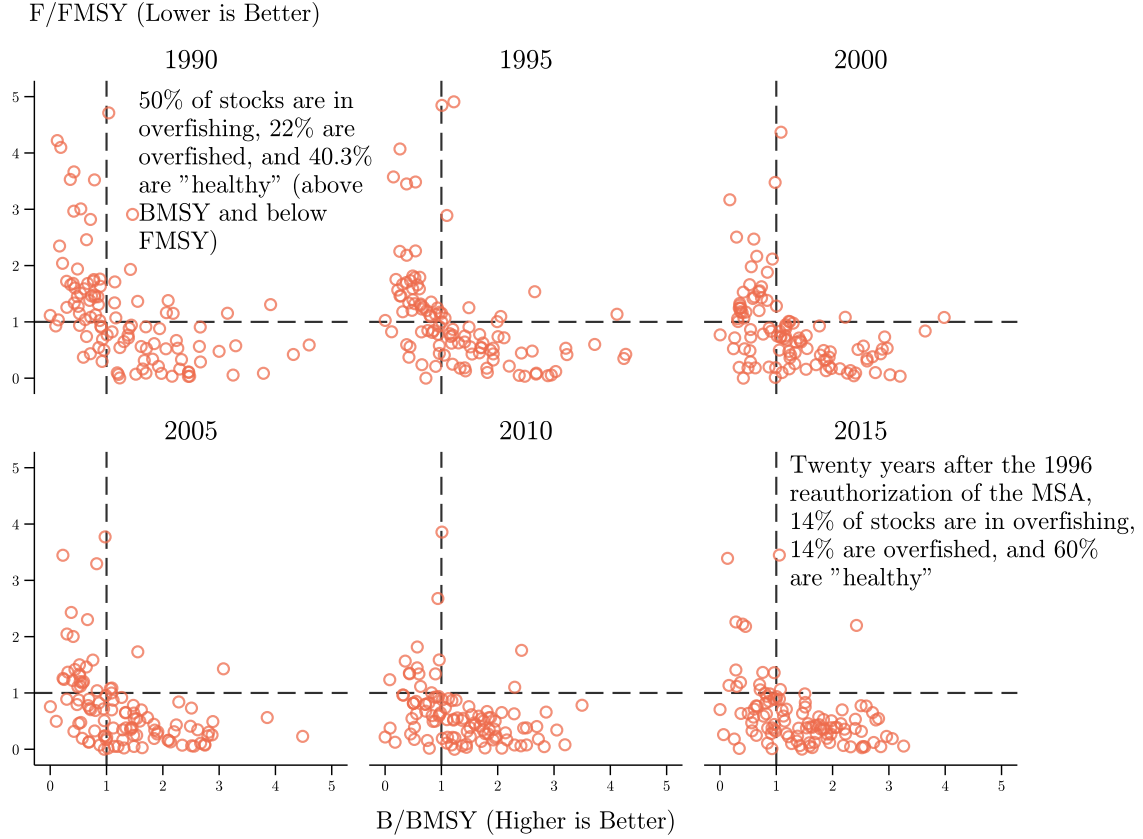
For US stocks, we complement their time series data with a timeline of status determinations and regulatory actions. We went through each of NOAA’s yearly Status of Stocks reports (NOAA Fisheries, 1997-2020) to record the years that fishery management councils designated a stock as “in overfishing,” near overfished, overfished, in rebuilding, and rebuilt. We validated these years with the information stored at NOAA’s Office of Sustainable Fisheries.⁷ We summarize the number of stocks by MSA designation for each year in Figure 3a. In the years before the 1996 MSA, half of the stocks were in overfishing, and more than 20% were overfished (Figure 2). By 2015, both of those shares fell to 14%. The number of stocks that experience overfishing or have biomass below their MSST drops in more recent years due to a lack of data: not all stocks have up-to-date assessments. Sixty of the 189 non-migratory and non-anadromous US stocks in our dataset entered rebuilding after the 1996 MSA. However, only 52 stocks have balanced biomass data from 1990-2016, 50 stocks have balanced catch data from 1990-2016, and 49 stocks have both. For the historical analysis, we also have data on 18 stocks whose biomass fell below their MSST before 1989. To date, this is the largest harmonized panel dataset of US fish stock populations and management.

We also gather data on the quantity and revenue of fish sold from the NOAA Fisheries One Stop Shop (NOAA FOSS 2021). In this database, fish landings and revenue are tallied by region and species, often a broader categorization than fish stock. When possible, we match species-region landings to their equivalent Stock SMART stock. In some cases, landings data combine 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

⁷ 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 designations.

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 (F_{MSY}), while the x-axis shows the biomass relative to the biomass target level (B_{MSY}). Stocks with F/F_{MSY} above one are experiencing overfishing. Stocks with low B/B_{MSY} values, generally below half of their B_{MSY} value (below 0.5 on the x-axis), are considered overfished. We truncate the axes at 5 to allow for easier visual inspection of the data.

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 have US revenue and landings data for 143 stocks (40 of our 60 treated stocks from 1990-2016).

4.2 Data from the European Union

We complement our US data with data from 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).⁸

⁸ Previous working paper versions also included data from Canada. In the Online Appendix, we briefly summarize the data issues that led to the decision to exclude Canadian stocks from the analysis.

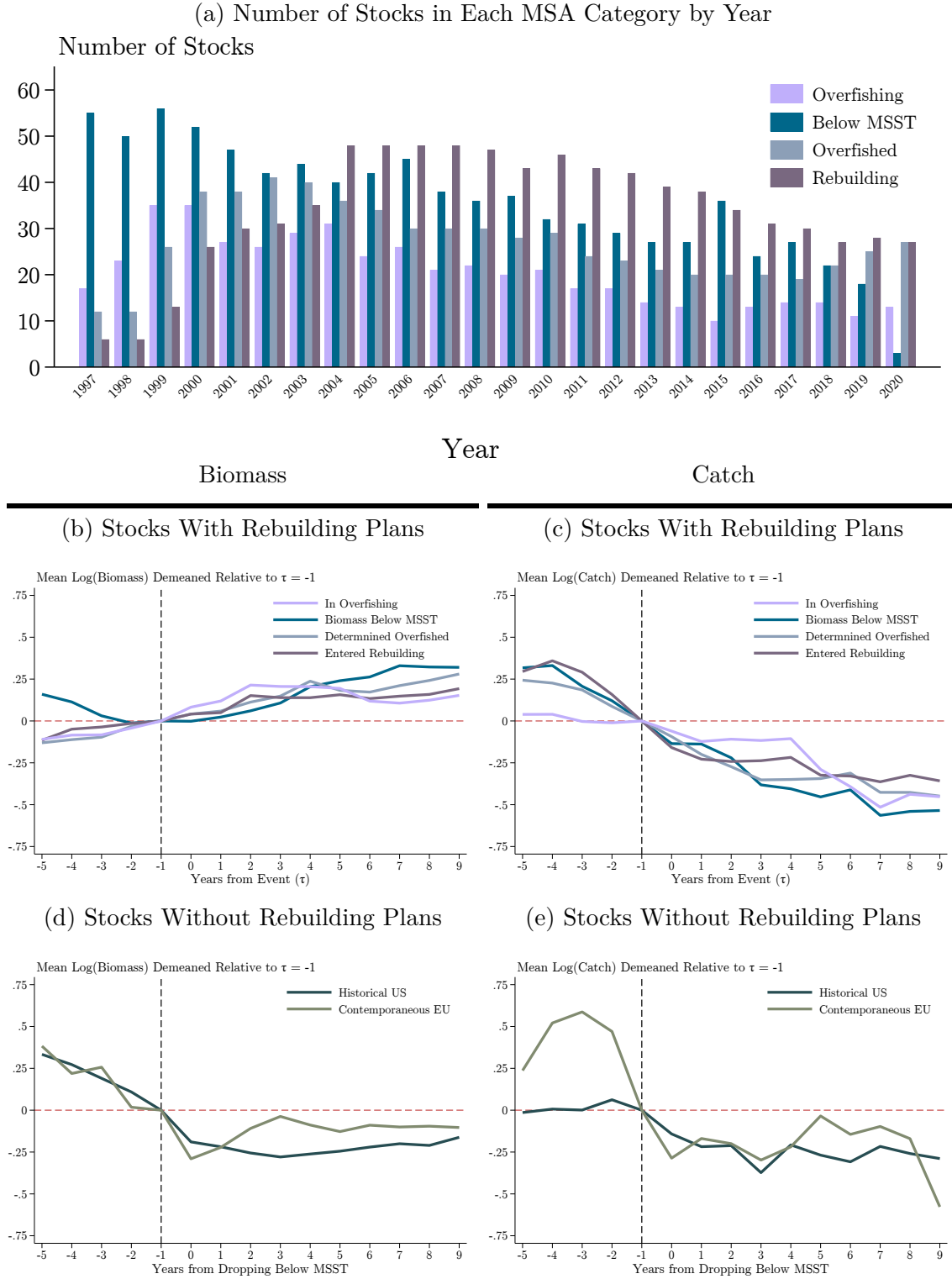
EU catch, biomass, and productivity time series data, as well as management reference points, were obtained from a 2020 European Commission report monitoring the Common Fisheries Policy, the primary EU fisheries law (EU 2013). The EU defines for each stock the Safe Biological Limit (SBL), equivalent to the MSST under the MSA. Catch data came from three sources: the ICES Stock Assessment Database (ICES 2022) for Northeast Atlantic stocks, and 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. There are a total of 293 EU stocks in our dataset, of which 46 dropped below their SBL at any point between 1990 and 2016, inclusive. Unfortunately, consistent reporting of landing and revenue data only start in 2006, which is too short a time series for our analysis. We explored alternative sources of data on landings, revenue, and ex-vessel prices from the Food and Agriculture Organization (FAO) and Sea Around Us (SAU). However, when we tried to validate the data with existing US and EU data, we found the FAO and SAU data were biased for the US and the EU and in opposite directions. The differences were also extremely large in some cases. This led us to not consider these data sources as informative regarding fishery revenue in the EU.

We summarize the key events of interest over time and the evolution of the main outcomes—biomass and catch—in Figure 3. For US stocks, we focus on the events: experiencing overfishing, biomass declining below MSST, receiving an overfished determination, or entering a rebuilding plan (Figures 3b-3c). For control stocks, we plot EU stock biomass declining below its SBL, and US stock biomass declining below its MSST in the pre-MSA time period (Figures 3d-3e).

4.3 Validating stock assessment data

Fish stock assessment reports are developed by NOAA fish scientists. They use peer-reviewed models to estimate fish populations and reference points. 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.” The data that we use for this analysis comes from the retrospective components of stock assessments. Their higher fidelity to historic observations make them more reliable than the predictions that managers use to make decisions. They benefit from the availability of full catch records and survey data, and are not affected to the same degree by the uncertainties

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



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).

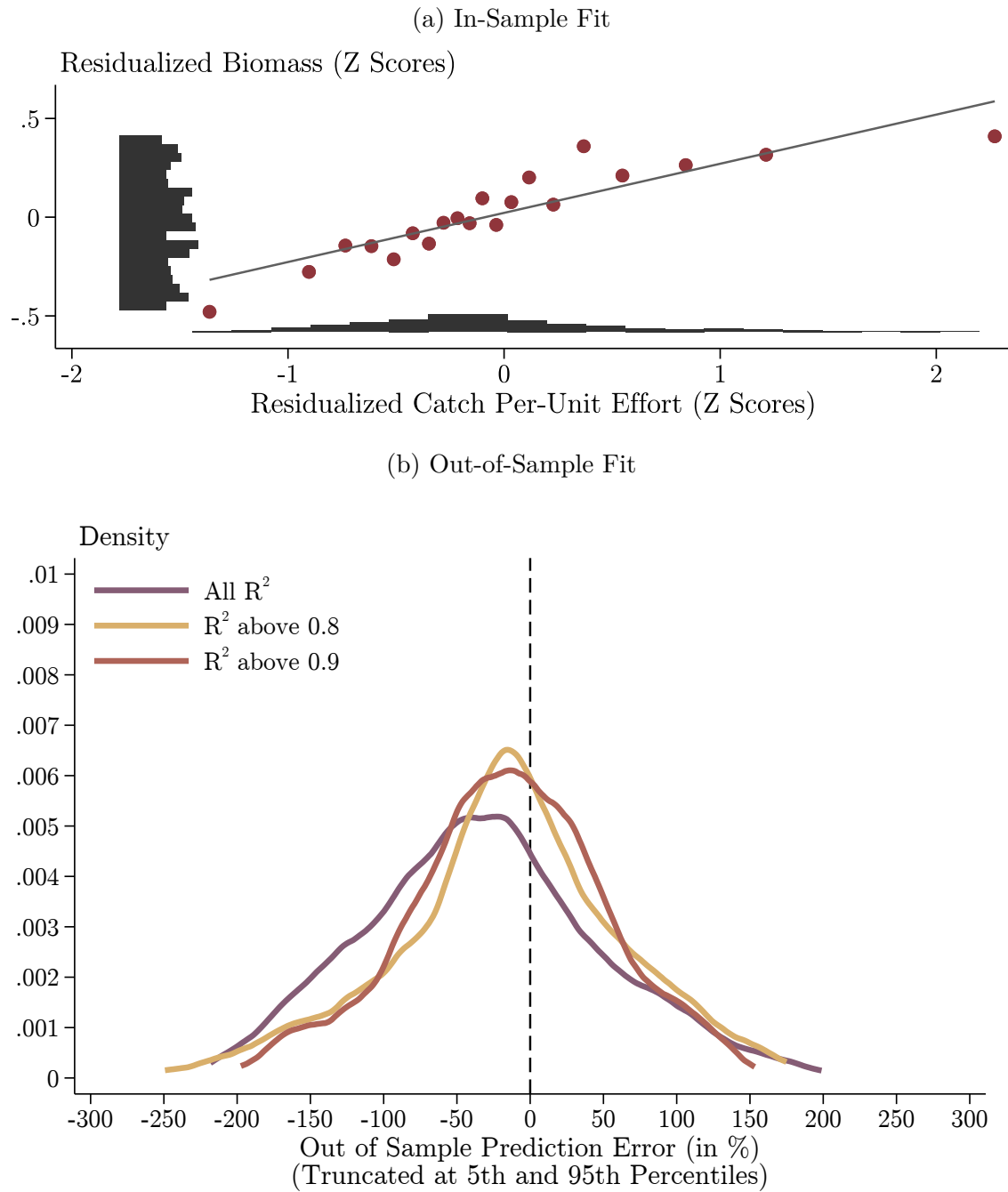
that managers face in real time regarding the management of the stock (see Section 3).

Stock assessment models are calibrated using observed data from NOAA abundance surveys and catch data from fishers. Survey data are reported in units of catch-per-unit-effort (CPUE). Catch data include landings that are sold at the dock, discards at sea, and bycatch, which is accidental catch of a species that fishers were not 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).

To verify that the stock assessments are consistent with the observed data, we perform two empirical validation exercises. First, we examine the in-sample fit by estimating a simple regression model linking the stock assessment output (biomass) to the key inputs (NOAA abundance sampling survey data and catch). We obtain the survey data records from NOAA’s Distribution Mapping and Analysis Portal, and we standardize the biomass, catch, and survey data by stock. Then we residualize the standardized biomass as a function of lagged standardized survey data and contemporaneous and lagged standardized catch, along with stock and year fixed effects. We repeat this residualization for the standardized survey data. We plot the relationship between the residuals of biomass and survey data (in z scores) in Figure 4a. There is a strong linear fit between the survey data and the assessed biomass. In other words, the survey data, which provides a proxy for stock abundance, is a strong predictor of assessed biomass.

In the second validation exercise, we run a regression on each stock, excluding one year at a time, using the same model as above. For each omitted year of data, we generate a predicted value for the assessed biomass. Because we are running the regression for each stock separately, we keep the data in levels and do not transform it into z-scores. In Figure 4b, we report the distribution of prediction errors. While some prediction errors are large, they are centered and concentrated around zero, especially for the models with high R-squared values. Overall, we find a strong in-sample and out-of-sample fit of biomass to survey and catch data, even though we are using a very simple regression specification that does not incorporate any biological theory, which the stock assessments do include. We interpret these results as evidence that the stock assessments are not generating artifacts that are not observed in the raw data inputs.

Figure 4: Validating the Stock Assessments Using Survey and Catch Data



Notes: Results from running two sets of tests to verify that the stock assessments are capturing features that appear in their raw data inputs instead of generating patterns that do not agree with the catch and survey data.

5 Estimating the Treatment Effect of The Magnuson-Stevens Act

In an ideal experiment, we would randomly assign rebuilding plans to stocks that have been depleted below their MSST. In practice, rebuilding plans are required by law for all stocks that fall below their MSST. Once that happens, the stock is publicly declared overfished, and a rebuilding plan is developed. 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.⁹ To avoid anticipatory effects, in our main analysis, we define the event of interest and first event year as the year the stock’s biomass dropped below its MSST (we report results for the other MSA events in the Online Appendix). If the year the stock was declared overfished happened before the stock declined below its MSST, we use this as our first event year.¹⁰ Our treated group of stocks are those that experience an event of interest and have ever entered a rebuilding plan.

US stocks that receive rebuilding plans (unhealthy stocks) are systematically different than US stocks that do not (healthy stocks). Rebuilding plans can also affect stocks that are not in a rebuilding plan, violating the stable unit treatment value assumption (SUTVA). For example, stocks in the same region could affect one another through the food web (Estes et al. 2011).¹¹ In addition, 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 other regions.

There are a small number of contemporaneous US stocks whose biomass fell below the MSST, but never went into rebuilding because their status was not accurately assessed at the time. New stock assessments revealed that these stocks should have received rebuilding plans, but did not. However, we do not use these stocks as a comparison group due to the potential SUTVA violations described above, as fishers could substitute effort from treated to untreated stocks, or fishing of these stocks could be constrained due to other overfished stocks. We document these sorts of spillovers in section 6.5.

⁹ There can be delays between each of these events. See Figure A4 for a summary of those delays.

¹⁰ This can happen in cases where the MSST value has changed due to an update in the science. See Online Appendix for more details.

¹¹ This is known as a trophic cascade effect.

The lack of a readily available comparison group is the key empirical challenge 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 an unhealthy 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 the European Union (EU), and (ii) a historical comparison group of stocks in the US that have data going back to 1984 or longer, when rebuilding was not required by law.

The EU’s 2013 amendment of the Common Fisheries Policy (CFP) called for rebuilding all commercial fish stocks above levels capable of producing MSY. It set a goal of reducing fishing mortality, F , below F_{MSY} by 2015, or 2020 at latest. The EU defines for each stock the Safe Biological Limit (SBL), equivalent to the MSST under the MSA. We will refer to the SBL as a MSST-equivalent reference point for the remainder of the paper.

In this contemporaneous comparison of US to EU stocks, our main empirical strategy is a staggered difference-in-differences that uses the different timing of stocks dropping below their MSST or MSST-equivalent. We use biomass data on EU stocks and their MSST-equivalent values for the stocks managed under the EU’s CFP. We consider this to be a valid comparison group because stocks in the EU are less likely to be affected by rebuilding plans taking place in the US. In addition, the US and the EU share similar stock assessment practices (Dichmont et al. 2016), fishing market structure (Swartz et al. 2010), and fishing gear and technologies (Bell et al. 2017).

Though some stocks in the EU are the same species as treated US stocks, we did not include them if their biomass was above their MSST-equivalent threshold. Even though they have similar biology and are part of similar markets, their population health, dynamics, and trajectories are not comparable. A stock being overfished is a necessary condition for it to serve as a plausible control. Otherwise, the parallel trends assumption is unlikely to hold.

In the historical comparison, we compare stocks before and after the 1996 reauthorization of the MSA. Before 1996, if a stock’s biomass fell below its MSST, it was not required to be rebuilt. Here, we define the event of interest and first event year as the year the stock’s biomass fell below its MSST in both the treated and control stocks. Our treated group of stocks are those that have ever entered a rebuilding plan after 1996. Stocks included in this analysis were below the MSST either before 1989 (control stocks), after 1995 (treated stocks), or both. If stocks are in both, then they are in the control group prior to 1989 and the treatment group after 1995. Their biomass either fell below MSST before 1989 and

stayed below MSST after 1995; or it fell below MSST before 1989, recovered, and fell below MSST again after 1995. We reserve the 1989 to 1995 period as the post-treatment period for control stocks. For stocks that were already below the MSST in the latter period, we assign 1995 as their first year of falling below the MSST.

Finally, we subset our data to the same stocks in both time periods. Focusing on the same stocks has the advantage of 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 have been changes to the market demand for these stocks; or changing environmental conditions could have affected the growth rate of fish stocks. We address these concerns in Section 6.7.

The key identifying assumption for both the contemporaneous and historical research designs is that the stocks that entered rebuilding would have developed along parallel trends to the control stocks in the absence of the policy treatment. Another assumption needed for causal interpretation is that untreated stocks do not experience spatial spillovers or leakage from treated stocks. Finally, we need to ensure stock assessments are not being manipulated to make a stock appear rebuilt when it is not. We evaluate to what degree is it likely that these assumptions are violated in sections 6.5 and 6.6.

In what follows, we provide more details about the estimation of each research design.

5.1 Contemporaneous Comparison 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 (2021). 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 effect 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’Haultfoeulle (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 (2021) 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:

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

Where y_{st} is the outcome of interest, in log points, for fishery stock s , in year t .¹² 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 10 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.¹³

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

¹² Explicitly, we use the inverse-hyperbolic-sine: $\log(x + \sqrt{1 + x^2})$.

¹³ Because we focus on the sets of leads and lags where the composition of stocks is the same (five years before and 10 years after the event) the weighted average simplifies to a simple average where each cohort receives the same weight.

5.2 Historical Comparison 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:

$$y_{st} = \sum_{\tau \neq -1} \beta_{\tau} \mu_{\tau} + \lambda_s + \mathbf{X}_{st} \boldsymbol{\theta} + \varepsilon_{st} \quad (2)$$

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, $\mathbf{X}_{st}$. 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 stock’s biomass falls below MSST, overfished determination, or the stock enters 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

We present the main results from the two research designs, contemporaneous and historical comparisons. We begin by reporting the results for the main outcome, fish stock biomass, and the main economic benefits of the policy, catch levels, in Section 6.1 and 6.2, respectively. We document the effects on the main instrument of the policy, fishing mortality, in Section 6.3. Then, we report results for rebuilt stocks in Section 6.4. Finally, we address concerns regarding leakage, potential issues with the measurement of biomass, and briefly summarize additional checks in Sections 6.5-6.7, and in the Online Appendix. All results

use a stock’s biomass falling below its MSST or MSST-equivalent as the event of interest for both treated and control stocks. Treated stocks are stocks that experience an event and have ever been placed in a rebuilding plan. Results for other events of interest (overfished determination, or entering a rebuilding plan) are in Table A1 and Figure A6.

6.1 Results for the Main Fishery Health Outcome: Stock Biomass

Using Equation (1) in the contemporaneous research design, treated US stocks have biomass levels that are 50.7% higher relative to the EU control stocks, on average, six to 10 years after the event (Table 1, Panel A, column 1).¹⁴ If we define our treated stocks as US stocks that experience an event and enter a rebuilding plan, our estimate is slightly higher, 52.2% (column 2). If we also include stocks for which we need to use a pseudo MSST value (see the Online Data Appendix for details), we recover an estimate of 63.2% (column 3). Excluding US stocks from the New England Fishery Management Council (NEFMC), which struggled with policy implementation and compliance (see Section 2 for more details), results in a biomass gain of 53.7% (column 4), or a gain of 69.9% when including stocks with pseudo MSST values (column 5). Finally, the results are robust to the inclusion of stock-level linear time trends, in addition to the year fixed effects (columns 6 and 7).

Growth in biomass is a dynamic process, and as such, we would expect to see biomass increasing several years after it has dropped below the MSST. There may also be a lag between the event and biomass recovery due to the time it takes to declare a stock overfished and implement a rebuilding plan (see Figure A4 for a summary of these delays). In Figure 5, we report the results from the contemporaneous and historical research designs. In the contemporaneous research design, prior to the event, US stocks were not systematically different, on average, than stocks that declined below their threshold in the EU (Figures 5a-5b). We start to see a precisely estimated divergence between treated US stocks and the EU control stocks five years after the event. Ten years after the event, US stock biomass is, on average, 58.4% higher relative to EU stocks, and is 70.2% higher when excluding New England stocks. We observe similar patterns when normalizing the biomass by the MSST, instead of using logged biomass (Figure A7).

In the historical comparison research design, we run two separate event studies for each time period. First, we estimate this “double event study” looking at stocks that experienced the *same condition*: having biomass below their MSST in a 15-year time window. Second, we narrow this comparison group to the set of stocks that entered rebuilding after 1995, but

¹⁴ After transforming the coefficient from log-points to percent increase, $0.507 = e^{0.41} - 1$

Table 1.
Contemporaneous Comparison of US to EU Stocks DD Estimation Results

Panel A. Log(Biomass) (<i>recovery lags due to time needed for reproduction</i>)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Event Time 1-5	0.10 (0.07)	0.10 (0.07)	0.15 (0.06)	0.13 (0.07)	0.18 (0.07)	0.16 (0.09)	0.25 (0.09)
Event Time 6-10	0.41 (0.14)	0.42 (0.14)	0.49 (0.13)	0.43 (0.16)	0.53 (0.15)	0.60 (0.21)	0.74 (0.21)
Within R^2	0.136	0.134	0.141	0.159	0.166	0.089	0.126
Observations	2,295	2,214	2,511	1,620	1,863	2,214	1,863
Clusters	85	82	93	60	69	82	69
Panel B. Log(Catch) (<i>decline reverses as biomass recovers</i>)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Event Time 1-5	-0.18 (0.14)	-0.18 (0.14)	-0.19 (0.13)	-0.24 (0.17)	-0.21 (0.15)	-0.11 (0.19)	-0.18 (0.20)
Event Time 6-10	-0.03 (0.27)	-0.06 (0.27)	-0.06 (0.24)	-0.29 (0.32)	-0.25 (0.28)	0.16 (0.43)	-0.14 (0.41)
Within R^2	0.057	0.058	0.055	0.064	0.061	0.051	0.056
Observations	2,295	2,214	2,511	1,620	1,863	2,214	1,863
Clusters	85	82	93	60	69	82	69
Ever Entered Rebuilding		X	X	X	X	X	X
Including Pseudo MSST			X		X		X
Excluding NEFMC Stocks				X	X		X
Linear Stock Trends						X	X

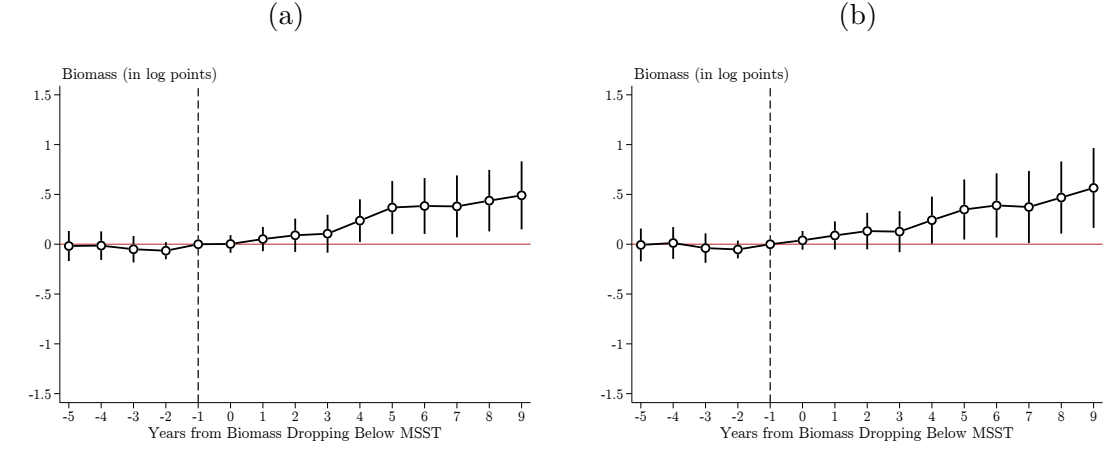
Notes: Estimation results from the DD specification in Equation (1). We report the linear combinations for the event time dummies after the stock drops below the MSST for the average of the first to fifth lags, and the sixth to tenth lags, excluding the top-coded lag coefficient. Column 1 includes all US stocks whose biomass dropped below the MSST. Column 2 narrows the treated sample to stocks that also entered a rebuilding plan. Column 3 expands the control group by including stocks with pseudo MSST values (see Section 4 for details). Column 4 repeats column 2, but excludes New England stocks (see Section 2 for details). Column 5 repeats column 4 but includes stocks with pseudo MSST values. Column 6 repeats column 2, but includes linear stock time trends. Column 7 repeats column 6 but includes pseudo MSST values, and excludes New England stocks. All regressions include stock and year fixed effects. Standard errors are clustered at the stock level.

Figure 5: Evidence for the Policy's Outcome: Fish Biomass Recovery

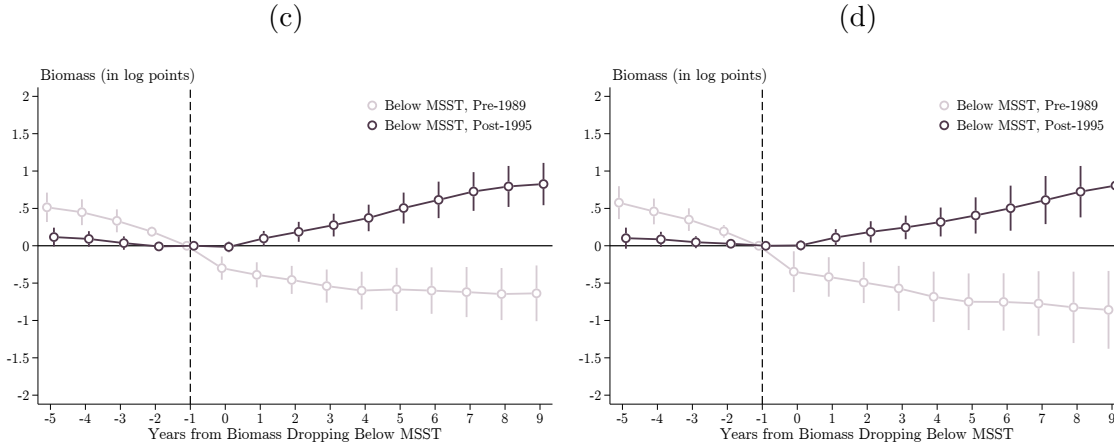
Including All US Stocks

Excluding New England Stocks

Contemporaneous Comparison, US to EU



Historical Comparison, Present-US to Past-US



Notes: Panels (a) and (b) report estimation results showing coefficients and 95% CIs for the DD specification in Equation (1). Panels (c) and (d) report estimation results from two separate regressions showing coefficients and 95% CIs for the specification in Equation (2). The results on the left column of the panels include all US stocks that ever entered rebuilding ($\#treated=49$), while those on the right exclude stocks in the New England Region ($\#treated=27$, see main text for details). Standard errors are clustered at the stock level.

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 increased in biomass after falling below their MSST only in the post-1995 period. During the pre-1989 period, their biomass continued to decline after going below the MSST. In Figure 5c, we plot the double-event-study results showing that in the five to 10 years after biomass fell below the MSST, biomass recovered, on average, by 97.9% post-1995, relative to its previous level. In the pre-1989 period, stock biomass continued to decline by an additional 44.9% after dropping below its MSST. These effects remain similar in magnitude when excluding New England stocks (Figure 5d), and when controlling for fuel prices and climate indices (see Figures A9a-A9b).

Note that the magnitudes from each regression are not directly comparable to one another because the baselines (the omitted categories) are different. For example, consider a stock with B_{MSY} and MSST values of 100 metric tons (MT), and 50, respectively. Assume the stock biomass declines from 55 to 45 MT from event time $\tau = -1$ to $\tau = 0$, then continues to decline by 40% in $\tau = 9$, lowering its biomass value to 27 MT. If the stocks recovers later, and then declines again, then the baseline at $\tau = -1$ is similar. However, if the new baseline at $\tau = -1$ in the post-1995 regression is still around its depleted level of 27 MT, then a 100% increase would lead to a biomass level of 54 MT. Therefore, it is incorrect to interpret the double event study as providing evidence for a 100% increase with treatment and 40% decline without treatment, for a combined treatment effect of rebuilding of 140% higher biomass.

To better compare the historical to the contemporaneous research design, we restrict the sample to the same stocks during two different time periods. Using stocks that met the conditions for a rebuilding plan in both time periods allows us to construct paired differences for each stock in each event time period relative to the year prior 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). We summarize the estimation results from this approach in Table 2. We find that when holding the composition of stocks constant, the difference in biomass, on average, in the five to 10 years after dropping below the MSST in the post-1995 regime is 163.8% (column 2). This is slightly higher than if we also include stocks that did not enter a rebuilding plan (column 1). This specification compares the difference in how biomass evolves in the years after meeting the condition for a rebuilding plan, relative to the difference in biomass in the year prior to meeting the condition. These results are robust to controlling for fuel prices and for climatic

indices (column 3, see Section 5.2 for details). In Figure A5, we plot the results of estimating the event-study specification on the paired differences.

Table 2.
Historic Comparison of US Stocks Post-1995 to Pre-1989 Estimation Results

	Log(Biomass)			Log(Catch)		
	(1)	(2)	(3)	(4)	(5)	(6)
Event Time 1-5	0.47 (0.13)	0.46 (0.15)	0.47 (0.16)	0.30 (0.15)	0.26 (0.16)	0.26 (0.17)
Event Time 6-10	0.93 (0.20)	1.00 (0.23)	1.04 (0.25)	0.60 (0.28)	0.64 (0.30)	0.67 (0.35)
Within R^2	0.332	0.383	0.393	0.086	0.095	0.096
Observations	448	393	387	398	353	347
Clusters	32	28	28	29	25	25
Ever Entered Rebuilding		X	X		X	X
Fuel & Climate Controls			X			X

Notes: Estimation results from the specification in Equation (2). All regressions include stock fixed effects. Regressions in columns 3 and 6 also include fuel price and climate indices controls. Standard errors are clustered at the stock level.

Both the contemporaneous and the historical comparisons speak directly to the potential scenarios we cover in the conceptual framework section (Figure 1b). The contemporaneous comparison focuses on the *difference* in the biomass trajectories with and without rebuilding plans. While we recover a positive difference in biomass between treatment and control stocks, we want to know whether the treated biomass is increasing in absolute terms, or just declining at a lower rate than the control group. The historical comparison focuses on the *separate* trajectories of the treated and untreated stocks. Stock biomass does appear to increase, on average, in the post-1995 regime when rebuilding plans are implemented. Our findings highlight that in the absence of a rebuilding plan, stock biomass does not recover, at least within the 10 years after stocks decline below their MSST. This finding aligns with the middle-ground scenario of the stock stagnating—neither collapsing nor reverting to the mean—in the absence of rebuilding plans (Figure 1).

To contextualize our results, we estimate the policy’s contribution to total biomass in US waters. Using our main result from the contemporaneous comparison, we estimate a total biomass increase of 947,412 metric tons by the tenth year after dropping below the MSST. However, we can perform this calculation for only the 31 treated stocks (out of 49 total) that

have their biomass data reported in metric tons, and not in a biomass proxy.¹⁵ Consequently, this is a lower bound for the total gain in biomass. To better anchor this number, we sum the biomass and commercial catch in 2016 for 119 US stocks for which we can convert these variables to metric tons. The total amount of commercial catch in the US is 2.74 million metric tons, and the total biomass value is 14.9 million metric tons.

6.2 Results for the Main Fishing Industry Outcome: Catch

Managers reduce Annual Catch Limits (ACLs) in order to lower fishing mortality when biomass is low. We would expect a reduction in catch in the early years of a rebuilding plan, and a return to baseline levels as the stock recovers. In Table 1, Panel B, we report the results of the contemporaneous research design for catch. We estimate that one to five years after stocks drop below their MSST, catch imprecisely declines (columns 1 to 7). This decline becomes smaller and remains noisily estimated, reflecting a near return to baseline levels in the six to 10 years after dropping below the MSST (column 1 to 3, and 6). However, when we exclude New England stocks, the reduction in catch persists even in the latter time period, albeit imprecisely estimated (columns 4, 5, and 7).

The results in Table 1 suggest that biomass can experience a meaningful recovery even without a large catch reduction in the short term. This is surprising given how reducing fishing mortality, seen as the key policy instrument, requires lowering catch. (We present fishing mortality results in the next section.) In Figure 6, we plot the catch results for the contemporaneous and historical research designs. In the contemporaneous research design, catch is similar between the US and EU stocks before the US stocks decline below their MSST. In the years after US stocks decline below their MSST, the estimates are negative, but confidence intervals are wide—masking potential heterogeneity (Figure 6a). Catch returns to baseline levels about six years after dropping below the MSST, and then appears to recover to above baseline levels. However, the confidence intervals only allow us to reject either large falls or gains in catch. When we exclude New England stocks (Figure 6b), we see a larger drop in catch in the first few years after the event and a recovery towards baseline levels. Again, the effects are imprecisely estimated. In Figure A12, we find that the intended rebuilding plan time frame (above or below 10 years) is an important dimension of heterogeneity. Stocks with rebuilding plans that are intended to take more than 10 years see a larger and more precisely estimated drop in catch.

¹⁵ We convert each stock’s biomass into metric tons. We take its biomass from one year before the event, and apply the average increase from the tenth year after the event. We sum these gains across the 31 stocks to arrive at the total biomass gain.

In the historical research design, we see that both treated and untreated US stocks experience a decline in catch as their biomass approaches the MSST. This is what we would expect to see, as lower biomass results in higher search costs and lower yields, conditional on effort levels remaining similar. Whether we include all US stocks or exclude New England stocks, we find that catch levels continue to decline even further after the stocks decline below the MSST (Figures 6c-6d). In this comparison, we do not find evidence that catch levels recover back to baseline. The linear combinations for the coefficients on catch in the five to 10 years after the event, highlight that stocks appear to stabilize at levels that are 22.3% and 55.6% lower, with or without New England stocks, respectively. The continued decline in catch might reflect the delay between the event and the implementation of a rebuilding plan. To better assess whether catch recovers to baseline levels, we examine stocks that were declared rebuilt in Section 6.4.

6.3 Results for the Main Policy Instrument: Fishing Mortality

Fishing mortality is the ratio between catch and biomass; it measures the utilization of the fishery. A rebuilding plan aims to reduce fishing mortality by lowering catch in the short term. However, as biomass recovers, catch can recover while fishing mortality remains constant.

We find meaningful heterogeneity in how fishing mortality evolves for treated US stocks after they fall below their MSST, the main event of interest. When we include all US stocks, in the contemporaneous comparison, we find that fishing mortality in the pre-event period is higher, on average, for US stocks relative to EU stocks (Figure 7a). In the post-event period, fishing mortality for US stocks declines compared to their pre-event period, but is not statistically different from EU stocks. This is likely due to New England’s struggle with policy implementation and compliance (see Section 2 for the fishery management issues in the New England region). When we exclude New England stocks from the analysis, post-event fishing mortality precisely declines for treated US stocks to 11.7% lower, on average, than EU stocks (Figure 7b). In addition, we do not detect any systematic differences between US and EU stocks in how fishing mortality evolves in the pre-event period.

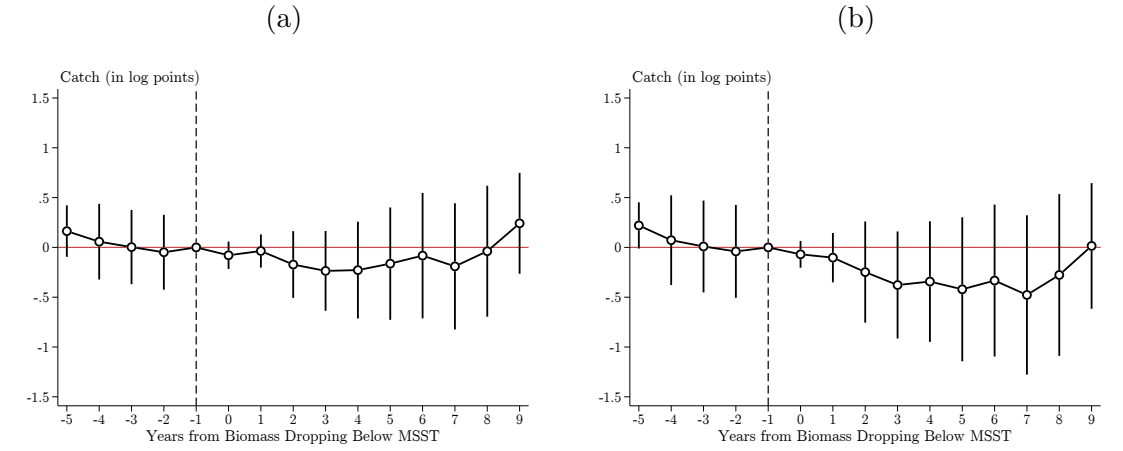
The results from the historical comparison show similar patterns. When all stocks are included, fishing mortality is imprecisely lower during the post-1995 period relative to the pre-1989 period (Figure 7c). However, these results again become precise when we exclude New England stocks. The fishing mortality of the treated stocks declined by 27.9% by the tenth year after the event during the post-1995 period (as shown in Figure 7d). In contrast,

Figure 6: Evidence for the Policy's Benefits: Sustaining Catch

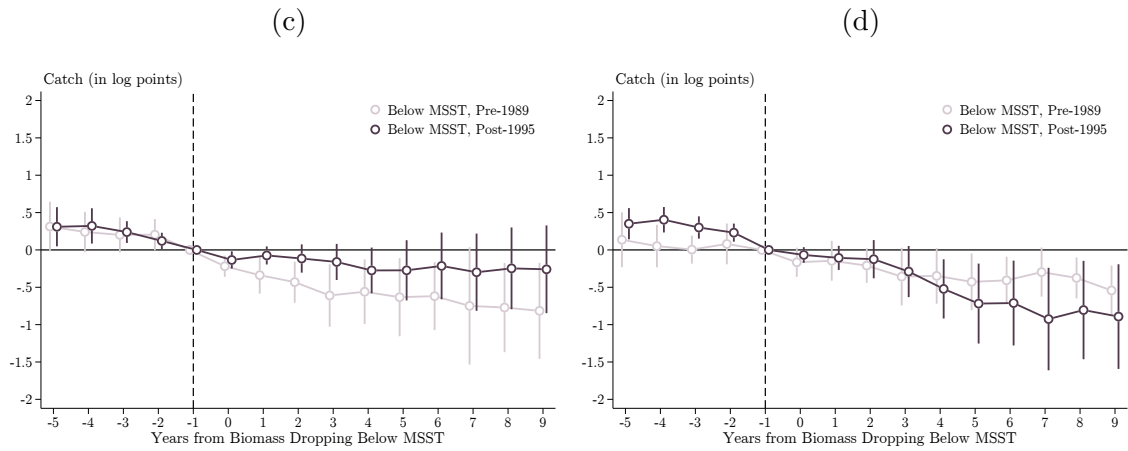
Including All US Stocks

Excluding New England Stocks

Contemporaneous Comparison, US to EU



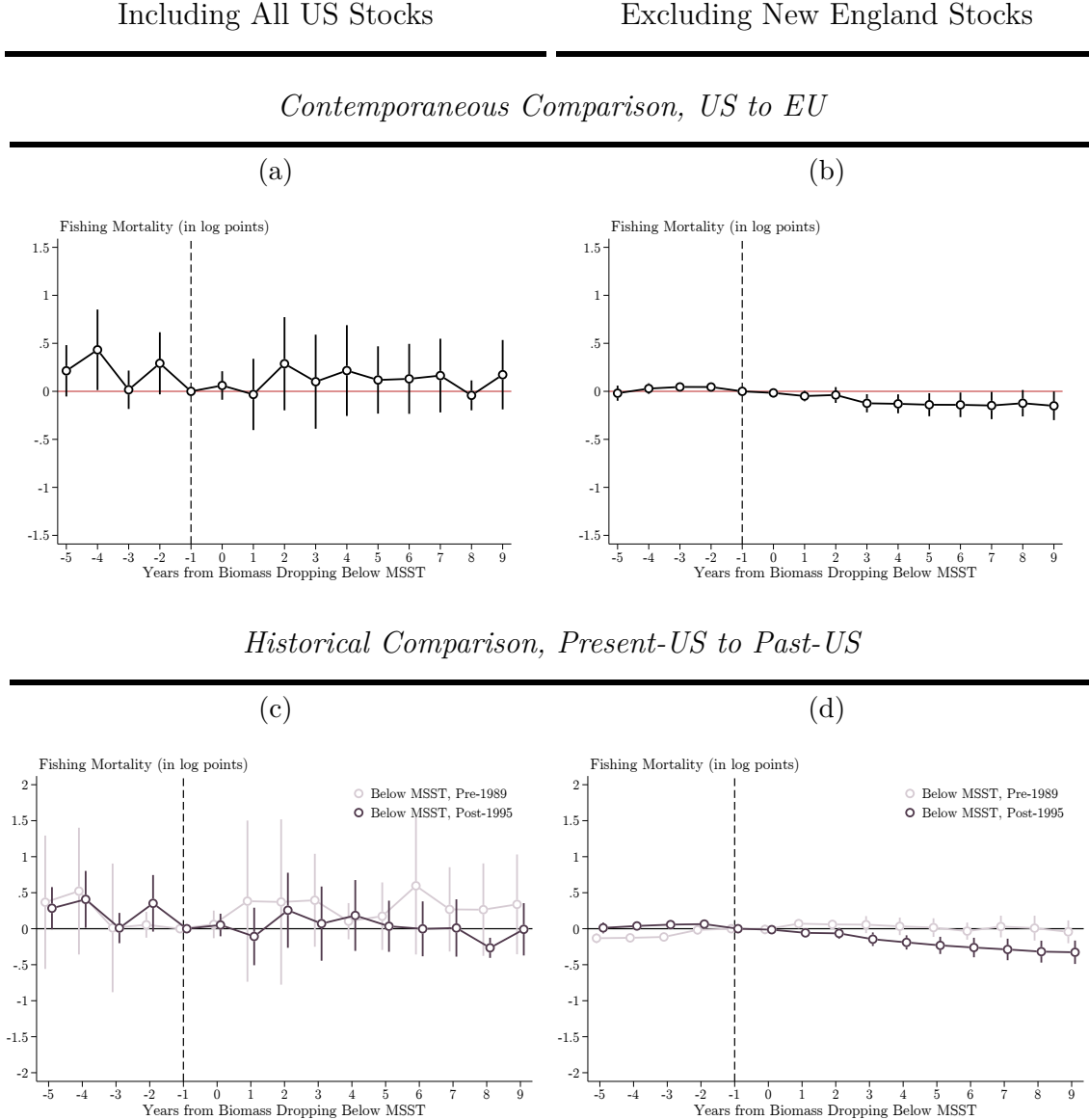
Historical Comparison, Present-US to Past-US



Notes: See Figure 5.

untreated stocks during the pre-1989 period did not experience a change in fishing mortality after the stocks declined below their MSST.

Figure 7: Evidence for the Policy's Instrument: Lowering Fishing Mortality



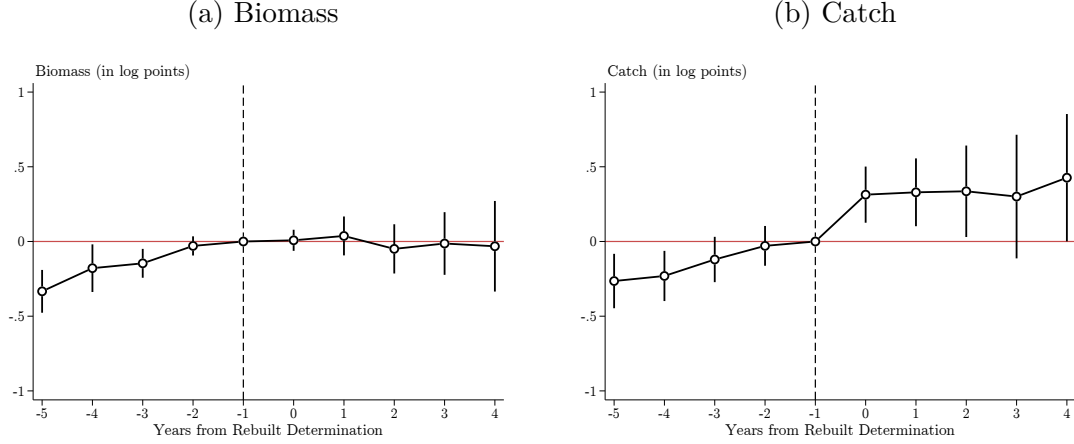
Notes: See Figure 5.

6.4 Results for Fisheries After Rebuilt Determination

Rebuilding plans take 10 years, on average. A successful rebuilding will lead to the recovery of the stock, allowing managers to increase catch without jeopardizing the biomass gains. In Figure 8, we focus on 37 stocks that were determined rebuilt. We estimate how biomass

and catch evolved following the rebuilt determination using the event study specification in Equation (2).

Figure 8: Biomass & Catch Following Rebuilt Determination



Notes: Estimation results showing coefficients and 95% CIs for the specification in Equation (2) that estimates the change in biomass or catch around the time of the stock receiving a rebuilt determination (when biomass is determined to be at or above B_{MSY}). Standard errors are clustered at the stock level.

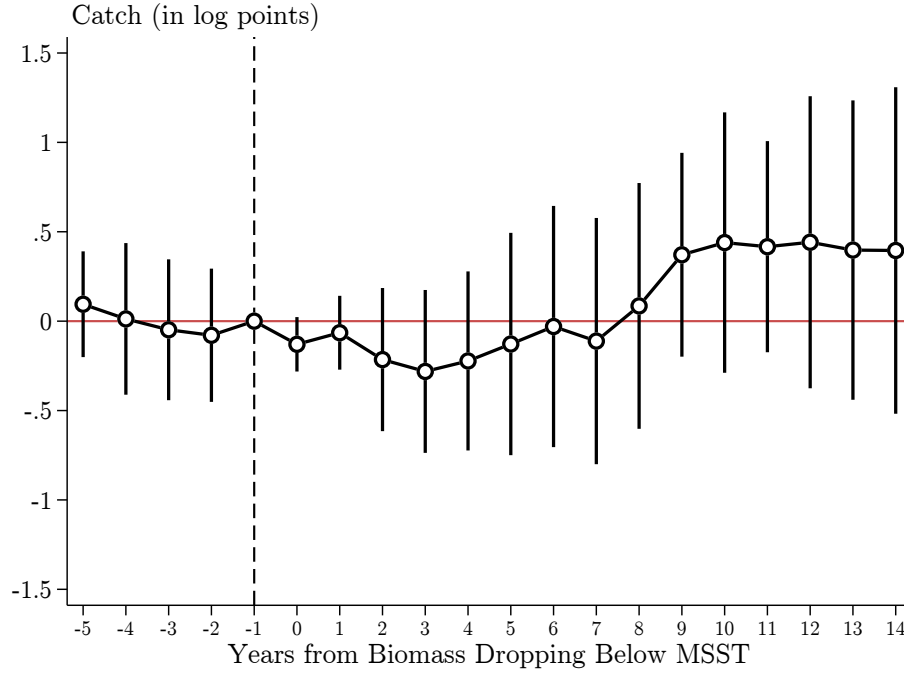
Stocks that receive a rebuilt determination experience steady biomass levels, but a sharp increase in catch, in the five years afterward. Biomass increases in the years leading to the rebuilt determination, but remains flat after (Figure 8a). Catch also increases in the years leading up to the rebuilt determination, but increases by about 36.8% in the first year after being classified as rebuilt (Figure 8b). The magnitude of the increase in catch remains stable, yet the estimates become less precise over time.

To further rule out alternative explanations for the recovery in catch, we modify the earlier contemporaneous comparison in two ways. First, we restrict the treatment group to the 37 US stocks that have ever been declared rebuilt. Second, we extend the event study time horizon to the 15 years after biomass falls below MSST, to capture stocks that start to exit rebuilding around the 10-year mark. In Figure 9a, we report that the catch of the treated stocks starts to imprecisely decrease three years after the event, then reverses and imprecisely increases six years after the event. Nine years after the event, catch levels are, on average, imprecisely above the level they were one year before the event. In the 10 to 15 years after the event, stocks that entered and exited rebuilding are imprecisely estimated to have 51.9% higher catch relative to stocks in the EU control group.

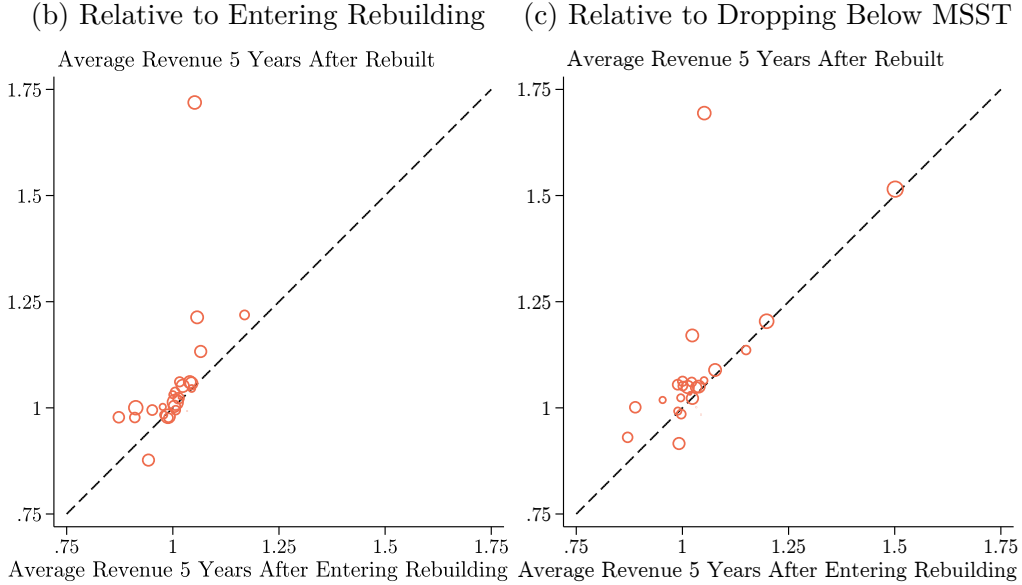
Another important outcome of fishery recovery is revenue. Unfortunately, revenue data for EU stocks is only widely available starting in 2006. Despite examining other datasets,

Figure 9: Catch & Revenue for Rebuilt Stocks

(a) Catch



Revenue Changes After Rebuilt Determination



Notes: (a) Estimation results showing coefficients and 95% CIs for the DD specification in Equation (1), for catch, for the 37 stocks that get determined as rebuilt. (b-d) Relative changes in revenue for US stocks that enter rebuilding and get determined rebuilt. Each dot size reflects the degree of recovery (percentage rebuilt), measured as the mean biomass post-rebuilt divided by the target level (B_{MSY}).

we were unable to obtain credible data for the EU before 2006 (see Section 4.2 for more details). This limits our ability to repeat previous analyses for revenue. However, for US stocks, we can compare their revenue (in 2020 USD) in the five years after they are rebuilt to the five years after they enter rebuilding. For each stock, we normalize the revenue relative to the mean revenue in the five years before entering rebuilding (Figure 9b), or to the five years before they drop below the MSST (Figure 9c). In both cases, we see that most stocks are located along or above the diagonal, reflecting that they have either recovered to their baseline revenue or exceeded it. To examine whether there is heterogeneity in revenue with respect to the degree of recovery, we use the ratio of biomass to the target level (B_{MSY}) in the post-rebuilt period as the weight for each stock. There does not appear to be a clear relationship between revenue and the health of the stock beyond its recovery above the target level. Finally, some stocks do see a decline in revenue in the five years after entering rebuilding (x-axis values below one). Only a few stocks fail to return to their previous revenue levels in the five years after rebuilding (y-axis values below one).

6.5 Evidence for Beneficial Spillovers & Ruling Out Leakage

There are several channels through which rebuilding plans can violate the stable unit treatment value assumption (SUTVA), either in the form of co-benefits for stocks in the US, or leakage to other US or non-US stocks. We use sub-samples and modifications to our specifications to examine the scope of potential spillovers. We are interested in quantifying these spillovers because they might present threats to the identification strategy, but also because they are interesting in their own right.

Beneficial spillovers (co-benefits) can occur because it is often difficult for fishers to target only one 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 fishery targeting that stock and its incidental catch in other fisheries. Some concurrently caught species will have their season closed early because the bycatch quotas of a stock in rebuilding have been met. Shortening the fishing season could lead to biomass gains for the stocks that are not in a rebuilding plan.

Stock assessments explicitly mention this type of restriction on stocks that are not in a rebuilding plan. For example, the 2016 stock assessment of the chilipepper rockfish—which never entered a rebuilding plan—describes how “catches have been greatly reduced as a consequence of trip limit reductions and area closures implemented to reduce catches

and rebuild populations of overfished species” (Field et al. 2016). Similarly, the 2011 stock assessment of the greenspotted rockfish highlights that it is not a highly sought fish, but is affected by regulations that are “intended to alter fishing mortality of primary targets and/or overfished species” (Dick et al. 2011).

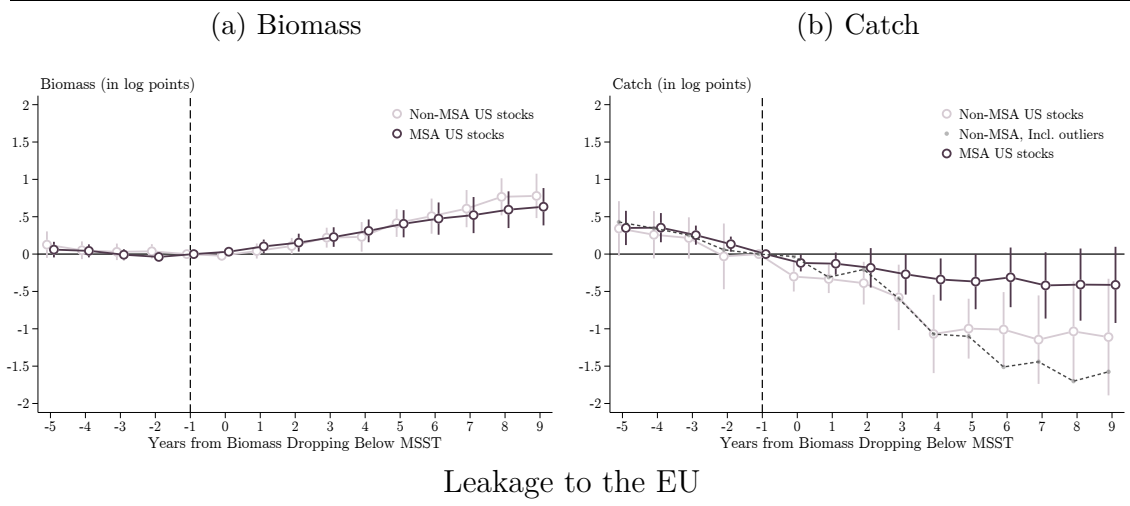
Our main analysis focuses on stocks that had their MSST defined well before 2007. However, for some US stocks, the biological reference points needed for management were only developed more recently. This could be because they have lower commercial value and were not prioritized for developing reference points, or due to challenges in the modeling their population dynamics. We use recently developed MSST values to identify stocks that we now know in hindsight dropped below their MSST, but did not receive a rebuilding plan because the information was not available to determine that they were overfished. These “would’ve, should’ve” stocks represent yet another group that experience biomass declining to overfished levels, similar to those in our main analysis, without receiving treatment.

We verify that out of 20 “would’ve, should’ve” stocks, 14 (70%) 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 those of the US stocks that entered rebuilding in Figure 10a. Stocks that we know in hindsight 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 these beneficial spillovers are real and meaningful in magnitude. In fact, we see that the catch levels for these stocks drop sharply, despite not entering rebuilding or being determined overfished (10b). The observed decline in catch is due to the restrictions placed on fish that are co-caught with other fish that do enter rebuilding plans, as discussed above. This result also confirms that contemporaneous US stocks are not a suitable comparison group, as they are affected by the treatment status of stocks with overlapping habitats.

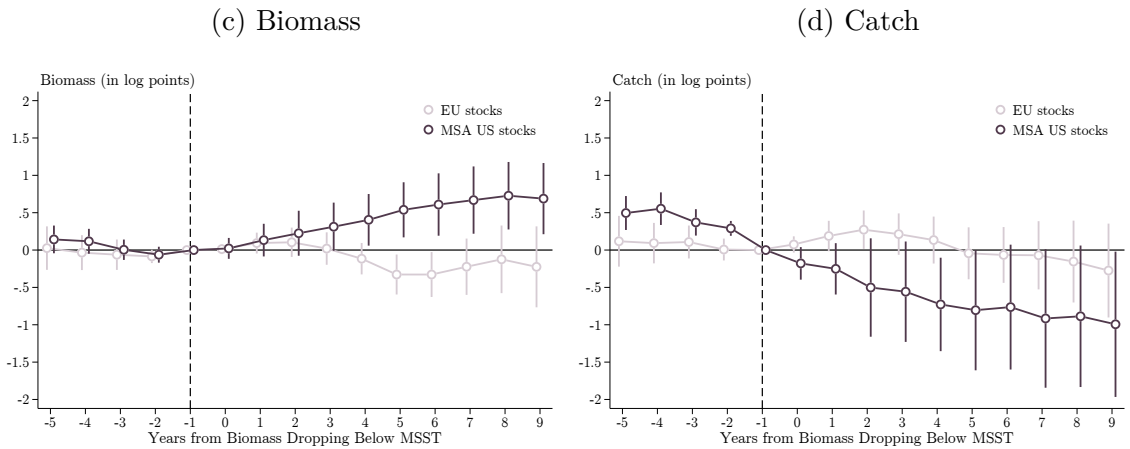
One other form of SUTVA violation is leakage. Within the US, leakage could occur if fishers shift their efforts from overfished stocks in rebuilding to healthier stocks. However, in the context of the US, this type of substitution of effort across stocks is often restricted. In many fisheries, especially 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, it would need to buy the permit, vessel, and gear from a current permit holder.¹⁶

¹⁶ Prices vary across fisheries. Sea Scallops permits—one of the most commercially valuable stocks—can fetch high prices. The sale of the so-called “Codfather’s” 11 sea scallop vessels and their associated per-

Figure 10: Summarizing Evidence for the Scope of Beneficial Spillovers & Leakage
US Spillovers



Leakage to the EU



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. In the case of US catch, for the non-MSA stocks, in panel (b), we report the coefficients and 95% CIs when excluding four outlier stocks (chilipepper - Southern Pacific coast, greenspotted rockfish - Pacific coast, walleye pollock - Bogoslof, and walleye pollock - Southeast Gulf of Alaska). We also report the coefficients (gray dashed line) from including those four outliers in the sample. In panel (a), we only report results that include the four outliers.

Another potential channel for leakage is through consumer demand shifting to other, more readily available fish. This could be through a direct response by consumers, or via 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 because we do not use contemporaneous US stocks as a control group in our analysis. In fact, one could argue that a desired outcome of fishery management is to shift some of the fishing pressure from unhealthy to healthy stocks.

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, fishers in other countries might respond to the higher prices by increasing their catch. This response would lower biomass for those stocks abroad, leading us to double-count the gain in US biomass and the decline in biomass elsewhere. 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 EU species respond after the same US species drop below the MSST. To do this, we set the event year for the non-US stock to the year that its US counterpart fell below its MSST.

Leakage from the US to the EU could appear in the following ways. First, we might observe that the EU stock’s biomass declines soon after the same US species drops below its MSST. Similarly, as a US stock’s catch levels drop after entering a rebuilding plan, we might expect the EU stock’s catch to increase proportionately. As the US stock recovers and catch levels return to baseline, we might also expect EU catch to level off, and biomass depletion to slow down or reverse.

In fact, the patterns we observe for EU stocks do not provide strong support for the existence of such leakage. In Figure 10c, we observe that an EU stock’s biomass starts to decline six years after its US counterpart drops below the MSST, yet that decline is short-lived and EU stocks quickly recover to their baseline levels. In addition, the drop in EU stock biomass is occurring during a time when, on average, US stock biomass is already starting to recover. In Figure 10d, we do see an imprecisely estimated increase in EU catch that starts around the time that US stocks drop below the MSST. However, this increase in catch tapers off quickly even though US catch continues to decline. These results support our interpretation of the contemporaneous results as not suffering from SUTVA violations that potentially lead us to double-count gains in biomass.

mits for \$46 million made the news when he was required to sell off all his vessels and permits for fish laundering.

6.6 Validating Fishery Recovery is Not Driven by Assessed Biomass Modeling

Throughout the main text we use biomass to measure the policy’s efficacy. One concern is the possibility that stock assessments may be somehow manipulated to create the appearance that populations are being successfully rebuilt. We address this in section 4.3, where we use catch data and survey data on fish abundance to demonstrate that there is strong agreement between the inputs to a stock assessment and its output of assessed biomass (see Figure 4). A second concern is that the assessed biomass might be higher simply due to a mechanistic relationship in the population biology model between lower catch levels and higher biomass. In other words, we want to reject that the higher biomass levels are simply a product of the theoretical model used to estimate biomass. We want to ensure that they are instead capturing a true signal about the status of the fishery.

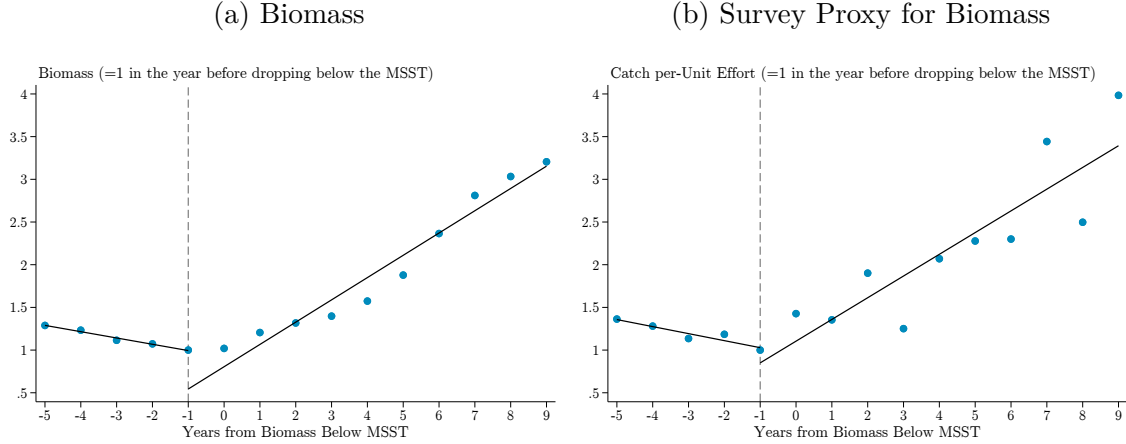
The survey data, measured as catch per unit effort (CPUE), are designed to estimate the abundance of fish in the fishery. We examine this raw data, which serves as a proxy for biomass, to see if it shows the same pattern as we observe for biomass after a stock declines below its MSST. Our comparison focuses on the 34 stocks that have received a rebuilding plan, and for which we have balanced data on both biomass and CPUE during the 1990 to 2016 period. To simplify interpretation and comparison between biomass and CPUE, for each stock, we normalize its biomass or CPUE data to be equal to one in the year just before it drops below its MSST. In Figure 11, we plot the binned means of either biomass or CPUE, re-centered around the year of dropping below the MSST.

Both biomass and CPUE exhibit a strong recovery, preceded by a slight downward trend prior to falling below the MSST (Figure 11). The fact that CPUE also increases suggests the increase in assessed biomass is not simply an artifact of the assessment process. On average, biomass increases threefold, while CPUE almost quadruples, in the 10 years after the event. These increases in magnitudes are meaningful; potentially highlighting the importance of using additional inputs (such as catch) as well as population biology to determine the stock’s status (its biomass).

6.7 Additional Threats to Identification & Interpretation

A remaining concern is that environmental conditions could be improving in US marine fisheries relative to conditions in the EU. If that were the case, our analysis could simply be capturing stock reproductive gains due to improved conditions, and incorrectly attributing

Figure 11: Fishery Recovery Observed in Biomass & Survey Proxy for Biomass



Notes: Binscatters for scaled biomass and CPUE data for 34 balanced stock during 1990 to 2016, that dropped below their MSST and subsequently entered rebuilding. CPUE acts as a proxy for fish abundance and is used in the assessment process as a key input in order to assess the stock's biomass.

that to the policy. Instead of trying to establish and measure the exact combination of environmental conditions that drive stock dynamics, we focus on the outcome of recruitment. Recruitment is measured by the biomass of juvenile stocks and is a proxy for population replenishment. If environmental conditions were improving, we would expect to see higher stock recruitment (i.e. higher growth rates). In Figure A14, we provide descriptive evidence that environmental conditions in the US are *deteriorating* rather than improving over time. Recruitment for treated stocks is lower than for historic US stocks and imprecisely declines compared to EU stocks.

In addition, we report the paired differences event study results for the historical comparison in Figure A5. The results show there are no systematic differences in catch prior to experiencing the event of interest (biomass declining below its MSST). We interpret this as suggestive evidence that demand for these stocks has not substantially changed in magnitude between the pre-1989 period and the post-1995 period. At least, not a magnitude that could provide an alternative explanation for the recovery in the biomass of the stocks.

Finally, we verify that the main contemporaneous results are not driven by outliers. We run a version of the analysis in which we exclude one stock at a time, either from the treatment or the control group. In Figure A13, we report the distribution of the coefficients we obtain from this process, along with the results we obtain using the full sample.

7 Conclusions

Regulating and conserving biological resources is challenging due to the complex dynamics that govern these processes and the inherent incompleteness of information about the state of the stocks. 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 exploit a scientific threshold that defines a stock as overfished to compare depleted stocks that receive rebuilding plans to depleted stocks that do not. Our findings confirm that while there is considerable heterogeneity, stocks managed under the MSA see improvements in biomass, on average, and that their catch and revenue recover after they are rebuilt. The MSA is an example of a policy that employs scientifically informed decision rules. Our findings suggest that the use of such pre-determined scientific thresholds to trigger policy interventions could be helpful in regulating other biological resources.

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Online Appendix

A.1 The Rebuilding of the Atlantic Spiny Dogfish

To better clarify the variables, definitions and thresholds, as well as how they interact, we plot the regulatory and stock health history of the Atlantic spiny dogfish in Figure A1. The stock was doing well in the early 90s, then increased fishing mortality led to reductions in biomass. The stock was designated as overfished in 1999. The rebuilding plan was implemented in 2002. The plan reduced fishing mortality, which reversed the trend in declining biomass and led to the stock being declared rebuilt in 2010. It is important to note that there is a lag between the stock being declared overfished and entering rebuilding. There is another lag before we observe declining fishing mortality, and another lag before observing biomass recovery.

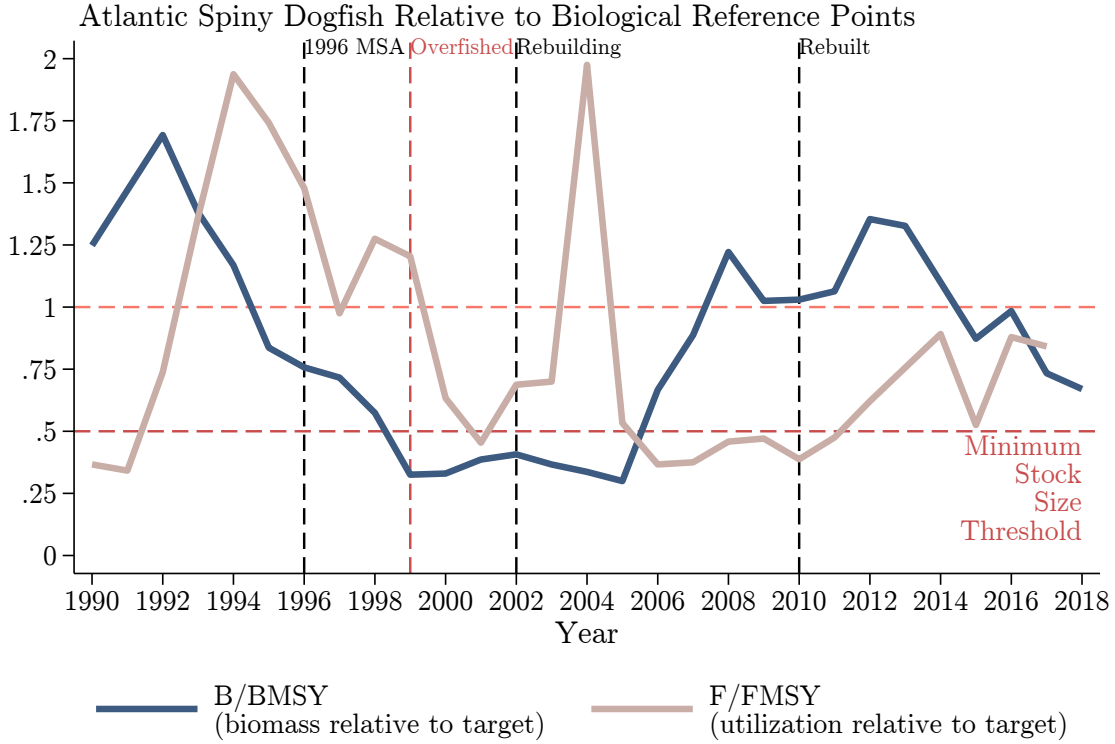
At face value, this appears to be a successful case study for the policy. A stock's biomass declined below healthy levels (B_{MSY}), and then declined below the regulatory threshold that considers it overfished (MSST). The stock received treatment by entering a rebuilding plan where management lowered catch. Finally the stock successfully rebuilt to sustainable levels (B_{MSY}). 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.

This example also clarifies the causal inference challenge of attributing the recovery of the fishery to the rebuilding plan. We cannot rule out other explanations such as natural variability in a stock's population dynamics. Causal inference can be especially challenging when variability is combined with measurement error in the estimated 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 Distribution of MSST to B_{MSY} ratios in the Main Sample

To better interpret the observed effect of the policy, it is important to keep in mind that the goal of the policy is often to double the biomass of the stock. This is because the MSST (the treatment threshold) is often set at 50% of the B_{MSY} (the target level). However, not all $\frac{MSST}{B_{MSY}}$ values are at 50%. In Figure A2, we plot the distribution of these values, where 30

Figure A1: MSA Management Example: Atlantic Spiny Dogfish



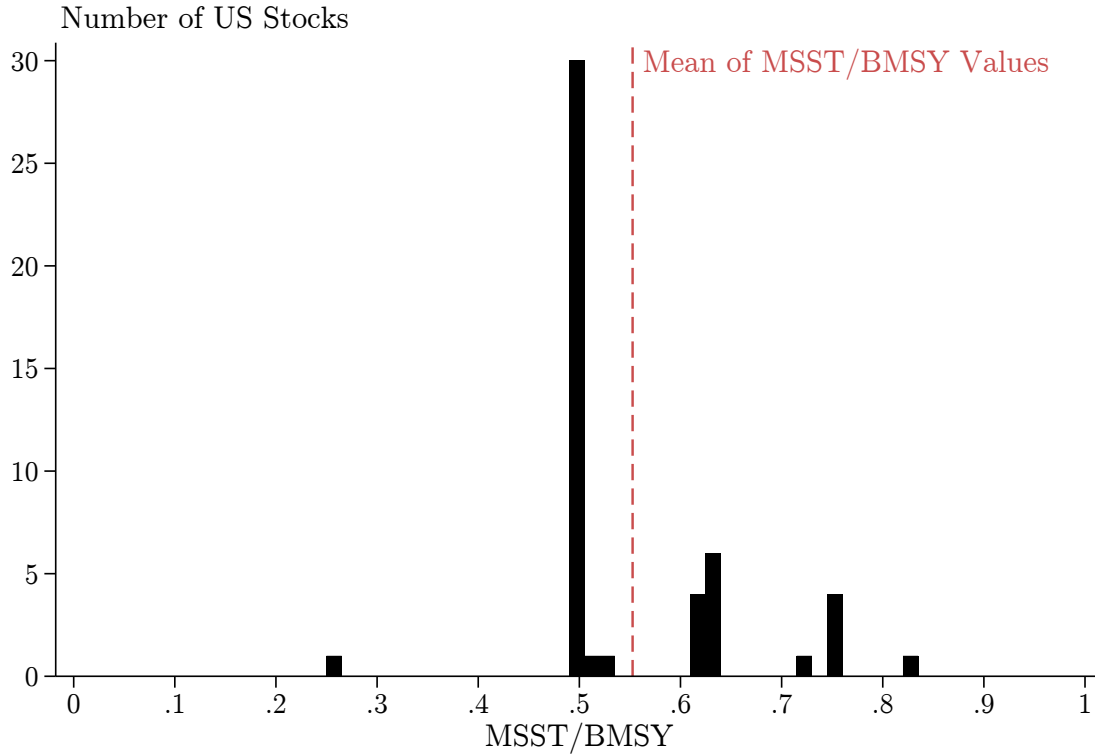
Notes: Plotting the biomass relative to the target biomass (B/B_{MSY}), and the fishing mortality relative to the target fishing mortality (F/F_{MSY}). When the stock is meeting both its targets, for biomass and fishing mortality, the values of B/B_{MSY} and F/F_{MSY} should be centered around one. When biomass drops below the Minimum Stock Size Threshold (50% of its B_{MSY} target), the Atlantic spiny dogfish is considered to be overfished (below the red dashed line). When the fishing mortality is above F_{MSY} , the stock is considered to be experiencing overfishing (above the coral dashed line).

of the 49 stocks have a ratio around 50%.

A.3 The Role of Scientific Uncertainty & Measurement Error in Triggering Rebuilding

We expand on the conceptual framework summarized in Figure 1 by plotting three scenarios that can lead to the incorrect timing of implementing a rebuilding plan. Setting the threshold too high (Figure A3a), will simply attribute the mean reversion process to the success of the rebuilding plan. Setting the threshold too low (Figure A3b), might risk the stock collapsing because of non-linearities in the recruitment process. Finally, even if the threshold is specified correctly, measurement error could incorrectly determine that the stock has fallen or not fallen below the MSST (Figure A3c).

Figure A2: Distribution of MSST to B_{MSY} Ratios



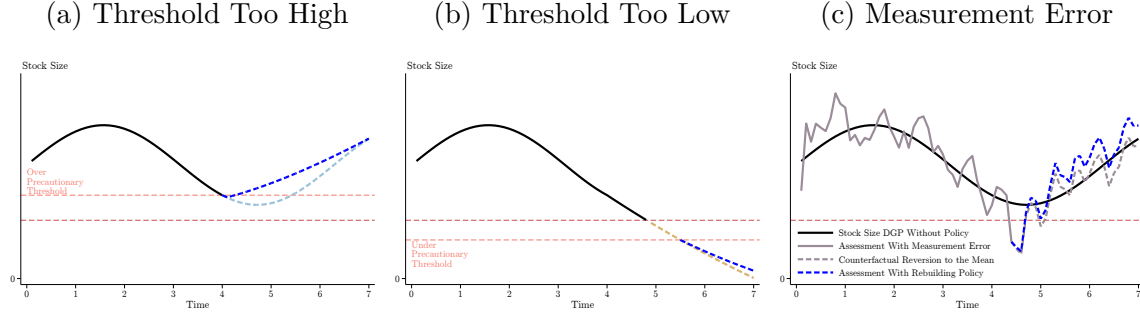
Notes: The distribution of the values of the MSST relative to the B_{MSY} level for the 49 stocks in the main treatment group sample (US stocks, that have ever entered a rebuilding plan).

A.4 Delay Between Overfished Determination & Rebuilding Plan

Under the MSA, regional management must develop and implement a rebuilding plan for stocks designated as overfished. The 2006 reauthorization of the MSA requires rebuilding plans to be implemented within two years following the overfished designation. Historically, many stocks experienced long delays between being declared overfished and entering a rebuilding plan. There can also be delays between when a stock's biomass declines below its MSST and when it is declared overfished.

We summarize these delays in Figure A4. Before the 2006 reauthorization of the MSA—which introduced the requirement to implement a rebuilding plan within two years of an overfished designation—delays were substantial. After 2006, fewer stocks were declared overfished, or entered rebuilding, and those that did saw mostly short delays. After 2006, the longer delays happened between the year a stock declined below its MSST and the year it was declared overfished. These delays could be due to changes in the science. At the time, the stock may have not even been considered overfished, but based on improved, scientific

Figure A3: Potential Implications of Scientific Uncertainty & Measurement Error



Notes: Summarizing scenarios under which the rebuilding policy could be unnecessarily triggered (panels a and c), or triggered too late (panel b).

estimates of the MSST, we now consider the stock to have been overfished (see the Online Data Appendix for more details on scientific changes to reference points over time). 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 the Endangered Species Act where their recovery plans would be governed by this Act.

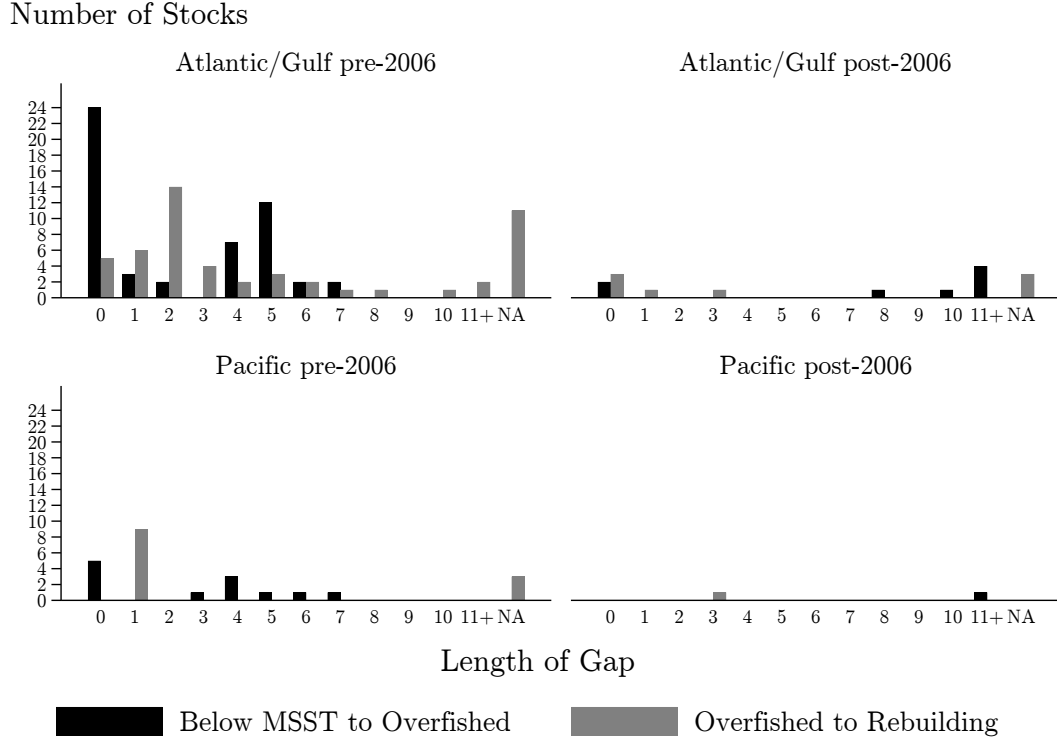
A.5 Event-Study Results for the Paired Differences Estimation

In the main text, we report a summary of the paired difference results in Table 2. Here we present the full event-study coefficients for biomass and catch, for the stocks that met the condition for rebuilding (biomass below the MSST) in both time periods (before and after the 1996-reauthorization of the MSA). The results for biomass (Figure A5a) show that compared to the years before rebuilding plans were required, stocks have more than doubled in biomass in the year after falling below the MSST. For catch, we note that in the pre-event period, catch levels are not systematically different, suggesting that there are no large changes to the demand for those stocks that might explain the recovery following the event. Similarly to biomass, catch levels recover for stocks that enter a rebuilding plan, relative to the evolution of catch after the event in the absence of the rebuilding treatment.

A.6 DD Results Centered Around Overfished Determination & Rebuilding Plan Implementation

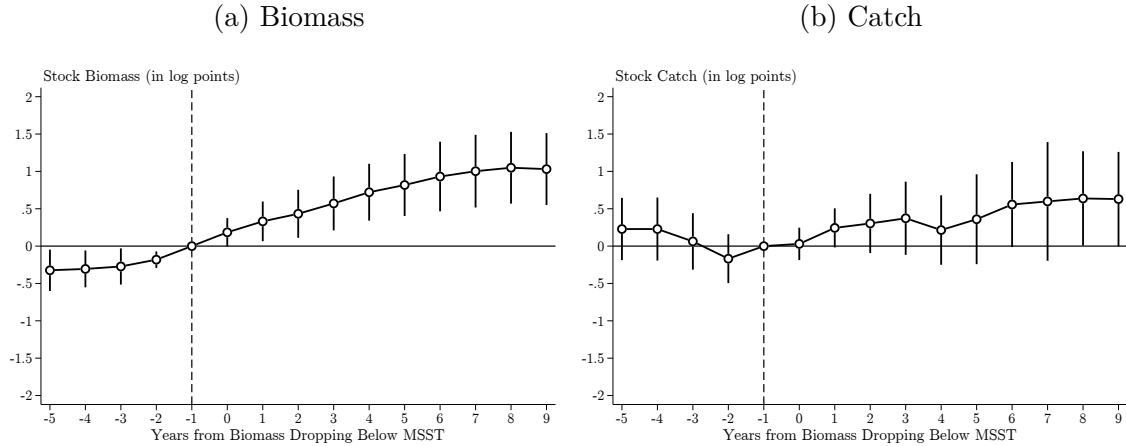
In the main text, we define the year a stock declines below its MSST as the event of interest. Here we examine different events as the treatment onset: the year a stock is declared over-

Figure A4: Years From Below MSST to Overfished to Rebuilding Plan



Notes: Summarizing the time, in years, between either the first year we observe the stock below its MSST and the first year it was declared overfished, as well as the number of years between a stock being declared overfished and the first year it entered a rebuilding plan, if any.

Figure A5: Paired-Differences Event Study Estimation Results

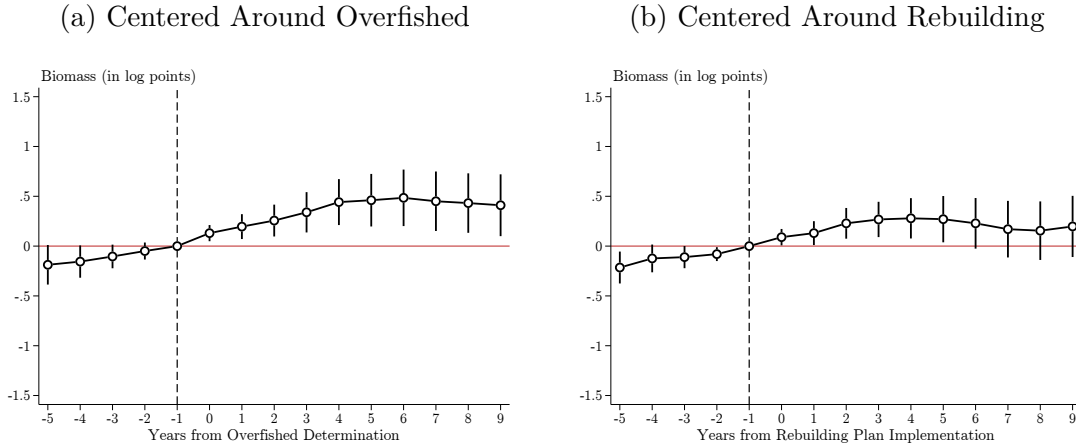


Notes: Estimation results showing coefficients and 95% CIs for the specification in Equation (2). Standard errors are clustered at the stock level.

fished and the year a stock entered a rebuilding plan. In Figure A6, we report results for the same specification in Equation (1), centering around the year a stock is declared overfished

or entered a rebuilding plan. Overall, we recover qualitatively similar results to those we report in the main text. However, under the MSA, treatment starts before the implementation of a rebuilding plan. In other words, increases in biomass can be observed before these alternative events of interest (see the main text for more details). We summarize these re-centered estimations in Table A1. The results for biomass (columns 1 to 3) demonstrate how the full effect we estimate is attenuated as some of the early gains in biomass are excluded from the treatment period, and instead become part of the pre-treatment trends. We also see that in the one to five years after the event—i.e., being declared overfished or entering rebuilding—the biomass increases more than it does in the one to five years after the stock falls below the MSST. The results for catch demonstrate a similar pattern, where once the stock has started to recover, we see catch levels increasing relative to one year before the event. Finally, the number of stocks in the sample slightly declines in columns 2, 3, 5, and 6 because we have fewer stocks with a 10-year balanced time window after these events.

Figure A6: The Effect of Rebuilding Plans on Stock Biomass Using Different Treatment Onsets



Notes: See Figure 5.

A.7 Using Normalized Biomass Instead of Logged Biomass

In the main text, we use logged values for all the outcomes. Here we report results from normalizing biomass by the MSST. In Figure A7, we report the same estimation as in Figure 5, only using normalized instead of logged biomass. We recover the same patterns, and similar magnitudes. However, the results are less precisely estimated in the contemporaneous comparison. Our emphasis in the main text is on the logged biomass results because it does

Table A1.
Contemporaneous Comparison Results When Centering Around Different Events

	Logged Biomass			Logged Catch		
	(1)	(2)	(3)	(4)	(5)	(6)
Event Time 1-5	0.10 (0.07)	0.27 (0.07)	0.20 (0.07)	-0.18 (0.14)	0.05 (0.13)	0.18 (0.16)
Event Time 6-10	0.42 (0.14)	0.45 (0.13)	0.20 (0.13)	-0.06 (0.27)	0.50 (0.26)	0.35 (0.22)
Within R^2	0.134	0.143	0.095	0.058	0.034	0.042
Observations	2,214	2,106	2,025	2,214	2,106	2,025
Clusters	82	78	75	82	78	75
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 for biomass, in log points, while columns 4-6 report results for catch, in log points. All regressions include stock and year fixed effects. Standard errors are clustered at the stock level.

not require normalizing by a value that changes over time, and for which there might be considerable uncertainty (see Online Data Appendix for details).

A.8 Historical Comparison Results Without Quadratic Time Trends

In the main text, results for the historical comparison include quadratic time trends (Figures 5c, 5d, 6c, 6d). In Figure A8, we repeat the estimation reported in the main text, but only include unit fixed effects without time trends. Overall, we recover similar trajectories for the outcomes after stocks enter rebuilding.

A.9 Historical Comparison Results With Fuel Prices and Climate Indices

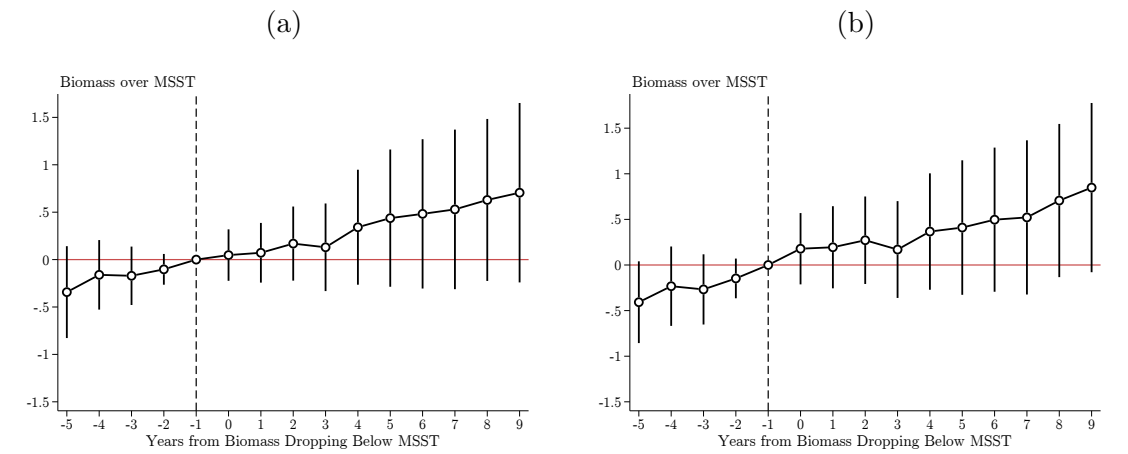
In the main text, in the historical comparison event study analysis, we include quadratic trends. Here we also add fuel prices and climate indices (see Online Data Appendix for

Figure A7: Evidence for the Policy's Outcome: Fish Biomass Recovery

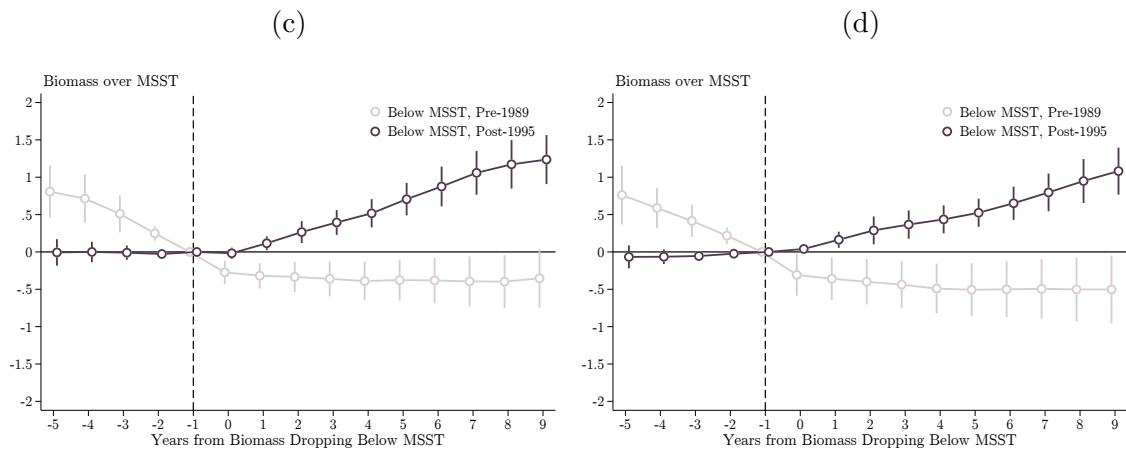
Including All US Stocks

Excluding New England Stocks

Contemporaneous Comparison, US to EU



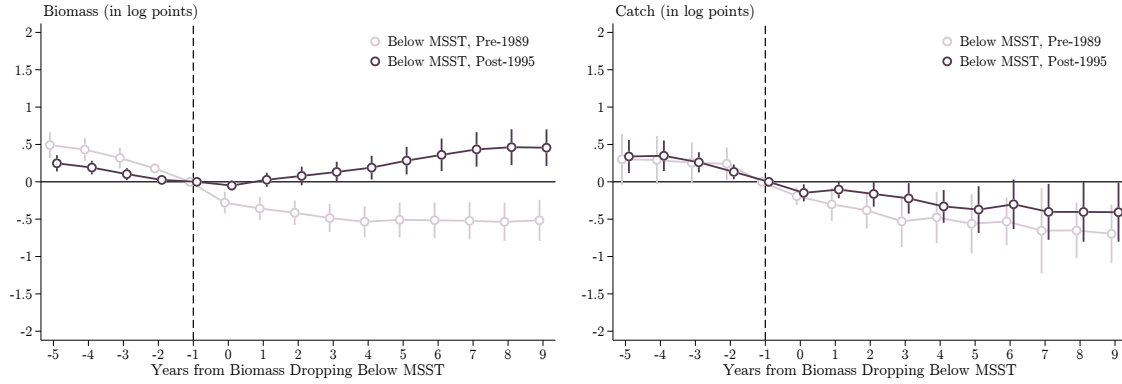
Historical Comparison, Present-US to Past-US



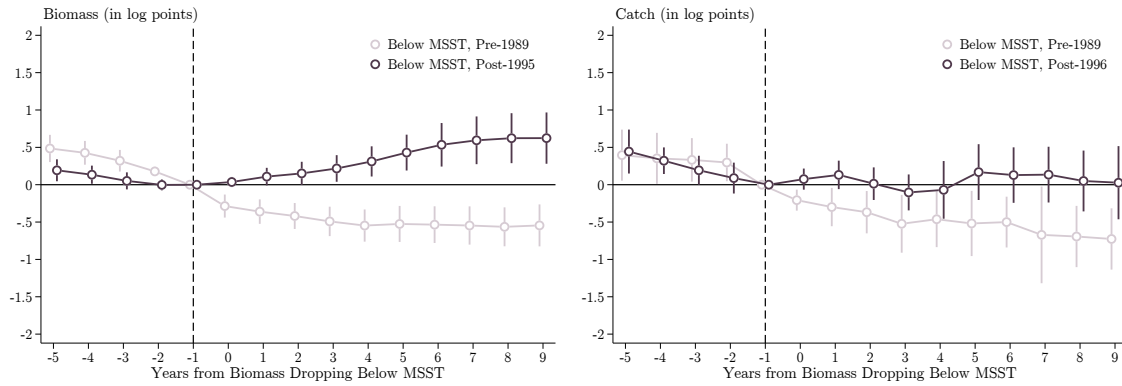
Notes: see Figure 5.

Figure A8: Estimation Results for the Historical 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

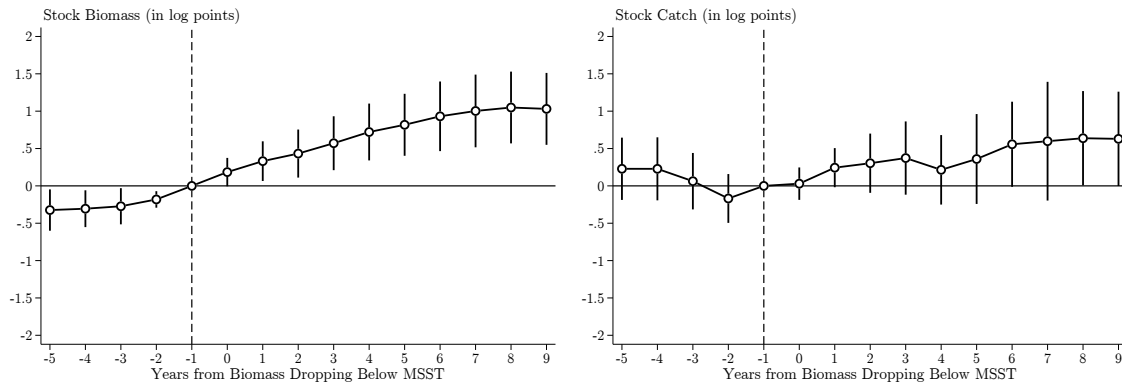


Holding Stock Composition Constant
(c) Biomass: Double-Event-Study (d) Catch: Double-Event-Study



(e) Biomass: Paired Differences

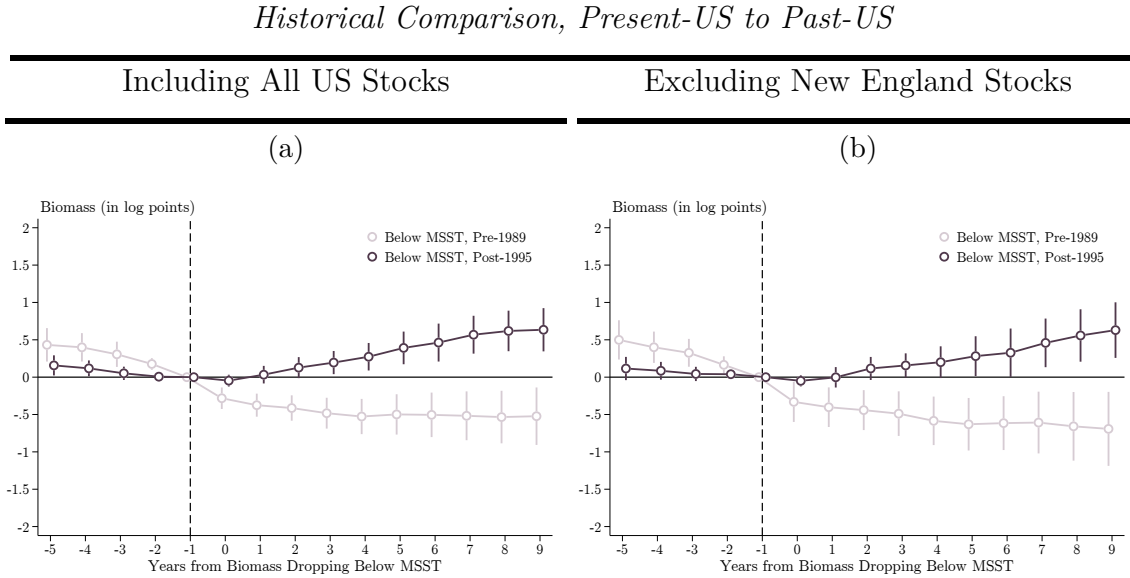
(f) Catch: Paired-Differences



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

more details) as additional time-varying controls. The results in Figures A9 and A10 recover similar patterns and magnitudes as the results in the main text. This means that costs, proxied by diesel fuel costs, and environmental conditions, proxied by climate indices, fail to explain the results we report in the main text.

Figure A9: Historical Comparison Biomass Results with Fuel & Climate Controls



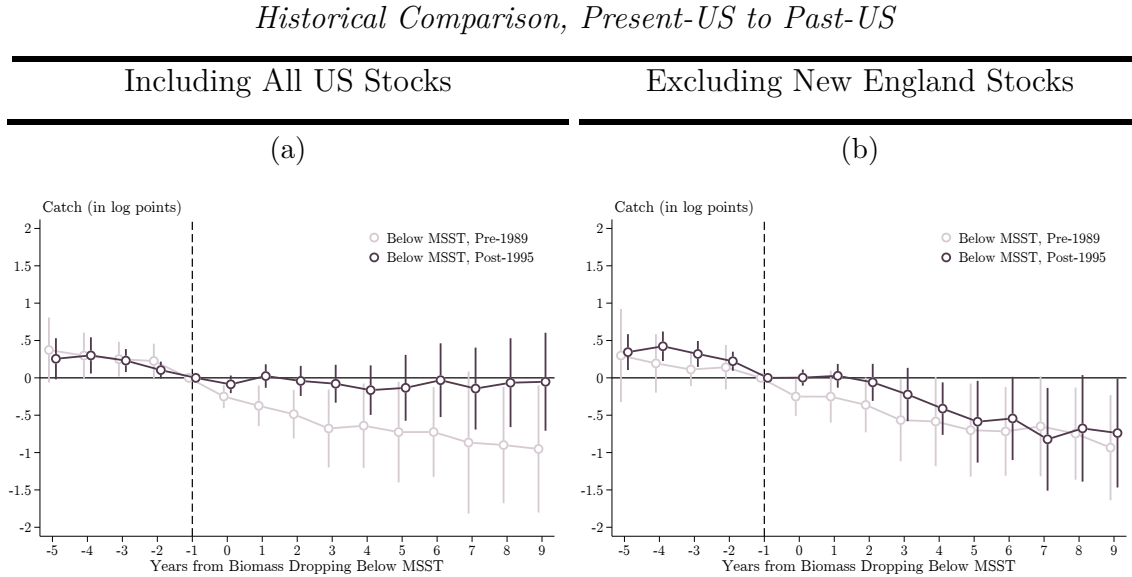
Notes: Version of Figure 5 (panels c and d) with controls for fuel prices and climate indices.

A.10 Stock-specific Estimation Results

In the main text, we report results for the historical comparison that examines stocks whose biomass declines below their MSST pre-1989 as well as post-1995. Here we report separately estimated regressions for the same set of stocks to fully describe the heterogeneity in Figures 5c and 6c. We use the same sample, but estimate a single regression for each stock. Each regression includes a dummy variable for being one to five years after declining below its MSST, and another dummy variable for being six to 10 years after declining below its MSST. These two coefficients are estimated relative to the omitted category of years before declining below its MSST. For each stock, we estimate four regressions: for biomass and catch outcomes, and for biomass declining below its MSST before 1989, and after 1995.

In Figure A11, we report the separately estimated coefficients for each stock on the effect of being six to 10 years after being below the MSST. We sort the stocks from top to bottom based on the lower bound of the 95% CI for the result on biomass, pre-1989. One immediate

Figure A10: Historical Comparison Catch Results with Fuel & Climate Controls



Notes: Version of Figure 6 (panels c and d) with controls for fuel prices and climate indices.

observations that arises from the figure is that nearly all stocks that dropped below their MSST, pre-1989, were still well-below their MSST six to ten years after dropping below that threshold. However, the results from after rebuilding plans were required show that several stocks increased in biomass in the six to ten years after having biomass below the MSST. Results for catch are more mixed with some stocks experiencing lower catch in both pre-1989 and post-1995 periods, while others switching from continued low catch to higher catch, or vice-versa.

For visual inspection of the stock-specific estimation results, we summarize them using kernel densities for the biomass and catch outcomes in Figures A11b and A11c. The distribution for both the effects on biomass and catch in the post-1995 are shifted to right relative to the results from pre-1989. More importantly, the pre-1989 distributions are centered around negative values, highlighting that with falling biomass levels, catch levels declined as well. The same stocks, however, experienced growth in biomass, as well as higher levels of catch, once harvest control rules and rebuilding provisions were put in place as part of the 1996-reauthorization of the MSA.

A.11 Heterogeneity by Length of First Rebuilding Plan

In the main text, we pool all the stocks in the treatment group regardless of their duration in a rebuilding plan. Under the MSA, stocks need to have a rebuilding plan that can build them back to B_{MSY} within 10 years with 50% probability of success. In some cases, there are biological considerations that provide exemptions for the 10-year requirement (e.g. long generation times, low fecundity, etc.). Here we use data collected on initial, intended, rebuilding plan time frame, as it was designated the first time the stock entered rebuilding. Subsequent updates to the rebuilding plan could also have altered the length of the plan. We focus on the initial length because it reflects the best available information at the time the stock entered rebuilding, and before any additional constraints were either realized or placed.

We define stocks as either having short or long rebuilding plans, below 10 years or above 11 years, respectively. There are 36 stocks with a short rebuilding plan, and 13 stocks with a longer rebuilding plan. The mean plan length is 17.5 years, with a standard deviation of 16.9 years, and with a minimum of four years, and a maximum of 95 years. This means that most, 73.5%, of the stocks in the treatment group are expected to be rebuilt in a period of under 10 years. It is worth noting that in the main text, as well as in this analysis, we center our event around the year the stock's biomass declines below its MSST, and not the time the stock entered rebuilding. For five stocks, we do not have a rebuilding time length because they were declared rebuilt before they received a full rebuilding plan with an intended time frame. We classify those stocks as having a short rebuilding plan.

Using this definition of short and long rebuilding plans, we modify the specification in Equation (1) to reflect this potential source of heterogeneity in response to the treatment. We include two sets of leads and lags, one set interacted with the dummy variable for having a short rebuilding plan, and one interacted with the dummy variable for having a long rebuilding plan. In Figure A12, we present the results from this single regression, for biomass and for catch.

US stock biomass increases for stocks with short and long rebuilding plans. However, those with a short rebuilding plan exhibit an earlier recovery pattern. Albeit, we cannot reject the null hypothesis that the effects are the same across the two groups. Indeed, by the tenth year after the stocks fall below their MSST, the two groups appear to have converged to about the same recovery level, relative to their baseline. Catch remains nearly flat and then recovers for stocks with a short rebuilding plan, but declines sharply for stocks with a long rebuilding plan. This reflects an important dimension of heterogeneity where some

stocks require a more intense rebuilding plan that places larger constraints on catch, for a longer period of time. Even though we can reject that the null hypothesis that there is no effect on catch for the long rebuilding plan group, the results are fairly noisy. Catch is precisely estimated to be 62.8% lower for stocks with long rebuilding plans when we combine the coefficients from the sixth to tenth years after declining below the MSST.

A.12 Examining Sensitivity to Outliers by Using Leave-One-Out Estimation

Extreme outliers in either the treated sample or the comparison sample could have a large influence on the results. To validate that our estimated average treatment effects in Table 1 are not due to extreme outliers, we repeat the estimation by leaving one stock out of the sample each time. Specifically, we repeat the cohort-weighted DD estimation by excluding from the sample either one of the treated or one of the control stocks. In Figure A13, we plot the distribution of the linear combination for the lagged effects for years one to five, and years six to 10. Overall, the jackknifing distributions are narrowly centered around the estimated coefficient from when we use the full sample (those reported in Table 1).

The results for catch, in the six to 10 years after dropping below the MSST, are more dispersed, and skewed to the left. This potentially reflects that excluding stocks that have either completed or nearly completed their rebuilding plans results in estimating a smaller recovery in catch. There are two cases where excluding one stock flips the sign of the result. The first case is when we exclude the EU stock, European capelin. In this case, the estimate is slightly positive for one to five years after the event. The second case is when we exclude the EU stock, European anchovy. The estimate is slightly negative for six to 10 years after the event. In both cases, these are stocks that experienced fishing moratoriums for several years.

A.13 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

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).

declined below their MSST was poor environmental conditions, caused by either long-term climatic oscillations or short-term shocks, then a reversal of the oscillations 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 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 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 A14a, 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 historical 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 A14b and A14c). In other words, more beneficial environmental conditions are not driving increases in biomass because recruitment-per-biomass is not differentially higher for stocks in the US relative to the non-US stocks or historical 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; Pershing et al. 2015), especially for US New England 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

¹⁸ Recruitment is often measured as a quantity of juvenile fish within a particular fish stock during a given year. Changes to habitat, upwelling, primary productivity, food availability, predators and temperature can all impact recruitment.

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).

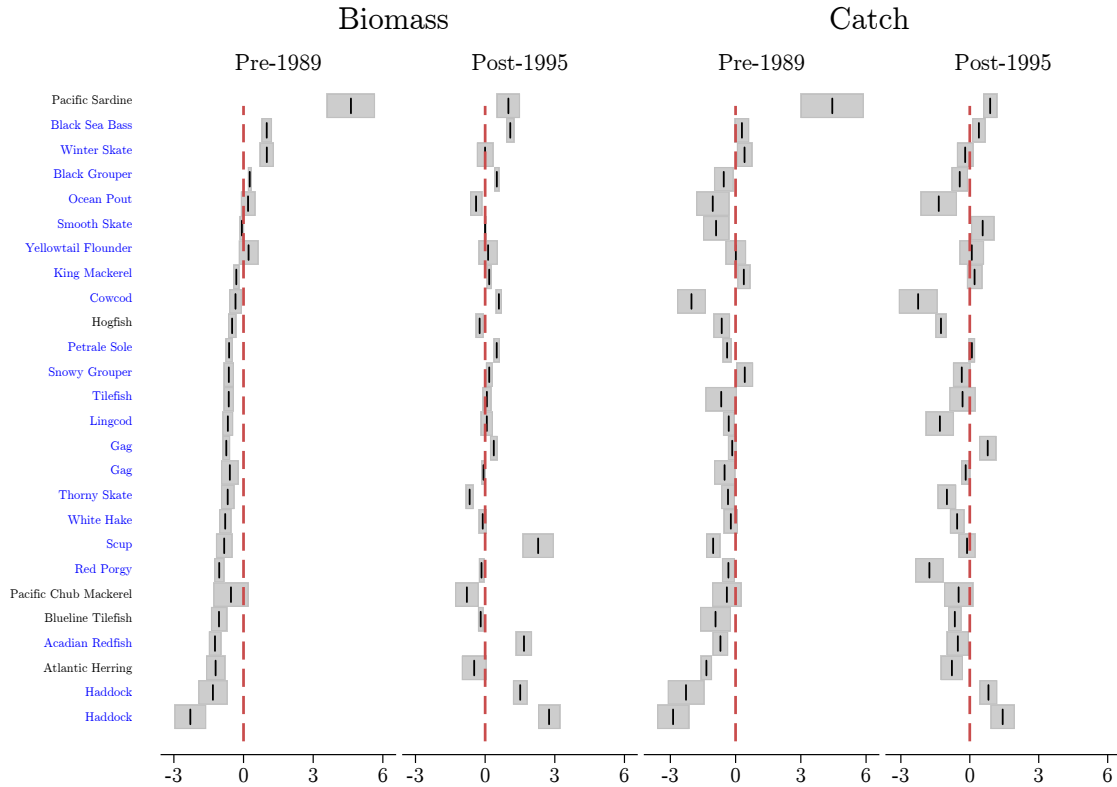
A.14 Suggestive Evidence for Compliance

In the main text, we discuss some of the challenges that the New England Fishery Management Council faced with fishers complying with fishery management and rebuilding plans. While we do not have quasi-experimental variation in the degree of compliance, we can explore this channel descriptively. In Figure A15, we plot the mean change in stock biomass during the first 10 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 10 years after entering rebuilding. This acts as a proxy for how fishers are complying with management decisions regarding the utilization of the stocks. The higher the catch is above the TAC, the lower the gain in biomass is. In other words, we observe a positive correlation between biomass change and compliance (where complying is when catch is below the TAC). This pattern is the same when we compare the change in biomass to the difference between MSY and TAC, otherwise known as a management buffer. This buffer is put in place when there is uncertainty in the science or ability for management to implement a policy. Though it is used for uncertainty, some regions put in zero buffer, while other regions put in a buffer for every stock.¹⁹ 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.

¹⁹ Lower TAC relative to the MSY reflects a larger precautionary buffer placed by stock managers.

Figure A11: Changes in Biomass & Catch Following Decline Below MSST, by Stock

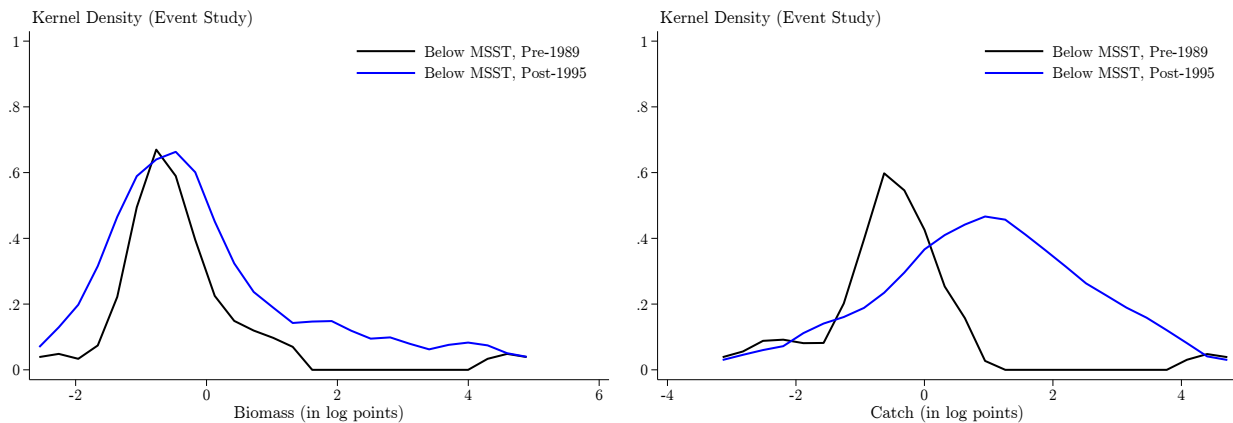
(a) Biomass & Catch, by Stock, Six to 10 Years Post-Event



Effects of Biomass Dropping Below MSST (in log points): 95% CI

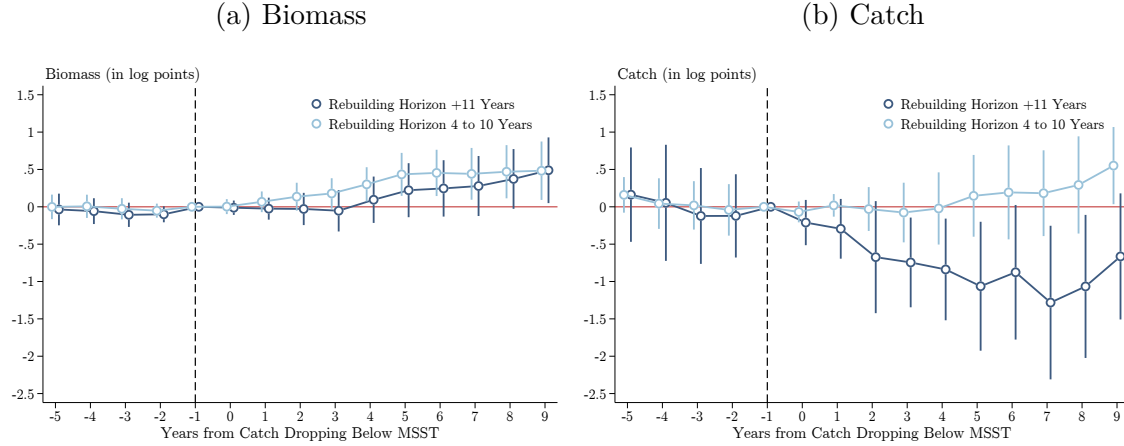
(b) Biomass

(c) Catch



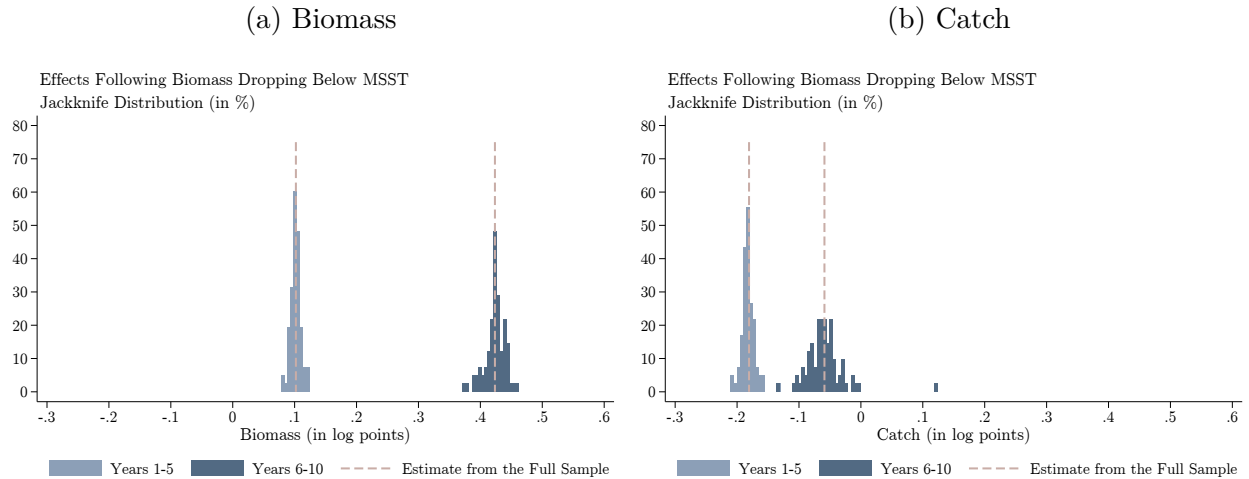
Notes: We report the estimates from a stock-by-stock regression, where we report the coefficient on a dummy variable for being six to 10 years after the event of dropping below the MSST. We repeat the estimation in pre-1989 and post-1995 periods, capturing the historical comparison when holding the composition of stocks constant (see Figure A5). Stock that are highlighted in blue are those that also entered a rebuilding plan post-1995. In Panels (b) and (c), we summarize the distribution of the coefficients by the time period for each outcome.

Figure A12: Contemporaneous Comparison Estimation Results for Intended Rebuilding Plan Length



Notes: Estimation results showing coefficients and 95% CIs for a modification of the specification in Equation (1). We interact the event time dummies with a dummy for either having a short (4 to 10 years) or long (over 11 years) rebuilding plan length. There are 36 stocks with a short rebuilding plan, and 13 stocks with a long rebuilding plan. Standard errors are clustered at the stock level.

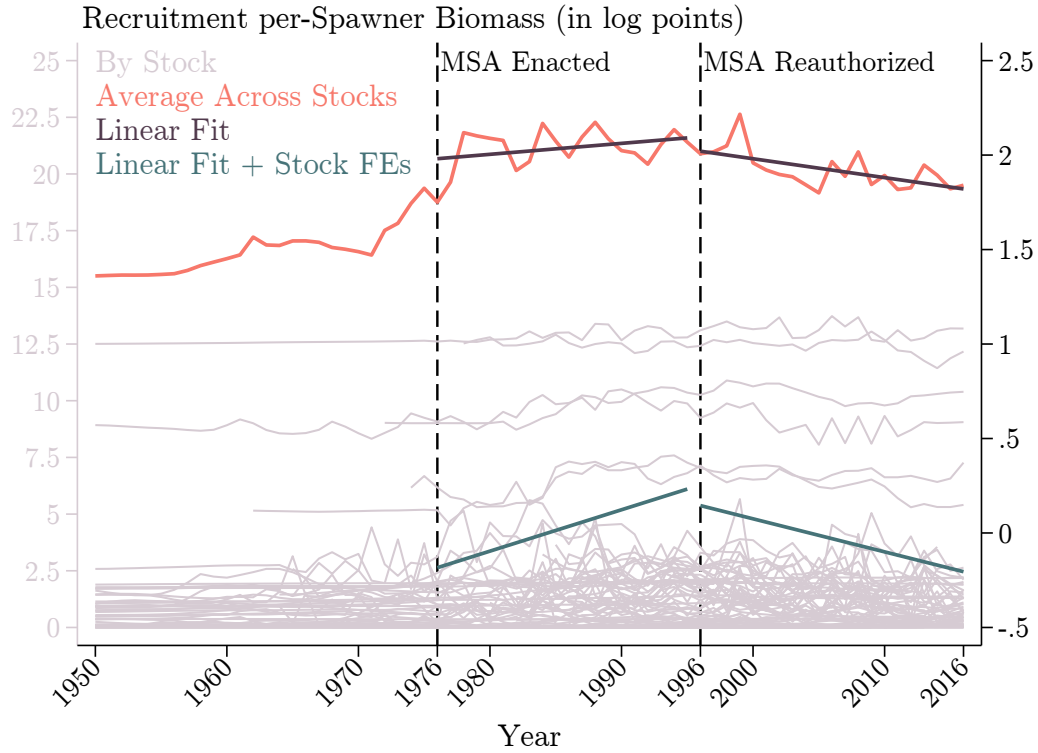
Figure A13: Contemporaneous Comparison Jackknifing Estimation Results



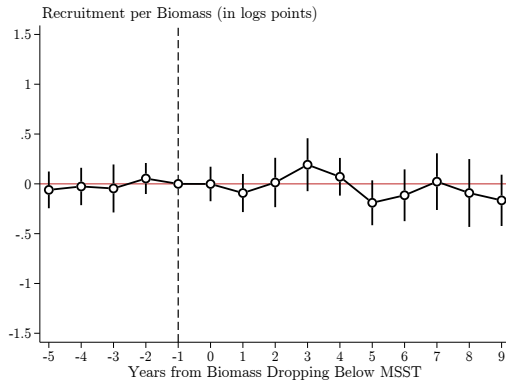
Notes: Repeating the estimation reported in Table 1, column 2, while excluding one stock from the sample in each iteration.

Figure A14: Assessing Changes in Stock Growth Dynamics

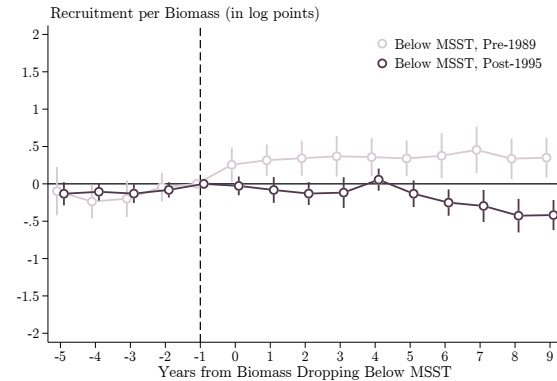
(a) Trends in Recruitment Dynamics



(b) Contemporaneous Comparison



(c) Historical Comparison

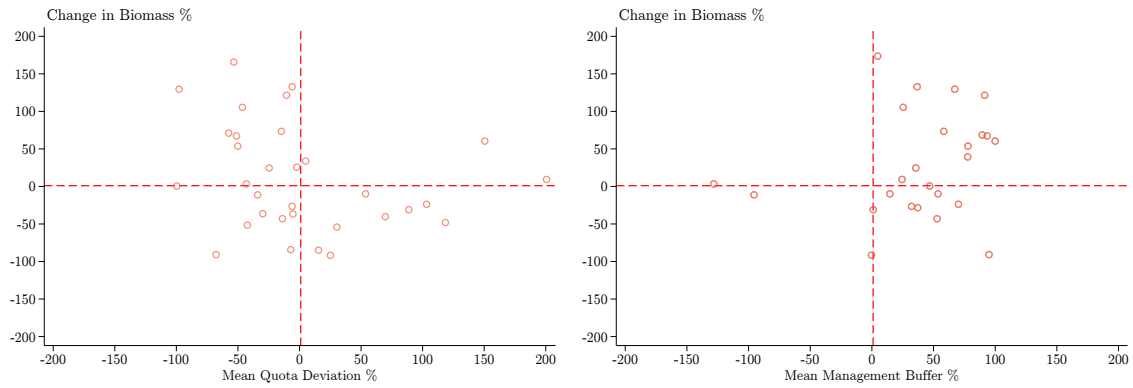


Notes: In panel (a), each gray line (left y-axis) corresponds to recruitment per-biomass of one stock over time. The coral line (right y-axis) is the average across stocks in each year. The linear fit lines (right y-axis), in dark purple and dark teal, are estimating a simple linear trend model either 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 5a, and panel (c) repeats the paired differences between the same stocks in the historical comparison group as in Figure 5c.

Figure A15: 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 10 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.

Online Data Appendix

B.1 US Data

B.1.1 Times Series and Reference Point Data

We sourced US stock biomass, catch, fishing mortality, and recruitment (productivity) data from NOAA’s Stock SMART (Status, Management, Assessments, & Resource Trends) database. Stock SMART collects its data from stock assessments, a scientific process that reports quantitative and qualitative information about a given stock, including time series data, biological reference points, and statuses regarding overfishing, overfished, approaching overfished, and rebuilt. These stock assessments typically result in a stock assessment report.

Stock SMART’s database is incomplete, resulting in stocks with missing time series, missing biological reference points, and mismatched units between the time series and reference point data. To fill in these gaps in data, we performed the following steps when encountering a stock with one or more of these issues. First, we would search through the stock assessment report published by the responsible scientific agency for the missing data. If the missing data was not found in the assessment report but the report alluded to its existence, we would then contact the stock assessors and request the missing data. Once the data was found or provided, we would populate the missing values in our dataset (see “Stock documentation and data cleaning.csv” for all manual entries and unit conversions). When a stock’s biological reference point did not match the units of its time series data, such as a stock’s MSST and its biomass time series, we would convert the reference point to match the units of the time series data.

A single stock can have multiple stock assessments over time, where each new stock assessment may supplement or completely update the time series and reference point data from the previous stock assessment. Stock SMART collects the data from stock assessments as far back as 2005. However, stock assessments do exist prior to 2005. In this study, we used the most recent stock assessment to use for each stock, unless it had limited data availability. In some cases, we chose an older assessment if it had a longer time series of data or possessed a variable (such as catch) that the newer assessment lacked. See “Stock documentation and data cleaning.csv,” in the supplementary files for the specific assessment year’s data we used for each stock in the study.

As of October 2021, Stock SMART contained data for 311 stocks. In this study, we excluded freshwater species or diadromous fish such as salmon whose biomass depend on

many land-based policies in addition to the MSA. We also excluded crab species because the fishing practices, stock assessment methods, and management actions can be quite different than other marine fisheries. In addition, we omitted highly migratory stocks, and stocks that were managed under international agreements which are outside the purview of the MSA.

Choosing one stock assessment also means we are using the set of reference points (MSY , B_{MSY} , $MSST$, and F_{MSY}) that were calculated and reported in that assessment, and applying them to the time series of the stock. This decision leaves reference points constant for the entirety of a given stock's time series. The implication is that the $MSST$ reference point may not reflect whether the $MSST$ was crossed in an earlier period of a stock's time series, due to changes in fishery selectivity, weight at age, maturity at age, or natural mortality.

Constructing a dataset that reflects annual changes in reference points over a stock's entire time series is currently not viable due to a lack of readily available data, especially prior to 2005. In some cases, reference points are reported in different units that cannot be easily converted from one type to another. For example, one assessment could report a B_{MSY} value in kilograms per tow (reflecting reliance on survey data and potentially no population biology model), whereas a subsequent assessment might report B_{MSY} in metric tons. In more extreme examples, one assessment can report the reference point in eggs, and another assessment in number of individuals or in metric tons.

In addition to time series data from Stock SMART, we compile a time series dataset of stock survey data from NOAA's Distribution Mapping and Analysis Portal. Biomass time series data reported from Stock SMART are typically the output of a model used in a stock assessment to estimate a stock's biomass. An input of these models is, among other collected data, survey data. Survey data are gathered via bottom trawl surveys, where a research boat (a trawler) will go fishing. Researchers use the same boat and gear and will fish at the same time every year. They also grid off the ocean and trawl the same number of times in each grid. They will catch, identify, measure, and dissect the fish. Bottom trawl surveys provide data for stocks such as length, age, gender, and diet. The total amount of a particular stock captured during these surveys are a preliminary measure of its abundance, typically measured in kilograms per tow. We use survey data to validate that the stock assessment data does not deviate significantly from observed data.

B.1.2 Landings and Revenue Data

US landings and revenue data were collected from NOAA's Fisheries One Stop Shop (FOSS) Landings System database. FOSS reports annual commercial and recreational landings and

revenue data at the stock-region and stock-state levels sourced from regional partners that collect these data. Landings are the amount of fish of a particular species that are sold. Landings data is required to be reported by permitted dealers who buy the fish. This is different from catch which include landings, bycatch, and discards and is estimated from the stock assessments. For some fisheries, third-party observers are placed with dealers and on fishing boats to verify landing and catch data, including discards and bycatch.

FOSS does not always follow the same stock grouping conventions as Stock SMART. For example, Stock SMART distinguishes between three separate stocks of Atlantic cod within New England (Georges Bank, Eastern Georges Bank, and Gulf of Maine) whereas FOSS only has one. When possible, we match each FOSS stock to its corresponding Stock SMART stock. When we encounter a discrepancy in stock classification between the two databases, we sum the catch of same species stocks within the same region, and distribute the landings and revenue data to each stock based on its share of total catch that it makes up in that region.

B.1.3 Management Determination Data

We compiled data on when stocks were declared overfished or entered a rebuilding plan primarily from NOAA’s Status of Stocks (SOS) reports. These annually released reports list changes in determination statuses for stocks across each fishery management council, namely, experiencing overfishing, approaching overfished, overfished, entering rebuilding, currently in rebuilding, and determined rebuilt. We convert these SOS reports into a time series for each of these statuses, then merge this dataset with the stock data we collected from Stock SMART. In addition, we verified our stock status data with internal documents obtained from NOAA, specifically for the earliest SOS reports, which used the overfishing and overfished determinations interchangeably. These documents also allowed us to verify the original rebuilding plan lengths for stocks which were determined overfished and required a rebuilding plan. These original rebuilding plan lengths may differ from the length the actual rebuilding plan had. It is worth noting that our data on stock status is more accurate than what is available in public records. Our quality assurance process resolved several inaccuracies that were never corrected in publicly available records.

B.1.4 Catch Limit Data

We use catch limit data to examine fishers’ compliance with imposed limits on harvest of rebuilding stocks, as well as management’s setting of precautionary buffers between MSY and

the prescribed catch limit. Our catch limit dataset was constructed by combining catch limit data from each jurisdiction. North Pacific catch limit data were sourced from NOAA’s Alaska Catch Accounting System, which provides yearly catch limit values for groundfish stocks in the Bering Sea/Aleutian Islands and Gulf of Alaska. Regional fishery management councils and science centers provided yearly ACL data for Pacific groundfish stocks and yearly ACL data for both New England and Mid-Atlantic stocks. Annual ACL data for South Atlantic and Gulf of Mexico stocks were taken directly from the NOAA Fisheries Southeast Region Annual Catch Limit (ACL) Monitoring website, which provided ACL data along with each stock’s commercial and recreational landings data.²⁰ Lastly, additional data were collected and existing data were verified from catch limit data gathered from a FOIA request to NOAA for these values.²¹

B.1.5 Fuel Prices and Climate Indices Data

We included versions of our estimates involving US Stocks with controls for fuel and climate. We sourced fuel data from the US Energy Information Administration (EIA) database, which has retail prices of diesel fuel in dollars per gallon from 1978-2020. For climate data, we collected climate indices from three sources covering different regions. For the US Atlantic coast stocks, we use the North Atlantic Oscillation (NAO), which provides monthly values from 1951-2021. To merge the NAO with our yearly time series, we take the average from December to March for each year. For Pacific coast stocks managed by the US, we use the El Niño/Southern Oscillation (ENSO) index by taking the annual average of its monthly index values from 1980-2021. Lastly, for North Pacific US stocks, we merge data from the Arctic Oscillation index (AO), also by computing the yearly average of the monthly values from 1951-2021.

B.2 EU Data

B.2.1 Time Series and Reference Point Data

EU time series and reference point data is primarily sourced from the Common Fisheries Policy monitoring report from 2020. This report compiled the time series and reference point data for Northeast Atlantic stocks reported by The International Council for the Exploration of the Sea (ICES) Stock Assessment Database, and for Mediterranean stocks reported by

²⁰ <https://www.fisheries.noaa.gov/southeast/sustainable-fisheries/southeast-region-annual-catch-limit-acl-monitoring>. Accessed: 10/31/2022

²¹ FOIA request number is DOC-NOAA-2022-001089

the EU’s Scientific, Technical and Economic Committee for Fisheries database, and FAO’s validated stock assessment forms.

B.3 Defining Pseudo MSST Values

Some stocks in our EU dataset did not have MSST-equivalents. (The EU MSST equivalent was the Safe Biological Limit, SBL.) Reasons for this absence are typically due to a lack of sufficient data to calculate values on which MSST is based, namely B_{MSY} and MSY. For stocks missing their MSST or MSST-equivalents, we calculated a pseudo MSST value using a rule from Canada’s DFO. First, a B_{MSY} proxy equal to 50% of the stock’s maximum historical biomass (in cases where the B_{MSY} is also absent) was created. Then, The pseudo MSST was defined as half of this proxy value. If a stock had a B_{MSY} value already, we simply took half of this value and set it as our pseudo MSST. This aligns with the observations that most US stocks have their MSST set at 50% of their B_{MSY} (see Figure A2. None of the figures reported in the main text make use of stocks that we created pseudo MSSTs for, and only when explicitly stated in the appendix figures are these stocks included. For the US, we constructed pseudo MSSTs for 66 stocks, of which 28 stocks have their biomass drop below their pseudo MSST. For EU stocks, we created 142 pseudo MSSTs, and 64 of those stocks’ biomass dropped below their pseudo MSST.

B.4 Canada Data

B.4.1 Time Series and Reference Point Data

Previous working paper versions included data on Canadian stocks. Here we briefly summarize the data to explain why we ultimately decided to exclude Canada from the analysis. Canada’s Fisheries and Oceans department (DFO) does not centralize its stock assessments in the same way that NOAA does with Stock SMART. In addition, the DFO uses different terminology with regard to reference points. The MSST equivalent is referred to as the Limit Reference Point (LRP). For simplicity, we refer to all reference points under which a rebuilding plan would be recommended for a given stock as the MSST. 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. However, this database is missing many management reference points.

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 the RAM time series data and that units matched between the time series and reference points. Stocks which had reference points from the Oceana Audit but were not listed in RAM were manually added from stock assessment reports we digitized. As explained above, for stocks with missing reference points, we followed DFO guidelines, setting their B_{MSY} equal to half of their maximum historical biomass and defining a pseudo-MSST equal to half of this B_{MSY} proxy.²² Out of the 107 Canadian stocks for which we were able to obtain data for, 66 have biomass that dropped below the MSST-equivalent value. However, only 28 of those rely on an official MSST-equivalent value, while 38 rely on a pseudo value. In addition, many Canadian stocks can cross from Canadian to US waters—potentially resulting in an unclear treatment status and violating SUTVA. Out of the 28 stocks that fell below the official MSST-equivalent value, 11 were such transboundary stocks.

Due to the low number of stocks with an official MSST-equivalent value and a non-transboundary status, we ultimately decided to exclude Canadian stocks from the analysis. Results with Canadian stocks are available upon request.

²² 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.