# Ecological indicators display reduced variation in North American catch share fisheries

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**A growing push to implement catch share fishery programs is based partly on the recognition that they may provide stronger incentives for ecological stewardship than conventional fisheries management. Using data on population status, quota compliance, discard rates, use of habitat-damaging gear, and landings for 15 catch share programs in North America, I tested the hypothesis that catch share systems lead to improved ecological stewardship and status of exploited populations. Impacts of catch share programs were measured through comparisons of fisheries with catch shares to fisheries without catch shares or by comparing fisheries before and after catch shares were implemented. The average levels of most indicators were unaffected by catch share implementation: only discard rate, which declined significantly in catch share fisheries, showed a significant response. However, catch share fisheries were distinguished by markedly reduced interannual variability in all indicators, being statistically significant for exploitation rate, landings, discard rate, and the ratio of catch to catch quotas. These impacts of catch shares were common between nations and ocean basins and were independent of the number of years that catch share programs had been in place. These findings suggest that for the indicators examined, the primary effect of catch shares was greater consistency over time. This enhanced consistency could be beneficial to fishery systems and might also be an indication of more effective management.**

dedicated access privilege | marine conservation | sustainable fisheries | ecological stewardship

One of the most important research challenges in sustainability science is identifying the policy instruments that promote sustainable use of ecosystems. Broadly prescribed simple solutions to complex problems can be ineffective or even dangerous (1), yet there is often a dearth of quantitative policy assessments that identify the types of ecological responses and the social-ecological contexts in which they are likely to be manifest (2). Indeed, tools are often prescribed based on untested assumptions, and post hoc or adaptive evaluation of policy effectiveness are often absent (3, 4).

Marine ecosystems and fisheries, once considered healthy and inexhaustible, are now widely viewed to be substantially impacted by human activities (5). The policy challenges facing fisheries management are multifaceted, but primary among them is the need to change the incentive structure of management so that users of natural resources are more likely to promote long-term sustainability and stewardship of the resource (6–9). A method often advocated to produce these incentives is to grant fishing participants dedicated access privileges, whereby individuals or groups of participants are allotted a percentage of the total allowable catch quota. Also termed "catch share" programs, these fishery programs have been implemented throughout the world (10) and there is a growing push to initiate new catch share programs throughout North America (11) and globally (12).

The primary rationale for implementing catch share programs is to promote more economically efficient exploitation of renewable resources (13–15). However, there are at least two reasons why catch share programs might also improve ecological stewardship and lead to improved ecological conditions in marine ecosystems: (*i*) These programs are largely successful at ending the "race for fish" (10, 16) pervasive among open access fisheries where participants compete for the largest possible share of the catch quota (17, 18). The race for fish leads to overcapitalized fishing fleets, push for higher catch quotas, and wasteful or destructive fishing efforts, such as ghost fishing and incidental catch of nontarget species. (*ii*) Catch shares may create an incentive for long-term sustainable use of the resource. That is, fishing participants may be better ecological stewards because they stand to directly suffer the consequences of overexploitation (7) and directly benefit from maintaining high stock sizes of exploited populations (19, 20).

Although catch share fishery programs are widely touted as a solution to promote improved sustainability of marine ecosystems and fisheries, catch shares have only begun to be quantitatively assessed to identify the types of benefits that they produce and the design elements or social-economic contexts in which benefits are realized. Those analyses that have been conducted used different data and analyses to reach markedly divergent conclusions. Costello et al. (21) used the most widely available data—fishery landings—to identify whether catch share fishery systems are less prone to collapse. They found that collapses, defined as a drop in landings to a low percentage of the previous maximum, were less common in catch share fisheries compared with other fisheries. However, Chu (22) examined trends in the biomass levels of harvested populations and found little evidence for changes in mean levels or in the rates of population change following catch share implementation. This finding highlights the fact that fishing is one of several factors that dictate the dynamics of marine populations, but also suggests that catch shares do not necessarily lead to changes in population status. In a qualitative review of case studies, Branch (23) found anecdotal evidence supporting the hypothesis that habitat damage and fishing effort were reduced, and assessment and management improved, in catch share fisheries, but also found counter examples and identified the need for a quantitative analysis that directly compared conditions across fisheries.

Here I tested the hypothesis that catch share programs lead to improved ecological stewardship and status of targeted populations by compiling data on ecologically relevant fishery indicators, and quantitatively measuring their responses to catch share implementation via comparative analyses. Direct measures of ecological impacts included the two metrics commonly used to gauge the status of harvested populations—population biomass and exploitation rate—and also the amount of fishing effort from habitat-damaging gears (bottom trawls and dredges). Measures of ecological stewardship included discard rate (the fraction of target

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species catch that is not retained, a wasteful practice that potentially influences population status) and the compliance of fisheries to annual catch quotas (catch:quota ratios). Finally, I considered how catch shares affected the production capacity of fishery systems by gauging the response of fishery landings to catch share implementation. Although these indicators do not gauge all aspects of ecological sustainability, they represent those that are commonly reported and are readily comparable across fisheries.

## Results

Data were collected on North American catch share fisheries (individual quotas, individual transferable quotas, and cooperatives; Table S1), and the effects of catch shares were estimated through one of three comparative methods. The first method used a single time series that spanned the period before and after catch share implementation to quantify the change in the time series (before/after comparison). The second method used two time series, one from a catch share fishery and a second from a reference time series to estimate the differences between the two (between-fisheries comparison). To ensure that reference fisheries were appropriate for the catch share fishery, this type of comparison was used when multiple sectors were fishing the same population (one of these sectors was in a catch share program, the second was not). The third method used time series data from a catch share and a reference fishery such that both spanned the time period before and after catch share implementation (reference fisheries targeted the same species in nearby locations). This final method of comparison provides the greatest control for potential confounding effects, and is analogous to a before/after control impact (BACI) comparative design. Of the 22 catch share fisheries that were examined (representing most major North American catch share fisheries), 15 had data for at least one indicator that could be used in one of the three comparison methods (Table 1). Across all fisheries and indicators, a total of 54 comparisons were used to estimate responses to catch share implementation. All time series data are presented in Figs. S1–S5.

Changes that fishery indicators associated with catch share implementation were estimated as response ratios (24) of the mean and the variance. The response ratio of the mean gauged how the mean levels of the indicators responded to catch share implementation. The response ratio of the variance measured changes in the interannual variability that coincided with catch share implementation (see *Methods*). Estimated response ratios for each fishery and indicator are provided in Table S2 but here I summarize general trends here. Overall, the mean levels were relatively unresponsive to catch share implementation; 17 of the fishery/indicator combinations had a 25% or greater change in the mean, and only two of these were significantly different from zero (Table 2). In contrast, large changes in the variance were frequent and tended to consist of reduced variance in catch share fisheries. Only nine analyses indicated a 25% or greater increase, whereas 42 indicated a 25% or greater reduction in variance in catch share fisheries. Nearly one-half of these response ratios were significant from zero (Table 2).

The Alaska sablefish fishery illustrates the common result of small and inconsistent response of the mean to catch share implementation but larger and more consistent response of the variance (Fig. 1). This fishery entered into a catch share program in 1995, whereas the sablefish fishery in U.S. continental waters remained in a conventional management program. Using the BACI method of comparison, there was a small but significant increase in the mean catch-quota ratio (22% increase) compared with the U.S. continental fishery; the catch- quota ratio declined from 1.3 to 1.0 in the Alaska fishery, but declined more sharply in the reference fishery (Fig. 1). Exploitation rates and landings both exhibited small (*ca.* 15%) but significant reductions in the mean, and population biomass had no change in the mean. In contrast, the response ratios for the variances all indicated large and statistically significant reductions in the variability of the catch share fishery (Fig. 1).

Because the time series were not derived from controlled experiments, unknown confounding variables may affect the estimated response ratio for any individual time series. I therefore conducted a meta-analysis of response ratios, which calculated the average responses over all fisheries, to derive more robust estimates of catch share impacts. This meta-analysis provided even stronger evidence for widespread reductions in the variance following catch share implementation (Fig. 2). There were substantial (>30%) reductions in the average interannual variance for all six indicators, and these reductions were statistically significant for exploitation rate, discard rate, catch quota, and landings (*P* values for biomass and effort were 0.45 and 0.16, respectively). Of the statistically significant responses, the variance reduction ranged from 62% (landings) to 90% (discard rate). In contrast, the averaged responses of the mean were small (Fig. 2). Only two indicators (discard rate and effort) changed by more than 10%, and the largest response was an approximately 30% reduction (discard rate). Only discard rate exhibited a significant overall reduction in the mean.

To evaluate why population biomass and exploitation rates exhibited little change in the mean values, I examined these metrics relative to management targets for two periods: the 3 years immediately before catch share implementation, and the 3 most recent years of data (Table S3). Large increases in population biomass and reductions in exploitation rate are expected if populations were initially overdepleted, and fishing exploitation rates were too high. Management targets (e.g., population biomass and exploitation rate that produces maximum sustainable yield) were explicitly stated for eight catch share fisheries. Before catch share implementation, five of eight of fisheries had population biomass levels that exceeded the management target, and only one was substantially below the target (the average ratio of population biomass to management target was 1.23). In the most recent years, the ratio of population biomass to target biomass was reduced for six of these fisheries, and the average ratio was closer to unity (mean = 1.03), but ranged from 0.5 to 1.54. There was therefore a general downward movement of population status toward the management target. Before catch share implementation, three fisheries had exploitation rates that exceeded the target rates, but after catch shares were in place, all fisheries had exploitation rates below the target rate.

To determine whether the less-controlled methods of comparisons (before/after, $n = 27$; between fisheries, $n = 5$) tended to produce different estimates than the most controlled comparisons (BACI, $n = 23$), I compared average effect sizes for

**Table 1. Fisheries and data used in analysis**

| Species | Location | Year catch share |
|---|---|---|
| Atlantic herring | Gulf of St. Lawrence | 1983 |
| English sole | British Columbia (Hecate Strait) | 1997 |
| Northern shrimp | Newfoundland and Labrador | 1987 |
| Ocean quahog | Mid-Atlantic | 1990 |
| Pacific cod | British Columba | 1997 |
| Pacific hake | U.S. Contintental Pacific | 1997 |
| Pacific halibut | British Columbia | 1991 |
| Pacific halibut | Gulf of Alaska | 1995 |
| Sablefish | British Columba | 1990 |
| Sablefish | Gulf of Alaska | 1995 |
| Sea scallop | Bay of Fundy | 1997 |
| Sea scallop | Georges Bank (Canada) | 1986 |
| Snow crab | Newfoundland and Labrador | 1996–1997 |
| Surf clam | Mid-Atlantic | 1990 |
| Walleye pollock | E. Bering Sea | 1999–2000 |

**Table 2. Frequency of substantial (magnitude >25%) shifts in either the mean or variance following catch share implementation for each indicator**

| | | Mean | | Variance | |
|---|---|---|---|---|---|
| Metric | No. | 25% increase | 25% decrease | 25% increase | 25% decrease |
| Biomass | 12 | 1 (0) | 1 (0) | 5 (3) | 7 (4) |
| Exploitation rate | 12 | 2 (0) | 4 (0) | 1 (1) | 10 (5) |
| Discards | 3 | 0 (0) | 2 (0) | 0 (0) | 3 (1) |
| Effort | 3 | 0 (0) | 1 (0) | 0 (0) | 2 (0) |
| Catch:quota | 13 | 1 (1) | 2 (1) | 2 (0) | 10 (6) |
| Landings | 11 | 1 (0) | 2 (0) | 1 (0) | 10 (6) |

Figures in parentheses indicate the numbers of each that were statistically significant ($P < 0.05$). In general, the variance was more likely to exhibit substantial shifts from catch share implementation. Catch:quota is the ratio of catch to the catch quota, and discarding refers to the fraction of the target species catch that is not retained.

each indicator and method of comparison. The estimated response ratios derived through the three measures were generally similar to each other, although the BACI-based comparisons tended to predict larger declines in variance than the before-after comparisons [i.e., the most controlled comparisons yielded the largest estimated effect sizes; Table S4 for mean (SE) for each indicator and method]. To provide a more direct comparison, I also estimated response ratios using the before/after method for each time series for which the BACI method was applied. This comparison revealed little consistent difference in effect sizes between methods (Fig. 3).

Potential covariates that might explain variation in fishery responses were explored in more detail. There was no effect of time (years of post-catch share data) on the estimated effect size (weighted linear regression; $P$ value range: 0.25–0.92). The mean response ratios were similar in the Atlantic and Pacific Ocean fisheries, and also did not differ between Canada and U.S. fisheries (analysis omitted effort and discard rates because of small sample sizes; Table S4). The average variance reduction tended to be more pronounced in Pacific compared with Atlantic Ocean fisheries, but was not significant for any indicator (see Table S4). There was no consistent difference in the response ratios between U.S. and Canada fisheries, although the average variance reduction of catch:quota was significantly greater in U.S. fisheries. No other comparison was significant ($P > 0.2$; see Table S4).

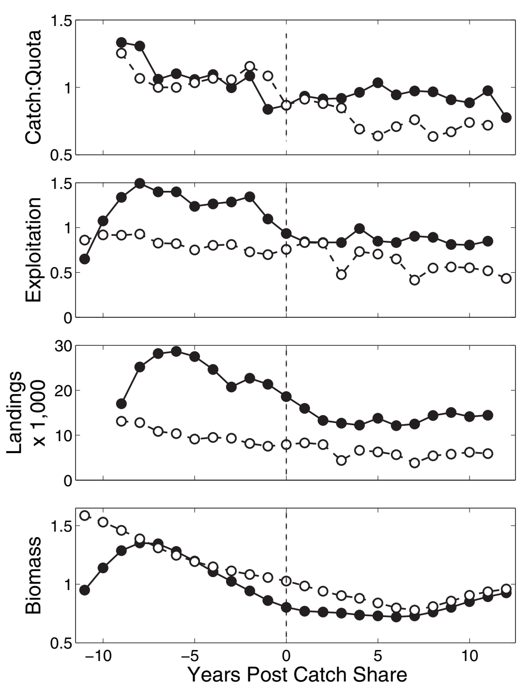


**Fig. 1.** Comparison of time dynamics between a catch share (solid circles and lines, Alaska sablefish) and a reference fishery (empty circles, dotted lines; U.S. continental sablefish). Exploitation rate and population biomass are expressed as ratios of observed levels to management targets. The interannual variances of the catch share fishery were significantly reduced following catch share implementation. Changes in the mean were small and variable among indicators.

## Discussion

Here I assessed whether North American catch share fishery programs promoted ecological stewardship leading to improved ecological conditions and greater production capacity of fisheries. By performing controlled comparisons, I showed the nature of ecological responses that were common among these fisheries, finding that the primary response was improved predictability and consistency. Notably, there was little evidence for higher population levels, lower exploitation intensity, or increased landings. These findings imply that in North American fisheries, the primary effect of catch share programs with respect to the ecological responses examined here has been to make fisheries more predictable, whereby fleet behavior and population status were more consistent, and a key ecosystem service (e.g., landings) was maintained at more stable levels.

The finding of reduced variance in catch share fisheries was not anticipated, but raises several questions regarding the underlying causes and the implications for the ecological sustainability of fisheries. More consistent and predictable fisheries may provide tangible benefits for improving the scientific advice in support of fisheries policies. Evaluation of management strategies (25), for instance, can be made more precise if fisheries respond to management in predictable ways. One important way that the fisheries in the present study responded to catch shares was to sharply reduce interannual variability in the catch:quota ratio; catch share fisheries generally captured all of the annual catch quotas and avoided quota overages. Viable explanations for this response include the end to the race-to-fish, improved catch reporting systems, and changes in the incentive structure whereby individual fishing participants are penalized for exceeding their own individual quotas and may trade quotas within a fishing season (26, 27). The result is vastly reduced "implementation error," one of the three sources of uncertainty that can contribute to fishery collapses (28).

Reduced variance in population status (e.g., exploitation rates) in catch share fisheries might also be an indication that management is more effective at maintaining stocks near their management reference points (i.e., they avoid large declines in abundance through excessive exploitation rates and adapt policies as environmental conditions change). This response may reflect the

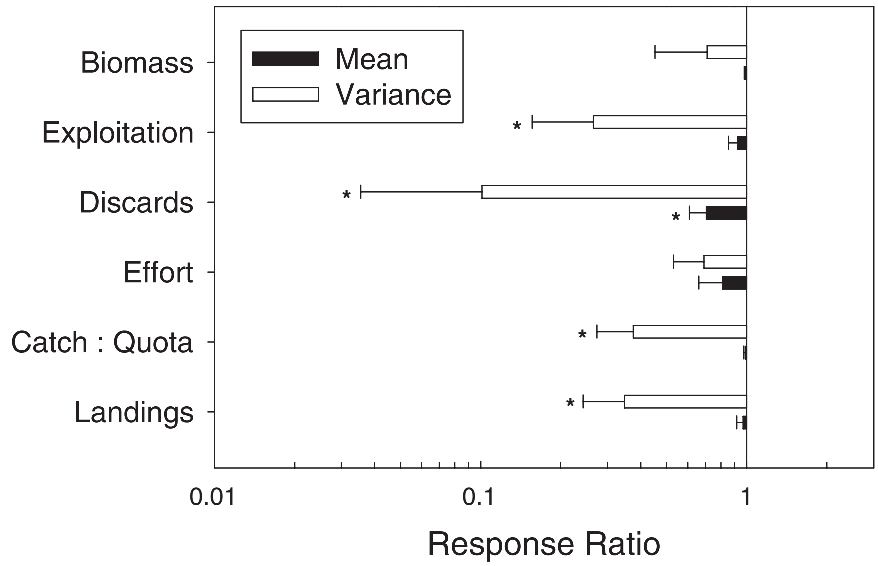


**Fig. 2.** Average (SE) response ratios from catch share implementation for the six fishery indicators, estimated from all fisheries via meta-analysis. Response ratios greater than 1 imply an increase, ratios less than 1 imply a decrease in the mean (solid bars) or variance (empty bars). $*P < 0.05$.

incentives that catch shares provide to participants for improving assessment and advocating for more conservative catch quotas (23); when management targets were specified, exploitation rates were always below the target levels following catch share implementation, and population biomass tended to move toward target levels. The enhanced consistency in population biomass and exploitation rates is reflected in the landings data, which exhibited significantly reduced variability in the present study and in the study by Costello et al. (21), suggesting that catch share fisheries may provide a more stable delivery of fishery products. Data are needed from a much larger number of fisheries to confirm the hypothesis that population status and exploitation rates are better maintained near management targets in catch share fisheries.

The large reductions in variability stand in sharp contrast to the responses of the mean levels of the indicators. The small response revealed through meta-analysis is partly due to the fact that there was notable divergence in the responses among fisheries. For example, the Canadian offshore scallop fishery witnessed a substantial decrease in effort and a moderate increase in population biomass following catch share implementation, whereas the Canadian sablefish fishery exhibited an increase in exploitation rate and decrease in population biomass. Also, catch share programs introduce economic incentives to reduce exploitation rates

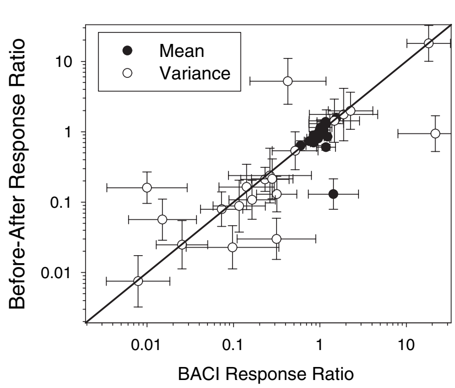


**Fig. 3.** Comparison of response ratios (SE) calculated using a BACI or a before/after comparison. The solid line denotes the 1:1 relationship.

and maintain fished populations at increased levels only if these actions would increase the profitability of the fishery (19). For the fisheries where management targets were available, many had relatively high population biomass and low exploitation rates relative to the levels that maximize long-term landings.

Although the sample size was small ($n = 3$), discard rate was the only indicator that exhibited a significant reduction in the mean following catch share implementation. This response is notable because there has been considerable debate as to whether catch shares introduce incentives to increase or decrease discard rates. The end of the race-to-fish that commonly accompanies catch share programs may promote the wasteful practice of high grading (29, 30), where only the most valuable portion of the catch is retained and the rest is discarded so that it does not count against the quota. Alternatively, if there is an opportunity cost associated with catching low-valued individuals then fishers may avoid practices that catch them (26). Also, discarding of target species may be avoided if participants have a long-term ownership stake in the resource, as high rates of discarding could diminish future fishing opportunities. It is notable that discard rates in two fisheries were declining before catch share implementation (Fig. S5), suggesting that other policies or changes in fishing practices may have also contributed to reduced discarding. Still, if these observations reflect general phenomena, and appropriate incentive structures are in place, then it is possible that the incentives that discourage discarding outweigh the incentives that promote discarding.

Evaluating the effectiveness of policy implementation via retrospective analysis is potentially confounded by two factors. (*i*) Implementation of a policy might coincide in time or space with other changes. In the present study, controls for this confounding effect came from the use of closely matched reference fisheries for one-half of the estimates (22 BACI, five between-fishery comparisons). (*ii*) Unlike true experiments, assignment of treatments is not randomized, so there may be a selection bias. This type of problem can lead to considerable bias in evaluating policy effectiveness when the traits that predispose selection also predispose particular outcomes (31). Costello et al. (21) used a weighting scheme in their comparison of landings data between catch share and reference fisheries, where the weighting of reference fisheries was based on covariates or traits that were associated with catch share implementation (taxonomic and geographic characteristics of fisheries). Here, I used strict criteria for comparison: reference time series came from either a different sector of the same fishery or from a different fishery that targeted the same species with similar gear in a nearby location. The requirements for strong similarities between catch share and reference fisheries should act to minimize the potential for inaccurate estimation because of selection bias.

Widely divergent opinions have been expressed regarding the expectation that catch share programs lead to more sustainable fishing practices (7, 32). Some have noted that catch shares do not remove all incentives for poor ecological stewardship (33, 34) and that the expected benefits should depend critically on the design of the catch share program (35, 36). There are now ample experiences with catch share programs to permit rigorous quantitative evaluation of their effectiveness. Analyses are presently needed to identify elements of catch share programs and the social-ecological contexts that promote favorable outcomes. That is, we should expect catch shares to be effective in some contexts and less effective in others (36). Indeed, there was considerable variability in the responses of fisheries analyzed in the present study (Table S2). Notably, multiple Atlantic cod (*Gadus morhua*) stocks in Canada collapsed in the early 1990s, despite several catch share programs that were implemented in the previous decade (the complicated patchwork of catch shares among fishery sectors and stocks, and the absence of data for appropriate reference fisheries precluded the inclusion of these fisheries in the present analysis). Effectiveness of catch share programs may depend on extent of observer coverage, catch overage penalties, and also the security, durability, exclusivity, and transferability of the catch shares (15, 37). The catch share programs in North America that formed the basis for the present analysis do not provide strong contrasts in these elements or sufficient sample sizes to permit an examination on how these properties dictate the responses to catch share programs. Analysis of a larger set of catch share programs is needed to identify effective design elements and the fishery systems where favorable outcomes are likely.

Like most policy tools for sustainable use of natural resources, we should not expect any single instrument to be effective in all instances (1). Catch share programs are but one potential method for improving fisheries management; others include no-take marine reserves and ocean zoning (38, 39), ecosystem-based management (40), and adoption of more precautionary policies (41). Identification of robust and effective policies will benefit from further quantitative assessments that examine the combined benefits realized when catch shares are implemented along with other policy tools.

## Methods

Data were taken from stock assessment documents and other government reports. In some cases data in reports were provided directly from assessment scientists (see *SI Data and Data Sources*). In all cases I looked for potential reference fisheries for comparisons. Analyses were restricted to time series that contained a minimum of 5 years of pre-catch share (before/after and BACI) and post-catch share data (all methods). When making between-fishery comparisons (where different fishery sectors were compared), data were generally not available for pre-catch share time periods. This method was not used to compare exploitation rate or population biomass, which are affected by the cumulative impacts from all fishing sectors. Inclusion in the analysis was based on the availability of data to permit one of the three methods of comparison, except for two fisheries that were excluded because the small spatial scale of management (geoduck and Pacific herring fisheries from British Columbia, Canada) made data analysis and comparisons at larger scales difficult. Data on incidental catch of nontarget species was sought after, but was insufficiently available to be included in the analysis. I excluded portions of time series if they were substantially impacted by other regulatory or ecological changes. Data used for each fishery and indicator are described in *SI Data and Data Sources*.

I estimated the effect of catch share programs on the mean ($\mu$) and on the interannual variance ($\sigma^2$) for each time series. Moving average (MA) time series models were used for all methods of comparison. The MA model provided the most straightforward way to account for serial dependency of the data and to model changes in the mean through time. Each method of comparison had a different set of parameters estimated, but common to each was an estimate of the log-response ratio (24).

The MA model assumes that the annual deviations from the mean are autocorrelated and that error terms $\varepsilon(i)$ are independent and normally distributed with a mean 0 and variance $\sigma(i)^2$. By assuming that the influence of $\varepsilon(i-k)$ on the state variable $Y$ in year $i$ equals $\theta^k$, then the model simplifies to Eq. **1**:

$$\begin{aligned} Y(i) &= \mu(i) + \eta(i) \\ \eta(i) &= \theta\eta(i-1) + \varepsilon(i) \end{aligned} \quad [1]$$

The three different methods of comparison are reflected in the different ways that $\mu$ and $\sigma^2$ are estimated (Eqs. **2**–**5**). For the before/after comparison, I modeled the mean $\mu_{cs}(i)$ and and variance $\sigma^2{}_{cs}$ $(i)$ in the catch share fisheries:

$$\mu_{cs}(i) = \mu_{0,cs}\exp[X(i)\alpha_\mu]; \sigma^2_{cs}(i) = \sigma^2_{0,cs}\exp[X(i)\alpha_{\text{var}}], \quad [2]$$

where $X$ is a dummy variable equaling zero for time periods before catch share implementation and one thereafter, $\mu_{0,cs}$ and $\sigma^2{}_{0,cs}$ are the pre-catch share mean and variance, and $\alpha_\mu$ and $\alpha_{var}$ are the log response ratios of the mean and variance, respectively. By modeling the response as a multiplicative factor, the resulting parameter estimates are independent of the measurement units or scale of the time series and the natural log scale linearizes the effect size (24).

For the between-fisheries comparison, $\mu$ and $\sigma^2$ are assumed constant over time but vary between fisheries. Eq. **1** was applied to the reference fishery to derive the estimated reference mean $\mu_{ref}$ and variance $\sigma^2_{ref}$. For the catch share fishery, the mean and variance was

$$\mu_{cs} = \mu_{ref}\exp(\beta_\mu); \sigma^2_{cs} = \sigma^2_{ref}\exp(\beta_{\text{var}}), \quad [3]$$

where $\beta_\mu$ and $\beta_{var}$ are the log-response ratios used to estimate effects of catch share programs. $\theta$ was assumed to be identical between reference and catch share fisheries.

The BACI comparison accounted for preexisting differences between catch share and reference fisheries ($\beta$) and for temporal changes in the time series that are common between both fisheries ($\delta$). Thus the mean and variance in the reference fishery in year $i$ are represented as

$$\mu_{ref}(i) = \mu_{0,ref}\exp[X(i)\delta_\mu]; \sigma^2_{ref}(i) = \sigma^2_{0,ref}\exp[X(i)\delta_{\text{var}}], \quad [4]$$

where $\mu_{0,ref}$ and $\sigma^2{}_{0,ref}$ are the initial mean and variance in the reference time series. The mean and variance in the catch share fishery are

$$\mu_{cs}(i) = \mu_{ref}(i)\exp[X(i)\alpha_\mu + \beta_\mu]; \sigma^2_{cs}(i) = \sigma^2_{ref}(i)\exp[X(i)\alpha_{\text{var}} + \beta_{\text{var}}] \quad [5]$$

Here the parameters $\alpha_\mu$ and $\alpha_{var}$ are the effect sizes of interest: they describe the shifts that were unique to the catch share fishery. Because of the large number of parameters for the BACI analysis, I considered four alternative models: the full model, $\delta_{var}$ only, $\delta_\mu$ only, and no $\delta$ terms. I used response ratios of the best fitting models as determined by AICc (42).

Whenever data were available, BACI analysis was used to generate estimates of response ratios; 22 of the 54 data time series (representing 8 of the 15 fisheries) met the data requirements for the BACI comparison (see *SI Data and Data Sources*). When a BACI comparison was not possible, I used the between-fishery comparison if there were multiple sectors operating in the fishery ($n = 5$), or the before/after comparison method ($n = 27$).

Maximum-likelihood estimates of all parameters and their SEs were calculated numerically using Matlab. Statistical significance of estimates was evaluated using likelihood ratios.

Random-effects models were used for meta-analysis of response ratios across fisheries. Here I treated the result from each individual fishery as a single replicate and only considered indicators for which there was a minimum of three estimates. Briefly, random effects models assume that each response ratio represents a draw from a population of response ratios. Random effects estimation aims to calculate the average response and the precision therein. Details on this calculation are provided elsewhere (43). Average response ratios were calculated for each indicator by pooling estimates among the three comparison methods. Sources of variation in response ratios were then explored in more detail. I evaluated whether the three comparison methods produced different effect sizes by estimating the random effects average (SE) response ratio for each comparison method and making pairwise comparisons using the Z-test. The same procedure was used to evaluate whether the average effect sizes varied by nation (U.S. or Canada) or by ocean basin (Atlantic or Pacific). Because there were too few fisheries to consider all possible combinations of nation and ocean, I performed each analysis separately. I evaluated whether older catch share programs showed stronger response ratios by using weighted linear regression of response ratio vs. years post-catch share data. Regression weights were equal to the inverse of the variance of each point estimate.

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