



Catch shares, fisheries, and ecological stewardship: a comparative analysis of resource responses to a rights-based policy instrument

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Abstract

Rights-based approaches are potentially promising tools to meet conservation objectives in natural resource management. Here, we evaluated how population status and fishery production respond to catch shares, a rights-based policy instrument in fisheries whereby participants are granted a right to harvest a fraction of the allowable catch. By analyzing time series of landings, exploitation rate, and population biomass for >150 fisheries, we find that catch shares tended to dampen variance in fishery landings and exploitation rate, that they had no effect on population biomass, and that the responses were unrelated to population status prior to catch shares. Variance dampening was strongest when harvesting rights were durable and secure but was absent otherwise. Reductions in exploitation rate were strongest in multispecies fisheries with high levels of at-sea observers. Although benefits are not guaranteed, successful catch share programs share common elements that can be incorporated in the design of future programs.

Introduction

Environmental degradation of common-pool natural resources—rangelands, forests, and fisheries—is commonly attributed to weak or poorly defined property rights. In the absence of well-defined access or ownership rights, short-term interests take precedence over long-term sustainability, leading to actions that erode the productive capacity of ecosystems (Hardin 1968). Although it is clear that property rights are not always necessary (Ostrom *et al.* 1999) and are not sufficient to ensure long-term sustainability (references in Crow *et al.* 2008), there is a growing emphasis in conservation biology and management to strengthen and clarify property rights as a way to align long-term ecological and conservation goals

with individual economic interests (Hanna *et al.* 1996; Berkes *et al.* 2006). Rights-based approaches are representative of a broader class of market-based policy instruments (e.g., certification, pollution taxes, and cap-and-trade programs) that provide economic incentives to meet ecological goals and promote innovation to that end (Stavins 2003; Costello *et al.* 2010).

Marine fisheries are one of the most pervasive anthropogenic disturbances impacting marine ecosystems (Halpern *et al.* 2008). Conventional “command and control” management measures may have limited success in meeting ecological goals because of increases in fishing capacity through technological innovation, the tendency to make risk-prone policy decisions to protect short-term interests, and unanticipated changes in fishing behavior

in response to regulations (Degnbol & McCay 2006; Beddington *et al.* 2007). Rights-based instruments may be more effective if they better align users' economic incentives with environmental goals for resource management (Hilborn *et al.* 2005; Fujita & Bonzon 2006; Costello *et al.* 2010). In fisheries, rights-based systems are those in which specific harvest or access rights are granted to individuals or groups (e.g., fisher organizations or cooperatives). When harvest rights are specified in terms of a fraction of the allowable catch, these systems are often called "catch shares," and have been identified as a promising tool to end the pattern of fishery development that leads to resource degradation (Fujita *et al.* 1998; Grafton *et al.* 2006; Beddington *et al.* 2007; Worm *et al.* 2009).

There is growing evidence that catch shares have detectable impacts on marine living resources and ecosystems. One benefit of catch shares is that they eliminate perverse incentives leading to a race-to-fish, whereby individuals compete to capture the highest possible fraction of the quota (Copes 1986). This activity leads to high rates of discarded catch, higher incidental catch of nontarget species, and potential habitat degradation (Sutinen 1999; Branch 2009). Catch share fisheries are less likely to experience a collapse in landings (Costello *et al.* 2008) or to have excessive overfishing (Melnychuk *et al.* 2012), and they lead to better compliance with catch limits (Branch 2009; Melnychuk *et al.* 2012). However, Essington (2010) found that catch shares had a pronounced dampening effect on the interannual variance of ecological metrics in North American fisheries, but had little effect on the mean levels of most metrics. Similarly, Melnychuk *et al.* (2012) did not find evidence that catch shares were, on average, closer to their management targets than other fisheries. Thus, there remains considerable uncertainty regarding the type and extent of conservation benefits that catch shares produce and the types of fishery systems where these effects are most pronounced.

Specific attributes of catch share programs might be particularly important in dictating their effect on the population status of exploited resources. Indeed, there is a growing appreciation that policy instruments must be designed to match the ecological, economic, and social systems in which they are implemented (Ostrom 2007, 2009). In fisheries, we might expect different responses between single- and multispecies fisheries because of the greater management challenges that the latter commonly face (Murawski 1991), especially with respect to matching catches to quotas (Sanchirico *et al.* 2006; Branch & Hilborn 2008). Attention has also been given to the strength of harvesting (or property) rights as a proxy for the ecological stewardship incentive that they are thought to provide (Hanna *et al.* 1996; Arnason 2005), so that substantial effects should be associated with strong

and clear harvesting rights. Alternatively, effects of catch shares may not result from the allocation of rights per se, but instead from other changes in fisheries that accompany their implementation. For example, Bromley (2009) argued that the benefit of catch shares may derive from the use of strict catch quotas to limit fishing mortality. If true, then catch shares should have little effect where quotas are already in place. Implementation of catch shares may also be accompanied by improved monitoring and enforcement, such as at-sea or dockside observers producing more accurate and rapid data on catch and catch composition.

Here, we conducted the first large-scale analysis of catch shares that measured the changes in key population and fishery metrics following catch share implementation and to related these responses to attributes of catch shares and fisheries. Specifically, we evaluated changes in exploitation rate (the fraction of fish harvested annually), population or stock biomass, and total landed catch ("landings") across a broad range of fisheries from around the world, using a variety of system attributes as covariates. Following Essington (2010), we evaluated changes in the mean levels of these indicators as well changes in the interannual variability that follows catch share implementation. This paper provides the most comprehensive analysis to date of how implementing catch shares affects the status of fished populations and identifies the attributes of fishery and catch shares that make effects more pronounced.

Methods

We conducted a comparative analysis using a diverse data set to identify response of landings, exploitation rate, and population biomass to catch share implementation. These are the most commonly and consistently reported metrics in fisheries, and include the two primary measures of population status: exploitation rate and population biomass. Landings provide a measure of the productive capacity of the fishery. Other ecologically relevant information—total fishing effort, unretained catch (discard), and bycatch (incidental capture of nontarget species)—were not available for most fisheries. Here, we describe the data used for analysis and provide an overview of the statistical procedures.

All time-series data were obtained from the RAM legacy database (Ricard *et al.* 2012), which is the most extensive database of stock assessments (i.e., population models used to estimate time series of biomass and exploitation rate) presently available. Data predominantly are composed of commercial fisheries from Australia, New Zealand, USA, Canada, and Europe, but

stock assessments from developing countries were also included where available. These data included 84 catch share and 140 reference fisheries (Table S1). Data on catch share program attributes were collected via telephone or e-mail interviews with experts from each fishery (see Supporting Information).

Our analysis was designed to describe changes in fishery time series coinciding with the implementation of catch shares, while accounting for other time-dependent trends in the response variables. We did not fit a mechanistic model of stock and fleet dynamics, but instead employed a general statistical model to estimate changes in fisheries when catch shares are introduced. It is designed to answer the question: do population sizes, exploitation rate, and landings have a different mean level or degree of variability after catch shares compared to time-dependent trends in other fisheries.

We provide details of the model and estimation procedure in the Supporting Information, but here identify the key characteristics. First, the model explicitly includes temporal autocorrelation in the time series while describing changes in the mean and variance through time through a modified version of the method used by Essington (2010). Second, the model includes both catch share and reference fisheries to track the time-dependent changes in the absence of catch shares and to identify changes unique to catch share fisheries. Third, we account for interdependence of responses among fisheries operating within the same regions via a multilevel framework. Fourth, we relate average catch share effects within a region to characteristics of fisheries and catch share programs within those regions. Fifth, effects of catch shares are estimated as log-response ratios to allow for comparison of responses across fisheries and regions.

A key feature of our analysis is that we compare time-dependent changes in catch share fisheries in each region to ensembles of reference fisheries using a multilevel framework (Gelman & Hill 2007). The multilevel framework allowed us to (1) estimate regional-scale average effects of catch shares on fisheries and to determine how these are related to fishery and catch share attributes and (2) estimate time-dependent changes in fishery time series unrelated to catch shares by describing changes in the mean and standard deviation within and across regions. The multilevel structure means that the individual fishery effect sizes are presumed to be draws from a regional-scale distribution of effect sizes; the nested structure of the analysis allowed us to estimate effects at the scales of individual fisheries as well as average effects within regions. Regions were specified based on nations and ocean to account for large-scale differences in population status induced by climatic variability as well as other policies instituted by regional fisheries management organi-

zations. Management of fisheries in most of these regions is overseen by a single nation, though some regions combined fisheries from several nations (Europe, where marine fisheries are jointly managed under the Common Fisheries Policy, and South America). Because attributes of catch share programs and fisheries tended to be similar among fisheries within a region, we focused on effects that were manifest at the regional scale; that is, how do average effects of catch shares in one region compare to other regions?

We evaluated how the effect of catch shares varied according to several covariates hypothesized to be important. To this end, our estimation procedure explicitly considered the extent to which regional-scale catch share effects were linearly related to each covariate (see Supporting Information). We considered several measures of the strength of harvesting right: exclusivity, durability/security, and transferability, but found there was insufficient contrast in transferability among regions to permit analysis of this covariate. Exclusivity was measured as the proportion of catch in a fishery that was allocated to a catch share program. Durability/security were binary responses (yes/no) that covaried completely (durability is the longevity of the harvesting right, security is the likelihood of a harvesting right being realized), so we evaluated them as a single response. We also tested whether catch share effects were weaker in fisheries that were managed via catch quotas prior to catch share implementation, that is, we tested whether the primary benefit was the quota. In addition, we tested whether the response to catch shares was related to the degree of at-sea observer coverage, the change in levels of at-sea observer coverage that accompanied catch shares, the degree of industry participation in developing the catch share program, and whether the fishery was primarily a single-species or a multispecies fishery. The latter could be more responsive if catch shares improve the ability to match catches to quotas in multispecies fisheries.

Results

Catch shares induced a diversity of responses in fisheries (Figure 1; see also Figures S1–S3). To illustrate what commonly observed effect sizes imply about dynamics of fishery time series, we plotted the predicted mean and 90% posterior prediction range for three exploitation rate time series, where exploitation = fraction of biomass caught annually (Figure 1). Petrale sole in British Columbia, Canada, exhibited a strong response in both the mean and standard deviation in exploitation rate, both of which decreased markedly following catch share implementation. Southeast Australia school whiting showed a

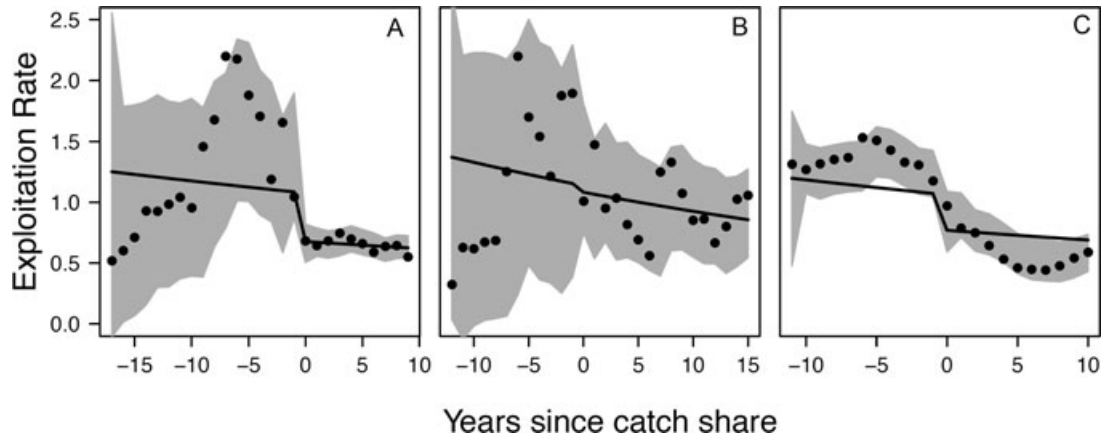


Figure 1 Three types of responses to catch share implementation. Each panel depicts the time series of exploitation rate (standardized so that each time series has a mean = 1; solid points), the fitted mean values (in Eq. 1–2: solid line) and the 90% posterior prediction interval (gray area). (A) British Columbia petrale sole; (B) Southeast Australia school whiting; (C) New Zealand red rock lobster. Year = 0 represents the year of catch share implementation.

Table 1 Summary of individual fishery responses to catch share implementation; each table entry lists the number of fisheries for which there was a significant change in the time-series standard deviation or mean; significance was based on 90% posterior probability credibility intervals; numbers in parenthesis indicate the total number of catch share fisheries for each metric

	Standard deviation response		Mean response	
	No. of increase	No. of decrease	No. of increase	No. of decrease
Landings (51)	3	17	0	3
Exploitation Rate (54)	2	14	0	7
Biomass (54)	8	12	1	2

decrease in standard deviation but no change in the mean exploitation rate, whereas New Zealand red rock lobster (stock = CRA2) exhibited reduced mean exploitation rate but no change in standard deviation.

Despite variation in individual fishery responses, we detected some notable patterns. For all three metrics (biomass, exploitation rate, and landings), we found stronger effect of catch shares on interannual variability than on the mean (Table 1). For example, the mean landings significantly ($P > 90\%$) changed in only three fisheries, but interannual standard deviation significantly changed after catch share implementation in 20 fisheries. For landings and exploitation rates, the response tended to be negative, that is, significant effects were associated with a decline in either the mean or standard deviation (Table 1). In contrast, the direction of response of population biomass was less consistent, exhibiting both positive and negative effects (Table 1).

We evaluated whether the small responses of mean exploitation rate and population biomass might be due to these metrics being already close to values that maximize landings (i.e., maximum sustained yield, MSY: exploitation rate = F_{MSY} , population biomass = B_{MSY}). If this was true, then the fitted response (catch share effect plus the regional average time trend, see Supporting Information) should be related to the ratio of $F:F_{MSY}$ and $B:B_{MSY}$ prior to catch share implementation. Contrary to the expectation, the fitted response did not show a strong relationship to precatch share conditions (here, averaged over the 5 years prior to catch share implementation, though similar results were obtained by using the entire precatch share period; Figure 2). This result was particularly striking for population biomass, where the majority of stocks had $B:B_{MSY} < 1$, yet many populations exhibited declines in biomass after catch share implementation (Figure 2).

The regional-scale average effect sizes were most pronounced for landings and exploitation rate, whereas there was little evidence of regional-scale effects for population biomass (Figure 3). For both landings and exploitation rate, the effect of catch shares on the mean and standard deviation tended to be negative, and no region had an effect size that was significantly greater than zero. For landings, we estimated significant reductions ($>90\%$ probability) in both mean and standard deviation for three regions and a significant reduction in the mean only in one region. Overall, the grand average (integrating over all regions) effect indicated a significant decline in mean landings (i.e., a negative log-response ratio; $P(<0) = 93\%$), equating to a roughly 10% reduction in landings after catch share implementation. Although the grand average effect on the standard deviation of landings was stronger (ca. 14% reduction), the estimate

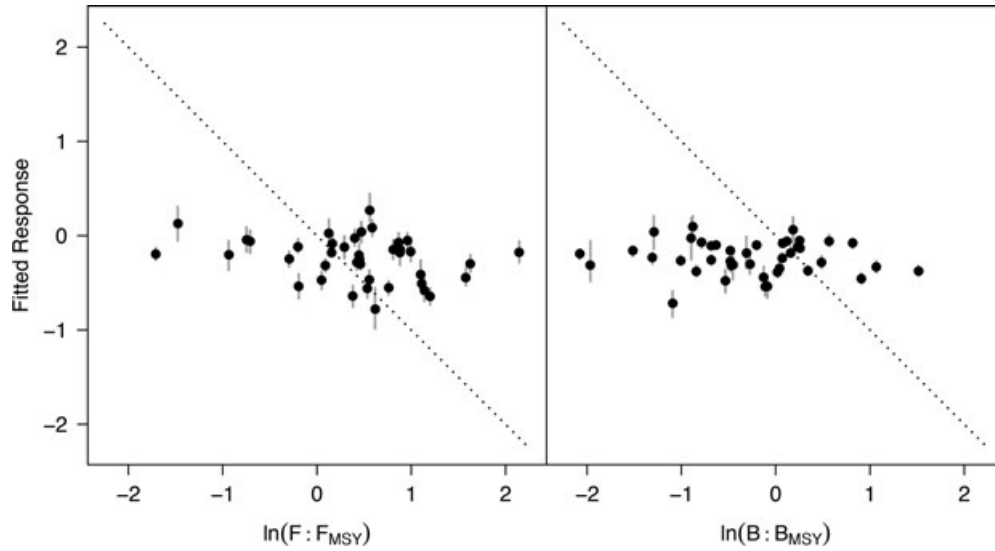


Figure 2 Comparison of precatch share exploitation rates and population biomass levels relative to those that produce maximum sustainable yield ($F:F_{MSY}$, $B:B_{MSY}$), and the estimated change in these metrics. If fisheries perfectly compensate by moving to F_{MSY} or B_{MSY} after catch shares were

introduced, all points would reside on the dotted line. Fitted response includes the catch share effect as well as the regional-scale time-dependent trend. Points are posterior means, gray lines are 50% posterior credibility intervals.

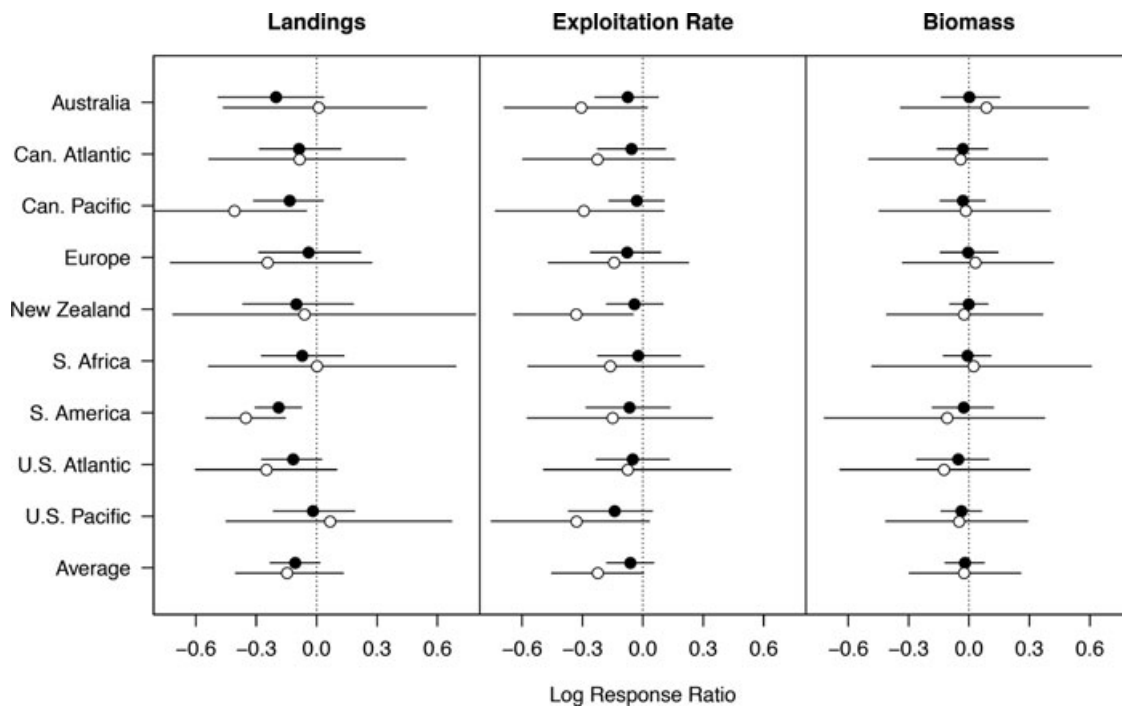


Figure 3 Regional mean effect sizes of catch shares on landings, exploitation rate, and biomass. Solid circles denote effect on the time-series means, empty circles denote effects on the time-series standard deviation. Symbols are the posterior mean effect sizes, lines are 90% posterior

credibility intervals. The final row indicates the average effect size that integrates over all regional effects. See Supporting Information for specific details on hierarchical analysis.

Table 2 Summary of regional fishery attributes for catch share fisheries. Data were not obtained for most European fisheries so are not presented here

	No. of catch share fisheries in analysis	Exclusivity ^a	Durability ^b	Transferable ^b	Single Species ^c	At sea observer coverage ^d	Quota management ^e	Industry involvement ^e
Australia	5	0.96	0.6	1.0	0.7	0.02	0.4	0.6
Can. Atlantic	7	0.93	0.7	1.0	0.3	0.17	0.7	0.9
Can. Pacific	10	0.92	0.9	0.9	0.1	0.77	1	0.9
New Zealand	17 (0)	0.85	1.0	1.0	0.7	0.05	0.05	0
S. Africa	2	1.00	0.0	1.0	0.0	0.50	1	0
S. America	3 ^f	0.76	0.0	0.5	1.0	0.05	1	0
U.S. Atlantic	2	0.97	1.0	1.0	1.0	0.02	1	1
U.S. Pacific	3	0.87	1.0	1.0	1.0	0.41	1	1

^aAverage proportion of catch allocated to catch share sectors.

^bProportion of catch share fisheries in each region classified as durable or transferable.

^cProportion of stocks that were fished primarily as part of single-species fisheries.

^dAverage proportion of trips that were covered by at-sea observers, averaged over all fisheries.

^eProportion of stocks that used quota management prior to catch share implementation, or the proportion of stocks in which the fishing industry advocated for and were involved in developing catch share program.

^fAttribute data available for two fisheries.

was less precise so the probability that this value was <0 was smaller (82%). For exploitation rates, no region exhibited a significant decline in the mean, but the standard deviation declined significantly in four regions (Figure 3). The grand average of the regional effects indicated a significant reduction in the standard deviation of exploitation rates (20% reduction, $P(<0) = 95\%$), but no significant effect on the mean ($P(<0) = 82\%$). The absence of regional scale effects on biomass is primarily attributed the absence of consistent effects across fisheries within regions (Figure S3), and also on the reduced statistical power caused by high temporal autocorrelation (Supporting Information contains additional evaluation of biomass responses).

There were notable differences among regions in the strength of harvesting rights and other fishery attributes (Table 2). Durability/security varied substantially across regions, whereas exclusivity tended to be high (>75% catch allocated to catch share sectors) across all regions. Only two catch share fisheries were not transferable (in-season or across seasons), which made the regional scores of this attribute nearly equivalent to each other. Other fishery attributes varied among regions more strongly. The proportion of each region's catch share fisheries that primarily targeted a single species, the extent of at-sea observer coverage, and industry participation in establishing catch shares varied widely across regions (Table 2). In most regions, catch shares were introduced to fisheries that already used catch quotas (Table 2).

We detected a marginally significant relationship between the durability/security of catch shares and the degree of variance dampening (Figure 4). For landings,

catch shares produced no effect in regions where catch shares were not durable/secure, but produced a 50% reduction in interannual variability when all catch shares within a region were durable/secure (Figure 5A). A slightly weaker relationship was observed for exploitation rate: variance dampening was pronounced in regions with durable/secure catch share programs, but had no effect in regions lacking these attributes (Figures 4 and 5B). The coefficients describing the effect of exclusivity were poorly estimated (Figure 4), reflecting the limited contrast in regional exclusivity scores.

The effect of catch shares on mean exploitation rate was associated with two fishery attributes (Figure 4). A significantly larger decrease in mean exploitation rate was estimated for regions that had higher at-sea observer coverage and higher proportion of multispecies fisheries (Figures 5C and D). These two predictor variables covaried strongly, which explains why their correlations with catch share effects were similar. There was no discernable effect of prior quota control management, degree of industry involvement, or change in at-sea observer coverage level on any response (Figure 4).

Discussion

This study contributes to a growing body of research that aims to relate governance and other facets of social systems to the status of ecological systems (Degnbol & McCay 2006; Liu *et al.* 2007; Carpenter *et al.* 2009; Ostrom 2009; Gutiérrez *et al.* 2011). Our analysis used high-quality data sets from fisheries from around the world to document the types and magnitudes of effects

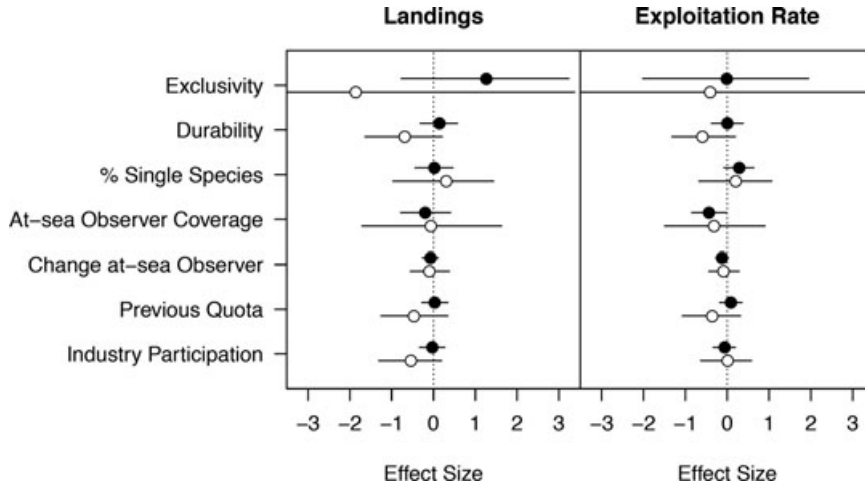


Figure 4 Estimated coefficients (mean, 90% credibility interval) relating effect of catch shares to regional fishery attributes. Effect size = 0 means that the regional average responses to catch shares were unrelated to the attribute. Solid circles denote effect on the time-series means, empty circles denote effects on the time-series standard deviation.

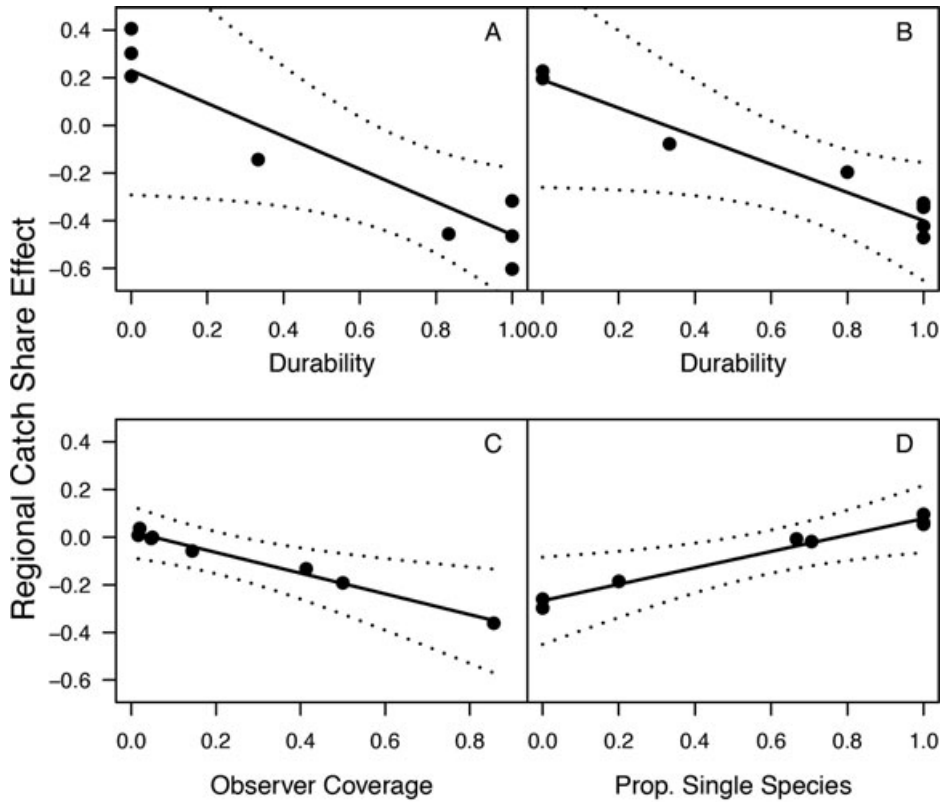


Figure 5 Fitted relationships between catch share effects and fishery attributes (for the significant effects observed in Fig. 4). Top two panels show the magnitude of variance dampening for landings (A) and exploitation rate (B) as explained by the proportion of fisheries deemed durable/secure. Bottom two panels show the catch share effects on mean exploitation

rate as function of degree of observer coverage (C) or the proportion of stocks fished in single species fisheries (D). Points are the fitted regional coefficients, solid lines are posterior means, and the dotted lines are 90% credibility intervals.

that rights-based policy instruments produce and to identify elements of fishery systems that amplify or diminish these effects. We confirmed and generalized the results of Essington (2010), finding that catch shares primarily act to dampen variability, but we also demonstrated that variance dampening is only present when the access right is durable and secure. We also find that, on average, catch shares are followed by reductions in exploitation rate in multispecies fisheries with high at-sea observer coverage. This work thereby substantially advances our understanding of the effects of rights-based approaches so that the conservation benefits of implementing novel programs can be better anticipated.

The prediction that rights-based approaches might foster ecological stewardship stems from the idea that rights better align participants economic incentives with ecological goals (Grafton *et al.* 2006). We had therefore expected that catch shares would result in reductions in exploitation rate and increases in population biomass when these population metrics were too high (exploitation rate) or too low (population biomass) before the new management strategy was introduced, relative to levels that would maximize catch. This expectation was not borne out—there was little to no relationship between catch share effects and the ratios $F:F_{MSY}$ or $B:B_{MSY}$. Although harvest rates tended to decrease after implementing catch shares, the response was generally too weak to eliminate overfishing. This finding is consistent with that of Melnychuk *et al.* (2012) who found that mean ratios of $F:F_{MSY}$ and $B:B_{MSY}$ did not differ between catch share and competitive quota-managed fisheries. By relating changes in individual fisheries to population status as we have done here strengthens the finding of Melnychuk *et al.* (2012) because it reduced the potential bias and confounding effects that may be present in cross-fisheries comparisons. We conclude that many of the elements of the fishing system—including the economic and social systems—that promoted overexploitation prior to catch shares largely persisted after catch shares were implemented (Clark 1990; Ostrom *et al.* 1999; Grafton *et al.* 2007).

There are at least two explanations for the variance dampening effect of access rights in fisheries. One, variance dampening might result from ending the race-to-fish (Sutinen 1999). When fishing fleets are not competing to catch the greatest share of the annual catch limit, the catch is taken at a slower pace and might therefore be better monitored and controlled within fishing seasons. There is strong evidence that catch shares improve quota balancing in multispecies fisheries (Sanchirico *et al.* 2006; Branch 2009), partly by slowing the pace of fishing throughout the fishing season. Two, the probability

that exploitation rates greatly exceed management targets in a given year is lower in catch share fisheries (Melnychuk *et al.* 2012). These periods of high exploitation rates can diminish population productivity and require future reductions in exploitation rate and catch levels to rebuild populations. By avoiding these periods of overexploitation, landings and exploitation rates can better be maintained at constant levels. The British Columbia petrale sole fishery (Figure 1) provides an example of both cyclical (precatch share) and steady (postcatch share) dynamics.

Our results suggest that this variance dampening effect depends on having durable and secure access rights. There was essentially no variance dampening in regions with nondurable/insecure harvesting rights, whereas the dampening was strong in regions with durable and secure rights. Theory suggests that durable and secure access rights promote decision making that maximizes long-term profitability and avoids short-term resource degradation (Deacon 1994). Durable and secure access might promote industry investment in research that improves the precision of stock assessments that are used to estimate annual catch limits (Branch 2009). Also, owners of durable/secure access rights may be less risk-prone and advocate for lower catch levels in the face of uncertain stock status (Branch 2009).

We applied a novel method to estimate impacts of a policy intervention that used ensembles of reference time series to tease apart effects attributable to a policy change from other confounding effects. This approach may be useful for future policy analyses, as it obviates the need to identify closely matched pairs of systems as a way to deal with the counterfactual (the change that would have occurred in catch share fisheries had catch shares not been implemented). In the present application, this ensemble-based comparative approach was critical, as the analysis revealed substantial time-dependent trends in nearly all metrics (Figure S4).

This work advances our understanding of how rights-based approaches may contribute to meeting ecological goals in natural resource management. The nature of responses to rights-based approaches in fisheries (variance dampening) appears to be fundamentally different from those in terrestrial systems, where property rights have been linked to reduced deforestation rates (Deacon 1994; Nelson *et al.* 2001). Moreover, ecological responses varied across regions, apparently related to the strength of access right and other attributes of the fishery system. Thus, application of rights-based policy tools should be accompanied by a consideration of the types of responses that they are likely to produce and the socioecological context where these responses are strongest.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Number of catch share/reference fisheries used in time-series analysis by region.

Figure S1. Estimated effects of catch share on the mean (μ ; left panel) and standard deviation (σ , right panel) of landings for each fishery.

Figure S2. Estimated effects of catch share on the mean (μ ; left panel) and standard deviation (σ , right panel) of exploitation rate for each fishery.

Figure S3. Estimated effects of catch share on the mean (μ ; left panel) and standard deviation (σ , right panel) of population biomass for each fishery.

Figure S4. Estimated regional time-dependent trends in landings, exploitation rate, and population biomass.

Figure S5. Fishery mean biomass response versus (A) landings response and (B) exploitation rate response.

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