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# Can catch share fisheries better track management targets?

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## Abstract

Fisheries management based on catch shares – divisions of annual fleet-wide quotas among individuals or groups – has been strongly supported for their economic benefits, but biological consequences have not been rigorously quantified. We used a global meta-analysis of 345 stocks to assess whether fisheries under catch shares were more likely to track management targets set for sustainable harvest than fisheries managed only by fleet-wide quota caps or effort controls. We examined three ratios: catch-to-quota, current exploitation rate to target exploitation rate and current biomass to target biomass. For each, we calculated the mean response, variation around the target and the frequency of undesirable outcomes with respect to these targets. Regional effects were stronger than any other explanatory variable we examined. After accounting for region, we found the effects of catch shares primarily on catch-to-quota ratios: these ratios were less variable over time than in other fisheries. Over-exploitation occurred in only 9% of stocks under catch shares compared to 13% of stocks under fleet-wide quota caps. Additionally, over-exploitation occurred in 41% of stocks under effort controls, suggesting a substantial benefit of quota caps alone. In contrast, there was no evidence for a response in the biomass of exploited populations because of either fleet-wide quota caps or individual catch shares. Thus, for many fisheries, management controls improve under catch shares in terms of reduced variation in catch around quota targets, but ecological benefits in terms of increased biomass may not be realized by catch shares alone.

**Keywords** Fishery management, individual transferable quota (ITQ), mixed-effects model, output controls, overfishing, propensity score matching

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## Introduction

Ongoing concern about the status of marine species and ecosystems, and the widespread perception that fisheries management has failed, has led to a proliferation of calls for management agencies to adopt specific policy measures. These include establishing no-take fishery reserves (Pauly *et al.* 2002; Myers and Worm 2005), using gear or effort restrictions (Cochrane 2002), and implementing precautionary and ecosystem-based approaches (Pikitch *et al.* 2004), all designed to better protect vulnerable marine species and ecological functions in addition to targeted stocks. A second group of approaches aims to improve fisheries performance by better aligning economic incentives with conservation objectives (Fujita *et al.* 1998; Grafton *et al.* 2006; Hilborn 2007). These are part of a general class of policy measures termed 'market-based approaches'. In fisheries, these applications have been largely limited to 'catch shares' whereby fishing participants are granted fixed proportions of the annual catch quota (e.g. individual transferable quotas, territorial user rights, co-operatives and community quotas), which in many countries offer secure, exclusive and durable access to fishing opportunities (Arnason 2005). Catch shares have been lauded as one of the promising paths toward improving fisheries management (Grafton *et al.* 2006; Beddington *et al.* 2007; Costello *et al.* 2008; Worm *et al.* 2009). Yet globally, their collective effectiveness has rarely been formally evaluated (for an exception see Sutinen 1999), and there have been critics of catch shares as well, generally surrounding issues of who benefits from the increased profitability under catch share fisheries (Copes 1986; Gibbs 2007; Bromley 2009).

Catch shares have been implemented in fisheries around the world and generally have been successful in improving the safety, product quality, year-round availability and economic performance of fisheries as judged by ex-vessel revenue of fishing participants (e.g. Dewees 1998). Recently, effects of catch share strategies on target populations and ecosystems have been reviewed, finding generally positive effects on target species, but mixed effects on the ecosystem as a whole (Branch 2009). Costello *et al.* (2008) found that landings were less likely to collapse to low levels in catch share fisheries compared with other management systems, although landings are a problematic measure of stock collapse (Wilberg and Miller 2007; de Mutsert *et al.* 2008; Branch *et al.* 2011). Chu (2009) found mixed results of catch share implementation on fish biomass, with some populations increasing and others decreasing. Essington (2010) compared catch share and reference fisheries in North America, finding that the primary response of introducing catch shares was a marked decrease in the interannual variance of several biologically relevant variables, possibly resulting from more effective management keeping fished stocks closer to management targets and reducing the probability of annual catches exceeding annual quotas.

Here, we use a new global database of fisheries to develop and test the hypothesis that biologically relevant response variables more closely track management targets in catch share fisheries. The biological or fishery performance measures that we use explicitly consider management targets: the ratio of total catch to total quota, which reflects the level of compliance for quota-managed fisheries; the ratio of annual exploitation rate to target exploitation rate, which reflects the level of fishing mortality relative to the reference point; and the ratio of biomass to target biomass, which reflects the population status relative to the reference point. We compare these measures among catch share and non-catch share fisheries while accounting for several potentially confounding covariates. We use three rigorous data analysis approaches to ensure consistency of observed effects. The incorporation of reference points is crucial for better understanding the nature of catch share responses, as theory predicts that not only the magnitude but also the direction of change following catch share implementation depends on the status of a fishery relative to these management benchmarks (Grafton *et al.* 2007). For instance, if exploitation rates are relatively low and population biomass is high at the onset of catch shares, there is an economic incentive to increase exploitation rates to the levels that maximize revenue. In contrast, if exploitation rates are too high or biomass levels are too low, there will generally be an economic incentive to rebuild the stock to more productive levels. Without considering management targets, opposite effects of catch shares would be observed for these two scenarios, whereas the common effect is a closer adherence to targets.

We draw expectations for what types of variables might be most responsive to catch shares by recognizing that fisheries management acts primarily to regulate fishing activity and catches. Thus, we expect variables closely tied to the amount of catch to be most responsive to policy measures. In catch share fisheries, the ratio of total catch to annual quota is expected to be close to 1 because fishing participants are often penalized for exceeding their own quota, and individual participants can often trade quota within a given year to avoid quota overages (Sanchirico *et al.* 2006). Exploitation rate (the fraction of vulnerable biomass captured each year) will be somewhat less responsive, because it depends on both landings and population size. That is, managers set harvest levels to reach a target exploitation rate but biomass estimates are imprecise. Lastly, population size (or biomass) may be the least responsive to catch shares because fishing and environmental conditions act together to dictate realized productivity, and because managers sometimes set biologically unsustainable quotas based on social concerns (Froese and Proelß 2010).

Regional differences in fisheries management are likely to impact successful biological outcomes; therefore, it is necessary to isolate the effects of catch shares across a range of regional management systems. To control for possible confounding factors, one important consideration is to separate the effects of catch shares from those of quota management. Bromley (2009) argued that many of the perceived benefits of catch shares may result simply from effective quota management regardless of whether catch shares are employed. Another key consideration is to account for the non-random application of catch shares; we do this by estimating the propensity for fisheries to be regulated by catch shares given a variety of covariates such as region, size and history of the fishery, and biological features of the stock. Finally, we anticipate that the effect of catch shares will be greatest for response variables most closely tied to management decisions and fishing fleet behaviour, i.e. greatest for catch:quota ratios, less for exploitation rates and least for stock biomass.

## Methods

Here, we provide a brief initial overview for the general audience before going into detailed descriptions of our methods. In our analysis, we examined trends in catches, exploitation rates and biomass over a common recent focal period for which we had the most data: 2000–2004. We focused on three response variable ratios: total catch to total quota ($C/Q$), annual exploitation rate to the target exploitation rate ($F/F_{\text{reference}}$) and biomass to the target biomass ($B/B_{\text{reference}}$). For each of these three variables, we quantified four responses by measuring the mean, variability around the management target and the frequency with which targets were exceeded. For each of these 12 response variable metrics of performance, (i) we compared fixed-effects models to evaluate the relative importance of catch control type, region and taxonomic/habitat association effects on the response variables; (ii) we used mixed-effects models to quantify the magnitude and direction of the catch control type effect on the response variables; and (iii) we compared response variables of catch share fisheries with those of non-catch share fisheries with a similar propensity for being in a catch share system. This overall approach is outlined in Fig. 1.

### Data sources

Time series data and reference point estimates were extracted from the RAM Legacy Stock Assessment Database (http://www.marinebiodiversity.ca/RAMlegacy/srdb/updated-srdb, last accessed 17 May 2011, the origin of which is the famous Ransom A. Myers Stock Recruitment Database) at the stock level (Ricard *et al.*, *in review, Fish and Fisheries*). These data were originally extracted from stock assessment documents that presented estimated annual biomass (either spawning stock, *SSB*, or total stock, *B*) and exploitation rates (either instantaneous fishing mortality, *F*, or exploitation ratios, *U* = total catch/total biomass), typically from age-structured models. Many assessments also estimated target reference points such as the values that would generate maximum sustainable yield, MSY (i.e. $SSB_{MSY}$, $B_{MSY}$, $U_{MSY}$ and/or $F_{MSY}$). In some cases, proxies for these MSY-based reference points were instead estimated (e.g. $F_{35\%}$ or $F_{40\%}$, the fishing mortality rate that would reduce spawning stock biomass per recruit to 35 or 40% of its unfished state, respectively). When multiple reference points were presented in assessments, the one that best represented the stated management target was used to calculate $B/B_{reference}$ or $F/F_{reference}$ ratios for each time series.

Catch and quota data were compiled from stock assessment documents, fishery management plans, on-line databases provided by governments or fisheries management councils or commissions and directly from fishery scientists or managers. Catch and quota data were taken from the same source wherever possible to ensure comparable treatment of fishing areas, fleets, recreational catches and discards. Analysis of catch:quota ratios was also at the stock level, so catches and quotas were often aggregated over fishing areas to cover the total area of assessed stocks. In a few cases, catch and quota data were listed for a pair of closely related and difficult to distinguish species, and these were included in the analysis as a single unit (see footnotes for Table S1 in the Supporting Information section).

We excluded some stocks from the dataset prior to analyses. We excluded 22 pelagic shark and tuna stocks because catch share programmes for these species are rare (although elasmobranch stocks were included in the analysis if they were part of a multispecies groundfish fishery). We excluded 12 rarely targeted stocks because catch shares operate mainly on targeted stocks; the targeting status of each stock was assessed through stock assessment documents and interviews with assessment scientists or managers familiar with the fishery. As the years

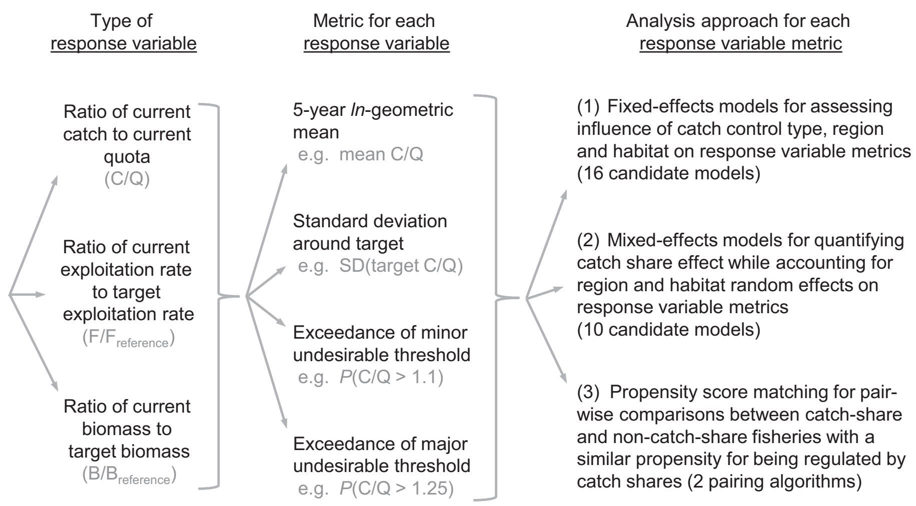


**Figure 1** Schematic of response variables and types of analyses used. Twelve response variables (3 types × 4 metrics) were used in each of three types of analyses. Shorthand notation for response variable types and metrics are shown in grey font; these abbreviations are commonly referred to in the text.

  

2000–2004 represented the focal period for our analysis (i.e. the most recent 5-year period for which time series data were available for most stocks), we dismissed data if catch shares or quota management were implemented during 2000–2004 (4 stocks). If all five years of data were not available for a particular response variable of a particular stock, or if reliable reference points could not be obtained (e.g. estimated reference points from stock assessments were not trusted by assessment scientists or surplus production model fits to time series data were poor; see Supporting Information), it was excluded from the analysis (193 stocks for at least one response variable, although some of these stocks were acceptable for other response variables if data were not missing). We also excluded 29 fisheries dominated by recreational landings (>50% of landings) because catch shares operate in the commercial sector. Finally, for our analyses of catch:quota and exploitation rates, we excluded 31 commercial fisheries under a moratorium during 2000–2004 (although these stocks were included in biomass analyses). After applying these filters, our database included 345 stocks with data for at least one of the three response variables (Table S1).

**Response variables and covariates**

*Types of response variables*

For our focal period of 2000–2004, some stocks ($n$ = 116) had annual estimates of all three response variables ($C/Q$, $F/F_{\text{reference}}$, and $B/B_{\text{reference}}$), while others ($n$ = 229) had annual estimates for only one or two of these variables over this period. For a particular response variable, stocks were only included if data for that variable were available for all years in the focal period. In some cases ($n$ = 81 for exploitation rates; $n$ = 89 for biomass), stock assessment documents did not provide target reference points. In these cases, a Schaefer (1954) surplus production model was fit to catch and total biomass data to estimate $U_{\text{MSY}}$ and $B_{\text{MSY}}$ reference points, provided at least 20 years of data were available (Worm *et al.* 2009; Hutchings *et al.* 2010). For cross-validation, we compared reference points estimated using the Schaefer model with those estimated from assessments. These were highly correlated for both $U/U_{\text{MSY}}$ and $B/B_{\text{MSY}}$ (in log space, correlation coefficients of $r = 0.773$ and $r = 0.769$ respectively; see Fig. S1 in the online Supporting Information). Additionally, we conducted a sensitivity test, repeating our analyses after excluding the stocks with only Schaefer model reference points, to test whether our conclusions were sensitive to Schaefer estimates.

*Metrics of response variables*

We quantified the extent to which each of the three fishery variables tracked management targets in four separate ways. We describe each of these in turn:

1. Mean response. The ln of the geometric mean of the yearly ratios over the 5-year period (i.e. the arithmetic mean of the ln-ratios) was calculated for each stock. For example, the mean catch:-quota ratio of a given stock over $n$ years is:

$$\text{Mean } C/Q = \frac{\sum_{1}^{n} \ln(C/Q)}{n}. \qquad (1)$$

2. Variability in response. The standard deviation around the target ratio of 1 (or 0 in ln-space) was calculated to represent the variability around management targets. The standard deviation around the target catch:quota ratio is:

$$\text{SD(target } C/Q) = \sqrt{\frac{\sum_{1}^{n} (\ln(C/Q))^2}{n}}. \qquad (2)$$

   Variation thus arises from the combined influence of fluctuations around the sample mean and the difference between the sample mean and the management target. Standard deviations were ln-transformed prior to analysis.
3. Exceedance of minor threshold. Whether or not a stock's ratio ($C/Q$, $F/F_{\text{reference}}$ or $B/B_{\text{reference}}$) exceeded an undesirable threshold value was calculated to address the asymmetrical management consequences of observing $C/Q > 1$, $F/F_{\text{reference}} > 1$ and $B/B_{\text{reference}} < 1$. These are undesirable states with catch greater than quota, fishing mortality higher than the reference point and biomass lower than the reference point. We thus calculated the proportion of stocks whose mean values exceeded (or for biomass, were less than) a predetermined threshold value ($C/Q > 1.1$, $F/F_{\text{reference}} > 1.1$, and $B/B_{\text{reference}} < 0.9$) and related the resulting values to the catch control type and other covariates.
4. Exceedance of major threshold. Instead of minor exceedance threshold values of 10% quota overages, overfishing or biomass depletion, we calculated whether or not the mean value exceeded

(or for biomass, was less than) the target value by a substantial amount ($C/Q > 1.25$, $F/F_{\text{reference}} > 1.5$ and $B/B_{\text{reference}} < 0.5$).

In total, four metrics were evaluated for three types of ratios, totalling 12 response variables (Fig. 1). These 12 variables were analyzed within each of three approaches described below.

*Predictor variables*

Stocks were categorized into four primary catch control types: catch shares (>75% of the total catch was under a catch share programme); partial catch shares (25–75% of total catch was under a catch share programme); fleet-wide quota cap only (fishery is regulated by catch quotas and <25% of catch was under a catch share programme); and effort control in which stocks were managed with input controls like days-at-sea limits or size-based limits. In cases where multiple fleets, multiple political jurisdictions or both commercial and recreational sectors were involved in the fishery for a stock, the control type was determined for each component and the overall control type for the stock was based on the proportions of catches in each component.

The implementation of catch share programmes is unlikely to be a random process: some fisheries may be more likely to enter into catch shares depending on the regional fisheries agencies, the history of the fishery and basic life-history characteristics of the stock. It may be these other factors that affect a response variable rather than catch shares *per se*. To control for these potentially confounding variables, we used propensity score (PS) weighting (Rosenbaum and Rubin 1983) to calculate the likelihood that a given stock would be in a catch share programme based on five covariates described below. This involved a logistic regression predicting the propensity score (ranging from 0 to 1) that each stock would be in a full catch share fishery (>75% of catch under catch shares) in 2000–2004 given its covariate values. Following Costello *et al.* (2008), we used these propensity scores as linear covariates in subsequent statistical analyses to account for the non-random selection process of catch share implementation. To guard against the possibility that use of the propensity scores in models did not perform as intended, we also conducted sensitivity analyses excluding the propensity scores (see Supporting Information).

Regional categories were assigned to each stock based on the geographic area and the primary management agency. Eleven broad regions were considered, shown in Fig. 2. Each fish stock was assigned one of the four habitat/taxonomic categories, aggregated from FishBase (Froese and Pauly 2010) categories of habitat association: demersal (including FishBase categories 'demersal' and 'bathydemersal'); benthopelagic ('benthopelagic' and 'bathypelagic'); pelagic ('pelagic', 'pelagic–neritic' and 'pelagic–oceanic') and reef-associated. All invertebrate stocks (primarily bivalves and crustaceans) comprised a fifth habitat/taxonomic category. Stocks included in analyses are summarized in Table 1 and listed in Table S1.

We also included three additional covariates: year of fishery development, average catch of fishery and maximum fish length. Year of development was defined as the first year that catches of the stock exceeded 25% of the historic maximum (as in Sethi *et al.* 2010), hypothesizing that some response variables might be affected by how long the fishery has been intensively fished, especially for long-lived species. Where time series of landings in stock assessments did not reach far enough into the past, the year of development was obtained from a nearby area or from global FAO landings data of the same species (Sethi *et al.* 2010). The second covariate, size of a fishery, was represented by the *ln* of average catch during 2000–2004 and considered because smaller fisheries may be particularly susceptible to fluctuations around management targets, and larger fisheries are typically of greater economic importance. The final covariate, maximum length ($L_{\max}$) was taken at the species level from FishBase for fish and from SeaLifeBase (Palomares and Pauly 2010) or research documents for invertebrates.

We analyzed the data using fixed-effects models and mixed-effects models, using the same sets of response variables and predictor variables. The fixed-effects models allowed us to assess the relative importance of regional, habitat and catch control factors, while the mixed-effects models allowed us to better focus on the catch control type effect. We explain each of these analyses below.

## Multimodel inference: fixed-effects models

We used model selection methods to choose the set of predictor variables that best explained the response variables. Main predictor variables were region (with up to 11 categories), habitat (five categories) and catch control type (three levels for

  

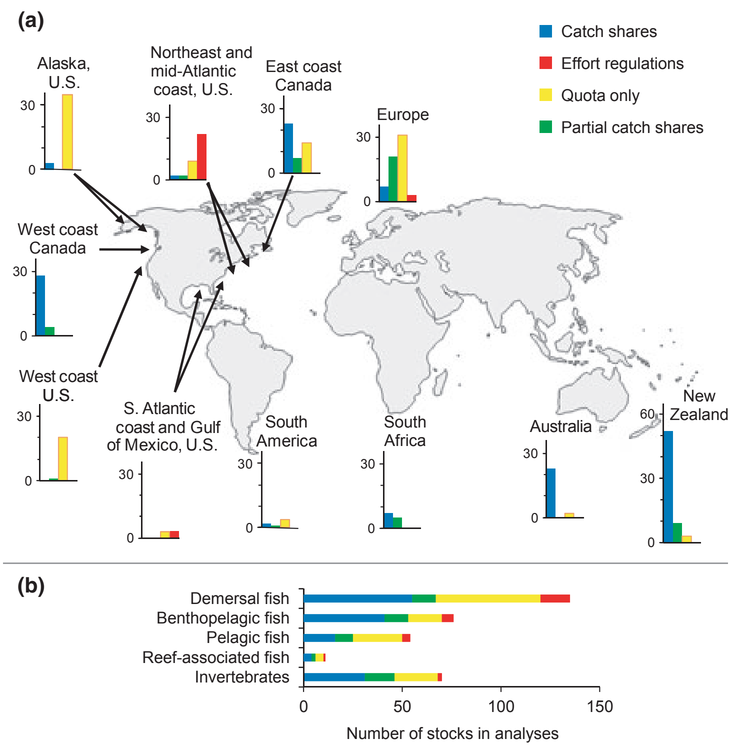


**Figure 2** Number of stocks included in analyses, shown by (a) region and (b) taxonomic/habitat association categories. Stocks are separated by four catch control types representing the 2000–2004 period: full catch shares (>75% of total catch under a catch share programme), partial catch shares (25–75% of total catch), fleet-wide quota-only (0–25% of total catch) and effort control. Stocks represented are included in at least one analysis of $C/Q$, $F/F_{\mathrm{reference}}$, or $B/B_{\mathrm{reference}}$ ratios.

$C/Q$ analyses and four levels for $F/F_{\mathrm{reference}}$ and $B/B_{\mathrm{reference}}$ analyses, including effort control). We *a priori* identified 16 alternative models that were compared for each response variable. We first generated all possible combinations that contained 0, 1, 2 or 3 of the main predictor variables as additive effects, which produced eight models. We also considered eight additional models that were similar to the first eight but also included an additional set of linear covariates: year of fishery development, average catch during 2000–2004 and $L_{\mathrm{max}}$. All models containing catch control type also included the propensity score covariate described above. All linear covariates were standardized to a mean of 0 and standard deviation of 1.

Separate analyses for the 12 response variables were conducted (3 variable types × 4 metrics). For the first two metrics (mean and variability), we used linear models and assumed normally distributed errors. For the last two metrics (whether stocks exceeded minor or major undesirable thresholds), we used generalized linear models with a logit link and a binomial probability density function. The log-likelihood and Akaike's Information Criterion (AICc, corrected for small samples; Burnham and Anderson 2002) were calculated for each model using the glm function in R (R Development Core Team, 2010). We used standardized rules of thumb to assess the degree of support for each model based on ΔAICc scores: models with AICc within 0–2 of the lowest value in the model set have similar levels of support from the data, models with AICc within 2–6 have sufficient support from the data to potentially be the best model within the set, while models with ΔAICc > 10 are not well supported compared with others (Burnham and Anderson 2002; Richards 2008).

### Parameter estimation: mixed-effects models

Region and taxonomic/habitat association categories may explain some of the variation in response variables, but our primary aim is to quantify an effect of catch control type regardless of the region or habitat from which a stock came. To complement

**Table 1** Number of stocks included in analyses of catch, exploitation rate and biomass relative to management targets.

| | $C/Q$ | | | $F/F_{reference}$ | | | | $B/B_{reference}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | CS | PCS | QO | CS | PCS | QO | $E$ | CS | PCS | QO | $E$ |
| Region | | | | | | | | | | | |
| USA–Alaska | 3 | | 25 | 3 | | 19 | | 2 | | 25 | |
| USA–West Coast | | 1 | 13 | | 1 | 14 | | | 1 | 17 | |
| Canada–West Coast | 26 | 4 | | 8 | 1 | | | 10 | 1 | | |
| Canada–East Coast | 19 | 6 | 10 | 4 | 1 | 2 | | 8 | 2 | 5 | |
| USA–Northeast/Mid-Atlantic Coast | 2 | | 6 | 1 | 2 | 6 | 21 | 1 | 2 | 7 | 22 |
| USA–S. Atlantic Coast/Gulf of Mexico | | | 3 | | | 2 | 3 | | | 2 | 3 |
| Europe | 7 | 16 | 24 | 6 | 15 | 17 | 3 | 6 | 18 | 19 | 3 |
| South Africa | 5 | 5 | | 4 | | | | 6 | | | |
| South America | | | 4 | 2 | 1 | 4 | | 2 | 1 | 3 | |
| Australia | 19 | | | 7 | | 1 | | 12 | | 2 | |
| New Zealand | 49 | 9 | 3 | 20 | 3 | 2 | | 20 | 3 | 2 | |
| Taxonomic/habitat association | | | | | | | | | | | |
| Demersal fish | 48 | 11 | 36 | 21 | 7 | 37 | 15 | 25 | 7 | 41 | 15 |
| Benthopelagic fish | 34 | 7 | 11 | 14 | 6 | 13 | 5 | 19 | 9 | 15 | 6 |
| Pelagic fish | 12 | 8 | 21 | 9 | 6 | 13 | 4 | 12 | 7 | 14 | 4 |
| Reef-associated fish | 4 | 2 | 3 | 2 | 1 | 2 | 1 | 2 | 1 | 3 | 1 |
| Invertebrates | 32 | 13 | 17 | 9 | 4 | 2 | 2 | 9 | 4 | 9 | 2 |
| Total | 130 | 41 | 88 | 55 | 24 | 67 | 27 | 67 | 28 | 82 | 28 |

Response variables are catch:quota ($C/Q$), current exploitation rate to reference exploitation rate ($F/F_{reference}$) and current biomass to reference biomass ($B/B_{reference}$). Numbers are separated by catch control type (CS, catch shares; PCS, partial catch shares; QO, no catch shares – quota only; $E$, effort control) and by either region or taxonomic/habitat association categories.

the fixed-effects model analysis, we also used generalized linear mixed-effects models in which region and habitat were treated as random effects (using the R package lme4; Bates and Maechler 2009). These allowed us to account for overall effects of region and habitat even though we were not explicitly interested in the nature of these effects, and to instead focus on the effect of control type. This approach also alleviated estimation problems arising from the lack of independence between control type and region; estimated standard errors of parameter estimates were often unstable when all variables were treated as fixed effects. We compared multiple candidate models differing in fixed effects in terms of AICc scores, with maximum likelihood optimization used for each model. We based inferences about the effects of predictor variables on estimated coefficients (for fixed effects) and conditional modes (for random effects) from the full model using restricted maximum likelihood optimization for the two linear metrics, i.e. mean response and SD (target).

Explanatory variables treated as fixed effects included catch control type (categorical) and four linear covariates: the propensity score for being in a catch share system, year of fishery development, average catch during 2000–2004 and $L_{max}$. Linear covariates were standardized prior to analyses. We considered five models that had none, two or all three of the linear covariates. These five models were considered either with or without control type and propensity score variables. The resulting 10 candidate models were considered for each of the 12 analyses (three response variable ratios × four metrics). The full model for each analysis involved all seven (for $C/Q$) or eight (for $F/F_{reference}$ and $B/B_{reference}$) fixed effects, without interactions among variables. Region and habitat were included as random effects in all models. When there were <10 stocks from a given region present in a dataset, two or more levels of region were aggregated in an 'other' category to maintain a minimum of 10 observations in each level of a random effect (Bolker *et al.* 2009). These aggregations involved: for $C/Q$, USA–Northeast/Mid-Atlantic Coast, USA–South Atlantic Coast/Gulf of Mexico and South America; for $F/F_{reference}$, Canada–East Coast, USA–South Atlantic Coast/Gulf of Mexico, South Africa, South America and Australia; and for $B/B_{reference}$, USA–South Atlantic Coast/Gulf of Mexico, South Africa and South America.

We conducted several sensitivity tests to data and model assumptions for the mixed-effects model analysis: (i) excluding propensity scores when catch control type was used as a predictor variable; (ii) removing $F_{reference}$ or $B_{reference}$ reference points estimated with a Schaefer surplus production model; (iii) excluding under-exploited stocks (with average $C/Q < 0.5$ during 2000–2004); (iv) excluding ICES (International Council for the Exploration of the Sea; in Europe) and NAFO (Northwest Atlantic Fisheries Organization, mainly off Eastern Canada) stocks, as MSY-based reference points are not used for management there; (v) excluding stocks under moratorium in 2000–2004 for the biomass analysis (recall they were already excluded for catch:quota and exploitation rate analyses); and (vi) excluding stocks under partial catch shares and effort control, as these catch control types had limited representation across regions.

### Propensity score matching

We used propensity score matching to confirm results from mixed-effects model analyses. Incorporating region and habitat as predictor variables into models as described above provides one means to separate their effect from the effect of catch control type. Another method of isolating the control type effect is to compare values of $C/Q$, $F/F_{reference}$ or $B/B_{reference}$ metrics among catch share and non-catch share fisheries that share a similar propensity for being in a catch share programme. As described earlier, catch share propensity scores (PS) describe the probability of a stock being under a full catch share programme during 2000–2004 based on its region, taxonomic/habitat association, year of development, average catch and $L_{max}$ value. A summary of propensity scores is shown in Figs S2 and S3 of the Supporting Information.

We used an all-possible-combinations approach to pair catch share fisheries with non-catch share fisheries under the constraint that their propensity scores had to be within 0.05 of each other. We then calculated the difference in the value of each response variable between them (mean responses were back-transformed to the linear scale). For each pair, the response variable value of the non–catch share fishery was subtracted from the value of the catch share fishery. The average difference over all pairs was calculated, with positive values indicating that on average catch share fisheries had larger values of the response than non-catch share fisheries, and negative values indicating the opposite (for the two binary metrics representing the frequencies of being in an undesirable state, the difference for each pair could only take on values −1, 0 or 1, but when averaged over all pairs of fisheries this yielded a wide range of possible response values). We also used a similar approach involving resampling for randomly pairing non-catch share and catch share fisheries of similar propensity; this second approach to propensity score matching (which produced similar results) is described in the Supporting Information.

## Results

We observed notable regional variation in the relative use of catch share programmes. For example, New Zealand, Southeast Australia, West Coast Canada and South Africa used catch shares almost exclusively, Alaska and West Coast USA had extensive quota management but infrequent use of catch shares during 2000–2004 and the USA Northeast/Mid-Atlantic Coast and USA South Atlantic Coast/Gulf of Mexico had a higher proportion of effort-controlled fisheries during the focal period (Fig. 2).

### Distributions of $C/Q$, $F/F_{reference}$ and $B/B_{reference}$ response variables

Across all stocks, the ratio of catch:quota was generally close to the management target of 1 with few stocks having $C/Q > 1.25$ (Fig. 3a–c). When separated by control type, quota compliance of many catch share fisheries was just below the target of 1 (Fig. 3a). When further separated by region, there was little variation among Eastern Canada, Western Canada and New Zealand (Fig. 3a). Australia has a slightly higher frequency of catches below quota because most of the stocks in the dataset are drawn from a multispecies fishery where quota on one species can constrain catches of other species. Distributions for partial catch share and quota-only fisheries also had a mode just below 1, but generally had greater spread than that for full catch shares. European partial catch share stocks, especially, had a wide range, some above and some below the target (Fig. 3b). Most quota-only fisheries from USA West Coast and Alaska had $C/Q < 1$.

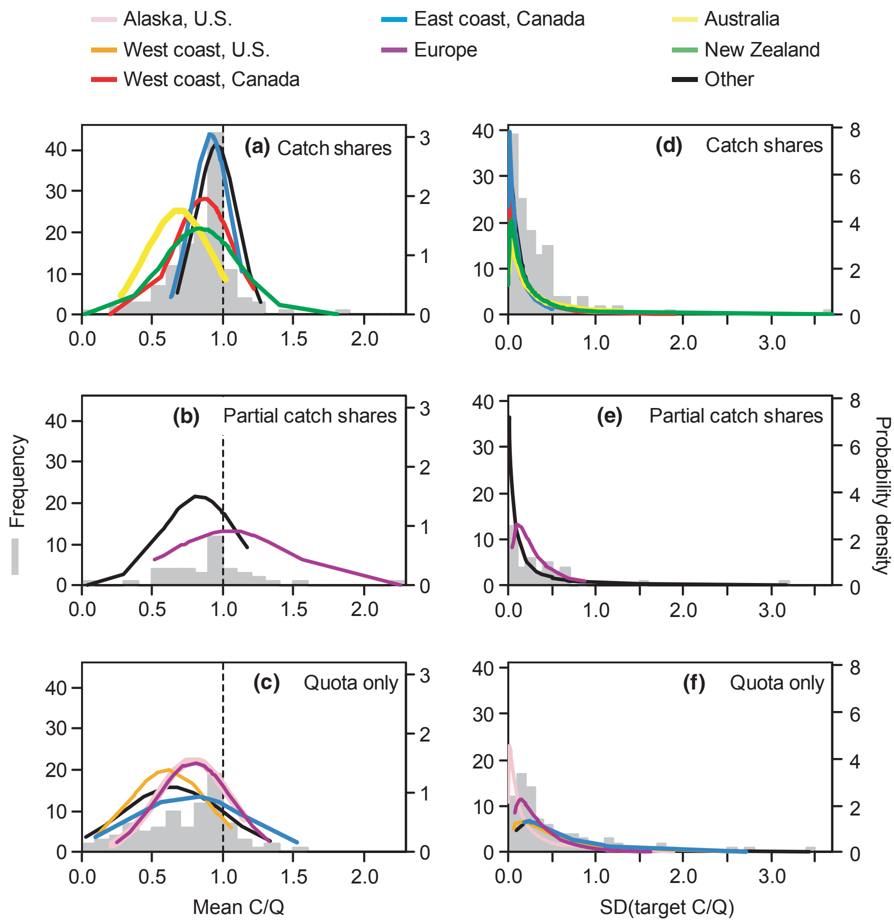


**Figure 3** Frequency distributions of catch/quota ratios within catch control types. Frequencies (grey bars) are separated by three catch control types, and show either (a–c) the ln-geometric mean response or (d–f) variation around the management target. Regions with ≥10 stocks of a particular control type have probability density functions shown; stocks from remaining regions are pooled in the 'other' category. Dashed line shows the management target for mean responses.

Compared to catch:quota, distributions of the ratios of $F/F_{\text{reference}}$ and $B/B_{\text{reference}}$ were wider (Figs 4 and 5). Although more than half the stocks in our analysis had $F$ below the target, major over-exploitation ($F/F_{\text{reference}} > 1.5$) occurred within all catch control types: 9% of stocks for full catch shares, 17% for partial catch shares, 13% for quota only and 41% for effort controls (Fig. 4a–d). There was considerable variation among regions in exploitation rates. Catch share fisheries from New Zealand generally had $F/F_{\text{reference}}$ below the management target, while those from other areas were centred near the target (Fig. 4a). European partial catch share fisheries were also centred near the target, although European quota-only fisheries and especially USA Northeast/Mid-Atlantic effort-controlled fisheries commonly experienced over-exploitation (Fig. 4b–d). In contrast, USA West Coast and Alaskan quota-only fisheries typically had $F/F$ reference < 1 (Fig. 4c).

Patterns consistent with exploitation rates were generally observed for biomass, with stronger variation among regions than among catch control types. New Zealand stocks under catch shares had a wide distribution of $B/B_{\text{reference}}$ values but were high (nearly 2) on average, Australian catch share stocks had biomass near the management target on average, while most West Coast Canada catch share stocks were below management targets (Fig. 5a). European stocks under partial catch shares and quota-only systems as well as USA Northeast/Mid-Atlantic stocks under effort controls also generally had low biomass, below the target of 1 (Fig. 5b–d). USA West Coast and Alaska quota-only fisheries

  

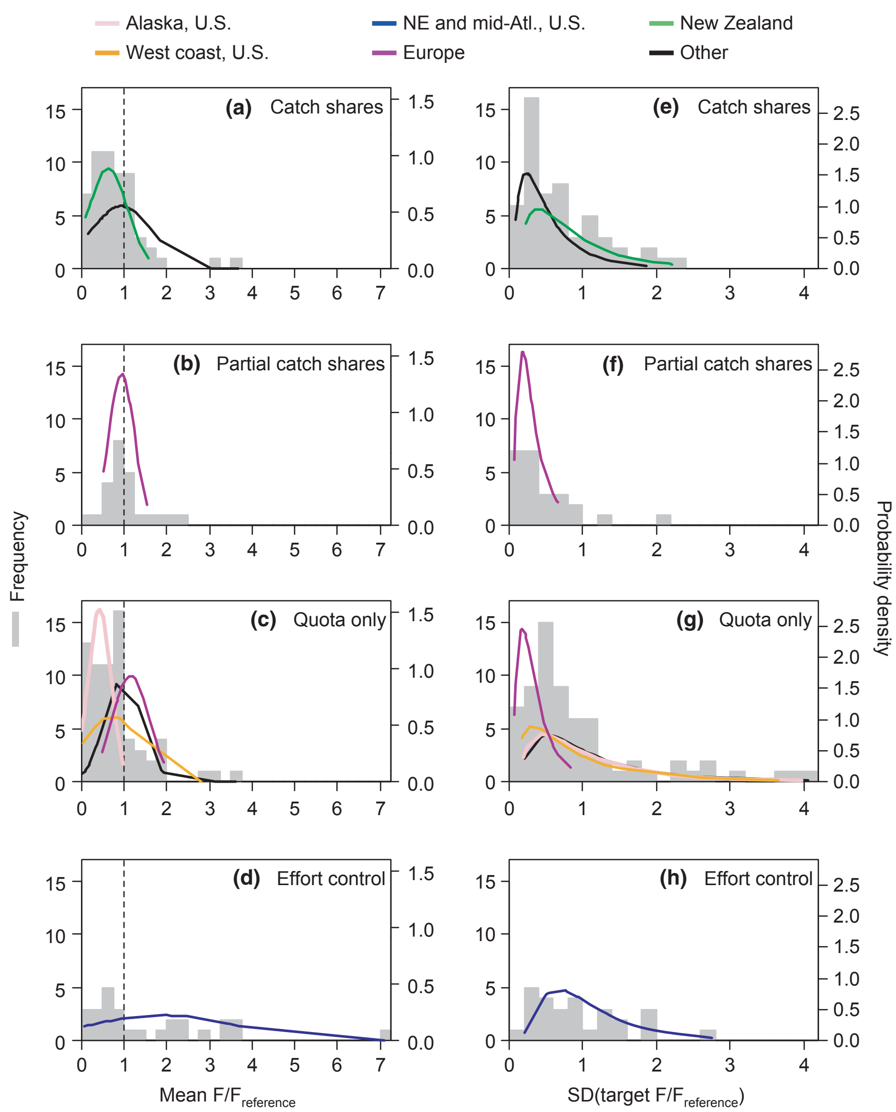


**Figure 4** Frequency distributions of current exploitation rate relative to reference exploitation rate within catch control types. Frequencies (grey bars) are separated by four control types and show either (a–d) the ln-geometric mean response or (e–h) variation around the management target. Regions with ≥10 stocks of a particular control type have probability density functions shown; stocks from remaining regions are pooled in the 'other' category. Dashed line shows the management target for mean responses.

typically had $B/B_{\text{reference}} > 1$ (Fig. 5c), which is consistent with their low exploitation rates.

Compared with mean responses, there was generally less variation among regions and among catch control types for SD (target) of all three response variables (Figs 3–5). Because variability around the management target incorporates not only variation around the sample mean but also between the sample mean and the target, SD (target $C/Q$) values were generally smaller than SD (target $F/F_{\text{reference}}$) or SD (target $B/B_{\text{reference}}$) values. For both mean and SD responses, it was challenging to compare control types within the same region, because data for most regions were dominated by a single control type. Only in Eastern Canada (for $C/Q$) and Europe (for all three ratios) were there ≥10 stocks in more than one control type group (Figs 3–5). Frequency distributions similar to Figs 3–5 but aggregated over all control types are shown in Fig. S5, with common axes. These clearly

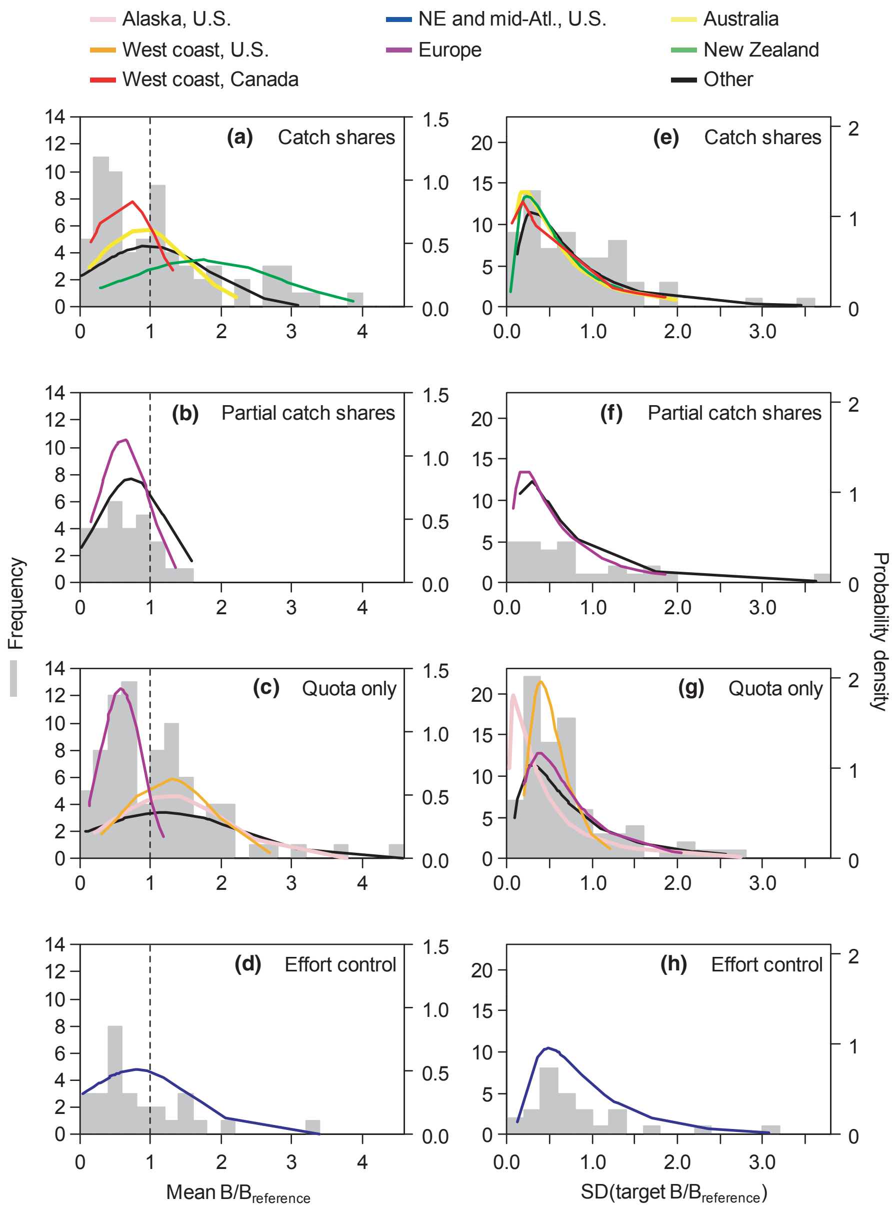


**Figure 5** Frequency distributions of current biomass relative to reference biomass within catch-control types. Frequencies (grey bars) are separated by four control types and show either (a–d) the ln-geometric mean response or (e–h) variation around the management target. Regions with ≥10 stocks of a particular control type have probability density functions shown; stocks from remaining regions are pooled in the 'other' category. Dashed line shows the management target for mean responses.

show the wider distributions of $F/F_{reference}$ and $B/B_{reference}$ compared with $C/Q$ ratios.

Mean responses of $C/Q$, $F/F_{reference}$ and $B/B_{reference}$ ratios do not reflect the asymmetries of consequences above and below the target value of 1 (i.e. there is typically greater management concern about quota overages, over-exploitation and depletion than their alternatives). Considering the proportion of stocks whose response variables exceed some threshold value allows this asymmetry to be evaluated. There was little apparent difference between catch share and quota-only fisheries in how frequently they overfished their quota (Fig. 6a), experienced over-exploitation (Fig. 6b) or

  

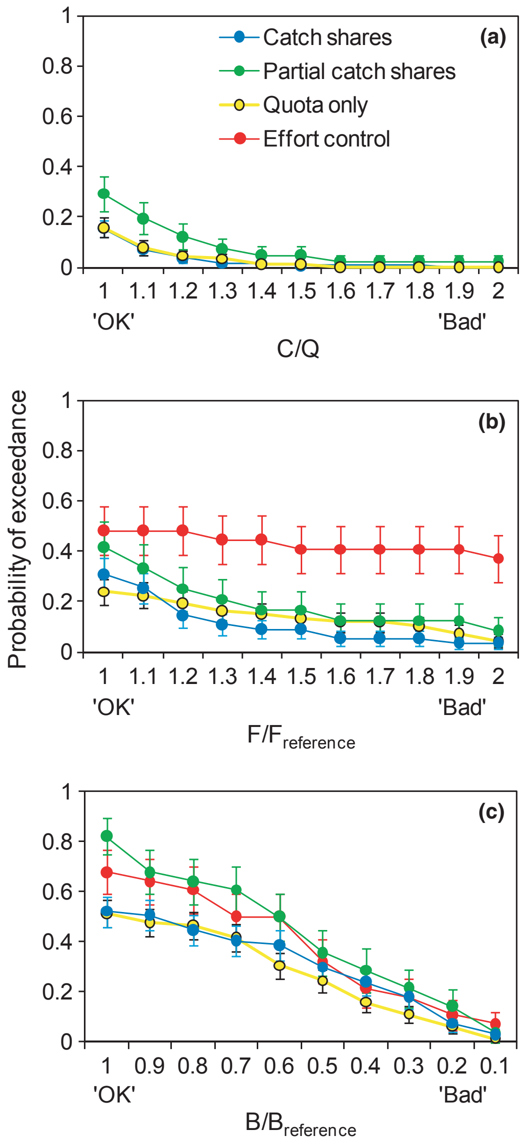


**Figure 6** Proportion of stocks whose ratios of (a) catch/quota, (b) current exploitation rate/reference exploitation rate or (c) current biomass/reference biomass exceed an undesirable threshold value. Proportions are given for a wide range of threshold values and are shown separately for four primary catch control types. Values to the left of each panel show relatively minor levels of quota overages, over-exploitation, or biomass depletion, while values to the right show more severe levels. Error bars show binomial SE.

had depleted biomass levels (Fig. 6c) regardless of the severity of the exceedance threshold. In contrast to these control types, partial catch share fisheries (25–75% of total landings within a catch share system) overfished their quota slightly more often, especially at levels of minor overages (Fig. 6a). Effort-managed fisheries had much higher frequencies of over-exploitation, especially at more severe threshold levels (Fig. 6b). Partial catch share fisheries and effort-managed fisheries both had higher frequencies of depleted stocks, especially at low threshold levels (Fig. 6c). However, these results shown in Fig. 6 may be confounded by regional or taxonomic/habitat association effects. Remaining sections present results from analyses aiming to isolate control type effects from those of other variables.

### Multimodel inference: fixed-effects models

Catch control type was as or more important than region and habitat as a predictor of $C/Q$ metrics, but was a much less important predictor for $F/F_{reference}$ and $B/B_{reference}$ metrics. The mean $C/Q$ was best predicted by two models: one based on the catch control and region, and the other consisting of catch control, habitat, development year, average catch and $L_{max}$ (Table 2). For SD (target $C/Q$), habitat and control type were both strongly supported, and there was some evidence that a model containing region was also important. For the two metrics expressing frequency of overages, control type, habitat and region all had weak to moderate levels of support (i.e. null models containing only an overall intercept had the strongest support; Table 2).

For exploitation rates, region and habitat effects were moderately supported while control type was only weakly supported for the mean response (Table 3). For SD (target $F/F_{reference}$), we found strong support for models containing both region and habitat as predictor variables (Table 3). Models containing region were strongly supported for the frequency of over-exploitation (Table 3; there was also weak support for control type effects on the frequency of major over-exploitation).

For biomass, regional and habitat effects were both strongly supported for the mean response and frequency of depletion (Table 4). Again, models containing habitat were strongly supported for variability around the management target, SD (target $B/B_{reference}$) (Table 4). There was little to no support for models containing control type on any biomass or exploitation rate metric after effects of region and habitat were accounted for. Full model selection results are listed in Tables S2–S4 of the Supporting Information.

**Table 2** Model selection results for metrics of catch:quota ratios.

| Model* | Response variable Mean | SD (target) | Small (10%) overage | Large (25%) overage |
|---|---|---|---|---|
| CControl + PS + Region + Habitat + avCatch + devYear + $L_{max}$ | 6.6 | **4.2** | 13.7 | 19.5 |
| CControl + PS + Region + avCatch + devYear + $L_{max}$ | 6.3 | 36.1 | 11.5 | 16.2 |
| CControl + PS + Habitat + avCatch + devYear + $L_{max}$ | **1.2** | **0.0** | **3.1** | 7.9 |
| CControl + PS + avCatch + devYear + $L_{max}$ | 7.1 | 37.2 | **1.1** | **3.3** |
| CControl + PS + Region + Habitat | **3.9** | **1.3** | 9.1 | 15.9 |
| CControl + PS + Region | **0.0** | 42.6 | **5.6** | 11.3 |
| CControl + PS + Habitat | 14.2 | 9.4 | **4.4** | **5.8** |
| CControl + PS | 10.1 | 38.4 | **4.6** | **3.6** |
| Region + Habitat + avCatch + devYear + $L_{max}$ | **4.7** | **5.2** | 11.5 | 14.2 |
| Region + avCatch + devYear + $L_{max}$ | 9.4 | 47.8 | 8.4 | 10.2 |
| Habitat + avCatch + devYear + $L_{max}$ | 7.3 | 11.8 | **3.6** | **4.3** |
| Intercept + avCatch + devYear + $L_{max}$ | 14.3 | 51.5 | **0.0** | **0.0** |
| Region + Habitat | 14.5 | 24.5 | 8.8 | 10.9 |
| Region | 10.0 | 50.7 | **5.9** | 6.2 |
| Habitat | 19.3 | 17.8 | **5.0** | **2.5** |
| Intercept | 16.0 | 48.4 | **4.0** | **0.3** |

Values are differences in AICc scores between each model and the AICc-lowest model in the set of 16 candidate models. Values are shown for four analyses: mean *C/Q*, variability around the management target and the proportion of stocks with *C/Q* that exceed two threshold values. All values of ΔAICc < 6 are boldfaced, and those <2 are also underlined. Refer to Table S2 (Supporting Information) for full AICc tables.

*Model covariates are: avCatch, average total catch during 2000–2004 period (ln-transformed); devYear, year of fishery development; $L_{max}$, maximum length; PS, propensity score for being in a catch share programme and CControl, catch control type, with levels of catch shares (>75% of total landings in catch shares), partial catch shares (25–75%), and quota only (<25%).

### Parameter estimation: mixed-effects models

We conducted exploratory data analyses prior to fitting mixed-effects models and analyses of standardized residuals after fitting models (see Supporting Information).

*Quota compliance*

Of the fixed effects considered, mean *C/Q* was most strongly influenced by control type and average catch during the 2000–2004 period (Fig. 7a). After controlling for other factors including the propensity of fisheries to be in a catch share programme, fisheries managed only with quotas tended to have lower *C/Q* than did catch share fisheries. While quota overages were infrequent for both of these control types, most catch share fisheries had *C/Q* just under 1 while quota-only fisheries were more often under-exploited (Fig. 3). Fisheries managed with partial catch shares had similar *C/Q* to full catch share fisheries (Fig. 7a). Overall, fisheries with greater average catch had higher *C/Q*.

Variability of catch:quota ratios around the management target was again most strongly influenced by catch control type and average catch (Fig. 7b). Fisheries with larger total catches had lower SD (target *C/Q*) compared with smaller ones (Fig. 7b and Fig. S5a). After controlling for covariates, quota-only fisheries had higher SD (target *C/Q*) on average (1.78) compared with catch share fisheries (1.37). This is partly an effect of under-exploited fisheries generally not being under catch shares. Fisheries managed with partial catch shares were intermediate between these types (Fig. 7b).

Catch control type effects were weaker for the frequency of quota overages (Fig. 7c,d). The apparent effect of more frequent overages for partial catch shares is likely confounded with regional or habitat effects, because variances for these random effects were not properly estimated (see Supporting Information). Year of development, $L_{max}$ and propensity score had little effect on any of the four metrics of catch:quota ratios (Fig. 7).

*Exploitation rates*

Catch control type did not have a significant effect on the mean $F/F_{reference}$; only development year had a significant effect, with earlier developing fisheries

**Table 3** Model selection results for metrics of current exploitation/reference exploitation rate ratios.

| Model* | Response variable<br>Mean | SD (target) | Minor (10%) over-exploitation | Major (50%) over-exploitation |
|---|---|---|---|---|
| CControl + PS + Region + Habitat + avCatch + devYear + $L_{max}$ | 7.4 | 10.1 | 18.0 | 12.0 |
| CControl + PS + Region + avCatch + devYear + $L_{max}$ | 9.4 | 13.7 | 11.5 | 6.4 |
| CControl + PS + Habitat + avCatch + devYear + $L_{max}$ | **3.8** | 32.3 | 14.3 | 10.2 |
| CControl + PS + avCatch + devYear + $L_{max}$ | **1.0** | 29.3 | 8.2 | **4.3** |
| CControl + PS + Region + Habitat | 9.8 | **4.3** | 15.2 | 12.4 |
| CControl + PS + Region | 8.2 | 10.2 | 8.5 | 7.2 |
| CControl + PS + Habitat | 11.2 | 31.0 | 12.1 | 8.4 |
| CControl + PS | **5.0** | 27.7 | 6.2 | **3.2** |
| Region + Habitat + avCatch + devYear + $L_{max}$ | **0.0** | **2.8** | 11.6 | 7.2 |
| Region + avCatch + devYear + $L_{max}$ | **1.3** | 8.8 | **5.0** | **0.0** |
| Habitat + avCatch + devYear + $L_{max}$ | **3.6** | 32.6 | 10.7 | 13.3 |
| Intercept + avCatch + devYear + $L_{max}$ | **1.5** | 32.9 | **5.0** | 7.0 |
| Region + Habitat | **3.8** | **0.0** | 6.2 | **5.8** |
| Region | **1.2** | 6.3 | **0.0** | **1.4** |
| Habitat | 14.2 | 34.8 | 11.5 | 13.7 |
| Intercept | 8.8 | 34.4 | **5.4** | 9.2 |

Values are differences in AICc scores between each model and the AICc-lowest model in the set of 16 candidate models. Values are shown for four analyses: mean $F/F_{reference}$, variability around the management target and the proportion of stocks with $F/F_{reference}$ that exceed two threshold values. All values of $\Delta$AICc < 6 are boldfaced, and those <2 are also underlined. Refer to Table S3 (Supporting Information) for full AICc tables.

*See Table 2 footnote for model covariate definitions; a fourth level of catch control type (CControl) is effort control.

typically having higher exploitation rates relative to target levels (Fig. 8a and Fig. S7ba). There was some suggestion of higher mean $F/F_{reference}$ in effort control fisheries compared with others, but error bars of coefficients overlapped broadly (Fig. 8a). None of the predictor variables showed significant effects on SD (target $F/F_{reference}$). Although no fixed-effect variables had an important influence on the frequency of exceeding minor over-exploitation thresholds (Fig. 8c), a strong effect of catch control type was detected on the frequency of exceeding major over-exploitation thresholds (Fig. 8d). Effort-managed fisheries experienced major over-exploitation more commonly than full catch share fisheries, while partial catch share and quota-only fisheries were intermediate between these.

*Biomass*

After accounting for other covariates, no effect of control type was observed for the mean response of $B/B_{reference}$ ratios, SD (target $B/B_{reference}$) or the proportion of stocks whose $B/B_{reference}$ ratios were depleted below various thresholds (Fig. 9; Table S7). Year of fishery development and average catch during 2000–2004 affected the mean biomass response and the probability of depletion metrics, with earlier developed fisheries (Fig. S7c) and smaller sized fisheries having lower biomass relative to target levels and higher frequencies of falling below both minor and major threshold levels (Fig. 9). Larger SD (target $B/B_{reference}$) was associated with smaller sized fisheries (Fig. S6c), earlier developing fisheries and stocks with longer $L_{max}$ (Fig. 9b). Estimates of region and habitat random effect for all analyses are presented in the Supporting Information.

We repeated the mixed model analyses under alternative assumptions or with filtered datasets to evaluate the sensitivity of the results to six alternative scenarios (see Methods). Estimated coefficient values of fixed effects rarely changed substantially under alternative cases compared with the base case scenario (see Supporting Information for details). Statistical support for differences among catch control categories changed for some response variables under some filtered datasets, but these changes from the base case were often because of poorly estimated random effects as a result of sample size reductions (see Supporting Information).

**Table 4** Model selection results for metrics of current biomass/reference biomass ratios.

| Model* | Response variable Mean | SD (target) | Minor (10%) depletion | Major (50%) depletion |
|---|---|---|---|---|
| CControl + PS + Region + Habitat + avCatch + devYear + $L_{max}$ | 6.8 | 15.5 | 7.9 | 11.7 |
| CControl + PS + Region + avCatch + devYear + $L_{max}$ | 18.2 | 21.5 | 11.8 | 24.0 |
| CControl + PS + Habitat + avCatch + devYear + $L_{max}$ | 31.1 | 8.4 | 11.8 | 8.6 |
| CControl + PS + avCatch + devYear + $L_{max}$ | 44.8 | 18.0 | 16.2 | 25.8 |
| CControl + PS + Region + Habitat | 18.9 | 33.8 | 13.8 | 32.1 |
| CControl + PS + Region | 33.9 | 35.6 | 25.9 | 40.4 |
| CControl + PS + Habitat | 59.5 | 30.2 | 25.2 | 37.9 |
| CControl + PS | 66.9 | 33.1 | 27.5 | 45.0 |
| Region + Habitat + avCatch + devYear + $L_{max}$ | **<u>0.0</u>** | 6.6 | **<u>0.0</u>** | **2.9** |
| Region + avCatch + devYear + $L_{max}$ | 12.9 | 12.6 | **5.8** | 15.7 |
| Habitat + avCatch + devYear + $L_{max}$ | 27.8 | **<u>0.0</u>** | 7.7 | **<u>0.0</u>** |
| Intercept + avCatch + devYear + $L_{max}$ | 42.6 | 9.9 | 12.8 | 18.4 |
| Region + Habitat | 18.5 | 27.6 | 6.9 | 25.9 |
| Region | 33.4 | 27.2 | 20.5 | 32.9 |
| Habitat | 59.5 | 23.3 | 25.1 | 30.2 |
| Intercept | 66.8 | 27.0 | 27.3 | 38.3 |

Values are differences in AICc scores between each model and the AICc-lowest model in the set of 16 candidate models. Values are shown for four analyses: mean $B/B_{reference}$, variability around the management target and the proportion of stocks with $B/B_{reference}$ below two threshold values. All values of ΔAICc < 6 are boldfaced, and those <2 are also underlined. Refer to Table S4 (Supporting Information) for full AICc tables.

*See Table 2 footnote for model covariate definitions; a fourth level of catch control type (CControl) is effort control.

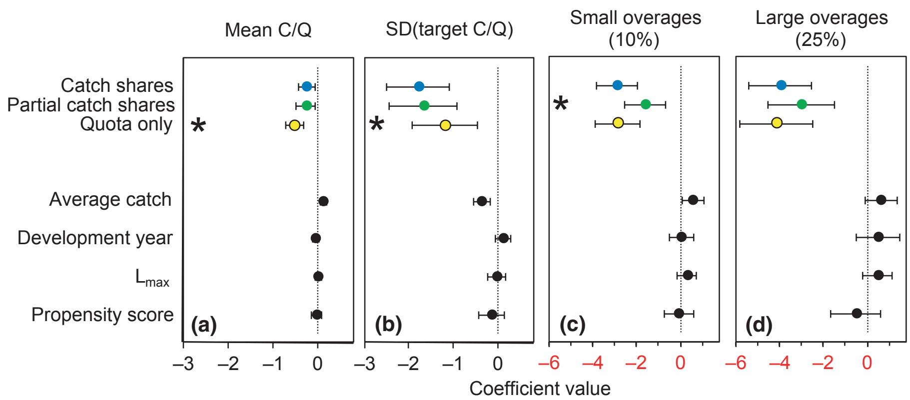


**Figure 7** Estimated coefficients of fixed effects on catch/quota ratios for (a) mean *C/Q*, (b) variation around the target ratio, and proportion of fisheries with (c) small or (d) large overages. Estimates were generated under the full model, with region and taxonomic/habitat association as random effects. Asterisks beside coefficients for catch control types indicate statistical differences compared to the catch share category. Error bars show 95% CI around restricted maximum likelihood (a,b) or maximum likelihood (c,d) estimates. Note that *x*-axis values differ between the 1st/2nd and 3rd/4th panels.

## Propensity score matching

To control for the non-random distribution of covariates between catch share and non-catch share fisheries, we conducted a pair-wise analysis of fisheries with a similar propensity for being under catch share management. Effects of region, habitat and other covariates are accounted for implicitly through their effect on propensity.

Variation around the management target of catch:quota was smaller for catch share fisheries than for non-catch share fisheries of similar

  

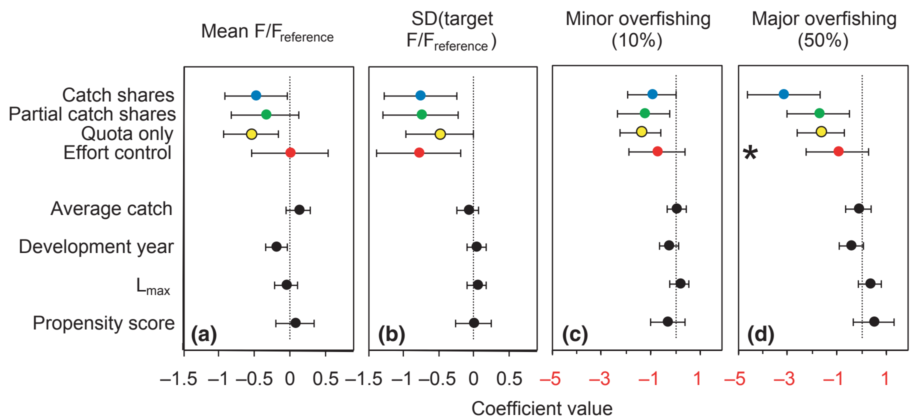


**Figure 8** Estimated coefficients of fixed effects on current exploitation rate relative to reference exploitation rate for (a) mean $F/F_{reference}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major overfishing. Estimates were generated under the full model, with region and taxonomic/habitat association as random effects. Asterisks beside coefficients for catch control types indicate statistical differences compared to the catch share category. Error bars show 95% CI around restricted maximum likelihood (a,b) or maximum likelihood (c,d) estimates. Note that *x*-axis values differ between the 1st/2nd and 3rd/4th panels.

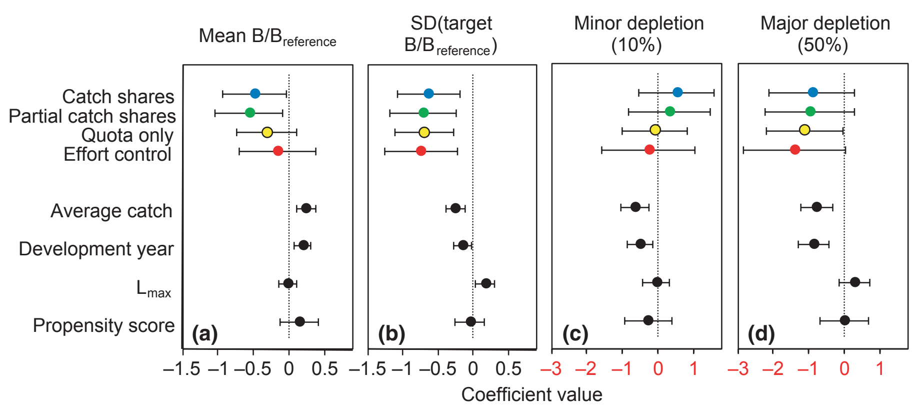


**Figure 9** Estimated coefficients of fixed effects on current biomass relative to reference biomass for (a) mean $B/B_{reference}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major biomass depletion. Estimates were generated under the full model, with region and taxonomic/habitat association as random effects. Error bars show 95% CI around restricted maximum likelihood (a,b) or maximum likelihood (c,d) estimates. Note that *x*-axis values differ between the 1st/2nd and 3rd/4th panels.

propensity (Fig. 10), supporting the mixed-effects model analysis. Catch share fisheries experienced major over-exploitation (1.5 times the management target) less frequently than fisheries under other catch control types (Fig. 10), also supporting the mixed-effects model analysis. This difference was not only the result of fisheries under effort control experiencing over-exploitation more frequently than other control types as it would appear from Fig. 6b, because when a similar analysis was restricted to full catch share and quota-only fisheries, catch share fisheries still had a lower frequency of major over-exploitation (results not shown). There was some suggestion that catch share fisheries had higher mean *C/Q* and lower mean $F/F_{reference}$ than non-catch share fisheries, but the differences were not significant. No biomass metrics differed between catch share and non-catch share fisheries.

## Discussion

We assessed whether catch share fisheries were more likely to track management targets than other

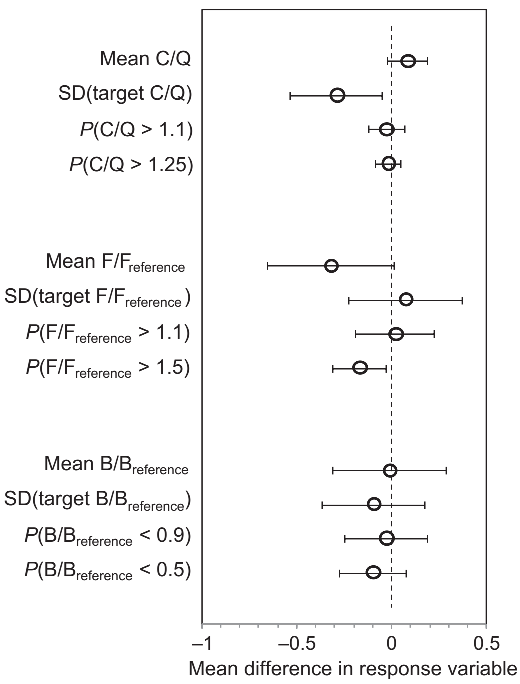


**Figure 10** Differences between response variables of paired catch share and non-catch share fisheries sharing similar propensity for being in catch shares. Response variable differences (value for catch share fishery minus value for non-catch share fishery) are shown for 12 analyses. All possible combinations of catch share and non-catch share fisheries were included provided that their propensity scores were <0.05 of one another. The mean differences of pairs are shown with 95% CI.

fisheries based on 345 stocks of 158 species from 11 regions. In terms of scope (four metrics for each of three variables), geographic breadth, accounting for additional factors, explicit consideration of management targets and multiple data analysis approaches, this study represents the most comprehensive analysis to date of the effect of catch shares on variables relevant to population biology and fishery performance. This analysis revealed that the strongest effects of catch shares were observed in reducing interannual variability in catches around target quotas. Stocks under catch shares experienced overexploitation rates less frequently than non-catch share stocks; however, catch shares did not have a detectable effect on any biomass-based response variables.

The strength of response to catch shares varied depending on how closely the variable was tied to direct management control: we observed catch share effects more commonly on metrics of catch:quota, less commonly on exploitation rate, and not at all on biomass metrics. For all three of our approaches, catch control type had a detectable effect on the variability around the management target for catch:quota. An effect on the mean catch:quota was observed in the fixed-effects and mixed-effects model approaches, but the mean response may be the least informative of the four metrics considered because most stocks had $C/Q < 1$ (Fig. 3). Because of the large number of stocks with low catch:quota, the mean $C/Q$ may not be a very sensitive metric as it would not detect differences in large magnitudes or frequencies of quota overages (arguments are similar for mean $F/F_{\mathrm{reference}}$ and mean $B/B_{\mathrm{reference}}$). Quota overages appeared to be more frequent in partial catch share fisheries in the mixed-effects model analysis, but this is likely a consequence of regional confounding given that this effect disappeared when ICES and NAFO stocks (where most partial catch share fisheries are located) were excluded from the analysis. Our results therefore support those found for North American fisheries by Essington (2010): catch share fisheries are less variable around target catch:quota compared with the fisheries managed only with quotas. In other words, implementing catch shares results in greater predictability in meeting annual quotas.

The reduced variability of catch share fisheries around quota targets likely results from the incentive structures associated with well-enforced catch share systems. When quota shares are allocated to individuals (fishermen, vessels or corporations) and enforcement is effective (e.g. at landing sites), the responsibility for not exceeding the quota falls on the individual rather than being spread among the fleet. In many catch share fisheries, quota underages can be carried forward to the next year, whereas quota overages are subject to penalties (Sanchirico *et al.* 2006). In contrast, competitive fisheries encourage individuals to catch as much as they can before fleet-wide total quota is exceeded (Branch *et al.* 2006a). In other words, individuals will gain all the rewards from their catch, while the entire fleet suffers the costs of total quota overages in terms of lower total quota the following year. Without a race to fish, fishers under catch shares can be more selective in terms of where, when and how they fish (as their fishing seasons are often longer), which typically reduces total fleet-wide overages and underages (Hartley and Fina 2001). The ability to lease quota under catch share systems also allows for more precise catch-to-quota matching, because individuals with overages can lease quota from those with underages. Conversely, when quota is not tradable (such as under trip limit management), no money can be made from underages and everyone tries to exactly match or exceed their allotment, or even worse, discards their overages (Branch *et al.* 2006b; Branch and Hilborn 2008).

When marine populations under catch share programmes are considered to be in favourable states, the positive consequences are often ascribed to catch shares themselves (Costello *et al.* 2008; Griffith 2008). Although catch shares may greatly assist in ending the race to fish and also bring economic benefits, the favourable status of stocks in terms of biomass or fishing mortality might more reasonably be ascribed to total quota caps being in place, not necessarily to the division of quota into individual shares (Bromley 2009). Few effects of catch control type were detected on metrics of exploitation rate or biomass, the exception being the frequency of major overfishing. The mixed-effects model analysis showed higher frequencies of overfishing in effort-controlled fisheries than in catch share fisheries, while quota-only fisheries were intermediate. Propensity score matching also revealed lower frequencies of major overfishing for catch share fisheries, even when they were compared only to quota-only fisheries (i.e. after effort-controlled fisheries were removed). Thus, our analyses support both sides of the debate: there is evidence that catch share stocks are less frequently overfished than stocks under fleet-wide quotas alone, but also evidence that stocks under quotas alone are less frequently overfished than stocks under effort control. This result makes intuitive sense: managers can more easily prevent overfishing using output controls compared with the input controls (Hilborn *et al.* 2005), and moreover, under catch shares quota holders should lobby for catch levels that maximize revenue (Pearse and Walters 1992; Grafton *et al.* 2006), including requesting cuts to the total quota (Branch 2009), thereby reducing over-exploitation.

Despite the recent widespread consideration of catch shares as a means to improve the status of marine populations (e.g. NOAA Catch Share Policy; http://www.nmfs.noaa.gov/catchshares, last-accessed 17 May 2011), we found little to no effect of catch control type on biomass, the key measure for long-term sustainability of catches. This is consistent with the results of a comparison of North American fisheries by Essington (2010), but differs somewhat from the results of Costello *et al.* (2008), who used landings data to quantify rate of collapse (landings <10% of maximum catch). Most likely, this discrepancy reflects the difference in metrics and method of analysis; others have cautioned against the use of landings data to represent stock status (Wilberg and Miller 2007; de Mutsert *et al.* 2008; Branch *et al.* 2011). Specifically, the 'collapses' of Costello *et al.* (2008) reflect biological and economic conditions that dictate dynamics of catch rates, while our data looked only at ecological elements related to collapse. The variation among catch control types in the frequency of overfishing did not result in variation in the frequency of biomass depletion. This is in part because biomass is affected not only by fishing, but also by environmental conditions (e.g. Coll *et al.* 2010; Link *et al.* 2010). Further, observed responses of biomass during the focal period of 2000–2004 may reflect not only the catch control type that was in place during this time, but also prior to it. Analyses of biomass may be susceptible to such 'legacy' effects if control types changed soon before the 2000–2004 period, especially for long-lived species. Several of the groundfish stocks we considered had catch shares implemented in the early 1990s for Southeast Australia or the late 1990s for West Coast Canada. West Coast Canada stocks had relatively low mean biomass under the regional random effect, so this could represent a low biomass legacy from the pre–catch share period. No other random effect modes were low for West Coast Canada or Australia in other metrics including the frequency of biomass depletion, however, so it does not appear as if legacy effects are responsible for any serious bias in our analyses. They are less likely to be of concern for catch:quota or exploitation rates, because these variables should more rapidly adjust to changes in management strategies. Even in regions that are less susceptible to possible legacy effects because of earlier establishment of catch shares, biomass declines were still observed. One has only to look at the several stocks from East Coast Canada (like northern cod; *Gadus morhua*, Gadidae) and Europe that declined and were under moratoria during 2000–2004 despite catch share management to realize that catch share programmes alone cannot prevent stock collapse.

Fishery sustainability depends on targets set by the management authority. If the estimated quota is too high or the management authority consistently sets the quota above scientific recommendations, then the fishery will not be sustainable even if the catch:quota ratio is close to 1. For example, Europe on average sets allowable catches at 50% above scientific recommendations as a direct consequence of the joint management of these fisheries by multiple countries, each with their own political pressures (Piet and Rice 2004). On the other hand, for some developing and exploratory fisheries, total annual quotas may be set at a higher level than the current capacity of the fishery, resulting in low catch:quota and high variation around the target ratio of 1. Low catch:quota can also arise in some multispecies fisheries where quota restrictions on one species impact catches of other species caught with it, or in regions where comprehensive assessments are conducted and quotas are set even for minor commercial stocks for which there may not be enough demand to catch the full quota. In addition, reported catch:quota ratios may be biased if illegal, unreported or discarded catches are not accounted for in official catch records. In terms of target reference points for exploitation rate and biomass, variation among regions exists in the types of $F_{\text{reference}}$ and $B_{\text{reference}}$ estimated and in how well these represent actual management targets. For some stocks, reference points based on MSY are considered targets, while for others, they are considered limit reference points and more conservative levels are used as the target. In some cases, proxies for MSY such as $F_{35\%}$ or $F_{40\%}$ are used to set quotas, and yet in other cases, quotas are set by different catch control rules. When target reference points were not stated in stock assessments, we used MSY reference points estimated by fitting a Schaefer surplus production model to time series of catch and total biomass. There was some variability between F and B reference points estimated from stock assessments and those we estimated with a Schaefer model, and on average, the Schaefer model results were somewhat more pessimistic with higher $U/U_{\text{MSY}}$ and lower $B/B_{\text{MSY}}$ (Fig. S1). Schaefer model reference points for F and B were used for at least one stock in all regions, but were the only reference points used for European stocks (as target reference points were not provided in ICES stock assessments). However, our assessment differs little from assessments of European stocks when $B_{\text{MSY}}$ is estimated in alternative ways (Froese and Proelß 2010), so our estimated reference points appear to be reasonable.

Regional effects may reflect fundamental biogeographic or ecosystem differences, but we suspect in this context they more likely indicate intrinsic properties of fishery management systems, including governance, cultural and economic differences as well as the historical 'legacy' effects of when and how the fisheries developed. Besides the use of catch shares, other characteristics often differ among regions, such as comprehensiveness of survey programmes, data availability or frequency of stock assessments, enforcement measures and the complexity of management systems as measured by the number of agencies involved (Smith 1994; Mora *et al.* 2009; Worm *et al.* 2009). Political or industry pressures for higher quotas are common but likely vary in their degree among regions, and overfishing of quotas may be especially problematic for transboundary stocks or in regions with a history of a large number of fishing participants, like in Europe (Sutinen 1999; Munro *et al.* 2004; Smith and Link 2005; Grafton *et al.* 2008; Froese and Proelß 2010). New Zealand, Alaska and the USA West Coast tended to have lower exploitation rates, higher biomass and lower frequencies of exceeding undesirable thresholds of exploitation rate or biomass, even after accounting for other covariates. In contrast, Europe and the USA Northeast and Mid-Atlantic Coast were associated with generally higher exploitation rates and higher frequencies of over-exploitation during 2000–2004; these regional differences support previous analyses (Worm *et al.* 2009). Canada's East Coast fisheries tended to have lower biomass and higher frequencies of major depletion (largely because of stocks under moratorium; when these were excluded the East Coast Canada effect disappeared). Regional variation was also linked to the year of fishery development: fisheries from some regions developed early (Europe, USA East and West Coasts) while many of the fisheries from other regions developed later (Australia, South America). When development year and other linear covariates were excluded from the fixed-effects models, the regional effect strengthened. Therefore, regional variation observed in global fisheries data should be accounted for before ascribing observed outcomes to particular factors like catch shares (Smith and Link 2005).

While the use of catch share programmes has been common for >20 years in some regions, other regions have only more recently begun to implement these management systems. There is presently a push, especially in the USA, to implement catch shares as seen in recent plans for Alaska crabs, Gulf of Alaska rockfish, West Coast groundfish, Gulf of Mexico red snapper and Northeast groundfish. Developing regions are particularly under-represented in our analysis, as we were only able to include stocks with reliable assessments or catch and quota data. From this global analysis, it appears that catch shares may assist fisheries in meeting their quota targets more consistently and may result in less frequent over-exploitation. However, the challenges and opportunities of implementing catch shares will likely differ on a fishery-by-fishery basis. Some tactics may work better in a particular region or fishery type than in others, and complications may arise for stocks that are highly migratory or have trans-boundary distributions. Even within the same country or region, details of how catch share programmes are designed and operated are crucial in whether they will allow the fishery to better meet management objectives (Dewees 1998; Arnason 2005). Because catch share programmes are very diverse in how they operate, an analysis quantifying which particular attributes of catch share systems lead to more successful outcomes would be particularly valuable at this time.

We were faced with the challenge of quantifying effects of particular policy measures using an unbalanced design. Some regions had little contrast in catch control types used (Fig. 2), which may lead to confounding between these factors in meeting management targets. Adaptive management experiments (Walters 1986) would ideally be used to isolate effects because of catch shares, but only rarely did we encounter sufficient catch control types within a region to allow proper comparisons let alone allow experimental approaches. Our analyses were designed to separate regional and control type effects or to account for region implicitly when assessing control type effects. These factors appear to have been separable for 10 of the 12 mixed model analyses (the exceptions being the frequencies of small and large quota overages in the generalized linear mixed models). Because of similar confounding that is likely to occur in future meta-analyses of global fisheries data, we encourage researchers to use a diversity of approaches and evaluate different types or metrics of response variables as we did to ensure consistency of inferences. When multimodel inference tends to converge, confidence in the overall results is heightened. Propensity score matching may be a promising approach; it is widely used in the medical literature for analysis of observational data where treatments are not assigned at random (Rosenbaum and Rubin 1983). Moving beyond case studies within a single region is important as these may give a misleading picture of catch share effects because of confounding with other regional factors.

There are multiple management tactics or possible solutions that can be used for ensuring that fisheries remain sustainable or for rebuilding those which have been depleted (Cochrane 2002; Worm *et al.* 2009). Catch shares are by no means a panacea for solving fisheries management problems (Gibbs 2007; Ban *et al.* 2009; Pinkerton and Edwards 2009). When used in concert with other policy measures, however – especially the appropriate establishment of quota caps for ensuring sustainable harvest (Bromley 2009) and when effectively enforced (Branch 2009; Parslow 2010) – catch shares do represent a viable tool for improving the ability to meet management objectives. Complete solutions will almost always require multiple tools used simultaneously (Ban *et al.* 2009; Smith *et al.* 2009; Worm *et al.* 2009).

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## Supporting Information

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

**Figure S1.** Cross-validations of (a) exploitation rate and (b) biomass reference points estimated with a Schaefer surplus production model to reference points estimated in stock assessments.

**Figure S2.** Average propensity score for being in a catch share system in 2000–2004 by (a) region, (b) taxonomic/habitat association, and (c) catch control type.

**Figure S3.** Relationship between propensity score for being in a catch share system in 2000–2004 and average catch during the period.

**Figure S4.** Frequency distributions of the differences between response variable values of randomly paired catch share and non-catch share fisheries sharing similar propensity for being in catch shares.

**Figure S5.** Frequency distributions of catch, exploitation rate, and biomass relative to management targets.

**Figure S6.** Relationship between the variation around the management target of (a) catch, (b) exploitation rate, or (c) stock biomass and the average catch of the fishery.

**Figure S7.** Relationship between recent (a) quota compliance, (b) exploitation rates or (c) stock biomass and the year the fishery was first developed.

**Figure S8.** Estimated modes of random effects on catch:quota ratios for (a) mean $C/Q$, (b) variation around the target ratio, and proportion of fisheries with (c) small or (d) large overages.

**Figure S9.** Estimated modes of random effects on current exploitation rate relative to reference exploitation rate for (a) mean $F/F_{\text{reference}}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major overfishing.

**Figure S10.** Estimated modes of random effects on current biomass to reference biomass for (a) mean $B/B_{\mathrm{reference}}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major biomass depletion.

**Table S1.** Stocks included in analyses.

**Table S2.** Model selection results for fixed-effects model analyses of catch:quota ratios: (a) mean $C/Q$; (b) SD(target $C/Q$); (c) small overages; (d) large overages.

**Table S3.** Model selection results for fixed-effects model analyses of exploitation rate ratios: (a) mean $F/F_{\mathrm{reference}}$; (b) SD (target $F/F_{\mathrm{reference}}$); (c) minor over-exploitation; (d) major over-exploitation.

**Table S4.** Model selection results for fixed-effects model analyses of biomass ratios: (a) mean $B/B_{\mathrm{reference}}$; (b) SD (target $B/B_{\mathrm{reference}}$); (c) minor depletion; (d) major depletion.

**Table S5.** Model selection results for mixed-effects model analyses of catch:quota ratios: (a) mean $C/Q$; (b) SD (target $C/Q$); (c) small overages; (d) large overages.

**Table S6.** Model selection results for mixed-effects model analyses of exploitation rate ratios: (a) mean $F/F_{\mathrm{reference}}$; (b) SD (target $F/F_{\mathrm{reference}}$); (c) minor over-exploitation; (d) major over-exploitation.

**Table S7.** Model selection results for mixed-effects model analyses of biomass ratios: (a) mean $B/B_{\mathrm{reference}}$; (b) SD (target $B/B_{\mathrm{reference}}$); (c) minor depletion; (d) major depletion.

**Data S1.** Supporting Information sections include: cross-validations of estimated biomass and exploitation rate reference points from Schaefer model fits; descriptions of catch share propensity scores and associated resampling analysis; and full descriptions of fixed effect model results and mixed effect model results which include exploratory data analyses, model validation, and sensitivity analyses.

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