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Can catch share fisheries better track management targets?

Michael C Melnychuk[1], Timothy E Essington[1], Trevor A Branch[1,], Selina S Heppell[2,*], Olaf P Jensen[3,*], Jason S Link[4*], Steven J D Martell[5,*], Ana M Parma[6,*], John G Pope[7,*] & Anthony D M Smith[8,*]*

[1]School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195, USA; [2]Dept. Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR 97331, USA; [3]Institute of Marine & Coastal Sciences, Rutgers University, 71 Dudley Rd., New Brunswick, NJ 08901, USA; [4]National Marine Fisheries Service, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA; [5]Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada; [6]Centro Nacional Patagónico, 9120 Puerto Madryn, Chubut, Argentina; [7]NRC (Europe) Ltd., The Old Rectory, Staithe Road, Burgh St. Peter, Beccles, Suffolk, UK; [8]Commonwealth Scientific and Industrial Research Organization, Wealth From Oceans Flagship, GPO Box 1538, Hobart, Tasmania 7001, Australia

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

Correspondence:
Michael C. Melnychuk, School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195, USA
Tel.: +1 (206) 817-6449
Fax: +1 (206) 685-7471
E-mail: mmel@uw.edu

*Order of authors arranged alphabetically.

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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 $B/B_{\text{reference}}$ or $F/F_{\text{reference}}$ 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

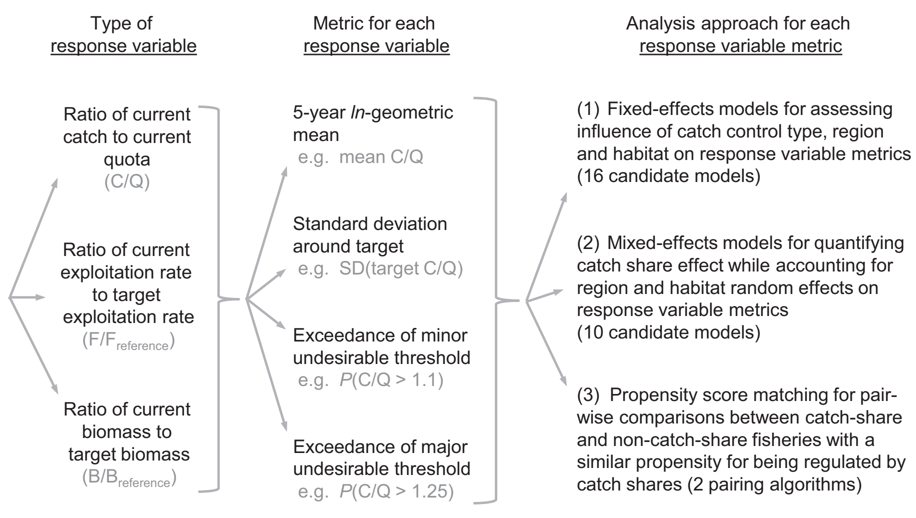

Figure 1 Schematic of response variables and types of analyses used. Twelve response variables (3 types × 4 metrics) were used in each of three types of analyses. Shorthand notation for response variable types and metrics are shown in grey font; these abbreviations are commonly referred to in the text.

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, $F/F_{\mathrm{reference}}$, and $B/B_{\mathrm{reference}}$), 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_{MSY} and B_{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_{MSY} and B/B_{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:

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

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:

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

   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, $F/F_{\mathrm{reference}}$ or $B/B_{\mathrm{reference}}$) exceeded an undesirable threshold value was calculated to address the asymmetrical management consequences of observing $C/Q > 1$, $F/F_{\mathrm{reference}} > 1$ and $B/B_{\mathrm{reference}} < 1$. 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 ($C/Q > 1.1$, $F/F_{\mathrm{reference}} > 1.1$, and $B/B_{\mathrm{reference}} < 0.9$) 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

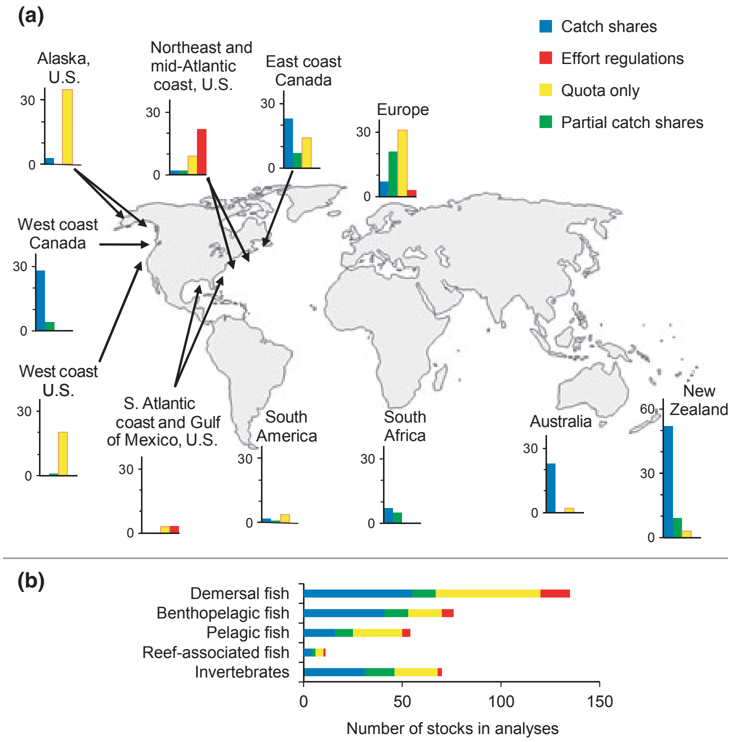

Figure 2 Number of stocks included in analyses, shown by (a) region and (b) taxonomic/habitat association categories. Stocks are separated by four catch control types representing the 2000–2004 period: full catch shares (>75% of total catch under a catch share programme), partial catch shares (25–75% 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 $L_{\max}$. 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 $C/Q < 1$.

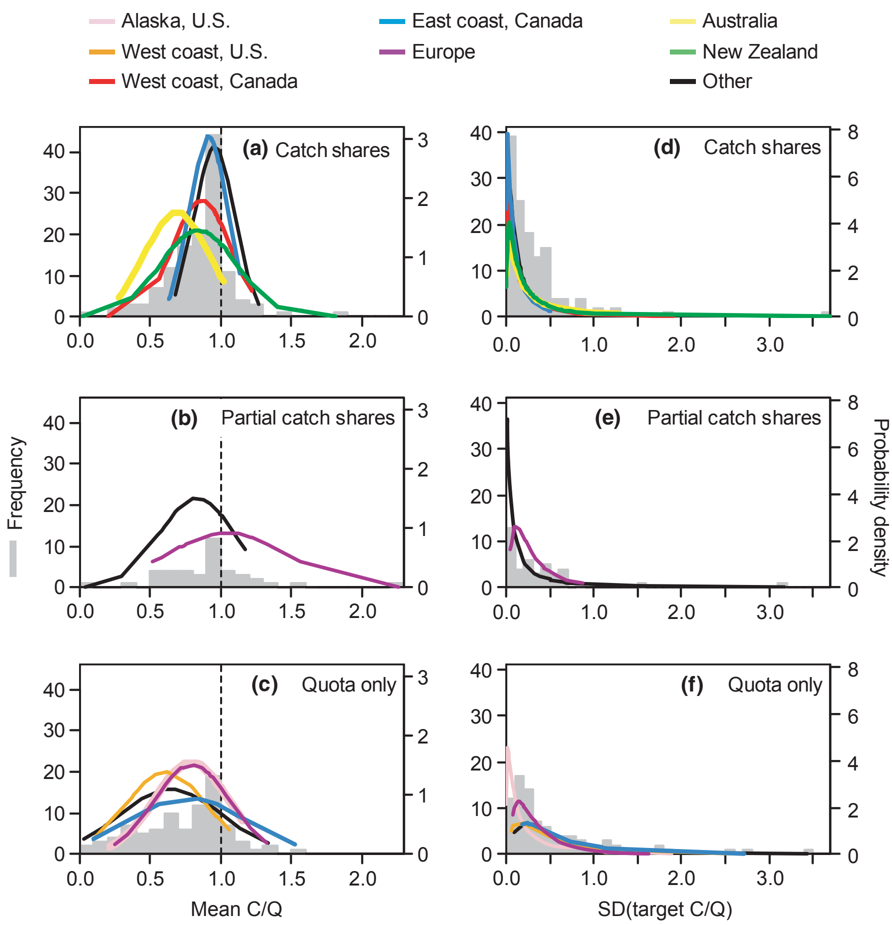

Figure 3 Frequency distributions of catch/quota ratios within catch control types. Frequencies (grey bars) are separated by three catch control types, and show either (a–c) the ln-geometric mean response or (d–f) variation around the management target. Regions with ≥10 stocks of a particular control 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 $F/F_{\mathrm{reference}}$ and $B/B_{\mathrm{reference}}$ were wider (Figs 4 and 5). Although more than half the stocks in our analysis had F below the target, major over-exploitation ($F/F_{\mathrm{reference}} > 1.5$) 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 $F/F_{\mathrm{reference}}$ 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 $B/B_{\mathrm{reference}}$ 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

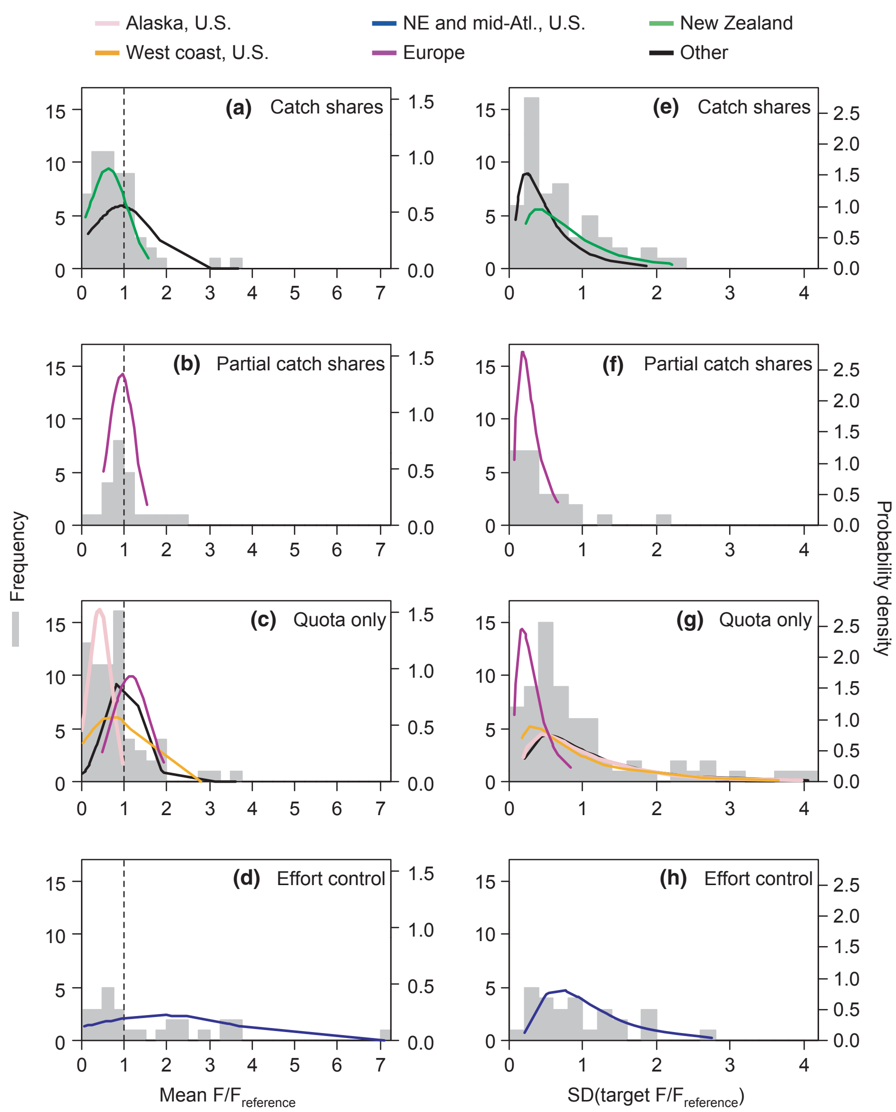

Figure 4 Frequency distributions of current exploitation rate relative to reference exploitation rate within catch control types. Frequencies (grey bars) are separated by four control types and show either (a–d) the ln-geometric mean response or (e–h) variation around the management target. Regions with ≥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

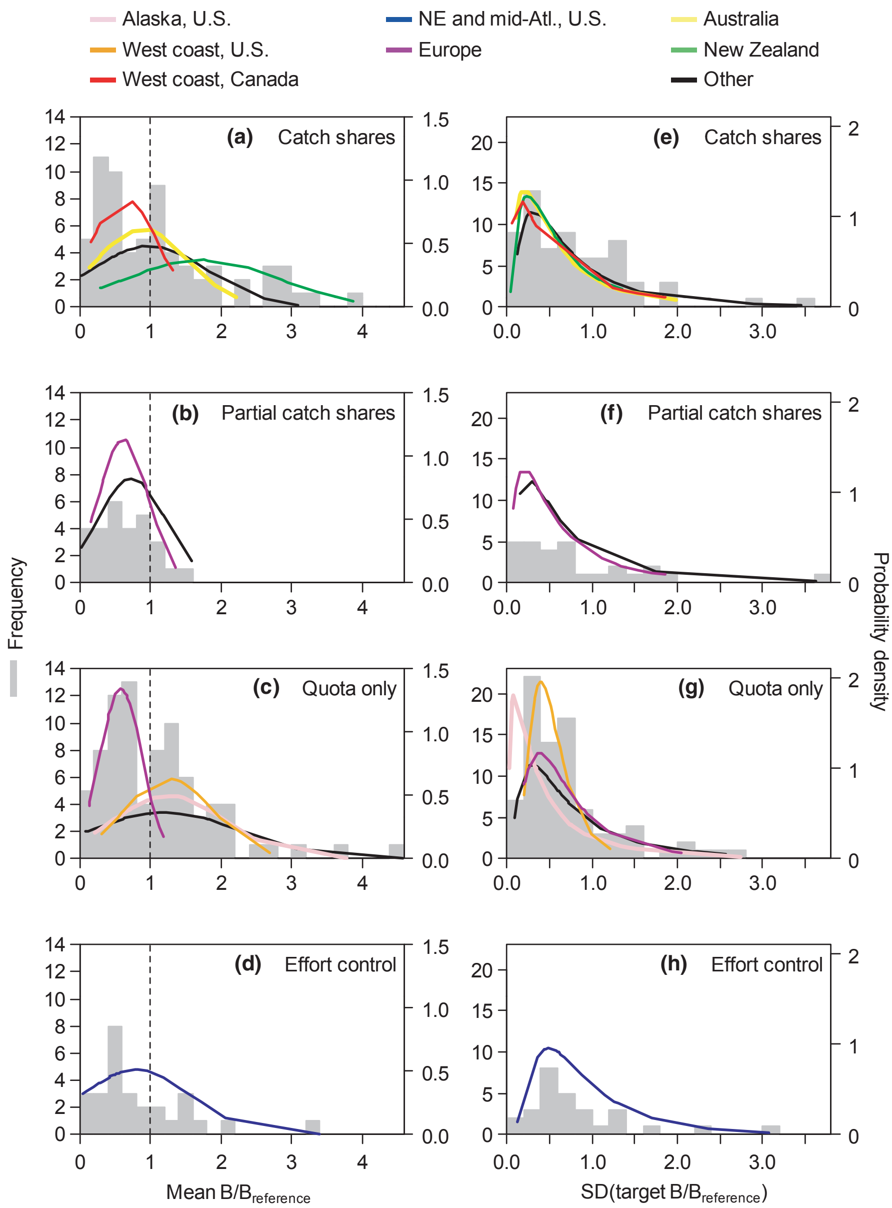

Figure 5 Frequency distributions of current biomass relative to reference biomass within catch-control types. Frequencies (grey bars) are separated by four control types and show either (a–d) the ln-geometric mean response or (e–h) variation around the management target. Regions with ≥10 stocks of a 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 $F/F_{\text{reference}}$ and $B/B_{\text{reference}}$ compared with C/Q ratios.

Mean responses of C/Q, $F/F_{\text{reference}}$ and $B/B_{\text{reference}}$ 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

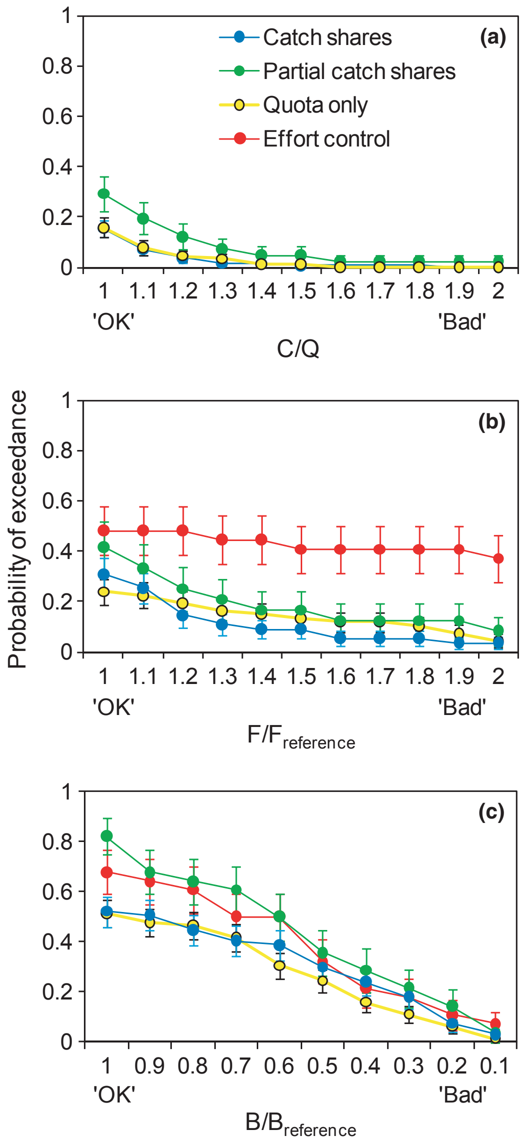

Figure 6 Proportion of stocks whose ratios of (a) catch/quota, (b) current exploitation rate/reference exploitation rate or (c) current biomass/reference biomass exceed an undesirable threshold value. Proportions are given for a wide range of threshold values and are shown separately for four primary 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 $F/F_{\text{reference}}$ and $B/B_{\text{reference}}$ 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 $F/F_{\text{reference}}$), 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 $B/B_{\text{reference}}$) (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.

	Response variable			
Model*	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.

	Response variable			
Model*	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}	**<u>1.0</u>**	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}	**<u>0.0</u>**	**2.8**	11.6	7.2
Region + avCatch + devYear + L_{max}	**<u>1.3</u>**	8.8	**5.0**	**<u>0.0</u>**
Habitat + avCatch + devYear + L_{max}	**3.6**	32.6	10.7	13.3
Intercept + avCatch + devYear + L_{max}	**<u>1.5</u>**	32.9	**5.0**	7.0
Region + Habitat	**3.8**	**<u>0.0</u>**	6.2	**5.8**
Region	**<u>1.2</u>**	6.3	**<u>0.0</u>**	**<u>1.4</u>**
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 ΔAICc < 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.

	Response variable			
Model*	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.

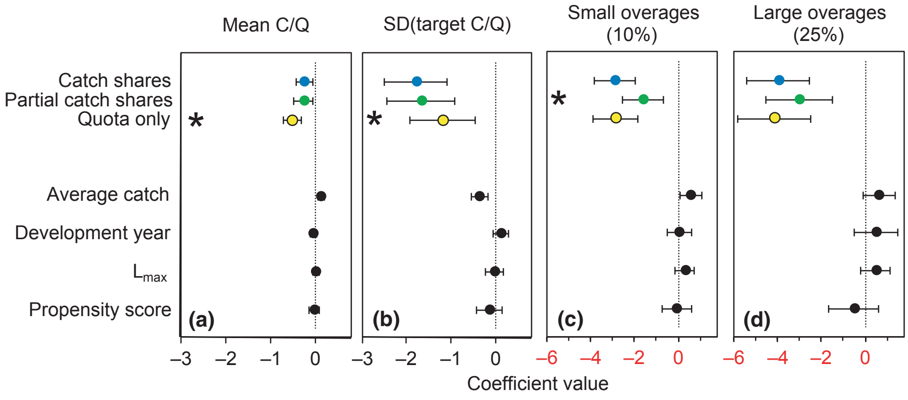

Figure 7 Estimated coefficients of fixed effects on catch/quota ratios for (a) mean C/Q, (b) variation around the target ratio, and proportion of fisheries with (c) small or (d) large overages. Estimates were generated under the full model, with region and taxonomic/habitat association as random effects. 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

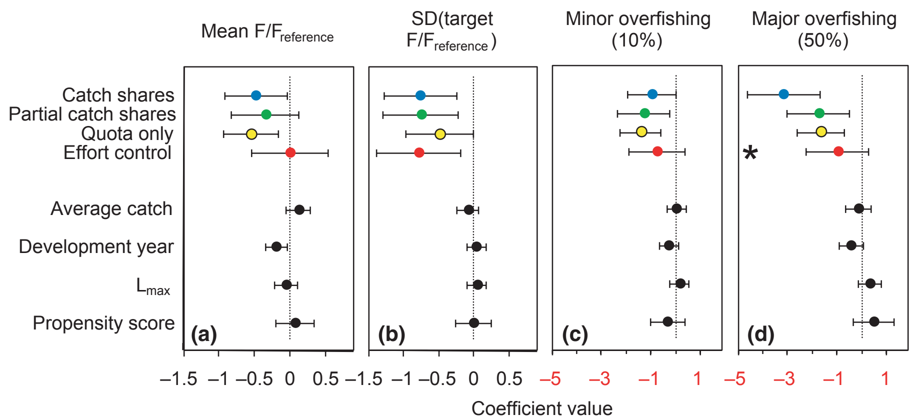

Figure 8 Estimated coefficients of fixed effects on current exploitation rate relative to reference exploitation rate for (a) mean $F/F_{reference}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major overfishing. Estimates were generated under the full model, 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.

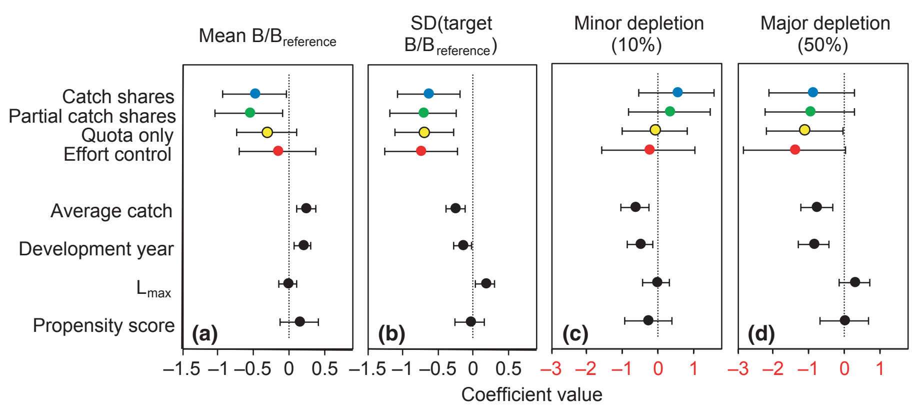

Figure 9 Estimated coefficients of fixed effects on current biomass relative to reference biomass for (a) mean $B/B_{reference}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major biomass depletion. Estimates were generated under the full model, with region 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

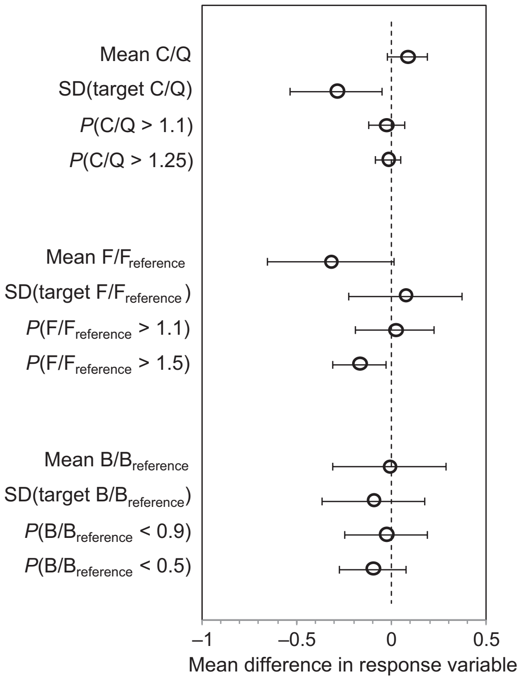

Figure 10 Differences between response variables of paired catch share and non-catch share fisheries sharing similar propensity for being in catch shares. Response variable differences (value for catch share fishery minus value for non-catch share fishery) are shown for 12 analyses. All possible combinations 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 $F/F_{\text{reference}}$ and mean $B/B_{\text{reference}}$). 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 $F_{\mathrm{reference}}$ and $B_{\mathrm{reference}}$ 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_{MSY} and lower B/B_{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_{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 $F/F_{\mathrm{reference}}$, (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 $B/B_{\text{reference}}$, (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 $F/F_{\text{reference}}$; (b) SD (target $F/F_{\text{reference}}$); (c) minor over-exploitation; (d) major over-exploitation.

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

Table S7. Model selection results for mixed-effects model analyses of biomass ratios: (a) mean $B/B_{\text{reference}}$; (b) SD (target $B/B_{\text{reference}}$); (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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Supporting Information

Melnychuk et al. (2011) Fish and Fisheries: Can catch share fisheries better track management targets?

Stocks included in analyses

Table S1 lists the stocks that were included in analyses of at least one response variable (catch:quota, annual exploitation/reference exploitation rate, or annual biomass/reference biomass). In a few cases, changes to the habitat categories after aggregating FishBase (Froese and Pauly, 2010) categories were made to better reflect the species' actual habitat association; these are noted in the table. Occasionally catch and quota data were aggregated over two sub-stocks, two species, or two sub-regions; these are also noted.

Cross-validations of estimated B_{MSY} and F_{MSY} reference points

Schaefer (1954) surplus production models were fit to catch and biomass data for all stocks in the database with ≥20 common years of catch and total estimated biomass. Reference points $B_{tot,MSY}$ and U_{MSY} (= MSY/ $B_{tot,MSY}$) were estimated from these fits. All Schaefer model fits were visually inspected, and if the model did not appear to adequately fit the catch and biomass time series data, the Schaefer model reference point estimates were discarded and not used in cross-validations or in primary analyses (7% of model fits were discarded). Schaefer model reference points were compared to those estimated in stock assessments, usually with an age-structured model. If the assessment used a surplus production model in the first place to estimate reference points, it was excluded from the cross-validation. We did not include oceanic tunas or sharks in the cross-validation to be consistent with our subsequent analyses.

Figure S1 shows a cross-validation of Schaefer model estimated reference points (ratios of $U_{current}/U_{MSY}$ and $B_{tot,current}/B_{tot,MSY}$) with reference points estimated in stock assessments (ratios of $U_{current}/U_{reference}$ (or alternatively $F_{current}/F_{reference}$) and $B_{current}/B_{reference}$, respectively). The 'current' value of U, F, or B represents the last year in the time series. Biomass estimates and reference points from assessments may be either total biomass or spawning stock biomass, but represent the same measure for ‘current’ and ‘reference’ values. Estimates of either fishing mortality (F) or exploitation rate (U, equal to catch/total biomass) from assessments are considered, but similarly represent the same measure for ‘current’ and ‘reference’ values. Ratios are plotted (and correlations are assessed) in log space to reduce the leverage of the few stocks with particularly high values.

Catch share propensity scores and resampling analysis

The logistic regression of a binary response variable indicating whether or not a stock was under full catch share management (>75% of total landings under catch shares) during the 2000–2004 period as a function of several stock attributes (region, habitat, year of fishery development, average catch during 2000–2004, and L_{max}) generated a propensity score for each stock, PS. These are summarized by region, taxonomic/habitat association, and catch control categories in Figure S2. After accounting for the covariates, some regions were more likely than others to have had fisheries under catch share programs (Fig. S2a). There was less variation among habitat categories, and larger standard deviations within each category (Fig. S2b). Although we only considered full catch share programs as a ‘success’ in the logistic regression, the order of the four control types makes intuitive sense: full catch shares had greatest PS, followed by partial catch shares, quota-only, and effort-managed fisheries (Fig. S2c).

Of the linear covariates considered, average catch had an especially large influence on PS, with larger-sized fisheries more likely to be under catch shares (Fig. S3). Note that some regions (U.S. West coast; U.S. South Atlantic coast/Gulf of Mexico) have estimated PS = 0 for all stocks, because during the 2000–2004 period there were no stocks under full catch shares in these regions that could be included in our analyses. These regions have both seen the recent establishment (after 2004) of catch share programs, so PS ≈ 0 should not be taken to mean that the establishment of catch shares is not possible for the stock, just that catch shares were uncommon or not used in the region during 2000–2004. Also note that the strong regional effect on PS weights can ‘pull up’ or ‘bring down’ weights of particular stocks in a region which are atypical with respect to use of full catch shares in the region. For example, so many Australian stocks are under full catch shares that even the non-catch share stocks (like the effort-managed Northern tiger prawn fisheries) have high PS. Similarly, so few European stocks are under full catch shares that even those which are (such as Icelandic stocks, which are all very likely to be under catch shares in actuality) have low PS.

As an alternative to the all-possible-paired combinations approach to propensity score matching that was described in the main text is a resampling approach. We used a resampling routine to randomly pair catch-share fisheries with non-catch-share fisheries of similar propensity score, and to then calculate the difference in the value of a response variable between them. For each analysis, one non-catch-share fishery was randomly selected to pair with each catch-share fishery under the similar constraint that their propensity scores had to be within 0.05 of each other. There were many catch-share stocks but few non-catch-share stocks with PS > 0.8 (Fig. S3), so to ensure that the same non-catch-share stocks were not repeatedly paired with these catch-share stocks, we only included catch-share stocks with PS < 0.8. For each pair, the response variable value of the non-catch-share fishery was again subtracted from the value of the catch-share fishery. The average difference over all pairs was calculated. This was repeated 10,000 times, and the distributions of differences were plotted.

In general, results from the resampling propensity score matching approach (Fig. S4) were similar to the all-possible-pairs approach (Fig. 10). Catch-share fisheries had reduced variability around the target C/Q ratio and less frequent exceedance of major over-exploitation thresholds, while no effects on biomass were observed. In contrast to the all-possible-pairs approach (also in contrast to the mixed-effects model results), however, a lower SD(target $F/F_{reference}$) was observed for catch-share fisheries under the resampling analysis (Fig. S4).

Full fixed-effects model results

In the main text, differences in AICc scores for each model and that of the lowest AICc score in the model set were presented (Tables 2–4). For each of 12 analyses, these 16 ΔAICc values were based on log-likelihood values and the number of parameters in the model. The full set of model selection results is shown in Tables S2–S4 for C/Q, $F/F_{reference}$, and $B/B_{reference}$ response variables, respectively.

In the main text, Figures 3–5 showed frequency distributions of response ratios separated by catch control types. The aggregated frequency distributions are shown in Figure S5. The relationships between SD(target) of the three response variables and average catch during 2000–2004 are shown in Figure S6, where larger sized fisheries typically had lower variation around the management target. The relationships between mean responses of C/Q, $F/F_{reference}$, or $B/B_{reference}$ and year of fishery development are shown in Figure S7, where earlier developed fisheries were typically associated with higher exploitation rates and lower biomass compared to later developing fisheries.

Full mixed-effects model results

In the main text, parameter estimates of fixed effects under the full model for each of 12 analyses were shown in Figures 7–9. In addition to the full model, 9 reduced models were compared using ΔAICc scores. Conclusions drawn from model selection were consistent with those drawn from whether 95% C.I. of fixed-effect coefficient estimates for the full model excluded zero. Detailed model selection results with AICc scores are shown in Tables S5–S7 for C/Q, $F/F_{reference}$, and $B/B_{reference}$ response variables, respectively. Also shown in these tables are the estimated variance parameters for random effects of region and habitat in each model (as well as residual deviance for the two linear models).

Conditional modes of the different levels of region and habitat random effects are shown in Figures S8–S10. These are centred around zero for each variable, and show that some regions or some habitat categories were associated with larger values of the response variables than others. Two sets of estimates are shown: one from the full model, and the other from the comparable model but without the control type fixed effect (i.e. the 6th model in Tables S5–S7, containing only three linear covariates and an overall intercept). There were occasionally differences between these sets of estimates, but for the most part, conditional modes of categories were similar between them. Variances of both random effects were estimable for 8 of 12 analyses, the exceptions being analyses of the frequency of small and large quota overages (where neither random effect was well-estimated; Fig. S8c,d) and the frequency of minor and major over-exploitation (where only the regional random effect was well-estimated; Fig. S9c,d). Estimated variances of random effects for several models in these four analyses were either zero or very small, largely due to sparse data for the binary response (e.g. the frequency of quota overages was much smaller compared to the frequency of biomass depletion; Fig. 6). This was apparent whether or not catch control type was included in the model (Figs. S8c,d and S9c,d). We now describe the estimates of random effects for each analysis.

Variance parameters of random effects were estimable for mean and SD(target) responses of C/Q, but were not properly estimated in most models for analyses of the frequency of quota overages (Fig. S8). For mean C/Q and SD(target C/Q), the variance parameter for habitat was greater than that for region in most models including the full model (Table S5a,b). Alaska, New Zealand and Canada's West Coast had relatively low SD(target C/Q) while South Africa, Canada's East Coast and Australia had relatively high SD(target C/Q). Invertebrate fisheries had relatively high mean C/Q and low SD(target C/Q), suggesting their catches were closer to the quota target than those of fish categories. Pelagic and benthopelagic stocks showed the opposite trend, with low mean C/Q and high SD(target C/Q), partly owing to several of these stocks being under-exploited (Fig. S8). For small overages, the variance parameter was not estimable for either region or habitat in half the models, including the full model (Table S5c). For large overages, the variance for habitat random effects was not estimable in any model, and the variance for region was only estimable in four of the models, ones that did not involve a fixed effect of control type (Table S5d). For these latter two metrics, the small estimated variance parameters (at or near zero) of both random effects suggest that the fixed-effect estimates are suspect, as none of the total variation is explained by either of the two random effects. Even in models without the added complexity of control type as a fixed effect, however, estimated variances of random effects were either zero or near zero (Fig. S8c,d), suggesting that the frequency of overage data were simply too sparse in most cases (e.g. Fig. 6a) to properly estimate these random effects.

Variance parameters of regional random effects were estimable for all four exploitation rate metrics, but those for habitat random effects were not properly estimated for the two frequency of over-exploitation metrics. Regional effects were especially strong for variability around the management target (Fig. S9b). Alaska had relatively low $F/F_{reference}$ and low frequencies of over-exploitation. Europe had high $F/F_{reference}$ and low SD(target $F/F_{reference}$) compared to other regions (i.e. European fisheries consistently had exploitation rates slightly above the management target on average). The U.S. Northeast/Mid-Atlantic Coast had relatively high SD(target $F/F_{reference}$) and high frequencies of major over-exploitation (Fig. S9b,d). Reef-associated fish and invertebrate fisheries had relatively high $F/F_{reference}$ and low SD(target $F/F_{reference}$) (i.e. they were more consistently experiencing over-exploitation slightly above the target rate compared to demersal, benthopelagic, and pelagic fish groups). The failure to properly estimate the variance parameter for the habitat random effect of over-exploitation frequency metrics may partly result from sparse over-exploitation data for most catch control types (Fig. 6b), but the regional random effects were estimable for these metrics so the fixed-effect estimates are considered reliable.

Variance parameters of random effects were estimable for all four biomass metrics. Regional effects were strong for the mean response, while habitat effects were stronger for variability around the management target (Fig. S10a,b). Alaska, the U.S. West Coast and New Zealand had relatively high $B/B_{reference}$, while Canada's East and West Coasts had lower biomass, all else equal. Demersal fish had relatively high biomass, while benthopelagic stocks had relatively low biomass. Pelagic and benthopelagic fish had relatively high SD(target $B/B_{reference}$), while reef-associated fish had relatively low SD(target $B/B_{reference}$) (Fig. S10b). In terms of the frequencies of minor or major biomass depletion, the variance parameter was greater in some models for region and in other models for habitat, but on average these variables had similar effect sizes (Table S7c,d). New Zealand and the U.S. West Coast (as well as Alaska for the minor threshold) had relatively low frequency of depletion, while Europe (for the minor threshold) or Canada's East Coast (for the major threshold) had a relatively high frequency of depletion (Fig. S10c,d). Consistent with results for the mean response, demersal fish had low frequencies of depletion, while benthopelagic stocks had high frequencies of depletion.

Exploratory data analyses

Prior to analyses, we conducted exploratory data analyses to ensure that model assumptions were satisfied (Bolker et al., 2009, Zuur et al., 2009b). There were no outliers in predictor or response variables. All three response variables were ratios; mean responses and SD(target) took on values $[0, \infty]$, while the other two metrics were binary responses. Mean C/Q values were rarely >1.5 (Fig. S5a) and mean $F/F_{reference}$ or $B/B_{reference}$ values were rarely >3 (Fig. S5b,c). A few values for SD(target) were occasionally >1 for C/Q and >2 for $F/F_{reference}$ or $B/B_{reference}$, but since variation around the target incorporates variation around the sample mean as well as deviation of the sample mean from the management target of 1, these SD(target) values seem reasonable.

There were rarely any obvious deviations from normality in the response variables (for the linear models). Although the means of response variables in Figures 4–5 and S5 appear to be skewed right for $F/F_{reference}$ and $B/B_{reference}$, they have been back-transformed to the linear scale for these histograms. Arithmetic means were calculated for the logarithms of the ratios (i.e. log-geometric means of the yearly ratios), and these values were the basis for analyses. The original distributions for mean $F/F_{reference}$ and mean $B/B_{reference}$ (i.e. log values) were slightly skewed left. SD(target) values were *ln*-transformed prior to analyses, so the apparent skew right in Figures 3–5 and S5 is of little concern. After log-transformation, there was a slight skew left in the distribution of SD(target C/Q).

There were rarely any obvious violations of the assumption of homogeneity of variances among categories of predictor variables or throughout the range of linear covariates. Slightly higher variance was observed at low maximum length (L_{max}) for logarithmic values of mean C/Q, SD(target C/Q), and SD(target $B/B_{reference}$) than at high L_{max}. There were no clear patterns of non-linearity in scatterplots of response variables and continuous predictor variables. We also checked for collinearity of continuous predictor variables using the variance inflation factor approach (Zuur et al., 2009a). The largest variance inflation factor among the covariates ranged from 1.09–1.29 across all analyses, suggesting negligible collinearity (compared with recommended thresholds of concern of 2, 3 or 10; Zuur et al., 2009a).

Model validation

After fitting mixed-effects models to data, we visually assessed whether standardized residuals were normally distributed, had similar variances among categorical predictor variables or throughout the range of continuous predictor variables, had any evidence of non-linearity with continuous predictor variables, and showed any non-linear or heterogeneity patterns when plotted against fitted values. Consistent with exploratory data analyses, there were no serious causes for concern about standardized residuals after model fitting. The distributions of standardized residuals were slightly skewed left for mean C/Q, SD(target C/Q), mean $F/F_{reference}$, and SD(target $B/B_{reference}$). There was a stronger skew right for the frequency of small and large quota overages, and for the frequency of major biomass depletion. No obvious linear or non-linear patterns were observed in plots of standardized residuals against fitted values for each of the 10 models in each of the 12 analyses. For mean C/Q, there were slightly larger variances of residuals at lower fitted values than at higher fitted values, across all models.

In some cases, departures from the assumption of homogeneity of variance only occurred in one or a few of the 10 models in each analysis, while in other cases it occurred across all models. There was slightly higher variance of standardized residuals at low L_{max} for mean C/Q, SD(target C/Q), and SD(target $B/B_{reference}$) than at high L_{max}, across all models. There was slightly higher variance at later years of development for mean C/Q than at earlier years of development, across all models. For the frequency of small quota overages, there was slightly greater variance for the partial catch share category in one model and for South Africa in two other models. The reef-associated category had smaller variances than other habitat categories for mean $F/F_{reference}$ (two models), mean $B/B_{reference}$, and the frequency of major biomass depletion (all models). For the frequency of minor over-exploitation, some regions (New Zealand, Canada West coast, U.S. West coast, Alaska) had smaller variances of standardized residuals than other regions (Europe, U.S. Northeast/Mid-Atlantic coast, other) across all models. For the frequency of major over-exploitation, the U.S. Northeast/Mid-Atlantic coast had larger variances than other regions (and effort-control fisheries had higher variances than other catch control types) across all models. For the frequency of major biomass depletion, some regions (New Zealand, U.S. West coast, Alaska, other) had smaller variances than others (Australia, Europe, U.S. Northeast/Mid-Atlantic coast, Canada West and East coasts) across all models.

Analyses under alternative assumptions

Mixed-effects model analyses were conducted not only for the base case, but for several variations on the base case to assess whether observed results were sensitive to certain assumptions. Alternative cases were compared to the base case in terms of estimated coefficients under the full model, as well as comparing ΔAICc scores or Akaike weights among candidate models (Akaike weights sum to 1 across all models in a model set, and larger weights are given to models with greater support, i.e. lower AICc scores). In general, results for alternative cases were similar to the base case, although in some cases, conclusions regarding the relative importance of control type vs. region and habitat or the specific relationships between control type categories changed. The few noticeable differences that did occur compared to the base case are described for each alternative case.

(i) ***Excluding propensity scores*** – In the base case, PS were included in models whenever catch control type was included as a factor. When PS was not included in models, one fewer parameter had to be estimated. There were minor shifts in the values of other linear covariates when PS was not included, but little change in coefficient estimates of control type categories. Based on Akaike weights, there were few changes in the overall effect of control type: the Akaike weight of models including the effect of control type increased for the frequency of minor quota overages, such that the first five models (those involving control type) contained 63% of the total weight, compared to 38% for the base case (Table S5). It also increased for mean $F/F_{reference}$, with control type models containing 36% of the total weight compared to 17% for the base case.

(ii) ***Excluding Schaefer model reference point estimates*** – In the base case, we included reference points F_{MSY} or B_{MSY} estimated with a surplus production model if target reference points $F_{reference}$ or $B_{reference}$ were not presented in stock assessments. Using only reference points presented in assessments considerably reduced sample sizes (from 173 to 91 for exploitation rates, and from 205 to 116 for biomass). As a result, estimation of random effects was generally poorer. Variance parameters were properly estimated in most base case models, but estimated variances of one or both random effects were at or near zero in at least some models for mean $F/F_{reference}$, SD(target $F/F_{reference}$), the frequency of over-exploitation, SD(target $B/B_{reference}$), and the frequency of depletion.

Some changes from the base case were also observed for fixed effects. This included larger standard errors around estimated coefficients of mean $F/F_{reference}$, frequencies of over-exploitation, and the frequency of major depletion. Based on Akaike weights, the overall effect of control type increased considerably for mean $F/F_{reference}$, with control type models containing 63% of the total weight compared to 17% for the base case. It also increased for the frequency of minor depletion (19% compared to base case 3%). For mean $F/F_{reference}$, the coefficient estimates of catch shares (CS) and quota only (QO) control types decreased, while those of partial catch shares (PCS) and average catch during 2000–2004 increased. For SD(target $F/F_{reference}$), the coefficient estimates of QO and effort (E) categories as well as PS increased. For the frequency of major over-exploitation, coefficient estimates of the year of development, CS, and QO decreased (for year of development, 95% confidence intervals no longer bracketed zero), while those of E and average catch increased. For mean $B/B_{reference}$, coefficient estimates of CS, QO, and L_{max} increased, while that of PCS decreased to such an extent that it differed from the catch share category (based on 95% C.I. for the difference). For the frequency of major depletion, the coefficient estimate of L_{max} switched from a small positive to a small negative value.

(iii) ***Excluding under-exploited stocks*** – In the base case, we included some stocks that had an average catch:quota ratio below 50% during 2000–2004. When these were excluded, sample sizes reduced from 259 to 227 for catch:quota, from 173 to 158 for exploitation rates, and from 205 to 191 for biomass. These reductions were not solely in the non-catch-share categories; for example, of the 32 excluded stocks for C/Q, 9 were under full catch shares, 2 were under partial catch shares, and 21 were under only quotas.

Compared to the base case, there were no longer differences between CS and QO for mean C/Q or SD(target C/Q) (based on 95% C.I. for the difference). Similarly, there was no longer a difference between CS and PCS for the frequency of small quota overages. Based on Akaike weights, the overall effect of control type decreased considerably for mean C/Q, with control type models containing 26% of the total weight compared to 94% for the base case, as well as for SD(target C/Q) (39% compared to base case 96%). Standard errors around coefficient estimates were generally smaller for mean C/Q and mean $B/B_{reference}$ compared to the base case. Estimation of random effects was in general slightly poorer than the base case for mean C/Q, mean $F/F_{reference}$, and frequencies of quota overages, with estimated variance parameters of one or both random effects at or near zero in at least some models.

(iv) ***Excluding ICES & NAFO stocks*** – Excluding all European stocks and the offshore Eastern Canada stocks in international waters considerably reduced sample sizes, from 259 to 203 for catch:quota, from 173 to 129 for exploitation rates, and from 205 to 151 for biomass. This alternative case served two purposes: (*a*) for stocks under these agencies, MSY reference points are likely least reflective of what the actual management targets are, so excluding these may lead to responses that better track targets; and (*b*) a large number of the partial catch share fisheries came from these regions (Table 1), so it provided a means to assess whether observed partial catch share effects were driven primarily by these regions. In particular, there was an observed difference between CS and PCS categories in the base case for the frequency of minor quota overages. This may be partly the result of variance parameters of random effects not being estimable for that particular analysis, but it also appears to be at least partly due to the influence of ICES and NAFO stocks: when these were excluded, the coefficient estimate for PCS decreased, and there was no longer a difference between CS and PCS categories (based on 95% C.I. for the difference). This suggests at least some degree of confounding between partial catch shares and regions, as might be predicted from Figure 1.

A few other changes from the base case were also observed. Based on Akaike weights, the overall effect of control type decreased considerably for mean C/Q, with control type models containing 40% of the total weight compared to 94% for the base case. It also decreased for SD(target C/Q) (63% compared to base case 96%), increased considerably for mean $F/F_{reference}$ (72% compared to base case 17%), increased for SD(target $F/F_{reference}$) (33% compared to base case 8%), and increased for the frequency of minor depletion (20% compared to base case 3%). Standard errors around coefficient estimates were generally larger for the frequencies of quota overages but smaller for SD(target $F/F_{reference}$). There was no longer a difference between CS and QO for mean C/Q or SD(target C/Q) (based on 95% C.I. for the difference). For the frequency of small quota overages, the estimated coefficient of average catch decreased while that of PS increased. For mean $F/F_{reference}$, the estimated coefficient of PCS increased. For SD(target $F/F_{reference}$), the estimated coefficients of QO and E categories increased, and were both significantly greater than the CS category. For the frequency of minor and major over-exploitation, the coefficient estimate of PCS increased. Estimation of random effects was in general slightly poorer than the base case. Estimated variance parameters of one or both random effects were at or near zero in at least some models for frequencies of quota overages, mean $F/F_{reference}$, SD(target $F/F_{reference}$), and frequencies of over-exploitation.

(v) ***Excluding stocks under moratorium*** – In the base case, we included stocks in analyses of biomass even if they were under a moratorium at any time during 2000–2004 (but they were not included for catch:quota or exploitation rate analyses). Excluding stocks decreased sample size for the biomass dataset from 205 to 181. There were only minor shifts in coefficient estimates of control type categories for mean $B/B_{reference}$. Based on Akaike weights, there was very little change in the overall effect of control type.

(vi) ***Excluding partial catch share and effort-regulated categories of control type*** – In the base case, we considered three (for catch:quota) or four (for exploitation rates and biomass) categories of catch control types. The partial catch share and effort-control categories, however, had smaller sample sizes than catch share and quota-only categories. Further, including only (full) catch share and quota-only categories may provide a more direct comparison of the effect of catch shares. When only catch share and quota-only categories are included, sample sizes were reduced from 259 to 218 for catch:quota, from 173 to 121 for exploitation rates, and from 205 to 149 for biomass.

Based on Akaike weights, the overall effect of control type decreased considerably for mean C/Q, with control type models containing 41% of the total weight compared to 94% for the base case. It also decreased for SD(target C/Q) (70% compared to base case 96%), decreased for the frequency of minor quota overages (14% compared to base case 38%), and increased for the frequency of minor (23% compared to base case 3%) and major (31% compared to base case 11%) over-exploitation. Coefficient estimates for CS and QO control types changed very little compared to the base case. In the reduced dataset, there was no longer a difference between CS and QO for mean C/Q or SD(target C/Q) (based on 95% C.I. for the difference). For the frequency of small overages, the coefficient estimate of average catch decreased. For the frequency of large overages, the coefficient estimate of L_{max} increased. There was very little change in coefficient estimates for either exploitation rates or biomass metrics. For the frequency of major over-exploitation, the estimated coefficient for year of development decreased slightly. Estimation of random effects was in general slightly poorer than the base case. Estimated variance parameters of one or both random effects were at or near zero in at least some models for frequencies of quota overages, frequency of major over-exploitation, and SD(target $B/B_{reference}$).

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Tables for Supporting Information

Table S1. Stocks included in analyses. Headings are abbreviated as R (region), H (taxonomic/habitat association), and CC (catch control type). An '×' indicates the stock is included in analyses for catch:quota (C/Q), exploitation rates ($F/F_{reference}$), or biomass ($B/B_{reference}$). Catch control types are abbreviated as: catch shares, CS; partial catch shares, PCS; quota only, QO, and effort control, E. Superscripts and footnotes denote changes to default habitat associations and aggregations of catch:quota data.

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
U.S. - Alaska								
	Demersal fish							
		Anoplopoma fimbria	Sablefish	Bering Sea/Aleutian Is./G. Alaska	CS	X	X	X
		Gadus macrocephalus	Pacific cod	Bering Sea/Aleutian Is.	QO	X	X	X
		Gadus macrocephalus	Pacific cod	G. Alaska	QO	X	X	X
		Hippoglossoides elassodon	Flathead sole	Bering Sea/Aleutian Is.	QO	X	X	X
		Hippoglossoides elassodon	Flathead sole	G. Alaska	QO	X	X	X
		Hippoglossus stenolepis	Pacific halibut	G. Alaska/W. coast Canada & U.S.	CS	X	X	
		Lepidopsetta polyxystra	Northern rock sole	Bering Sea/Aleutian Is.	QO	X	X	X
		Limanda aspera	Yellowfin sole	Bering Sea/Aleutian Is.	QO	X	X	X
		Microstomus pacificus	Dover sole	G. Alaska	QO		X	
		Pleurogrammus monopterygius	Atka mackerel	Bering Sea/Aleutian Is.	QO	X	X	X
		Pleurogrammus monopterygius	Atka mackerel	G. Alaska	QO	X		
		Sebastes aleutianus	Rougheye rockfish	Bering Sea/Aleutian Is.	QO			X
		Sebastes alutus	Pacific ocean perch	Bering Sea/Aleutian Is.	QO	X	X	X
		Sebastes alutus	Pacific ocean perch	G. Alaska	QO	X	X	X
		Sebastes borealis	Shortraker rockfish	Bering Sea/Aleutian Is.	QO		X	
		Sebastes polyspinis	Northern rockfish	Bering Sea/Aleutian Is.	QO		X	X
		Sebastes polyspinis	Northern rockfish	G. Alaska	QO	X	X	X
		Sebastes variabilis	Dusky rockfish	G. Alaska	QO		X	X
	Benthopelagic fish							
		Reinhardtius hippoglossoides	Greenland halibut	Bering Sea/Aleutian Is.	QO	X	X	X
		Theragra chalcogramma	Walleye pollock	Bering Sea	CS	X	X	X
		Theragra chalcogramma	Walleye pollock	G. Alaska	QO	X	X	X
	Pelagic fish							
		Clupea pallasii	Pacific herring	Sitka	QO	X		

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Clupea pallasii	Pacific herring	Togiak (Bristol Bay)	QO	X	X	X
	Invertebrates							
		Chionoecetes bairdi	Tanner crab	Bering Sea/Aleutian Is.	QO			X
		Chionoecetes opilio	Snow crab	Bering Sea	QO	X	X	X
		Lithodes aequispinus	Golden king crab	Aleutian Is. (E.)	QO	X [2]		X
		Lithodes aequispinus	Golden king crab	Aleutian Is. (W.)	QO			X
		Paralithodes camtschaticus	Red king crab	Bristol Bay	QO	X	X	X
		Paralithodes camtschaticus	Red king crab	Norton Sounds	QO	X		X
		Paralithodes camtschaticus	Red king crab	Pribilof Is.	QO			X
		Paralithodes platypus	Blue king crab	Pribilof Is.	QO			X
		Paralithodes platypus	Blue king crab	Saint Matthews Is.	QO			X
		Patinopecten caurinus	Wathervane scallop	Bering Sea	QO	X		
		Patinopecten caurinus	Wathervane scallop	Kodiak NE District	QO	X		
		Patinopecten caurinus	Wathervane scallop	Kodiak Shelikof District	QO	X		
		Patinopecten caurinus	Wathervane scallop	Prince William Sound	QO	X		
		Patinopecten caurinus	Wathervane scallop	Yakutat Area D	QO	X		
		Patinopecten caurinus	Wathervane scallop	Yakutat District 16	QO	X		
U.S. - West coast								
	Demersal fish							
		Anoplopoma fimbria	Sablefish	Coastwide	QO	X	X	X
		Eopsetta jordani	Petrale sole	N. coast	QO	X	X	X
		Eopsetta jordani	Petrale sole	S. coast	QO	X	X	X
		Microstomus pacificus	Dover sole	Coastwide	QO	X	X	X
		Parophrys vetulus	English sole	Coastwide	QO	X	X	X
		Raja rhina	Longnose skate	Coastwide	QO		X	X
		Reinhardtius stomias	Arrowtooth flounder	Coastwide	QO	X	X	X
		Sebastes alutus	Pacific ocean perch	Coastwide	QO			X
		Sebastes crameri	Darkblotched rockfish	Coastwide	QO			X
		Sebastes elongatus	Greenstriped rockfish	Coastwide	QO		X	
		Sebastes goodei	Chilipepper rockfish	S. coast	QO	X	X	X
		Sebastes melanostomus	Blackgill rockfish	Coastwide	QO	X	X	X
		Sebastolobus alascanus	Shortspine thornyhead	Coastwide	QO	X	X	X
		Sebastolobus altivelis	Longspine thornyhead	Coastwide	QO	X	X	X
	Benthopelagic fish							
		Merluccius productus [1]	Pacific hake	Coastwide	PCS	X	X	X
	Pelagic fish							
		Sardinops sagax	Pacific sardine	Coastwide	QO	X	X	X
		Scomber japonicus	Pacific chub mackerel	Coastwide	QO	X		

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Sebastes entomelas	Widow rockfish	Coastwide	QO			X
	Reef-associated fish							
		Sebastes flavidus	Yellowtail rockfish	N. coast	QO	X	X	X
		Sebastes pinniger	Canary rockfish	Coastwide	QO			X
West coast Canada								
	Demersal fish							
		Anoplopoma fimbria	Sablefish	Coastwide	CS	X	X	X
		Eopsetta jordani	Petrale sole	Coastwide	CS	X	X	X
		Gadus macrocephalus	Pacific cod	Hecate Strait	CS	X	X	X
		Gadus macrocephalus	Pacific cod	W. coast of Vancouver Is.	CS	X		
		Lepidopsetta bilineata	Rock sole	Hecate Strait	CS	X		
		Lepidopsetta bilineata	Rock sole	W. coast of Vancouver Is.	CS	X		
		Microstomus pacificus	Dover sole	Coastwide	CS	X		
		Ophiodon elongatus	Lingcod	Coastwide	PCS	X	X	X
		Parophrys vetulus	English sole	Hecate Strait	CS	X	X	X
		Parophrys vetulus	English sole	W. coast of Vancouver Is.	CS	X		
		Sebastes aleutianus	Rougheye rockfish	Coastwide	PCS	X		
		Sebastes alutus	Pacific ocean perch	Coastwide	CS	X		
		Sebastes borealis	Shortraker rockfish	Coastwide	PCS	X		
		Sebastes brevispinis	Silvergray rockfish	Coastwide	CS	X		
		Sebastes proriger	Redstripe rockfish	Coastwide	CS	X		
		Sebastes reedi	Yellowmouth rockfish	Coastwide	CS	X		
		Sebastolobus alascanus	Shortspine thornyhead	Coastwide	CS	X		
		Sebastolobus altivelis	Longspine thornyhead	Coastwide	CS	X		
	Benthopelagic fish							
		Squalus acanthias	Spiny dogfish	Coastwide	PCS	X		
		Theragra chalcogramma	Walleye pollock	Coastwide	CS	X		
	Pelagic fish							
		Clupea pallasii	Pacific herring	Central Coast	CS [3]	X	X	X
		Clupea pallasii	Pacific herring	Prince Rupert District	CS [3]	X	X	X
		Clupea pallasii	Pacific herring	Queen Charlotte Is.	CS [3]			X
		Clupea pallasii	Pacific herring	Straight of Georgia	CS [3]	X	X	X
		Clupea pallasii	Pacific herring	W. coast of Vancouver Is.	CS [3]			X
		Sebastes entomelas	Widow rockfish	Coastwide	CS	X		
	Reef-associated fish							
		Sebastes flavidus	Yellowtail rockfish	Coastwide	CS	X		
		Sebastes pinniger	Canary rockfish	Coastwide	CS	X	X	X
	Invertebrates							
		Panopea abrupta	Geoduck	Coastwide	CS	X		

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Parastichopus californicus	California sea cucumber	Coastwide	CS	X		
		Strongylocentrotus droebachiensis	Green sea urchin	Coastwide	CS	X		
		Strongylocentrotus franciscanus	Red sea urchin	Coastwide	CS	X		
East coast Canada								
	Demersal fish							
		Glyptocephalus cynoglossus	Witch flounder	NAFO 2J3KL	QO			X
		Glyptocephalus cynoglossus	Witch flounder	NAFO 3NO	QO			X
		Glyptocephalus cynoglossus	Witch flounder	NAFO 3Ps	PCS	X	X	X
		Glyptocephalus cynoglossus	Witch flounder	NAFO 4RST	QO	X		
		Hippoglossoides platessoides	American plaice	NAFO 4T	PCS	X		
		Hippoglossoides platessoides	American plaice	NAFO 3LNO	CS			X
		Hippoglossus hippoglossus	Atlantic halibut	NAFO 3NOPs4VWX5Zc	CS	X		
		Limanda ferruginea	Yellowtail flounder	NAFO 3LNO	CS	X	X	X
		Melanogrammus aeglefinus	Haddock	NAFO 4X5Y	CS	X		
		Melanogrammus aeglefinus	Haddock	NAFO 5Zejm	CS	X		
		Urophycis tenuis	White hake	NAFO 4VW	CS			X
	Benthopelagic fish							
		Gadus morhua	Atlantic cod	NAFO 2J3KL offshore	CS			X
		Gadus morhua	Atlantic cod	NAFO 3NO	PCS			X
		Gadus morhua	Atlantic cod	NAFO 3Pn4RS	QO			X
		Gadus morhua	Atlantic cod	NAFO 3Ps	CS	X	X	X
		Gadus morhua	Atlantic cod	NAFO 4TVn	CS			X
		Gadus morhua	Atlantic cod	NAFO 4X	CS	X		
		Gadus morhua	Atlantic cod	NAFO 5Zjm	CS	X		
		Reinhardtius hippoglossoides	Greenland halibut	NAFO 01ABCDEF	PCS	X		
		Reinhardtius hippoglossoides	Greenland halibut	NAFO 23KLMNO	QO	X	X	X
		Reinhardtius hippoglossoides	Greenland halibut	NAFO 4RST	QO	X		
		Squalus acanthias	Spiny dogfish	Northwest Atlantic	QO		X	X
	Pelagic fish							
		Clupea harengus[1]	Atlantic herring	NAFO 3KLOP	QO	X		
		Clupea harengus[1]	Atlantic herring	NAFO 4R	CS	X[4]		
		Clupea harengus[1]	Atlantic herring	NAFO 4T (fall spawners)	QO	X		
		Clupea harengus[1]	Atlantic herring	NAFO 4T (spring spawners)	QO	X		
		Clupea harengus[1]	Atlantic herring	Scotian Shelf and Bay of Fundy	CS	X		
		Mallotus villosus	Capelin	NAFO 4RST	PCS	X		
		Pollachius virens[1]	Pollock	NAFO 4VWX5Zc	CS	X	X	X
		Sebastes mentella & S. fasciatus	Redfish	NAFO 3O	PCS	X		
		Sebastes marinus & S. mentella	Redfish	NAFO 1	QO	X		

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Scomber scombrus	Atlantic mackerel	NAFO 34	QO	X		
	Invertebrates							
		Chionoecetes opilio	Snow crab	NAFO 2J3KLNOPs4R	CS	X		
		Chionoecetes opilio	Snow crab	Areas 20-24 (Scotian Shelf)	CS	X		
		Chionoecetes opilio	Snow crab	S. G. St. Lawrence	CS	X		
		Pandalus borealis	Northern shrimp	NAFO 4S	CS	X		
		Pandalus borealis	Northern shrimp	NAFO 0A(E.)+1	QO	X		
		Pandalus borealis	Northern shrimp	NAFO 2G-3K	CS	X		
		Pandalus borealis	Northern shrimp	NAFO 3L	QO	X		
		Pandalus borealis	Northern shrimp	SFA 13,14,15 (E. Scotian Shelf)	CS	X		
		Placopecten magellanicus	Sea scallop	SPA 1-6 (Bay of Fundy)	PCS	X		
		Placopecten magellanicus	Sea scallop	SFA 10-12,25-27 (Georges Bank)	CS	X	X	X
		Mactromeris polynyma	Arctic surfclam	NAFO 4Vsc	CS	X		
		Strongylocentrotus droebachiensis	Green sea urchin	LFA 38	CS	X		
U.S. - Northeast & Mid-Atlantic coast								
	Demersal fish							
		Glyptocephalus cynoglossus	Witch flounder	NAFO 5Y	E		X	X
		Hippoglossoides platessoides	American plaice	NAFO 5YZ	E		X	X
		Limanda ferruginea	Yellowtail flounder	Cape Cod/G. Maine	E		X	X
		Limanda ferruginea	Yellowtail flounder	Georges Bank	QO		X	X
		Limanda ferruginea	Yellowtail flounder	S. New England/mid-Atl. coast	E		X	X
		Lophius americanus	Monkfish	G. Maine/N. Georges Bank	E		X	X
		Lophius americanus	Monkfish	S. Georges Bank/mid-Atl. coast	E		X	X
		Lopholatilus chamaeleonticeps	Tilefish	Mid-Atlantic coast	E		X	X
		Melanogrammus aeglefinus	Haddock	Georges Bank	QO		X	X
		Melanogrammus aeglefinus	Haddock	NAFO 5Y	E		X	X
		Paralichthys dentatus	Summer flounder	Mid-Atlantic coast	QO	X	X	X
		Pseudopleuronectes americanus	Winter flounder	NAFO 5Z	E		X	X
		Pseudopleuronectes americanus	Winter flounder	S. New England/mid-Atl. coast	E		X	X
		Scophthalmus aquosus	Windowpane flounder	G. Maine/Georges Bank	E		X	X
		Scophthalmus aquosus	Windowpane flounder	S. New England/mid-Atl. coast	E		X	X
		Sebastes fasciatus	Acadian redfish	G. Maine/Georges Bank	E		X	X
		Stenotomus chrysops	Scup	Coastwide	QO	X		X
		Urophycis tenuis	White hake	G. Maine/Georges Bank	E		X	X
	Benthopelagic fish							
		Cynoscion regalis [1]	Weakfish	Coastwide	E			X
		Gadus morhua	Atlantic cod	Georges Bank	QO		X	X
		Gadus morhua	Atlantic cod	G. Maine	E		X	X

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Merluccius bilinearis [1]	Silver hake	G. Maine/N. Georges Bank	E		X	X
		Merluccius bilinearis [1]	Silver hake	S. Georges Bank/mid-Atl. coast	E		X	X
	Pelagic fish							
		Brevoortia tyrannus	Atlantic menhaden	Coastwide	E		X	X
		Clupea harengus [1]	Atlantic herring	Northwest Atlantic coast	QO	X	X	X
		Pollachius virens [1]	Pollock	NAFO 5YZ	E		X	X
		Scomber scombrus	Mackerel	G. Maine - Cape Hatteras	QO	X	X	X
	Invertebrates							
		Arctica islandica	Ocean quahog	Coastwide	CS	X		
		Homarus americanus	American lobster	Rhode Is.	E		X	X
		Illex illecebrosus	Northern shortfin squid	Northwest Atlantic coast	QO	X		
		Loligo pealeii	Longfin inshore squid	Coastwide	QO	X		
		Pandalus borealis	Northern shrimp	G. Maine	E		X	X
		Placopecten magellanicus	Sea scallop	Georges Bank	PCS		X	X
		Placopecten magellanicus	Sea scallop	Mid-Atlantic coast	PCS		X	X
		Spisula solidissima	Atlantic surfclam	Mid-Atlantic coast	CS	X	X	X
U.S. - Southern Atlantic coast & Gulf of Mexico								
	Benthopelagic fish							
		Rhomboplites aurorubens [1]	Vermilion snapper	S. Atlantic coast	E		X	X
	Pelagic fish							
		Brevoortia patronus	Gulf menhaden	G. Mexico	E		X	X
		Scomberomorus maculatus	Spanish mackerel	S. Atlantic coast	QO	X	X	X
	Reef-associated fish							
		Epinephelus morio	Red grouper	G. Mexico	QO	X	X	X
		Lutjanus campechanus	Red snapper	G. Mexico	QO	X [5]		
		Mycteroperca microlepis	Gag	S. Atlantic coast	E		X	X
Europe								
	Demersal fish							
		Lepidorhombus boscii	Fourspotted megrim	ICES VIIIc-IXa	QO		X	X
		Lepidorhombus whiffiagonis	Megrim	ICES VIIIc-IXa	QO	X	X	X
		Lepidorhombus whiffiagonis	Megrim	ICES VIIb-k,VIIIabd	QO	X		
		Lophius piscatorius	Anglerfish	ICES VIIIc,IXa	QO	X		
		Melanogrammus aeglefinus	Haddock	Faroe Plateau	E		X	X
		Melanogrammus aeglefinus	Haddock	Iceland	CS	X	X	X
		Melanogrammus aeglefinus	Haddock	ICES IIIa and North Sea	CS	X	X	X
		Melanogrammus aeglefinus	Haddock	ICES VIIb-k	QO	X		
		Melanogrammus aeglefinus	Haddock	Northeast Arctic	PCS	X	X	X
		Melanogrammus aeglefinus	Haddock	West of Scotland	CS	X	X	X

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Merluccius merluccius	Hake	Northeast Atlantic (northern)	QO	X	X	X
		Merluccius merluccius	Hake	Northeast Atlantic (southern)	QO	X		
		Pleuronectes platessa	European plaice	ICES IIIa	QO	X		
		Pleuronectes platessa	European plaice	ICES VIId	PCS	X		
		Pleuronectes platessa	European plaice	ICES VIIe	PCS		X	X
		Pleuronectes platessa	European plaice	ICES VIIf-g	QO	X	X	X
		Pleuronectes platessa	European plaice	Irish Sea	PCS	X	X	X
		Pleuronectes platessa	European plaice	North Sea	PCS	X		
		Solea vulgaris	Common European sole	Bay of Biscay	QO	X	X	X
		Solea vulgaris	Common European sole	Celtic Sea	PCS	X	X	X
		Solea vulgaris	Common European sole	Kattegat and Skagerrak	QO		X	X
		Solea vulgaris	Common European sole	ICES VIId	QO	X		
		Solea vulgaris	Common European sole	Irish Sea	QO	X	X	X
		Solea vulgaris	Common European sole	North Sea	CS	X		
		Solea vulgaris	Common European sole	W. English Channel	PCS	X	X	X
	Benthopelagic fish							
		Ammodytes marinus	Sand lance	North Sea	QO	X	X	X
		Gadus morhua	Atlantic cod	Baltic areas 22,24	QO		X	X
		Gadus morhua	Atlantic cod	Baltic areas 25-32	QO	X	X	X
		Gadus morhua	Atlantic cod	Coastal Norway	QO	X	X	X
		Gadus morhua	Atlantic cod	Faroe Plateau	E		X	X
		Gadus morhua	Atlantic cod	Iceland	CS	X	X	X
		Gadus morhua	Atlantic cod	Irish Sea	PCS	X	X	X
		Gadus morhua	Atlantic cod	Kattegat	QO			X
		Gadus morhua	Atlantic cod	North Sea	PCS			X
		Gadus morhua	Atlantic cod	Northeast Arctic	PCS	X	X	X
		Gadus morhua	Atlantic cod	West of Scotland	PCS			X
		Merlangius merlangus	Whiting	ICES IIIa,VIId and North Sea	PCS	X	X	X
		Merlangius merlangus	Whiting	ICES VIa	PCS	X		
		Merlangius merlangus	Whiting	ICES VIIe-k	QO	X	X	X
		Micromesistius poutassou	Blue whiting	Northeast Atlantic	PCS		X	X
		Reinhardtius hippoglossoides	Greenland halibut	Northeast Arctic	QO			X
		Trisopterus esmarkii	Norway pout	North Sea	QO	X	X	X
	Pelagic fish							
		Clupea harengus [1]	Atlantic herring	Iceland (summer spawners)	CS	X	X	X
		Clupea harengus [1]	Atlantic herring	Baltic areas 25-32	QO		X	X
		Clupea harengus [1]	Atlantic herring	Baltic area 30	QO	X	X	X
		Clupea harengus [1]	Atlantic herring	Baltic area 31	QO		X	X

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Clupea harengus [1]	Atlantic herring	ICES VIa(northern)	PCS	X	X	X
		Clupea harengus [1]	Atlantic herring	ICES VIa(southern)-VIIbc	QO	X		
		Clupea harengus [1]	Atlantic herring	North Sea	PCS	X	X	X
		Clupea harengus [1]	Atlantic herring	Irish Sea (northern)	PCS	X	X	X
		Engraulis encrasicolus	Anchovy	ICES VIII	QO	X		
		Mallotus villosus	Capelin	Barents Sea	PCS			X
		Mallotus villosus	Capelin	Iceland	CS	X	X	X
		Pollachius virens [1]	Pollock	Faroe Plateau	E		X	X
		Pollachius virens [1]	Pollock	ICES IIIa,VI and North Sea	PCS	X	X	X
		Pollachius virens [1]	Pollock	Northeast Arctic	PCS	X	X	X
		Scomber scombrus	Mackerel	Northeast Atlantic	PCS	X	X	X
		Sprattus sprattus	Sprat	Baltic areas 22-32	QO	X	X	X
		Sprattus sprattus	Sprat	North Sea	QO	X		
	Invertebrates							
		Nephrops norvegicus	Nephrops lobster	ICES IIIa	QO	X		
		Nephrops norvegicus	Nephrops lobster	ICES VIIIab	QO	X		
		Nephrops norvegicus	Nephrops lobster	ICES VIIIc	QO	X		
South Africa								
	Demersal fish							
		Merluccius capensis	Shallow-water cape hake	Coastwide	CS		X	X
		Merluccius paradoxus	Deep-water cape hake	Coastwide	CS	X		X
	Pelagic fish							
		Dissostichus eleginoides	Patagonian toothfish	Subantarctic - Prince Edward Is.	CS			X
		Engraulis encrasicolus	Anchovy	Coastwide	CS	X	X	X
		Sardinops sagax	Sardine	Coastwide	CS	X	X	X
	Invertebrates							
		Haliotis midae	South African abalone	Coastwide	CS	X		
		Jasus lalandii	S. African W. coast rock lobster	Area 7	PCS	X		
		Jasus lalandii	S. African W. coast rock lobster	Area 8	PCS	X		
		Jasus lalandii	S. African W. coast rock lobster	Areas 1-2	PCS	X		
		Jasus lalandii	S. African W. coast rock lobster	Areas 3-4	PCS	X		
		Jasus lalandii	S. African W. coast rock lobster	Areas 5-6	PCS	X		
		Palinurus gilchristi	Southern spiny lobster	S. coast	CS	X	X	X
South America								
	Benthopelagic fish							
		Macruronus magellanicus	Patagonian grenadier	S. coast	QO	X [6]	X	X
		Merluccius hubbsi	Argentine hake	N. coast	PCS		X	X
		Merluccius hubbsi	Argentine hake	S. coast	CS		X	X

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F$_{ref}$	B/B$_{ref}$
		Micromesistius australis	Southern blue whiting	S. coast	QO	X[7]	X	
	Pelagic fish							
		Engraulis anchoita	Argentine anchoita	N. coast	QO	X	X	X
		Engraulis anchoita	Argentine anchoita	S. coast	QO	X	X	X
		Trachurus murphyi	Chilean jack mackerel	Chilean EEZ and offshore	CS		X	X
Australia								
	Demersal fish							
		Centroberyx gerrardi	Bight redfish	SE Shelf	QO			X
		Genypterus blacodes	Ling	SE Shelf (E.)	CS	X	X	X
		Genypterus blacodes	Ling	SE Shelf (W.)	CS			X
		Nemadactylus macropterus	Jackass morwong	SE Shelf	CS	X	X	X
		Neoplatycephalus richardsoni	Tiger flathead	SE Shelf	CS	X		X
		Platycephalus conatus	Deepwater flathead	SE Shelf	QO		X	X
		Sillago flindersi	School whiting	SE Shelf	CS	X	X	X
	Benthopelagic fish							
		Centroberyx affinis	Redfish	SE Shelf	CS	X		
		Hoplostethus atlanticus	Orange roughy	SE Shelf (E.)	CS	X	X	X
		Hoplostethus atlanticus	Orange roughy	SE Shelf (W.)	CS	X		
		Hyperoglyphe antarctica	Blue eye trevalla	SE Shelf	CS	X		
		Macruronus novaezelandiae	Blue grenadier	SE Shelf	CS	X	X	X
		Rexea solandri	Common gemfish	SE Shelf	CS			X
		Sebastes melanops	Blue warehou	SE Shelf (W.)	CS			X
		Seriolella brama	Blue warehou	SE Shelf (E.)	CS			X
		Seriolella punctata	Silverfish *(silver warehou)*	SE Shelf	CS	X	X	X
		Zenopsis nebulosus	MIrror dory	SE Shelf	CS	X		
		Zeus faber	John dory	SE Shelf	CS	X		
	Pelagic fish							
		Sardinops sagax	Pilchard *(sardine)*	S. Australia	CS	X		
	Reef-associated fish							
		Pseudocaranx dentex	Silver trevally	SE Shelf	CS	X		
	Invertebrates							
		Haliotis laevigata	Green-lipped abalone	Tasmania	CS	X		
		Haliotis rubra	Black-lipped abalone	Tasmania	CS	X		
		Haliporoides sibogae	Royal red prawn	SE Shelf	CS	X		
		Jasus edwardsii	Rock lobster	Tasmania	CS	X	X	X
		Pseudocarcinus gigas	Tasmanian giant crab	Tasmania	CS	X		
New Zealand								
	Demersal fish							

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Callorhinchus milii	Elephantfish	Countrywide	CS	X		
		Chelidonichthys kumu	Red gurnard	Countrywide	CS	X		
		Genypterus blacodes	Ling	LIN 6b	CS		X	X
		Genypterus blacodes	Ling	LIN 72	CS	X [8]	X	X
		Genypterus blacodes	Ling	LIN 7WC-WCSI	CS		X	X
		Genypterus blacodes	Ling	LIN 3,4	CS	X	X	X
		Genypterus blacodes	Ling	LIN 5,6	CS	X	X	X
		Helicolenus percoides	Sea perch	Countrywide	CS	X		
		Hydrolagus bemisi	Pale ghost shark	Countrywide	CS	X		
		Hydrolagus novaezealandiae	Dark ghost shark	Countrywide	CS	X		
		Kathetostoma giganteum	Stargazer	Countrywide	CS	X		
		Latridopsis ciliaris	Blue moki	Countrywide	CS	X		
		Metanephrops challengeri	Scampi	Countrywide	QO	X		
		Mustelus lenticulatus	Rig	Countrywide	CS	X		
		Nemadactylus macropterus	Tarakihi	Countrywide	CS	X		
		Parapercis colias	Blue cod	Countrywide	CS	X		
		Plagiogeneion rubiginosum	Rubyfish	Countrywide	CS	X		
		Polyprion oxygeneios & P. americanus	Groper	Countrywide	CS	X		
		Pseudocyttus maculatus	Smooth oreo	Chatham Rise	CS	X [9]	X	X
		Pseudocyttus maculatus	Smooth oreo	West end of Chatham Rise	CS		X	X
		Pseudophycis bachus	Red cod	Countrywide	CS	X		
		Seriolella caerulea	White warehou	Countrywide	CS	X		
	Benthopelagic fish							
		Allocyttus niger	Black oreo	West end of Chatham Rise	CS	X [10]	X	X
		Allocyttus niger	Black oreo	OEO1,6	CS	X [11]		
		Beryx splendens & B. decadactylus	Alfonsino	Countrywide	CS	X		
		Galeorhinus galeus	School shark	Countrywide	CS	X		
		Hoplostethus atlanticus	Orange roughy	Mid-east coast	CS	X		
		Hoplostethus atlanticus	Orange roughy	ORH3B	CS	X		
		Hyperoglyphe antarctica	Bluenose	Countrywide	CS	X		
		Lepidopus caudatus	Frostfish	Countrywide	CS	X		
		Macruronus novaezelandiae	Hoki	E. New Zealand	CS	X [12]	X	X
		Macruronus novaezelandiae	Hoki	W. New Zealand	CS		X	X
		Merluccius australis	Southern hake	Chatham Rise	CS	X	X	X
		Merluccius australis	Southern hake	Sub-Antarctic	CS	X	X	X
		Micromesistius australis	Southern blue whiting	Aukland,Bounty,Pukaki	CS	X		
		Micromesistius australis	Southern blue whiting	Campbell Is. Rise	CS	X	X	X

R	H	Species name	Common name	Sub-region	CC	C/Q	F/F_{ref}	B/B_{ref}
		Mugil cephalus	Grey mullet	Countrywide	CS	X		
		Rexea solandri	Common gemfish	Countrywide	CS	X	X	X
		Sebastes melanops	Blue warehou	Countrywide	CS	X		
		Seriolella punctata	Silver warehou	Countrywide	CS	X		
		Thyrsites atun	Barracouta	Countrywide	CS	X		
		Trachurus declivis, T. novaezelandiae & T. murphyi	Jack mackerels	Countrywide	CS	X		
		Zeus faber	John dory	Countrywide	CS	X		
	Pelagic fish							
		Arripis trutta	Australian salmon	Countrywide	QO	X	X	X
		Dissostichus mawsoni	Antarctic toothfish	Ross Sea	QO	X	X	X
	Reef-associated fish							
		Chrysophrys auratus	New Zealand snapper	SNA 8	PCS	X	X	X
		Chrysophrys auratus	New Zealand snapper	SNA 1	PCS	X		
		Pseudocaranx dentex	Trevally	TRE 7	CS	X	X	X
	Invertebrates							
		Haliotis iris	New Zealand abalone *(paua)*	PAU 5A	CS	X	X	X
		Haliotis iris	New Zealand abalone *(paua)*	PAU 5B	CS	X	X	X
		Haliotis iris	New Zealand abalone *(paua)*	PAU 5D	PCS	X	X	X
		Haliotis iris	New Zealand abalone *(paua)*	PAU 7	CS	X	X	X
		Haliotis iris	New Zealand abalone *(paua)*	PAU 2	PCS	X		
		Haliotis iris	New Zealand abalone *(paua)*	PAU 3	PCS	X		
		Haliotis iris	New Zealand abalone *(paua)*	PAU 4	CS	X		
		Jasus edwardsii	Red rock lobster	CRA 1	PCS	X		
		Jasus edwardsii	Red rock lobster	CRA 2	PCS	X		
		Jasus edwardsii	Red rock lobster	CRA 3	PCS	X		
		Jasus edwardsii	Red rock lobster	CRA 4	PCS	X	X	X
		Jasus edwardsii	Red rock lobster	CRA 5	CS	X		
		Jasus edwardsii	Red rock lobster	CRA 7	CS	X	X	X
		Jasus edwardsii	Red rock lobster	CRA 8	CS	X	X	X
		Jasus edwardsii	Red rock lobster	CRA 6	CS	X		
		Nototodarus gouldi & N. sloanii	Arrow squid	Countrywide	CS	X [13]		
Total						259	173	205

[1] Some habitat classifications were changed from those listed in FishBase to more accurately represent the species. Changes included: Pacific hake (*Merluccius productus*) to benthopelagic; Atlantic herring (*Clupea harengus*) to pelagic; pollock (or saithe,

Pollachius virens) to pelagic; weakfish (*Cynoscion regalis*) to benthopelagic; silver hake (*Merluccius bilinearis*) to benthopelagic; and vermilion snapper (*Rhomboplites aurorubens*) to benthopelagic.

[2] Catch and quota for U.S. Alaska - Aleutian Islands golden king crab are pooled over eastern and western segments.

[3] Although British Columbia herring fisheries are technically a co-operative, they operate much like a catch share fishery (J. Schweigert, *pers. comm.*)

[4] Catch and quota for Canada 4R Atlantic herring are pooled over spring and fall spawners.

[5] Catch and quota for U.S. Gulf of Mexico red snapper are pooled for eastern and western sub-stocks.

[6] Argentine Patagonian grenadier is otherwise known as merluza de cola.

[7] Argentine Southern blue whiting is otherwise known as polaca.

[8] Catch and quota for New Zealand ling LIN 72 and LIN 7WC-WCSI are pooled.

[9] Catch and quota for New Zealand Chatham Rise smooth oreo (*Pseudocyttus maculatus*) and black oreo (*Allocyttus niger*) are pooled.

[10] Catch and quota for New Zealand West end of Chatham Rise black oreo (*Allocyttus niger*) and smooth oreo (*Pseudocyttus maculatus*) are pooled.

[11] Catch and quota for New Zealand OEO 1,6 black oreo (*Allocyttus niger*) and smooth oreo (*Pseudocyttus maculatus*) are pooled.

[12] Catch and quota for New Zealand hoki are pooled for eastern and western sub-stocks.

[13] Catch and quota for New Zealand arrow squid are separated by trawl and jig gear types

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. Header abbreviations are: k, number of parameters; $-2 \cdot ln(L)$, two times the negative log-likelihood (i.e. deviance); AICc, Akaike Information Criterion scores corrected for small sample sizes; ΔAICc, difference in AICc with that of the lowest value across models; and R^2, the proportion of variance explained by the model.

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
(a) Mean C/Q					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	21	60.6	406.8	6.6	0.19
CControl + PS + Region + avCatch + devYear + L_{max}	17	62.8	406.6	6.3	0.16
CControl + PS + Habitat + avCatch + devYear + L_{max}	11	64.8	401.4	1.2	0.13
CControl + PS + avCatch + devYear + L_{max}	7	68.6	407.3	7.1	0.08
CControl + PS + Region + Habitat	18	61.7	404.1	3.9	0.07
CControl + PS + Region	14	62.9	400.2	0.0	0.16
CControl + PS + Habitat	8	69.9	414.5	14.2	0.06
CControl + PS	4	71.1	410.3	10.1	0.05
Region + Habitat + avCatch + devYear + L_{max}	18	61.8	404.9	4.7	0.17
Region + avCatch + devYear + L_{max}	14	65.2	409.6	9.4	0.12
Habitat + avCatch + devYear + L_{max}	8	68.1	407.5	7.3	0.09
Intercept + avCatch + devYear + L_{max}	4	72.3	414.6	14.3	0.03
Region + Habitat	15	66.0	414.8	14.5	0.11
Region	11	67.1	410.3	10.0	0.10
Habitat	5	73.1	419.5	19.3	0.02
Intercept	1	74.5	416.2	16.0	0
(b) SD(target C/Q)					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	21	352.0	862.4	4.2	0.29
CControl + PS + Region + avCatch + devYear + L_{max}	17	412.7	894.2	36.1	0.17
CControl + PS + Habitat + avCatch + devYear + L_{max}	11	378.2	858.1	0.0	0.24

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
CControl + PS + avCatch + devYear + L_{max}	7	451.3	895.3	37.2	0.09
CControl + PS + Region + Habitat	18	357.6	859.4	1.3	0.28
CControl + PS + Region	14	434.4	900.7	42.6	0.12
CControl + PS + Habitat	8	402.1	867.5	9.4	0.19
CControl + PS	4	464.6	896.5	38.4	0.06
Region + Habitat + avCatch + devYear + L_{max}	18	363.1	863.3	5.2	0.27
Region + avCatch + devYear + L_{max}	14	443.3	905.9	47.8	0.10
Habitat + avCatch + devYear + L_{max}	8	405.8	869.9	11.8	0.18
Intercept + avCatch + devYear + L_{max}	4	488.8	909.6	51.5	0.01
Region + Habitat	15	401.6	882.6	24.5	0.19
Region	11	459.9	908.8	50.7	0.07
Habitat	5	425.6	875.9	17.8	0.14
Intercept	1	494.5	906.5	48.4	0
(c) Small overages					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	21	125.7	171.6	13.7	0.21
CControl + PS + Region + avCatch + devYear + L_{max}	17	132.9	169.5	11.5	0.17
CControl + PS + Habitat + avCatch + devYear + L_{max}	11	138.0	161.1	3.1	0.14
CControl + PS + avCatch + devYear + L_{max}	7	144.6	159.0	1.1	0.10
CControl + PS + Region + Habitat	18	128.1	167.0	9.1	0.20
CControl + PS + Region	14	133.8	163.5	5.6	0.16
CControl + PS + Habitat	8	145.7	162.3	4.4	0.09
CControl + PS	4	154.4	162.5	4.6	0.03
Region + Habitat + avCatch + devYear + L_{max}	18	130.6	169.4	11.5	0.18
Region + avCatch + devYear + L_{max}	14	136.6	166.3	8.4	0.15
Habitat + avCatch + devYear + L_{max}	8	144.9	161.5	3.6	0.09
Intercept + avCatch + devYear + L_{max}	4	149.8	157.9	0.0	0.06
Region + Habitat	15	134.7	166.7	8.8	0.16

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
Region	11	140.7	163.8	5.9	0.12
Habitat	5	152.7	162.9	5.0	0.05
Intercept	1	159.9	161.9	4.0	0
(d) Large overages					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	21	53.5	99.4	19.5	0.32
CControl + PS + Region + avCatch + devYear + L_{max}	17	59.6	96.1	16.2	0.24
CControl + PS + Habitat + avCatch + devYear + L_{max}	11	64.7	87.8	7.9	0.17
CControl + PS + avCatch + devYear + L_{max}	7	68.8	83.2	3.3	0.12
CControl + PS + Region + Habitat	18	57.0	95.8	15.9	0.27
CControl + PS + Region	14	61.4	91.1	11.3	0.21
CControl + PS + Habitat	8	69.1	85.7	5.8	0.12
CControl + PS	4	75.3	83.5	3.6	0.04
Region + Habitat + avCatch + devYear + L_{max}	18	55.2	94.1	14.2	0.29
Region + avCatch + devYear + L_{max}	14	60.3	90.1	10.2	0.23
Habitat + avCatch + devYear + L_{max}	8	67.6	84.2	4.3	0.14
Intercept + avCatch + devYear + L_{max}	4	71.7	79.9	0.0	0.08
Region + Habitat	15	58.8	90.8	10.9	0.25
Region	11	63.0	86.1	6.2	0.19
Habitat	5	72.1	82.4	2.5	0.08
Intercept	1	78.2	80.2	0.3	0

[1] All variables are treated as fixed effects. CControl represents catch control type, with levels of catch shares (>75% of total landings in catch shares), partial catch shares (25–75%), and quota only (<25%). Other covariates are: avCatch, average total catch during the 2000–2004 period (*ln*-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program.

Table S3. Model selection results for fixed-effects model analyses of exploitation rate ratios: (a) mean F/$F_{reference}$; (b) SD(target F/$F_{reference}$); (c) minor over-exploitation; (d) major over-exploitation. Header abbreviations are: *k*, number of parameters; $-2 \cdot ln(L)$, two times the negative log-likelihood (i.e. deviance); AICc, Akaike Information Criterion scores corrected for small sample sizes; ΔAICc, difference in AICc with that of the lowest value across models; and R^2, the proportion of variance explained by the model.

Model [1]	*k*	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
(a) Mean F/$F_{reference}$					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	127.5	490.8	7.4	0.25
CControl + PS + Region + avCatch + devYear + L_{max}	18	136.8	492.8	9.4	0.20
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	144.1	487.3	3.8	0.15
CControl + PS + avCatch + devYear + L_{max}	8	149.4	484.5	1.0	0.12
CControl + PS + Region + Habitat	19	135.2	493.2	9.8	0.21
CControl + PS + Region	15	141.9	491.7	8.2	0.17
CControl + PS + Habitat	9	156.5	494.7	11.2	0.08
CControl + PS	5	158.8	488.5	5.0	0.07
Region + Habitat + avCatch + devYear + L_{max}	18	129.6	483.5	0.0	0.24
Region + avCatch + devYear + L_{max}	14	138.2	484.8	1.3	0.19
Habitat + avCatch + devYear + L_{max}	8	151.7	487.1	3.6	0.11
Intercept + avCatch + devYear + L_{max}	4	157.5	484.9	1.5	0.08
Region + Habitat	15	138.3	487.3	3.8	0.19
Region	11	143.9	484.7	1.2	0.16
Habitat	5	167.4	497.6	14.2	0.02
Intercept	1	170.3	492.2	8.8	0
(b) SD(target F/$F_{reference}$)					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	88.0	426.8	10.1	0.34
CControl + PS + Region + avCatch + devYear + L_{max}	18	95.4	430.4	13.7	0.29
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	115.6	449.1	32.3	0.14
CControl + PS + avCatch + devYear + L_{max}	8	119.7	446.1	29.3	0.11
CControl + PS + Region + Habitat	19	89.1	421.1	4.3	0.34
CControl + PS + Region	15	97.6	426.9	10.2	0.27
CControl + PS + Habitat	9	119.3	447.8	31.0	0.11

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
CControl + PS	5	123.1	444.5	27.7	0.08
Region + Habitat + avCatch + devYear + L_{max}	18	89.6	419.6	2.8	0.33
Region + avCatch + devYear + L_{max}	14	98.1	425.6	8.8	0.27
Habitat + avCatch + devYear + L_{max}	8	122.0	449.4	32.6	0.09
Intercept + avCatch + devYear + L_{max}	4	128.4	449.6	32.9	0.04
Region + Habitat	15	92.0	416.8	0.0	0.31
Region	11	100.7	423.1	6.3	0.25
Habitat	5	128.3	451.5	34.8	0.04
Intercept	1	134.3	451.1	34.4	0
(c) Minor over-exploitation					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	171.8	222.6	18.0	0.17
CControl + PS + Region + avCatch + devYear + L_{max}	18	175.7	216.2	11.5	0.16
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	193.0	218.9	14.3	0.07
CControl + PS + avCatch + devYear + L_{max}	8	196.0	212.9	8.2	0.06
CControl + PS + Region + Habitat	19	176.8	219.8	15.2	0.15
CControl + PS + Region	15	180.1	213.2	8.5	0.13
CControl + PS + Habitat	9	197.6	216.7	12.1	0.05
CControl + PS	5	200.5	210.8	6.2	0.04
Region + Habitat + avCatch + devYear + L_{max}	18	175.7	216.2	11.6	0.16
Region + avCatch + devYear + L_{max}	14	179.0	209.7	5.0	0.14
Habitat + avCatch + devYear + L_{max}	8	198.5	215.3	10.7	0.05
Intercept + avCatch + devYear + L_{max}	4	201.4	209.6	5.0	0.03
Region + Habitat	15	177.8	210.8	6.2	0.15
Region	11	181.0	204.6	0.0	0.13
Habitat	5	205.7	216.1	11.5	0.01
Intercept	1	208.0	210.1	5.4	0
(d) Major over-exploitation					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	110.5	161.2	12.0	0.29
CControl + PS + Region + avCatch + devYear + L_{max}	18	115.1	155.6	6.4	0.26
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	133.5	159.4	10.2	0.15
CControl + PS + avCatch + devYear + L_{max}	8	136.6	153.5	4.3	0.13

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
CControl + PS + Region + Habitat	19	118.6	161.6	12.4	0.24
CControl + PS + Region	15	123.4	156.4	7.2	0.21
CControl + PS + Habitat	9	138.5	157.6	8.4	0.11
CControl + PS	5	142.1	152.4	3.2	0.09
Region + Habitat + avCatch + devYear + L_{max}	18	116.0	156.4	7.2	0.26
Region + avCatch + devYear + L_{max}	14	118.6	149.2	0.0	0.24
Habitat + avCatch + devYear + L_{max}	8	145.6	162.5	13.3	0.07
Intercept + avCatch + devYear + L_{max}	4	148.0	156.2	7.0	0.05
Region + Habitat	15	122.0	155.0	5.8	0.22
Region	11	126.9	150.6	1.4	0.19
Habitat	5	152.5	162.9	13.7	0.02
Intercept	1	156.4	158.5	9.2	0

[1] All variables are treated as fixed effects. CControl represents catch control type, with levels of catch shares (>75% of total landings in catch shares), partial catch shares (25–75%), quota only (<25%), and effort control. Other covariates are: avCatch, average total catch during the 2000–2004 period (*ln*-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program.

Table S4. Model selection results for fixed-effects model analyses of biomass ratios: (a) mean $B/B_{reference}$; (b) SD(target $B/B_{reference}$); (c) minor depletion; (d) major depletion. Header abbreviations are: *k*, number of parameters; $-2\cdot ln(L)$, two times the negative log-likelihood (i.e. deviance); AICc, Akaike Information Criterion scores corrected for small sample sizes; ΔAICc, difference in AICc with that of the lowest value across models; and R^2, the proportion of variance explained by the model.

Model [1]	*k*	$-2\cdot ln(L)$	AICc	ΔAICc	R^2
(a) Mean $B/B_{reference}$					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	99.6	485.4	6.8	0.41
CControl + PS + Region + avCatch + devYear + L_{max}	18	110.5	496.8	18.2	0.34
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	126.1	509.8	31.1	0.25
CControl + PS + avCatch + devYear + L_{max}	8	140.8	523.5	44.8	0.16
CControl + PS + Region + Habitat	19	109.6	497.5	18.9	0.35
CControl + PS + Region	15	123.5	512.5	33.9	0.27
CControl + PS + Habitat	9	149.6	538.1	59.5	0.11
CControl + PS	5	161.8	545.5	66.9	0.04
Region + Habitat + avCatch + devYear + L_{max}	18	101.1	478.6	0.0	0.40
Region + avCatch + devYear + L_{max}	14	112.8	491.5	12.9	0.33
Habitat + avCatch + devYear + L_{max}	8	129.5	506.4	27.8	0.23
Intercept + avCatch + devYear + L_{max}	4	145.2	521.2	42.6	0.14
Region + Habitat	15	114.6	497.1	18.5	0.32
Region	11	128.9	512.0	33.4	0.23
Habitat	5	156.0	538.1	59.5	0.07
Intercept	1	168.4	545.4	66.8	0
(b) SD(target $B/B_{reference}$)					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	118.7	521.4	15.5	0.25
CControl + PS + Region + avCatch + devYear + L_{max}	18	128.3	527.4	21.5	0.19
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	128.9	514.2	8.4	0.19
CControl + PS + avCatch + devYear + L_{max}	8	141.0	523.8	18.0	0.11
CControl + PS + Region + Habitat	19	134.6	539.7	33.8	0.15
CControl + PS + Region	15	142.3	541.4	35.6	0.10
CControl + PS + Habitat	9	148.1	536.0	30.2	0.06

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
CControl + PS	5	156.7	539.0	33.1	0.01
Region + Habitat + avCatch + devYear + L_{max}	18	119.3	512.5	6.6	0.25
Region + avCatch + devYear + L_{max}	14	128.6	518.4	12.6	0.19
Habitat + avCatch + devYear + L_{max}	8	129.2	505.9	0.0	0.18
Intercept + avCatch + devYear + L_{max}	4	141.3	515.7	9.9	0.11
Region + Habitat	15	136.8	533.4	27.6	0.14
Region	11	142.8	533.0	27.2	0.10
Habitat	5	149.3	529.1	23.3	0.06
Intercept	1	158.3	532.8	27.0	0
(c) Minor depletion					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	216.2	265.7	7.9	0.24
CControl + PS + Region + avCatch + devYear + L_{max}	18	229.9	269.6	11.8	0.34
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	243.9	269.6	11.8	0.14
CControl + PS + avCatch + devYear + L_{max}	8	257.2	274.0	16.2	0.09
CControl + PS + Region + Habitat	19	229.5	271.6	13.8	0.19
CControl + PS + Region	15	251.1	283.7	25.9	0.11
CControl + PS + Habitat	9	264.1	283.0	25.2	0.07
CControl + PS	5	275.0	285.3	27.5	0.03
Region + Habitat + avCatch + devYear + L_{max}	18	218.1	257.8	0.0	0.23
Region + avCatch + devYear + L_{max}	14	233.4	263.6	5.8	0.18
Habitat + avCatch + devYear + L_{max}	8	248.8	265.5	7.7	0.12
Intercept + avCatch + devYear + L_{max}	4	262.4	270.6	12.8	0.07
Region + Habitat	15	232.2	264.7	6.9	0.18
Region	11	255.0	278.3	20.5	0.10
Habitat	5	272.6	282.9	25.1	0.04
Intercept	1	283.1	285.1	27.3	0
(d) Major depletion					
CControl + PS + Region + Habitat + avCatch + devYear + L_{max}	22	171.9	221.5	11.7	0.30
CControl + PS + Region + avCatch + devYear + L_{max}	18	194.0	233.7	24.0	0.21
CControl + PS + Habitat + avCatch + devYear + L_{max}	12	192.8	218.4	8.6	0.22
CControl + PS + avCatch + devYear + L_{max}	8	218.8	235.6	25.8	0.11

Model [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	R^2
CControl + PS + Region + Habitat	19	199.7	241.8	32.1	0.19
CControl + PS + Region	15	217.6	250.1	40.4	0.12
CControl + PS + Habitat	9	228.8	247.7	37.9	0.07
CControl + PS	5	244.4	254.7	45.0	0.01
Region + Habitat + avCatch + devYear + L_{max}	18	173.0	212.7	2.9	0.30
Region + avCatch + devYear + L_{max}	14	195.2	225.4	15.7	0.21
Habitat + avCatch + devYear + L_{max}	8	193.0	209.7	0.0	0.22
Intercept + avCatch + devYear + L_{max}	4	219.9	228.1	18.4	0.11
Region + Habitat	15	203.1	235.7	25.9	0.17
Region	11	219.3	242.7	32.9	0.11
Habitat	5	229.6	239.9	30.2	0.07
Intercept	1	246.1	248.1	38.3	0

[1] All variables are treated as fixed effects. CControl represents catch control type, with levels of catch shares (>75% of total landings in catch shares), partial catch shares (25–75%), quota only <25%), and effort control. Other covariates are: avCatch, average total catch during the 2000–2004 period (*ln*-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program.

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 . Shown are four quantities estimated under maximum likelihood (number of parameters (k), negative log-likelihood, Akaike Information Criterion corrected for small sample sizes, difference in AICc with that of the lowest value across models), and variances of random effects, estimated under restricted maximum likelihood for the two linear models.

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
(a) Mean C/Q							
CControl + PS + avCatch + devYear + L_{max}	10	387.3	408.2	1.7	0.004	0.019	0.259
CControl + PS + devYear + L_{max}	9	397.5	416.2	9.7	0.016	0.002	0.268
CControl + PS + avCatch + devYear	9	387.8	406.5	0.0	0.005	0.016	0.258
CControl + PS + avCatch + L_{max}	9	388.4	407.1	0.6	0.003	0.020	0.259
CControl + PS	7	399.0	413.5	7.0	0.018	0.002	0.267
Intercept + avCatch + devYear + L_{max}	7	398.9	413.3	6.8	0.013	0.023	0.262
Intercept + devYear + L_{max}	6	408.4	420.8	14.3	0.011	0.004	0.277
Intercept + avCatch + devYear	6	399.8	412.1	5.6	0.016	0.020	0.262
Intercept + avCatch + L_{max}	6	400.3	412.6	6.1	0.011	0.024	0.263
Intercept	4	410.7	418.8	12.3	0.013	0.003	0.277
(b) SD(target C/Q)							
CControl + PS + avCatch + devYear + L_{max}	10	848.9	869.8	2.1	0.079	0.476	1.477
CControl + PS + devYear + L_{max}	9	861.2	879.9	12.2	0.122	0.289	1.546
CControl + PS + avCatch + devYear	9	848.9	867.7	0.0	0.079	0.467	1.472
CControl + PS + avCatch + L_{max}	9	850.8	869.6	1.9	0.052	0.491	1.492

Model (fixed effects) [1]	k	$-2\cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
CControl + PS	7	862.5	876.9	9.2	0.093	0.278	1.550
Intercept + avCatch + devYear + L_{max}	7	861.5	875.9	8.2	0.173	0.548	1.505
Intercept + devYear + L_{max}	6	875.7	888.1	20.4	0.051	0.321	1.639
Intercept + avCatch + devYear	6	861.7	874.1	6.4	0.179	0.514	1.501
Intercept + avCatch + L_{max}	6	864.0	876.4	8.7	0.112	0.559	1.528
Intercept	4	876.9	885.1	17.4	0.042	0.281	1.641
(c) Small overages							
CControl + PS + avCatch + devYear + L_{max}	9	144.3	163.0	3.0	0	0.083	
CControl + PS + devYear + L_{max}	8	150.1	166.6	6.6	0.039	0	
CControl + PS + avCatch + devYear	8	146.1	162.6	2.6	0	0.191	
CControl + PS + avCatch + L_{max}	8	144.4	161.0	1.0	0	0.078	
CControl + PS	6	153.2	165.5	5.5	0.219	0.151	
Intercept + avCatch + devYear + L_{max}	6	149.7	162.1	2.1	0.037	0.021	
Intercept + devYear + L_{max}	5	154.3	164.5	4.5	0.363	0	
Intercept + avCatch + devYear	5	151.9	162.1	2.1	0.066	0.105	
Intercept + avCatch + L_{max}	5	149.8	160.0	0.0	0.068	0.033	
Intercept	3	157.0	163.1	3.1	0.404	0.102	
(d) Large overages							
CControl + PS + avCatch + devYear + L_{max}	9	68.8	87.5	5.4	0	0	
CControl + PS + devYear + L_{max}	8	71.9	88.5	6.4	0	0	
CControl + PS + avCatch + devYear	8	70.8	87.4	5.3	0	0	

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
CControl + PS + avCatch + L_{max}	8	69.9	86.5	4.4	0	0	
CControl + PS	6	75.3	87.7	5.6	0	0	
Intercept + avCatch + devYear + L_{max}	6	71.7	84.1	2.0	0.002	0	
Intercept + devYear + L_{max}	5	75.2	85.4	3.3	0.725	0	
Intercept + avCatch + devYear	5	73.2	83.5	1.4	0.006	0	
Intercept + avCatch + L_{max}	5	71.9	82.1	0.0	0	0	
Intercept	3	77.2	83.3	1.2	0.514	0	

[1] Model covariates are: avCatch, average total catch during 2000–2004 period (log-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program; 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%).

Table S6. Model selection results for mixed-effects model analyses of exploitation rate ratios: (a) mean F/F$_{reference}$; (b) SD(target F/F$_{reference}$); (c) minor over-exploitation; (d) major over-exploitation. Shown are four quantities estimated under maximum likelihood (number of parameters, negative log-likelihood, AIC corrected for small sample sizes, difference in AICc with that of the lowest value across models), and variances of random effects, estimated under restricted maximum likelihood for the two linear models.

Model (fixed effects) [1]	*k*	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
(a) Mean F/F$_{reference}$							
CControl + PS + avCatch + devYear + L_{max}	11	465.3	488.9	5.1	0.055	0.044	0.859
CControl + PS + devYear + L_{max}	10	467.0	488.3	4.5	0.048	0	0.879
CControl + PS + avCatch + devYear	10	465.5	486.9	3.1	0.054	0.041	0.856
CControl + PS + avCatch + L_{max}	10	471.7	493.0	9.2	0.092	0.060	0.868
CControl + PS	8	473.2	490.1	6.3	0.079	0	0.889
Intercept + avCatch + devYear + L_{max}	7	471.3	485.9	2.1	0.089	0.052	0.851
Intercept + devYear + L_{max}	6	472.1	484.6	0.8	0.076	0	0.873
Intercept + avCatch + devYear	6	471.3	483.8	0.0	0.087	0.048	0.847
Intercept + avCatch + L_{max}	6	477.7	490.2	6.4	0.137	0.067	0.863
Intercept	4	478.6	486.9	3.1	0.118	0	0.885
(b) SD(target F/F$_{reference}$)							
CControl + PS + avCatch + devYear + L_{max}	11	410.3	433.9	9.2	0.175	0.094	0.583
CControl + PS + devYear + L_{max}	10	411.1	432.4	7.7	0.173	0.068	0.586

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
CControl + PS + avCatch + devYear	10	411.0	432.3	7.6	0.176	0.106	0.580
CControl + PS + avCatch + L_{max}	10	410.9	432.3	7.6	0.182	0.096	0.580
CControl + PS	8	412.3	429.2	4.5	0.182	0.080	0.580
Intercept + avCatch + devYear + L_{max}	7	413.9	428.6	3.9	0.157	0.112	0.580
Intercept + devYear + L_{max}	6	415.1	427.6	2.9	0.160	0.082	0.585
Intercept + avCatch + devYear	6	414.3	426.8	2.1	0.157	0.122	0.577
Intercept + avCatch + L_{max}	6	415.0	427.5	2.8	0.165	0.117	0.579
Intercept	4	416.5	424.7	0.0	0.169	0.093	0.580
(c) Minor over-exploitation							
CControl + PS + avCatch + devYear + L_{max}	10	194.6	216.0	10.3	0.327	0	
CControl + PS + devYear + L_{max}	9	194.8	213.9	8.2	0.346	0	
CControl + PS + avCatch + devYear	9	195.6	214.7	9.0	0.315	0	
CControl + PS + avCatch + L_{max}	9	196.0	215.1	9.4	0.420	0	
CControl + PS	7	197.6	212.3	6.6	0.441	0	
Intercept + avCatch + devYear + L_{max}	6	196.7	209.2	3.5	0.556	0	
Intercept + devYear + L_{max}	5	196.7	207.1	1.4	0.560	0	
Intercept + avCatch + devYear	5	197.4	207.8	2.1	0.548	0	
Intercept + avCatch + L_{max}	5	198.5	208.8	3.1	0.711	0	
Intercept	3	199.6	205.7	0.0	0.713	0	

Model (fixed effects) [1]	k	$-2\cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
(d) Major over-exploitation							
CControl + PS + avCatch + devYear + L_{max}	10	135.6	157.0	6.4	0.393	0	
CControl + PS + devYear + L_{max}	9	135.8	154.9	4.3	0.392	0	
CControl + PS + avCatch + devYear	9	137.8	156.9	6.3	0.306	0	
CControl + PS + avCatch + L_{max}	9	138.4	157.5	6.9	0.489	0	
CControl + PS	7	141.2	155.9	5.3	0.390	0	
Intercept + avCatch + devYear + L_{max}	6	139.9	152.4	1.8	0.767	0	
Intercept + devYear + L_{max}	5	140.2	150.6	0.0	0.787	0	
Intercept + avCatch + devYear	5	143.0	153.3	2.7	0.674	0	
Intercept + avCatch + L_{max}	5	142.5	152.9	2.3	0.920	0	
Intercept	3	146.5	152.6	2.0	0.814	0	

[1] Model covariates are: avCatch, average total catch during 2000–2004 period (log-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program; 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%).

Table S7. Model selection results for mixed-effects model analyses of biomass ratios: (a) mean $B/B_{reference}$; (b) SD(target $B/B_{reference}$); (c) minor depletion; (d) major depletion. Shown are four quantities estimated under maximum likelihood (number of parameters, negative log-likelihood, AIC corrected for small sample sizes, difference in AICc with that of the lowest value across models), and variances of random effects, estimated under restricted maximum likelihood for the two linear models.

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
(a) Mean $B/B_{reference}$							
CControl + PS + avCatch + devYear + L_{max}	11	473.8	497.2	7.3	0.185	0.064	0.544
CControl + PS + devYear + L_{max}	10	487.4	508.5	18.6	0.345	0.082	0.564
CControl + PS + avCatch + devYear	10	473.9	495.0	5.1	0.183	0.063	0.542
CControl + PS + avCatch + L_{max}	10	485.4	506.5	16.6	0.242	0.063	0.569
CControl + PS	8	498.0	514.7	24.8	0.357	0.083	0.588
Intercept + avCatch + devYear + L_{max}	7	477.5	492.0	2.1	0.157	0.066	0.546
Intercept + devYear + L_{max}	6	493.5	505.9	16.0	0.160	0.085	0.587
Intercept + avCatch + devYear	6	477.5	489.9	0.0	0.157	0.064	0.543
Intercept + avCatch + L_{max}	6	489.5	501.9	12.0	0.224	0.066	0.570
Intercept	4	504.4	512.6	22.7	0.224	0.087	0.606
(b) SD(target $B/B_{reference}$)							
CControl + PS + avCatch + devYear + L_{max}	11	501.4	524.7	8.6	0.025	0.134	0.655
CControl + PS + devYear + L_{max}	10	511.1	532.3	16.2	0.024	0.017	0.709
CControl + PS + avCatch + devYear	10	508.9	530.0	13.9	0.037	0.157	0.669
CControl + PS + avCatch + L_{max}	10	506.4	527.5	11.4	0.042	0.125	0.662

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
CControl + PS	8	524.6	541.3	25.2	0.047	0.040	0.731
Intercept + avCatch + devYear + L_{max}	7	501.5	516.1	0.0	0.013	0.134	0.648
Intercept + devYear + L_{max}	6	511.7	524.1	8.0	0.017	0.014	0.700
Intercept + avCatch + devYear	6	509.3	521.7	5.6	0.021	0.163	0.663
Intercept + avCatch + L_{max}	6	506.7	519.1	3.0	0.032	0.122	0.654
Intercept	4	524.9	533.1	17.0	0.040	0.042	0.719
(c) Minor depletion							
CControl + PS + avCatch + devYear + L_{max}	10	247.1	268.2	9.3	0.502	0.294	
CControl + PS + devYear + L_{max}	9	257.4	276.3	17.4	0.374	0.439	
CControl + PS + avCatch + devYear	9	247.1	266.0	7.1	0.501	0.294	
CControl + PS + avCatch + L_{max}	9	254.1	273.0	14.1	0.771	0.285	
CControl + PS	7	263.9	278.5	19.6	0.648	0.488	
Intercept + avCatch + devYear + L_{max}	6	248.6	261.0	2.1	0.532	0.317	
Intercept + devYear + L_{max}	5	258.8	269.1	10.2	0.385	0.453	
Intercept + avCatch + devYear	5	248.6	258.9	0.0	0.533	0.319	
Intercept + avCatch + L_{max}	5	255.8	266.1	7.2	0.823	0.312	
Intercept	3	265.8	272.0	13.1	0.691	0.526	
(d) Major depletion							
CControl + PS + avCatch + devYear + L_{max}	10	203.8	224.9	8.4	0.300	0.607	
CControl + PS + devYear + L_{max}	9	216.5	235.4	18.9	0.279	0.427	
CControl + PS + avCatch + devYear	9	205.5	224.4	7.9	0.309	0.642	

Model (fixed effects) [1]	k	$-2 \cdot ln(L)$	AICc	ΔAICc	Random effect variances		
					Region	Habitat	Residual
CControl + PS + avCatch + L_{max}	9	219.5	238.5	22.0	0.664	0.461	
CControl + PS	7	232.9	247.5	31.0	0.568	0.326	
Intercept + avCatch + devYear + L_{max}	6	204.3	216.7	0.2	0.272	0.611	
Intercept + devYear + L_{max}	5	216.6	226.9	10.4	0.277	0.428	
Intercept + avCatch + devYear	5	206.2	216.5	0.0	0.309	0.651	
Intercept + avCatch + L_{max}	5	220.0	230.3	13.8	0.650	0.464	
Intercept	3	233.2	239.3	22.8	0.537	0.322	

[1] Model covariates are: avCatch, average total catch during 2000–2004 period (log-transformed); devYear, year of fishery development; L_{max}, maximum length; PS, propensity score for being in a catch share program; 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%).

Figures for Supporting Information

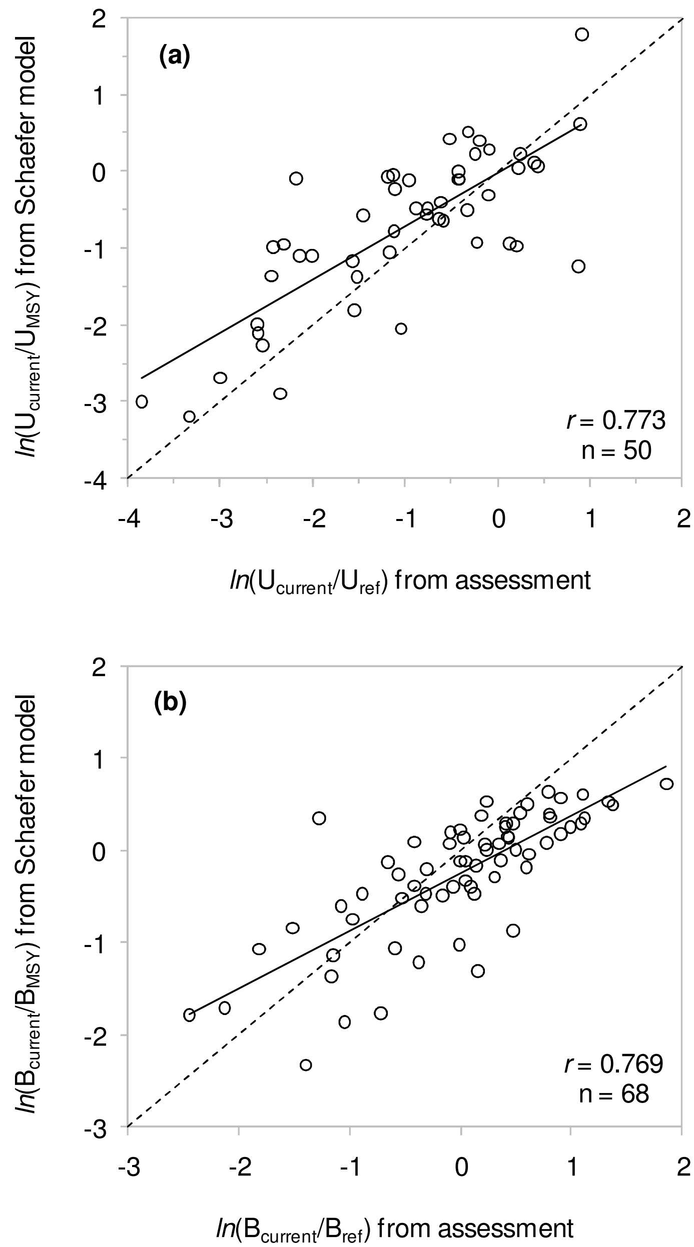


Figure S1. Cross-validations of (a) exploitation rate and (b) biomass reference points estimated with a Schaefer surplus production model to reference points estimated in stock assessments. From Schaefer model fits, estimates of $U_{current}/U_{MSY}$ or $B_{tot,current}/B_{tot,MSY}$ are shown. From assessment model fits, estimates of $U_{current}/U_{reference}$ (or alternatively $F_{current}/F_{reference}$) or $B_{current}/B_{reference}$ are shown for the corresponding stock. Ratios are plotted in log space. Sample size and correlation coefficients are indicated.

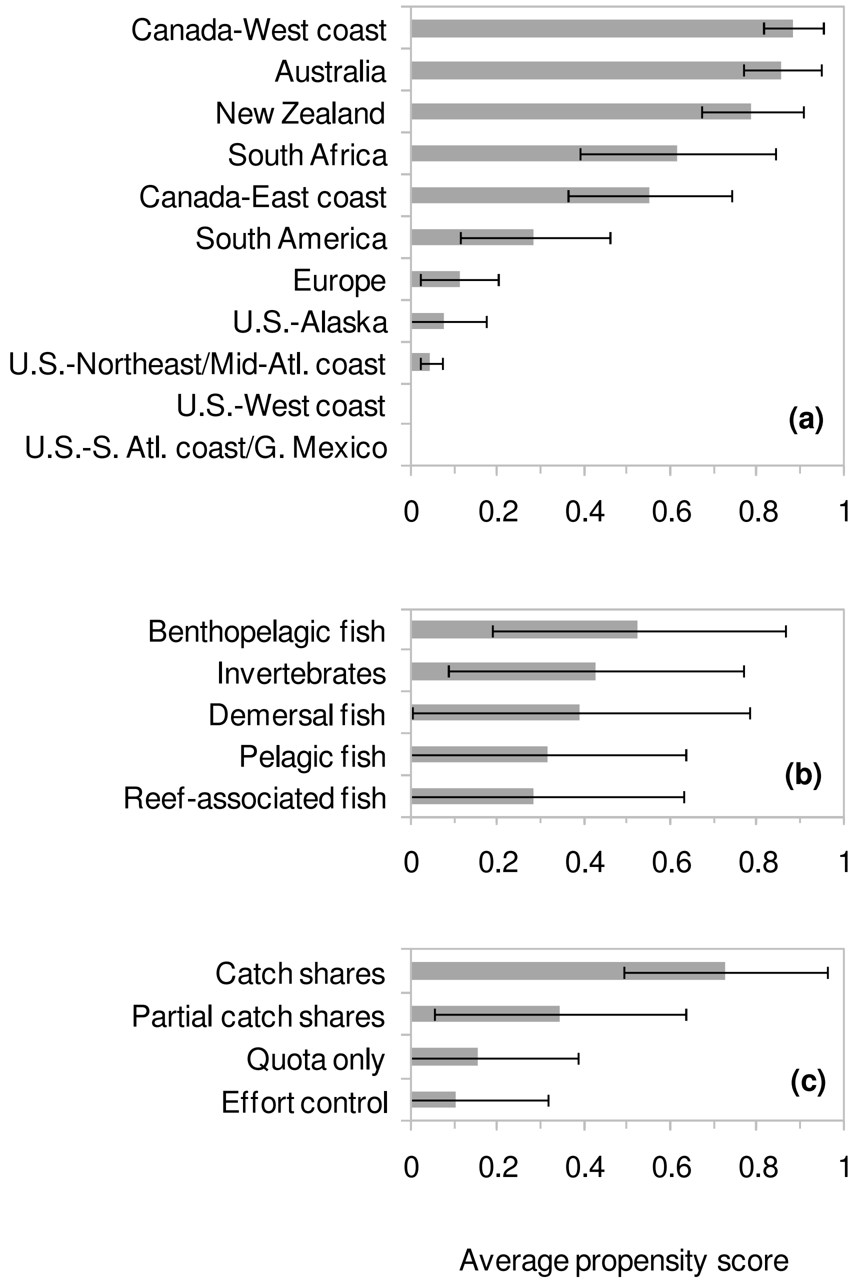


Figure S2. Average propensity score for being in a catch share system in 2000-2004 by (a) region, (b) taxonomic/habitat association, and (c) catch control type. Propensity scores were calculated for each stock and averaged across categories. Error bars show S.D.

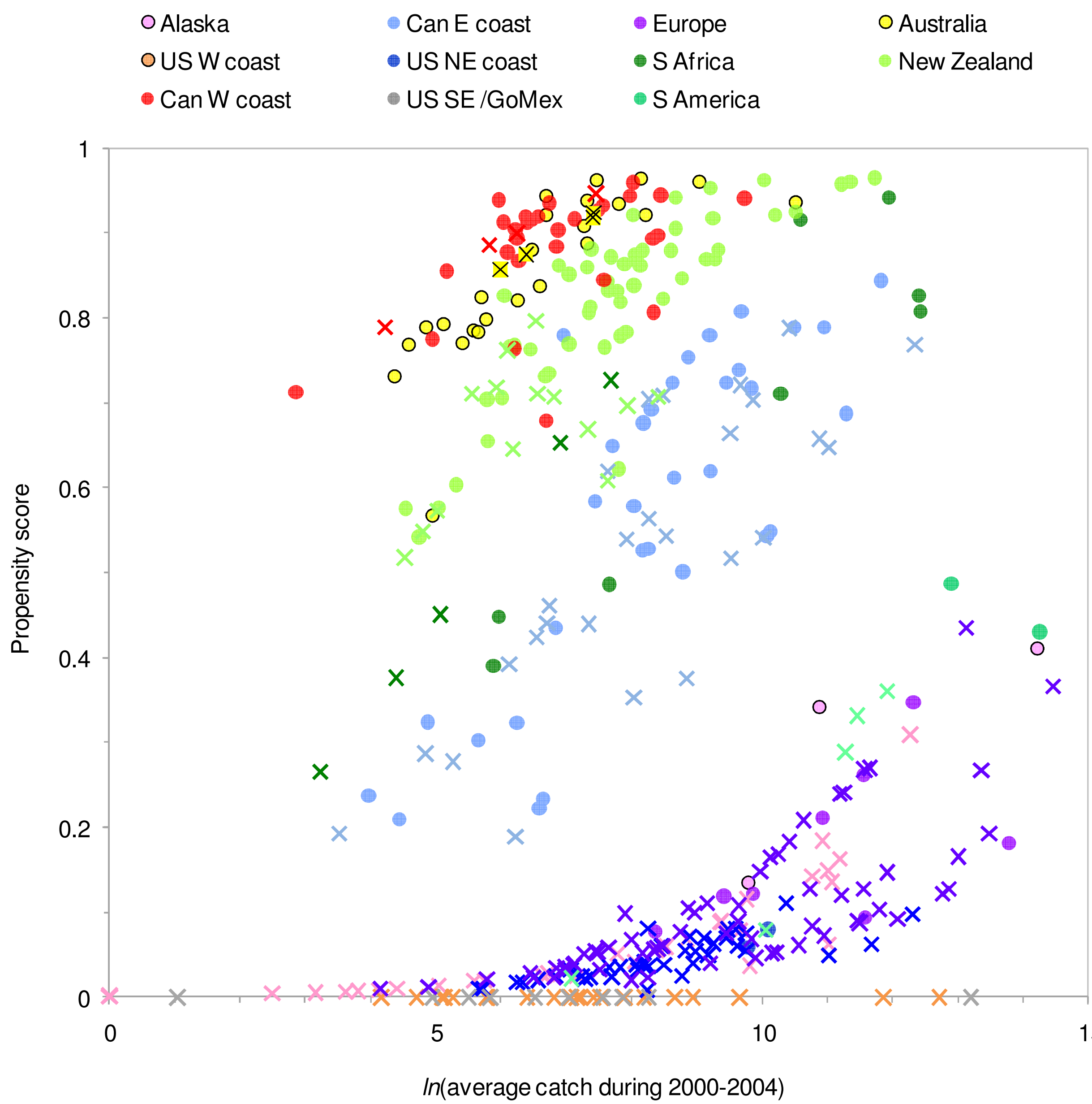
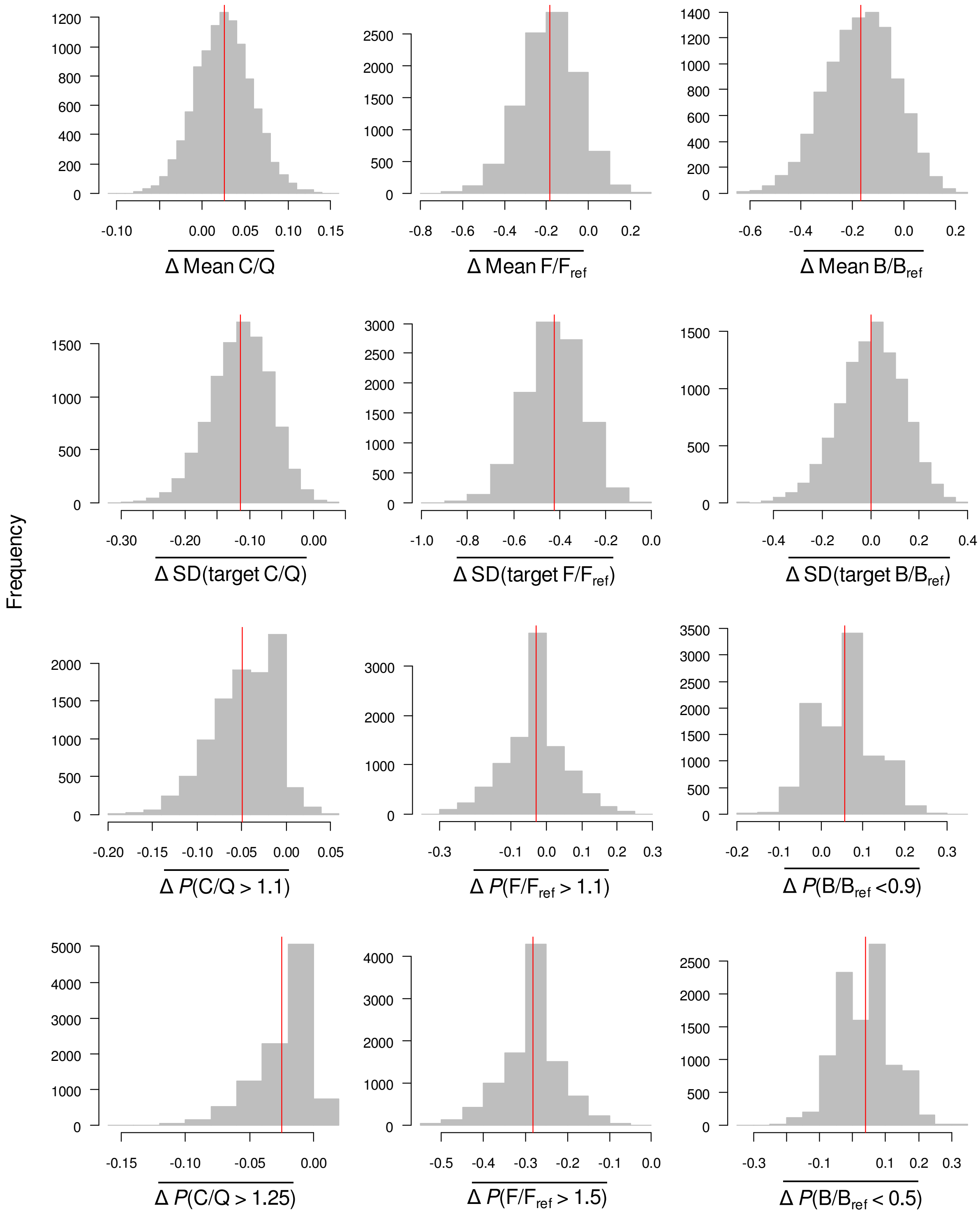


Figure S3. Relationship between propensity score for being in a catch share system in 2000-2004 and average catch during the period. Propensity scores are shown by region. Circles represent stocks under full catch shares (>75% of total catch), while X's represent other stocks (partial catch shares, quota only, or effort-control). Average catch and region were two of the predictor variables involved in the estimation of propensity scores.

Figure S4 (next page). 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. For each of three response variables (catch:quota, current exploitation rate/reference exploitation rate, current biomass/reference biomass) and four metrics (mean response, variation around the management target, proportion of fisheries exceeding two undesirable thresholds), average differences between response variable values (catch share minus non-catch share) are shown ($\overline{\Delta\text{response}}$). For each stock under catch shares, a non-catch share fishery with a PS within 0.05 was randomly selected (only catch share stocks with PS < 0.8 were included), the difference of the response variable was calculated, and the average difference across pairs of stocks was calculated; this was repeated 10,000 times.



Frequency
Δ Mean C/Q
Δ Mean F/F_ref
Δ Mean B/B_ref
Δ SD(target C/Q)
Δ SD(target F/F_ref)
Δ SD(target B/B_ref)
Δ P(C/Q > 1.1)
Δ P(F/F_ref > 1.1)
Δ P(B/B_ref <0.9)
Δ P(C/Q > 1.25)
Δ P(F/F_ref > 1.5)
Δ P(B/B_ref < 0.5)

Figure S4

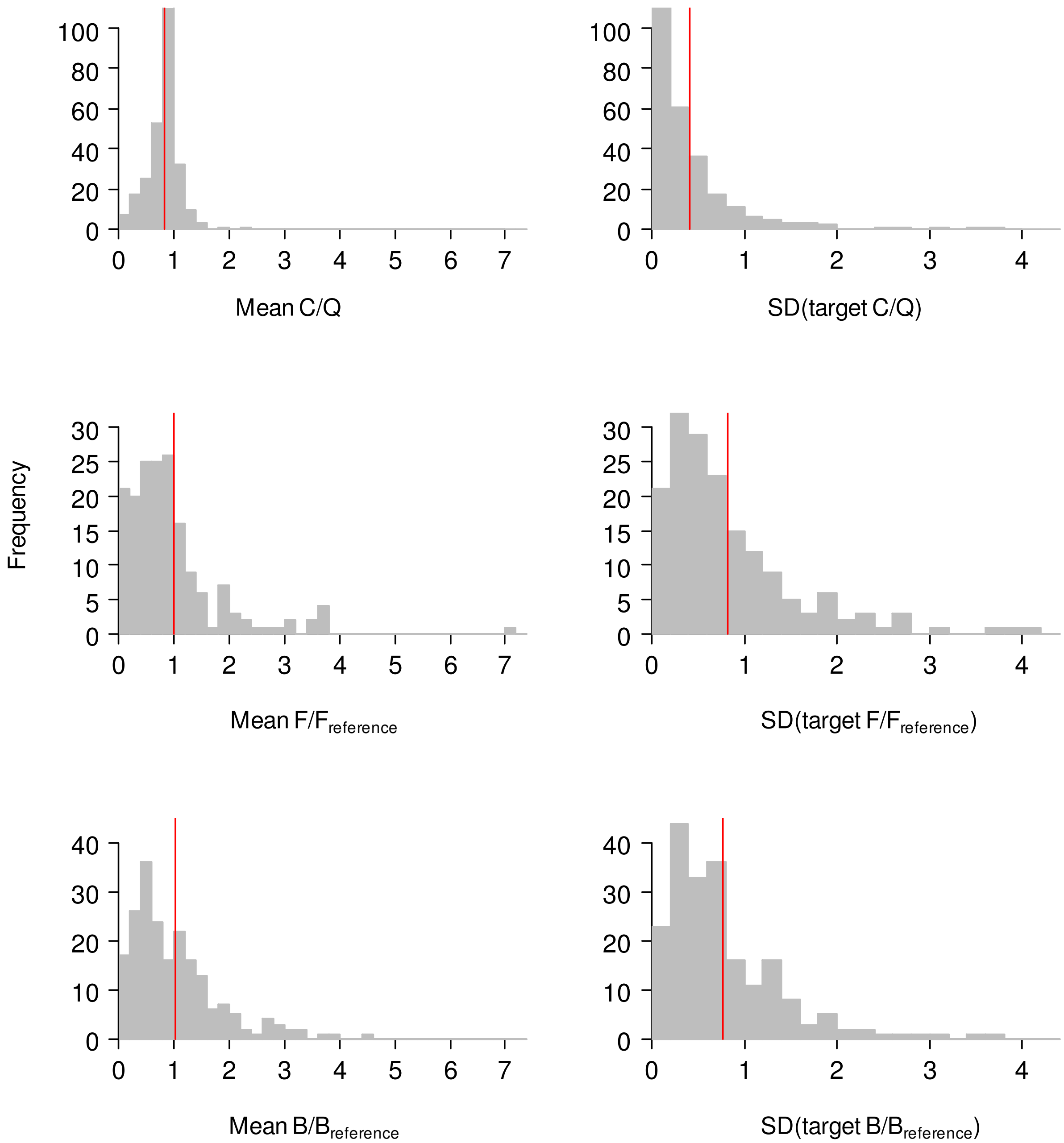


Figure S5. Frequency distributions of catch, exploitation rate, and biomass relative to management targets. Frequencies are shown for the mean response as well as variation around the target. Vertical red lines show the mean of values within each histogram.

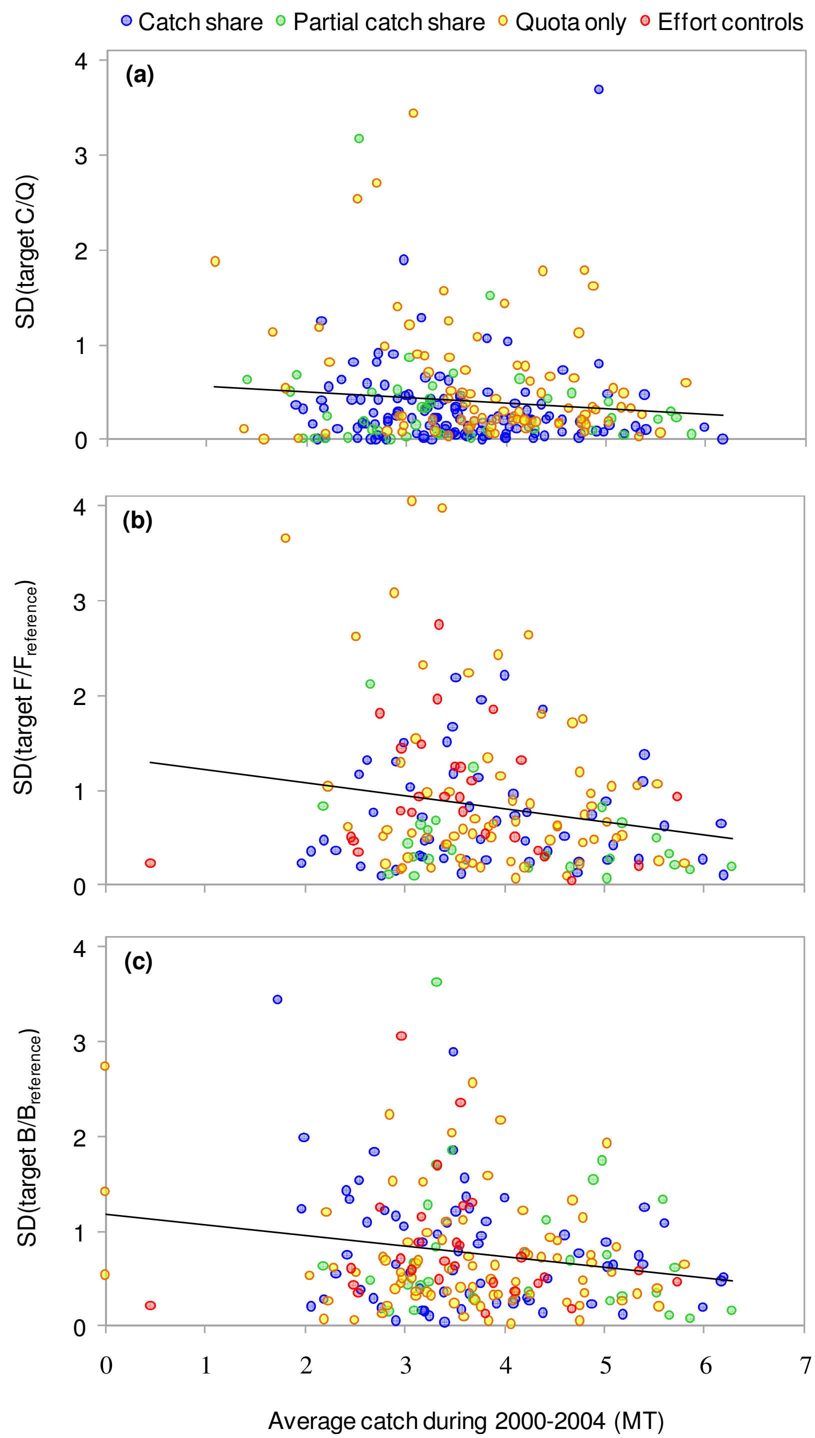


Figure S6. Relationship between the variation around the management target of (a) catch, (b) exploitation rate, or (c) stock biomass and the average catch of the fishery. Standard deviations around the target ratio are calculated for each stock as a sum of squares around the target of 1 during the 2000-2004 period, and are separated by four catch control types. Solid line shows the best fit regression line with all data points pooled. Average catches during 2000-2004 are shown on a log scale.

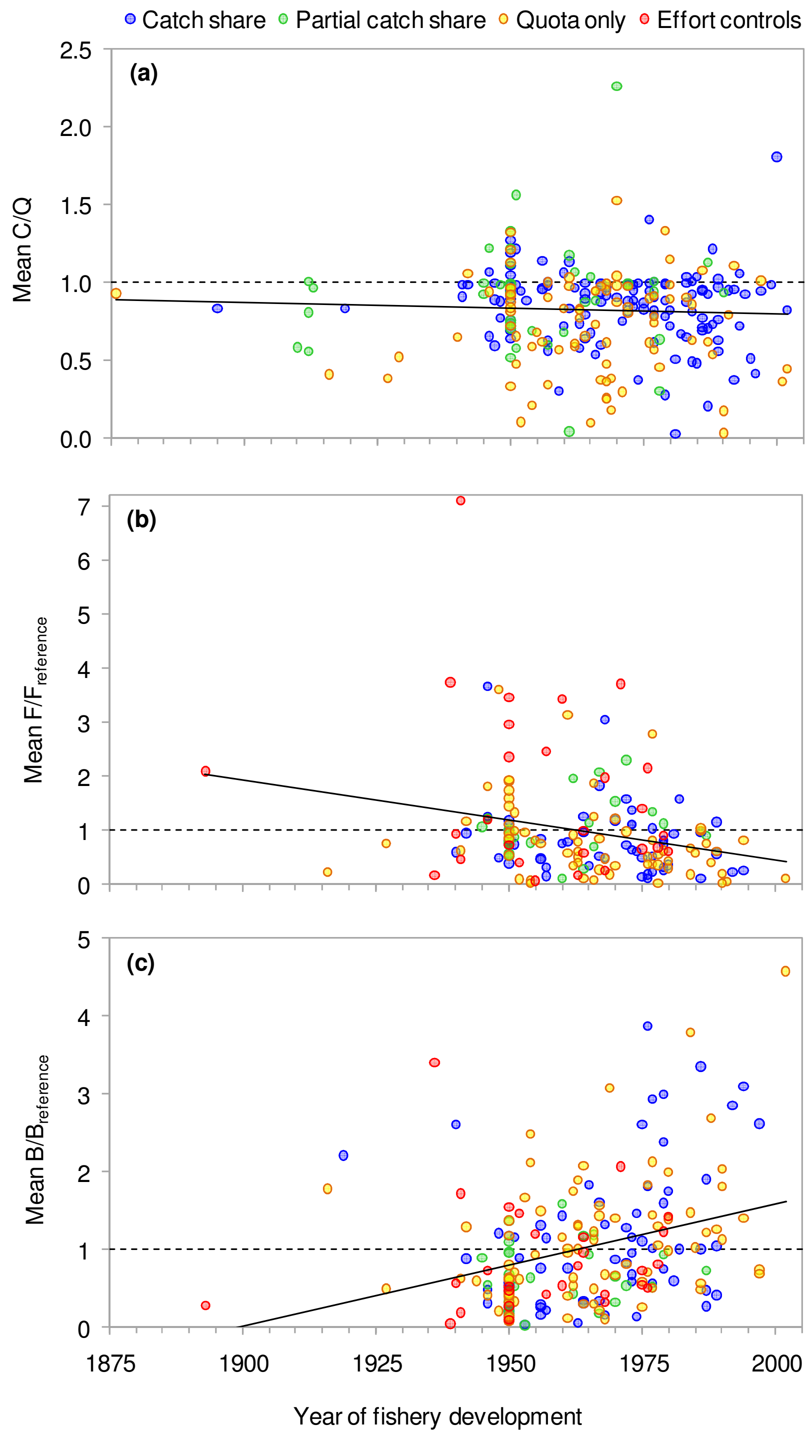


Figure S7. Relationship between recent (a) quota compliance, (b) exploitation rates, or (c) stock biomass and the year the fishery was first developed. Means of ratios during the 2000-2004 period are shown for each stock, separated by four catch control types. Year of development is defined as the first year in which landings reached 25% of the historic maximum landings of the stock. The solid line shows the best fit regression line with all data points pooled, and the dotted line shows the target of 1. Note different axis values in (a-c).

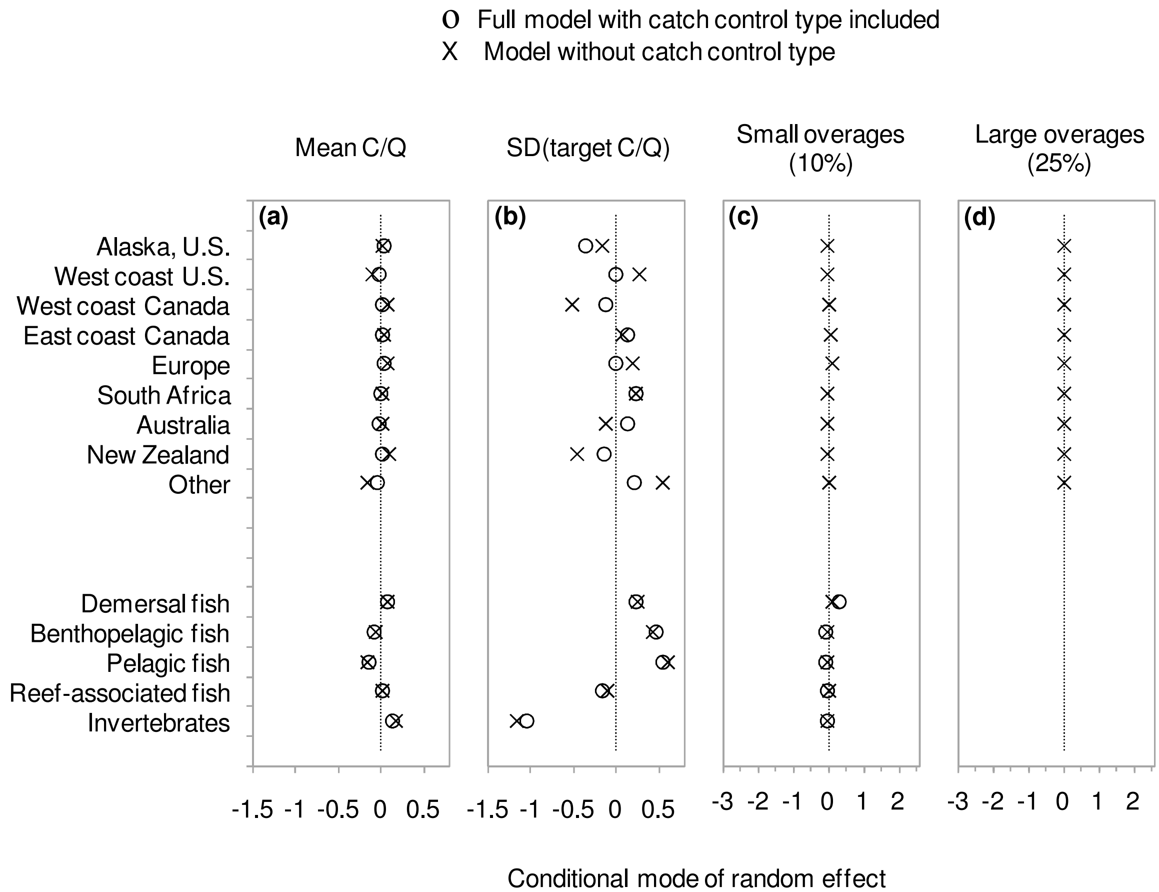


Figure S8. Estimated modes of random effects on catch:quota ratios for (a) mean C/Q, (b) variation around the target ratio, and proportion of fisheries with (c) small or (d) large overages. Estimates were generated under the full model (1st model in Table S5) or the comparable model without propensity score and control type effects (6th model). Missing series of random effect modes for regions (in c,d) and/or habitat associations (in d) indicate that the variance of the random effect was not estimable. Note that x-axis values differ between the 1st/2nd and 3rd/4th panels.

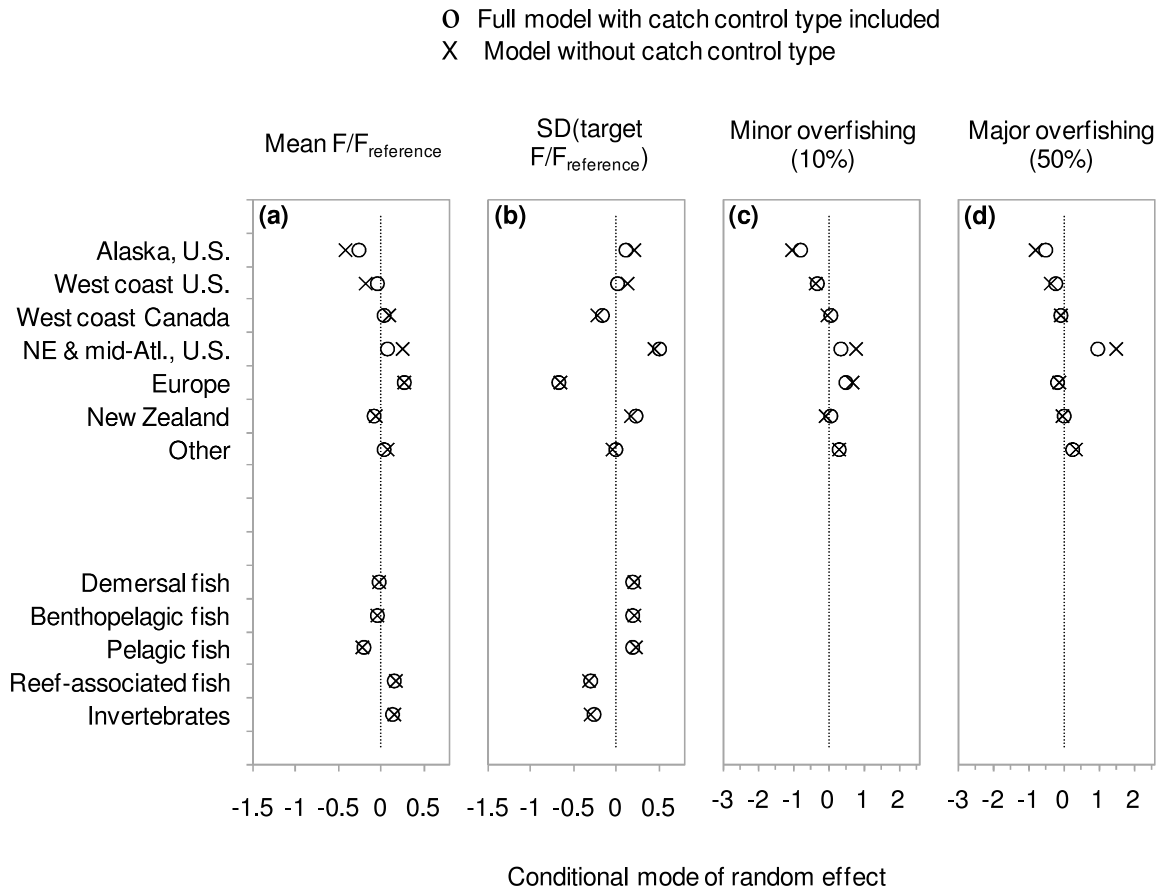


Figure S9. Estimated modes of random effects on current exploitation rate relative to reference exploitation rate for (a) mean F/F$_{\text{reference}}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major overfishing. Estimates were generated under the full model (1st model in Table S6) or the comparable model without propensity score and control type effects (6th model). Note that x-axis values differ between the 1st/2nd and 3rd/4th panels.

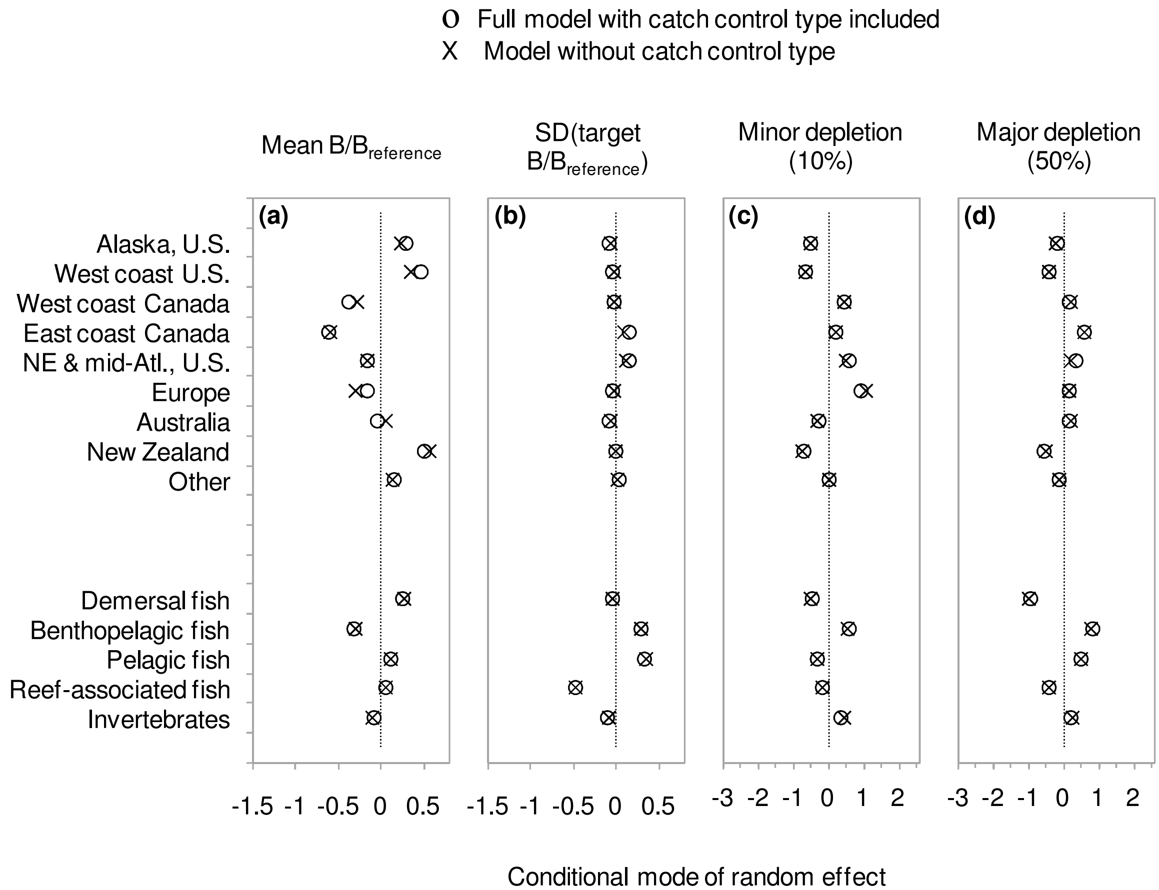


Figure S10. Estimated modes of random effects on current biomass to reference biomass for (a) mean $B/B_{reference}$, (b) variation around the target ratio, and proportion of fisheries with (c) minor or (d) major biomass depletion. Estimates were generated under the full model (1st model in Table S7) or the comparable model without propensity score and control type effects (6th model). Note that x-axis values differ between the 1st/2nd and 3rd/4th panels.