Rev Fish Biol Fisheries (2014) 24:561–575
DOI 10.1007/s11160-013-9307-9

RESEARCH PAPER

The adaptive capacity of fishery management systems for confronting climate change impacts on marine populations

Michael C. Melnychuk · Jeannette A. Banobi · Ray Hilborn

Received: 9 September 2012 / Accepted: 27 February 2013 / Published online: 14 March 2013

Abstract Global climate change will affect the abundance, distribution, and life history timing of many exploited marine populations, but specific changes are difficult to predict. Management systems in which harvest strategies and tactics are flexible in responding to unpredictable biological changes are more likely to succeed in maintaining productive populations. We explore the adaptability of fisheries management systems in relation to oceanic warming rates by asking how two important management characteristics vary with temperature changes for >500 stocks. (1) Harvest control rules, a framework for altering fishing pressure in response to changes in the abundance of targeted species (primarily due to fishing), may provide the capacity for harvest policies to change in response to climate-driven abundance declines also. (2) Seasonal openings with flexible dates that involve in-season monitoring may allow managers to better respond to possible changes in the timing of life-history periods like spawning to prevent fishing seasons falling out of sync with species' phenology. Harvest control rules were widely used across industrialized fisheries including in regions that experienced relatively high oceanic warming rates, but after controlling for regional factors we found no association between ocean warming and the use of harvest control rules. Flexible-date seasonal openings were rare compared to fixed-date seasonal openings, but tended to occur in areas with the greatest warming rates while fisheries without seasonal closures tended to occur in areas with the least observed temperature changes. We found no consistent evidence of recent ocean warming effects on the current biomass or exploitation rates relative to management targets of 241 assessed marine populations. Together, these results suggest that the oceanic areas expected to have the greatest climate impacts on populations do at least tend to contain fisheries that demonstrate the potential for adaptability to unpredictable climate impacts.

Keywords Fisheries management · Climate change · Global warming · Fish biomass · Exploitation rate · Meta-analysis

Electronic supplementary material The online version of this article (doi:10.1007/s11160-013-9307-9) contains supplementary material, which is available to authorized users.

M. C. Melnychuk (✉) · J. A. Banobi · R. Hilborn
School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195-5020, USA
e-mail: mmel@u.washington.edu

Introduction

Uncertainty is pervasive in fisheries science and management. Uncertainty arises through several aspects of management systems, including field sampling, estimating population abundance, determining appropriate catch limits, and implementing those catch limits (Rosenberg and Restrepo 1994). For several decades, considerable effort has been put into developing stock assessment techniques and management strategies that are robust in the face of these uncertainties (Walters 1986; Hilborn and Walters 1992; Walters and Martell 2004). In addition to helping to deal with uncertainties currently faced today, flexibility in management systems is likely to be important for uncertainties that may arise in the future.

Sea surface temperatures in many regions of the world are rising (Stock et al. 2011), and these temperature changes will have uncertain effects on marine populations (Jennings and Brander 2010). Changes in the abundance of stocks are likely (Kell et al. 2005; Cheung et al. 2010; Fulton 2011), acting primarily through changes in recruitment, growth and natural mortality. Shifts in the ranges of species (Drinkwater 2005; Perry et al. 2005; Portner and Knust 2007), in the timing of life history events (Hutchings and Myers 1994; Sims et al. 2004), and in the trophic interactions within ecosystems have also been documented or hypothesized as possible outcomes of a changing ocean climate. Sea surface temperature changes are not uniform in the world's oceans, some areas have been warming faster than others (Hobday and Pecl SI: WFC Hotspots). Even though such changes in marine populations may occur slowly, over decades, it is unknown whether the world's current fisheries management systems will be able to deal adequately with them. The adaptability of some management systems may provide a capacity to confront unpredictable climate-driven impacts on populations. There are many avenues through which management systems may be flexible or adaptable to biological unknowns; two of the more common ways include the use of harvest control rules and use of seasonal closures.

A harvest control rule is a fishery management strategy for altering catches in response to abundance changes of a targeted stock. Typically, fishing pressure on the stock is reduced when the estimated biomass is depleted below some threshold level, usually termed the target biomass reference point, and in some cases targeted fishing stops when biomass is depleted below a lower threshold termed the limit reference point (e.g., Restrepo et al. 1998; Mace 2001). Such depletions are commonly caused by fishing but may also be due to environmental changes. Although harvest control rules rarely if ever explicitly consider consequences of climate change, they nevertheless represent the capacity for harvest policies to change in response to species changes in abundance, even if those changes are induced by climate factors.

Another example of flexibility in management systems is a seasonal opening to a fishery that uses flexible dates from year to year. In-season monitoring may occur in order to determine an optimal time to open the fishery, either to increase the value of the catch or to protect target or non-target species during sensitive times such as spawning. If seasonal opening or closure dates are instead the same year after year and no monitoring for the timing of species life history events occurs, then possible shifts in species phenology resulting from climate change may not be detected for several years as fishing seasons fall out of sync with phenology (Loher 2011).

In this paper, we explore the adaptability of current fisheries management systems in relation to oceanic warming rates. We focus on management attributes that may respond to biological changes, even though we recognize that climate change may also affect the social and economic dimensions of fisheries and also require adaptability in management systems. Specifically, we ask whether two aspects of management—use of harvest control rules and use of seasonal closures—vary in relation to recent sea surface temperature changes around the world. We present rates of sea surface temperature change for >550 fish and shellfish stocks from around the world and assess the associations between temperature warming rates and the use of harvest control rules and seasonal closures for these stocks. We do not suggest a directional hypothesis for these associations, but rather explore whether the management systems currently in place in rapidly-warming areas tend to be relatively flexible or relatively inflexible, as flexible approaches are expected to better cope with potential biological impacts of warming. Finally, we ask whether the current status of stocks (in terms of biomass and exploitation rates relative to management targets) varies with respect to recent temperature changes.

Methods

Stock-specific sea surface temperature changes

A world map of sea surface temperature changes between 1950 and 2005 at a 1° × 1° cell resolution, as described in an earlier paper in this issue (Hobday and Pecl SI: WFC Hotspots), was used as the basis for stock-specific temperature changes. A linear grayscale from black to white represented mean temperature changes from −1 to 2.5 °C. Outlines were overlaid onto 25 'warming hotspot' areas: the highest 10 % of all temperature change values in oceanic cells had lines drawn around the clusters of cells, and any clusters smaller than 5 × 5 cells (i.e., 5° × 5°) were removed (Hobday and Pecl SI: WFC Hotspots). We refer to this as the base map (Fig. 1).

For each of 551 stocks we found a reference map of the stock's distribution, which was either shown in a stock assessment report or compiled from online species mapping programs and specified jurisdictional boundaries of the stock. Using the scientific image processing program *ImageJ* (Schneider et al. 2012), we drew by hand an outline of the stock's distribution onto a magnified portion of the base map. All oceanic cells within this stock distribution outline were selected automatically in *ImageJ*, and a histogram of the grayscale values of contained cells was constructed (black outlines of warming hotspots were removed while tracing stock outlines). The mean grayscale value was calculated, and this was converted to a mean sea surface temperature change value for the stock's area ('mean ΔSST'). A second measure of sea surface temperature change was also considered for analyses, which was the proportion of a stock's area of distribution that overlapped with one or more hotspot areas on the base map ('% in hotspots'). To calculate this value, the number of cells that overlapped with any hotspot area was divided by the total number of cells in the stock's area of distribution. There were 35 stocks whose area of distribution had >50 % overlap with one or more hotspot areas, listed in Table S1 in the Electronic Supplementary Materials section.

Stock-specific management characteristics

Two main management characteristics were considered which relate to the capacity of management systems to alter specific practices in response to observed population changes. First, we identified the type of harvest control rule used for each stock. A hard harvest control rule was defined as there being some limit of estimated biomass below which targeted exploitation for the stock would cease (implying that a biomass limit reference point is estimated in stock assessments). A soft harvest control was defined as there being some circumstance under which a rebuilding or recovery program would be implemented for the stock if deemed necessary (this criterion was purposefully vague, as it varies across regions). A third category consisted of no harvest control rule. The second management characteristic involved the type

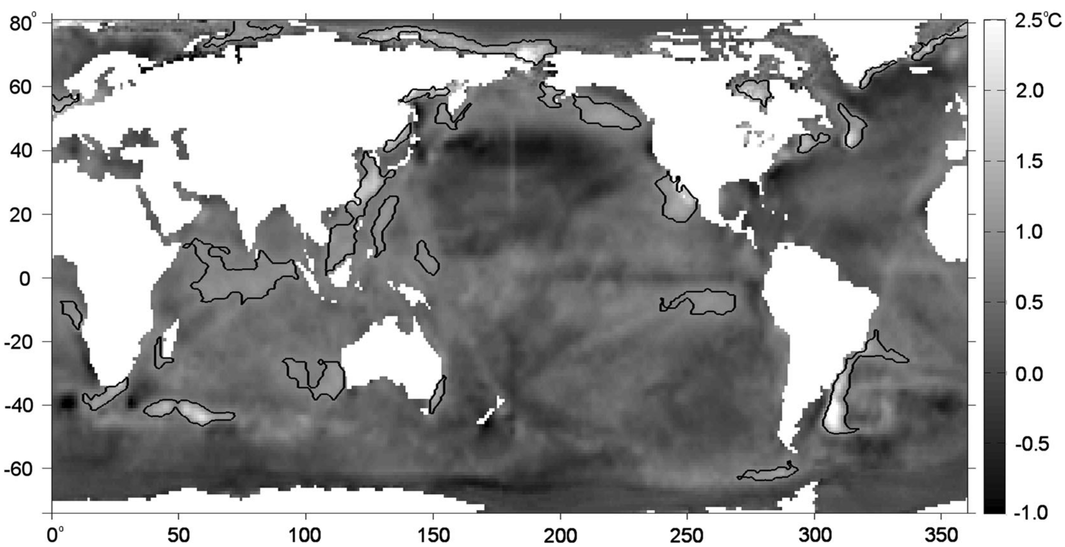

Fig. 1 Change in average sea surface temperature from 1950 to 2005. Temperature changes are shown for 1° × 1° cells. Outlines of 'warming hotspots' are shown, representing areas with the greatest rates of warming. Figure provided by A. Hobday, based on Hobday and Pecl SI: WFC Hotspots

of seasonal closures employed for the stock. Seasonal closures were considered to be either a short closure period within a main fishing season or the portion of the year closed to targeted fishing, but an end to the fishing season resulting simply from reaching the annual quota cap was not considered to be a seasonal closure. Categories were flexible-date closures, fixed-date closures, and no seasonal closures. Flexible-date closures imply that the opening and/or closing dates of the fishing season are not fixed year-to-year, and typically involve within-season monitoring to determine an appropriate date for opening the fishery.

To determine the harvest control rule and seasonal closure types for each stock, we reviewed stock assessment reports or fishery management plans, and conducted e-mail interviews with regional experts. Of the 551 targeted stocks with distribution area maps available and included in our analysis, harvest control rule and seasonal closure categorical designations were available for 540 and 437 stocks, respectively (Table 1).

Stock-specific current status

To represent current stock status, we examined ratios of biomass (B) and exploitation rate (F) relative to management targets. Management targets are often based on quantities that in the long run are expected to produce maximum sustainable yield (MSY), e.g., B_{MSY}, or a more conservative proxy for this quantity, e.g., $B_{40\%}$. We extracted time series and reference point information for B and F from the RAM Legacy Stock Assessment Database (Ricard et al. 2012), a publicly-available database in which outputs from stock assessment reports are compiled. Occasionally more than one reference point commonly assumed as a management target was available (e.g., B_{MSY} as well as $B_{40\%}$). Whatever was the explicitly stated management target for B and F is what we assumed for the denominator of B_{current}:B_{target} or F_{current}:F_{target}. Occasionally time series estimates were available but target reference points were not estimated or published. In these cases, a Schaefer (1954) surplus production model was fit to time series data of total catch and total biomass estimates to estimate MSY-based reference points, which were assumed as targets. The estimated ratios of B:B_{MSY} and F:F_{MSY} from a Schaefer model are a reasonable approximation to estimated ratios from age-structured models typically used in stock assessments (Worm et al. 2009; Melnychuk et al. 2012). We calculated the log-geometric mean of B_{current}:B_{target} or F_{current}:F_{target} ratios over the most recent 5 years of the available time series for each stock to represent current status. Ratios of biomass

Table 1 Number of stocks included in analyses from each of 11 regions

Region	N stocks with SST change data	N stocks with HCR data	N stocks with seasonal closure data	N stocks with B:B_{target} and/or F:F_{target} data
US Alaska	50	50	50	32
US W Coast	48	48	48	36
US NE/mid-Atlantic Coast	52	52	52	36
US SE Coast/Gulf Mexico	32	32	32	13
Canada W Coast	46	46	46	19
Canada E Coast	78	73	63	16
Europe	123	123	25	41
ICES areas I-VII, XIV, Baltic	(103)	(103)	(23)	(37)
ICES areas VIII-XII	(20)	(20)	(2)	(4)
Australia	49	49	49	15
New Zealand	61	55	60	25
Argentina	6	6	6	6
South Africa	6	6	6	5
Total	551	540	437	244

The 2nd–4th data columns are subsets of the first and/or exploitation rate estimates were available for 244 stocks (Table 1).

Data analyses

We related current management attributes for a stock to each of the two measures of warming rates from 1950 to 2005 experienced by the stock (mean change in sea surface temperature, and the proportion of a stock's distributional area that overlaps with hotspot areas). We assume that temperature changes over this period reflect current warming rates (Hobday and Pecl SI: WFC Hotspots). We assess overall patterns as well as regional patterns, as substantial differences in stock status and management characteristics generally occur across regions (Worm et al. 2009; Essington et al. 2012; Melnychuk et al. 2012). To aid visual presentation, we separated the two continuous temperature-related variables into three categories each. Low, medium, and high sea surface temperature change groups corresponded approximately to the 0–20th, 20–80th, and 80–100th percentiles of the distribution of 'mean ΔSST' from 1950 to 2005 for each stock. As the distribution of proportion of overlap between stock areas and hotspot areas was highly skewed, categories of low, medium, and high '% in hotspot' corresponded instead to 0–1 %, 1–20 %, and 20–100 %.

We compared the distribution of temperature-related variables among categories of management-related variables. The distribution of 'mean ΔSST' was near-normal, so we used a simple ANOVA to compare groups of harvest control rule types or seasonal closure types. The distribution of '% in hotspot' was highly skewed with many zeros, so we used a quasi-binomial generalized linear model (suitable for overdispersed proportions) to compare groups. We accounted for regional effects when assessing whether the type of harvest control rule used depended on temperature change variables, and accounted for taxonomic/habitat-association effects when assessing whether seasonal closure type depended on temperature change variables. We used the 'ordinal' package (version 2012.01-19; Christensen 2012) in R (version 2.14.1; R Development Core Team 2012) to perform mixed-effects ordinal regression, treating either region or taxonomic/habitat association as a random effect. Harvest control rule type was ordered as hard > soft > none, while seasonal closure type was ordered as flexible > fixed > none. Finally, we assessed the influence of temperature-related variables on current stock status using generalized linear mixed effects models with a log-link for the response variable ratios, treating region as a random effect.

We limited our analysis to targeted stocks, excluding stocks of no commercial value or ones typically only caught as bycatch in fisheries targeting other species. We focused our study on stocks for which management systems could be readily characterized or for which stock assessments were available. This resulted in the majority of included stocks being from regions of the world with industrialized fisheries and developed management systems.

Results

Sea surface temperature change in area of stock distribution

At a 1° × 1° cell resolution, average sea surface temperature changes in the world's oceans between 1950 and 2005 ranged from −0.94 to 2.44 °C (Fig. 1; Hobday and Pecl SI: WFC Hotspots). Areas of greatest warming, i.e., 'hotspots', occurred mostly along continental margins and across a wide range of latitudes (Fig. 1). Many of the identified hotspot areas overlapped with distributions of several fish or shellfish stocks for which fishery data were available, most notably the Eastern Bering Sea, Gulf of Alaska, Northeast Canada, Northeast US, the North Sea, Southeast Australia and South Africa.

Of the 551 stocks analyzed, mean temperature changes between 1950 and 2005 ranged from −0.79 to 1.33 °C (Fig. 2a). The 20th and 80th percentiles of the distribution of 'mean ΔSST' corresponded approximately to 0 °C and 0.75 °C. These were used to delineate categories of low (<0 °C), medium (0–0.75 °C) and high (>0.75 °C) temperature change categories for subsequent plotting. The area of distribution for 383 of the 551 stocks had <1 % overlap with any warming hotspot area (Fig. 2b). The remaining stocks had a wide range of overlap with hotspots: 86 stocks had between 1 and 20 % overlap, while 82 stocks had between 20 and 100 % overlap (the 35 stocks whose area of distribution had >50 % overlap with hotspots are listed in Table S1). These thresholds of 1 and 20 % were used to delineate categories of low, medium, and high proportions of stock area within hotspot areas (Fig. 2b).

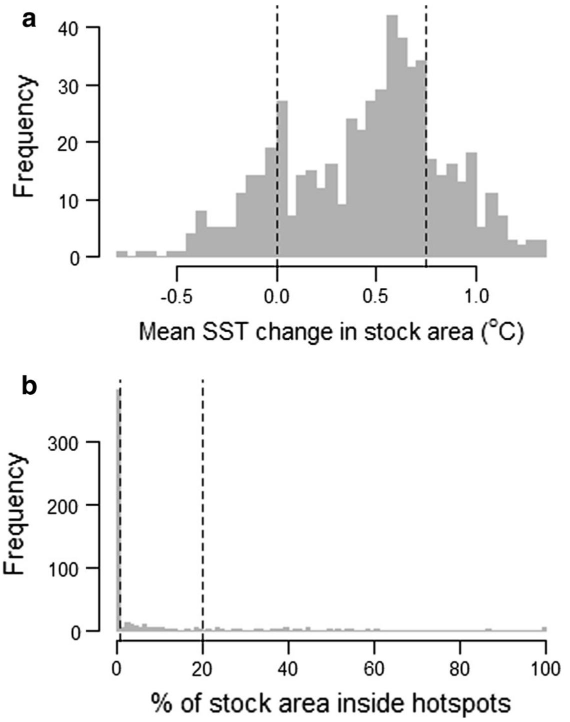

Fig. 2 Frequency distributions of: **a** mean sea surface temperature change from 1950 to 2005 within a stock's area of distribution; and **b** the proportion of a stock's area of distribution overlapping with warming hotspot areas. *Vertical dashed lines* show thresholds for categorical binning: **a** <0 °C, 0–0.75 °C, >0.75 °C; **b** 0–1 %; 1–20 %; >20 %

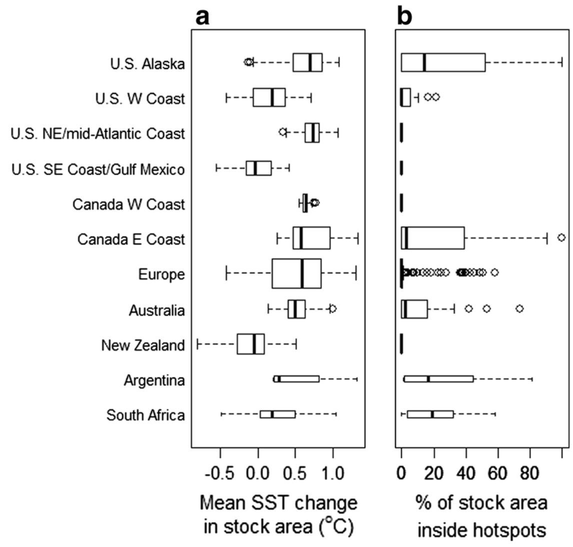

Fig. 3 Boxplots by region of: **a** mean temperature change from 1950 to 2005 within a stock's area of distribution; and **b** the proportion of a stock's area of distribution overlapping with warming hotspot areas. *Box* extremities and thick *vertical lines* denote 25th, 50th, and 75th percentiles

Regional differences were apparent in the average rate of temperature change experienced by assessed stocks. On average, stocks from the US Northeast Coast, Alaska, Eastern Canada, Europe, and Western Canada experienced relatively high temperature changes between 1950 and 2005, while stocks from New Zealand, the US Southeast Coast/Gulf of Mexico, and the US West Coast experienced little change in average temperature (Fig. 3a). Regions that contained several stocks with a substantial proportion of overlap between areas of distribution and identified hotspots included Alaska, East Coast Canada, Europe, Australia, Argentina, and South Africa (Fig. 3b).

Use of harvest control rules in relation to temperature change

There was little association between the overall use of harvest control rules and 'mean ΔSST' in stock distributional areas. Stocks managed with a hard harvest control rule, i.e., in which targeted fishing ceases when estimated biomass falls below an estimated limit reference point, had a grand mean temperature change of 0.43 °C (5th and 95th percentiles: −0.17, 1.00 °C; Fig. 4a). Stocks managed with a soft harvest control rule, i.e., in which circumstances exist that would call for a rebuilding plan to be enacted (0.49 °C; 5th and 95th percentiles: −0.28, 1.07 °C; Fig. 4b) and those managed without harvest control rules (0.41 °C; 5th and 95th percentiles: −0.31, 1.09 °C; Fig. 4c) had similar mean temperature changes (1-way ANOVA, $F_{2,537} = 2.23$, $p = 0.11$).

There was a stronger association between the overall use of harvest control rules and the second temperature variable, '% in hotspots'. Stocks managed with a hard harvest control rule had a grand mean of 12.3 % of their area that overlapped with hotspots; 45.5 % of these stocks had >1 % overlap (Fig. 4d). Stocks managed with a soft harvest control rule (grand mean 7.2 % overlap; 20.7 % of stocks with >1 % overlap; Fig. 4e) and those managed without a harvest control rule (grand mean 5.7 % overlap; 24.8 % of stocks with >1 % overlap; Fig. 4f) had a lower proportion of their area that overlapped with hotspots (quasi-binomial GLM, Wald test for differences with the hard harvest control rule group: $t_{\text{soft HCR}} = -2.53$, $p = 0.012$; $t_{\text{no HCR}} = -2.65$, $p = 0.008$).

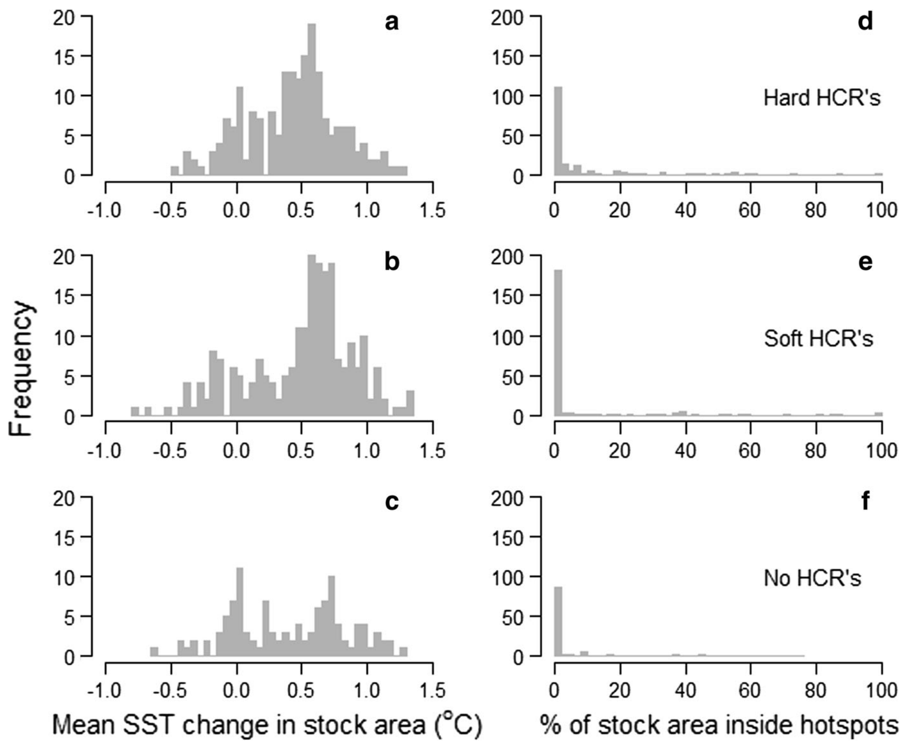

Fig. 4 Frequency distributions of mean temperature change from 1950 to 2005 within a stock's area of distribution (**a**–**c**) and the proportion of a stock's area of distribution overlapping with warming hotspot areas (**d**–**f**), separated by categories of hard, soft, and no harvest control rules

The use of harvest control rules and their association with temperature change variables varied considerably among regions. Hard harvest control rules were commonly used for managing stocks in Alaska, the US West Coast, Australia, and Eastern Canada, and these tended to be in areas with medium or high 'mean ΔSST' between 1950 and 2005 (Fig. 5a, b). Soft harvest control rules were commonly used for stocks in the Eastern US, Western and Eastern Canada, and Europe. Several other European stocks were managed without harvest control rules, and these tended to occur in areas of medium or high 'mean ΔSST' (Fig. 5a, b). Similarly, the majority of stocks whose areas of distribution had a medium or high '% in hotspots' were managed with hard harvest control rules (Fig. 5d, e), although several stocks in Europe in these high overlap categories were managed with soft or with no harvest control rules. Accounting for regional variation, there was no observed association between the use of harvest control rules and temperature change variables. With an ordered categorical response variable of hard > soft > no harvest control rules, and region treated as a random effect, there were no observed effects of 'mean ΔSST' ($\beta_{\text{mean }\Delta\text{SST}} = -0.38 \pm 0.28$ S.E., $z = 1.37$, $p = 0.17$) or '% in hotspots' ($\beta_{\%\ \text{overlap}} = 0.002 \pm 0.005$, $z = 0.40$, $p = 0.69$).

Seasonal openings and closures in relation to temperature change

Few stocks (31) were managed with flexible-date seasonal closures (Fig. 6a, d). Those that were had a wide range of 'mean ΔSST' experienced (grand mean 0.40 °C; 5th and 95th percentiles: −0.32, 1.15 °C; Fig. 6a). Stocks managed with fixed-date seasonal closures experienced greater rates of warming (0.56 °C; 5th and 95th percentiles: −0.10, 1.07 °C; ANOVA, $F_{2,370} = 32.0$, $p < 0.001$; post hoc comparison with flexible closure group, $t = 2.32$, $p = 0.02$; Fig. 6b). Those managed without seasonal closures experienced less change in mean temperature

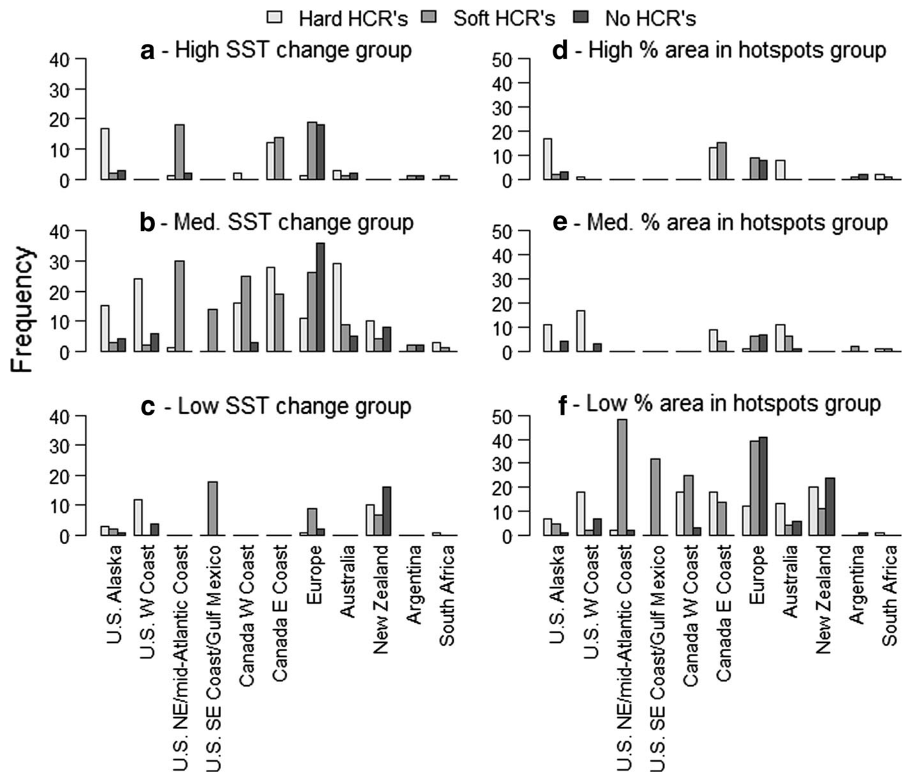

Fig. 5 Frequency barplots by region of stocks managed with hard, soft, or no harvest control rules. *Panels on left* separate categories of stocks whose areas of distributions experienced high (**a**), medium (**b**), or low (**c**) temperature changes between 1950 and 2005. *Panels on right* separate categories of stocks whose areas of distribution share high (**d**), medium (**e**), or low (**f**) proportions of overlap with warming hotspots

(0.25 °C; 5th and 95th percentiles: −0.39, 0.89 °C; post hoc comparison with flexible closure group, $t = -2.12$, $p = 0.035$; Fig. 6c).

There was a weaker association between '% in hotspots' and the type of seasonal closures. Stocks with flexible openings or closures had a grand mean of 7.1 % of their area overlapping with hotspots (Fig. 6d), those with fixed openings or closures had 11.2 % overlap (Fig. 6e), and those managed without flexible closures had 4.8 % overlap overall (Fig. 6f); these differences were not statistically significant (quasibinomial GLM, Wald test, $t_{\text{fixed closures}} = -0.99$, $p = 0.32$; $t_{\text{no closures}} = 0.76$, $p = 0.45$ relative to the flexible closure reference group).

The type of seasonal closure employed varied among taxonomic/habitat-association groups. Flexible closures were relatively more common in small pelagic fish than in other fish or invertebrate groups, particularly for stocks located within areas of greatest warming (Fig. 7a). Stocks in areas with low 'mean ΔSST' were more commonly managed without seasonal closures (Fig. 7c). The second temperature-related variable, '% in hotspots' showed different patterns: flexible closures were most common in stocks with low '% in hotspots' (Fig. 7f). Accounting for the variation among habitat-association groups (as a random effect), there was a strong association between the type of seasonal closures used and both temperature change variables. With ordered categories of flexible > fixed > no closures as the response variable, flexible closures were associated with greater 'mean ΔSST' and greater '% in hotspots', while no seasonal closures were associated with the lowest rates of temperature warming and least overlap between stock areas and hotspot areas ($\beta_{\text{mean ΔSST}} = 1.82 \pm 0.29$ S.E., $z = 6.17$, $p < 0.001$; $\beta_{\text{\% overlap}} = 0.012 \pm 0.005$, $z = 2.3$, $p = 0.021$).

Current stock status in relation to temperature change

There were no consistent relationships across regions between 'mean ΔSST' and either the ratio of current biomass to target biomass (Fig. 8) or the ratio of current exploitation rate to target exploitation rate (Fig. 9). In regions with a relatively large sample size and large range of temperature changes, even a flexible Lowess fit to the data showed little pattern. There was some hint of reduced biomass compared to

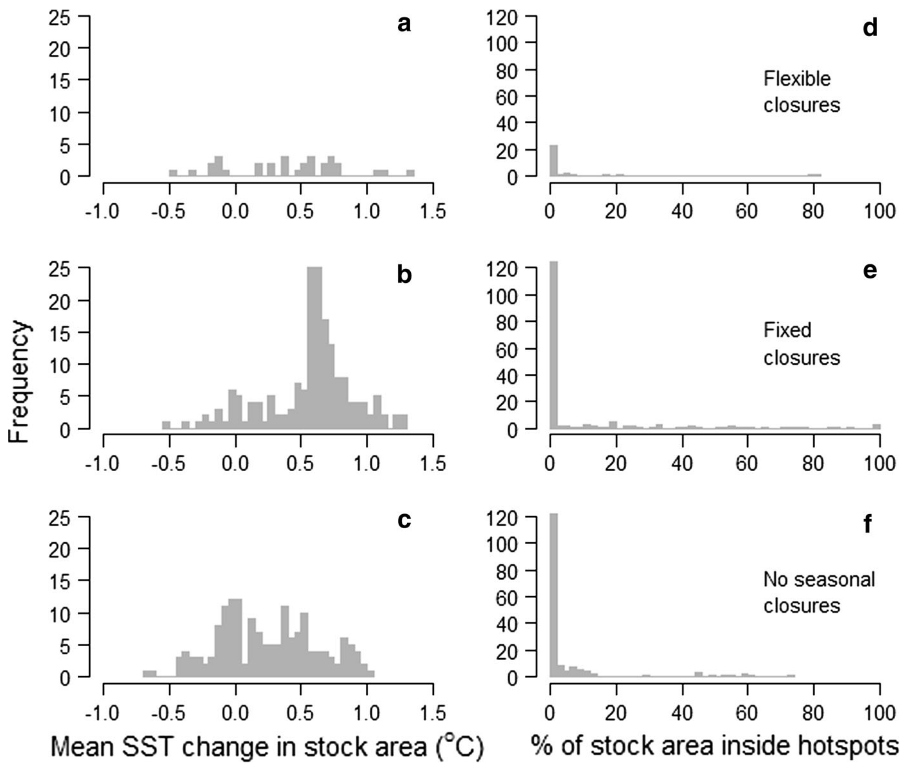

Fig. 6 Frequency distributions of mean temperature change from 1950 to 2005 within a stock's area of distribution (**a**–**c**) and the proportion of a stock's area of distribution overlapping with warming hotspot areas (**d**–**f**), separated by categories of flexible-date, fixed-date, and no seasonal closures

target levels in areas of greatest warming for Australian stocks (Fig. 8), but otherwise no patterns were evident. With region treated as a random effect, generalized linear models showed no effect of 'mean ΔSST' on either current biomass (Wald test, $\beta_{\text{mean }\Delta\text{SST}} = -0.14 \pm 0.14$ S.E., $t = -1.06, p = 0.24$; Fig. 8) or current exploitation rate ($\beta_{\text{mean }\Delta\text{SST}} = -0.06 \pm 0.29$, $t = 0.22$, $p = 0.43$; Fig. 9) compared to target levels. Similarly, there was no effect of '% in hotspots' on either biomass ($\beta_{\%\text{ overlap}} = -0.0006 \pm 0.0028$, $t = -0.21$, $p = 0.43$) or exploitation rate ($\beta_{\%\text{ overlap}} = -0.008 \pm 0.009, t = -0.88, p = 0.27$).

Discussion

The dynamics of marine populations will be affected by climate change, and flexibility in fishery management systems will be important for adequately responding to these changes. Population-level changes will likely involve shifts in abundance, distribution, and phenology such as spawning time, but for any given stock particular changes are difficult to predict. The use of harvest control rules and seasonal closures are indicative of management systems that have the capacity to respond to change. That is not to say that hard harvest control rules or flexible-date openings are always optimal, nor that these are the only flexible aspects of management systems; other management tactics may be used instead to effectively limit catch. For example, there are many stocks in New Zealand that are managed without the use of harvest control rules, but the management systems do regulate catch and maintain stocks at productive levels. It could further be argued that such systems provide even more flexibility for managers than hard harvest control rules. Management systems with flexible responses to abundance changes using soft harvest control rules, in place in regions such as Eastern and Western Canada and the US Northeast Coast, could therefore make these regions better prepared than others in fast-warming areas. Other management attributes can also be adapted to respond to possible biological changes in stocks. Flexible boundaries of closed areas (Cheung

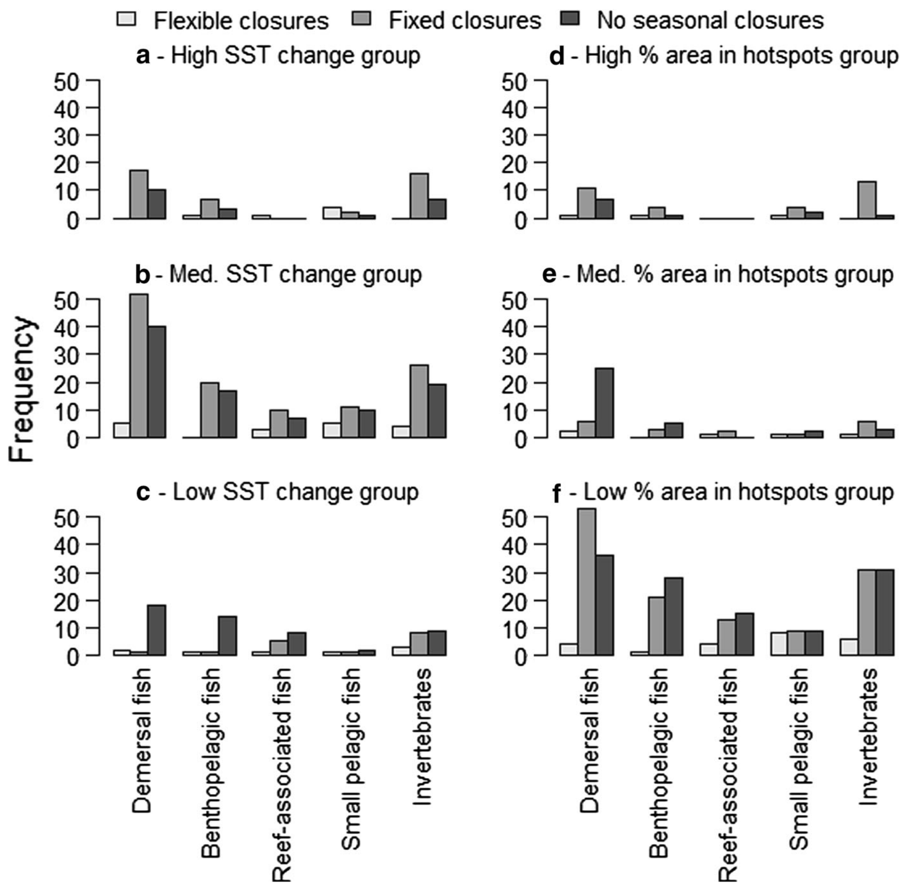

Fig. 7 Frequency barplots by habitat-association category of stocks managed with flexible-date, fixed-date, or no seasonal closures. *Panels on left* separate categories of stocks whose areas of distributions experienced high (**a**), medium (**b**), or low (**c**) temperature changes between 1950 and 2005. *Panels on right* separate categories of stocks whose areas of distribution share high (**d**), medium (**e**), or low (**f**) proportions of overlap with warming hotspots

et al. 2012) or area rotations may provide the capacity to respond to shifting stock distributions. Flexible hook and mesh size restrictions to target certain age and size classes may allow response to changing growth schedules. Whatever the strategies and tactics may be that are used to manage a population, flexibility in general is likely to be beneficial for confronting unpredictable climate change impacts.

Harvest control rules are in widespread use for assessed stocks around the world, especially in areas that have experienced the greatest rates of warming or have the greatest proportional overlap with hotspot areas (with several North Sea stocks as the most notable exceptions). We might have confidence that harvest control rules of existing management systems will be able to deal adequately with possible climate-driven abundance declines only if those climate-driven declines are within the range of abundance declines typically observed from fishing. If instead climate-driven declines were of greater magnitude than typical declines from fishing, those would be outside our range of experience with harvest control rules. Studies that have predicted abundance changes resulting from climate change are relatively scarce, as complex pathways are involved between temperature change and population dynamics, making prediction highly uncertain. A global study predicting changes in catch potential under climate change scenarios projected catch declines of up to 50 % in some areas (Cheung et al. 2010). An ecosystem model for the Southeast Australian shelf predicted median biomass declines for some trophic groups including demersal fish and increases for other trophic groups; the declines were of up to approximately 50 % of current

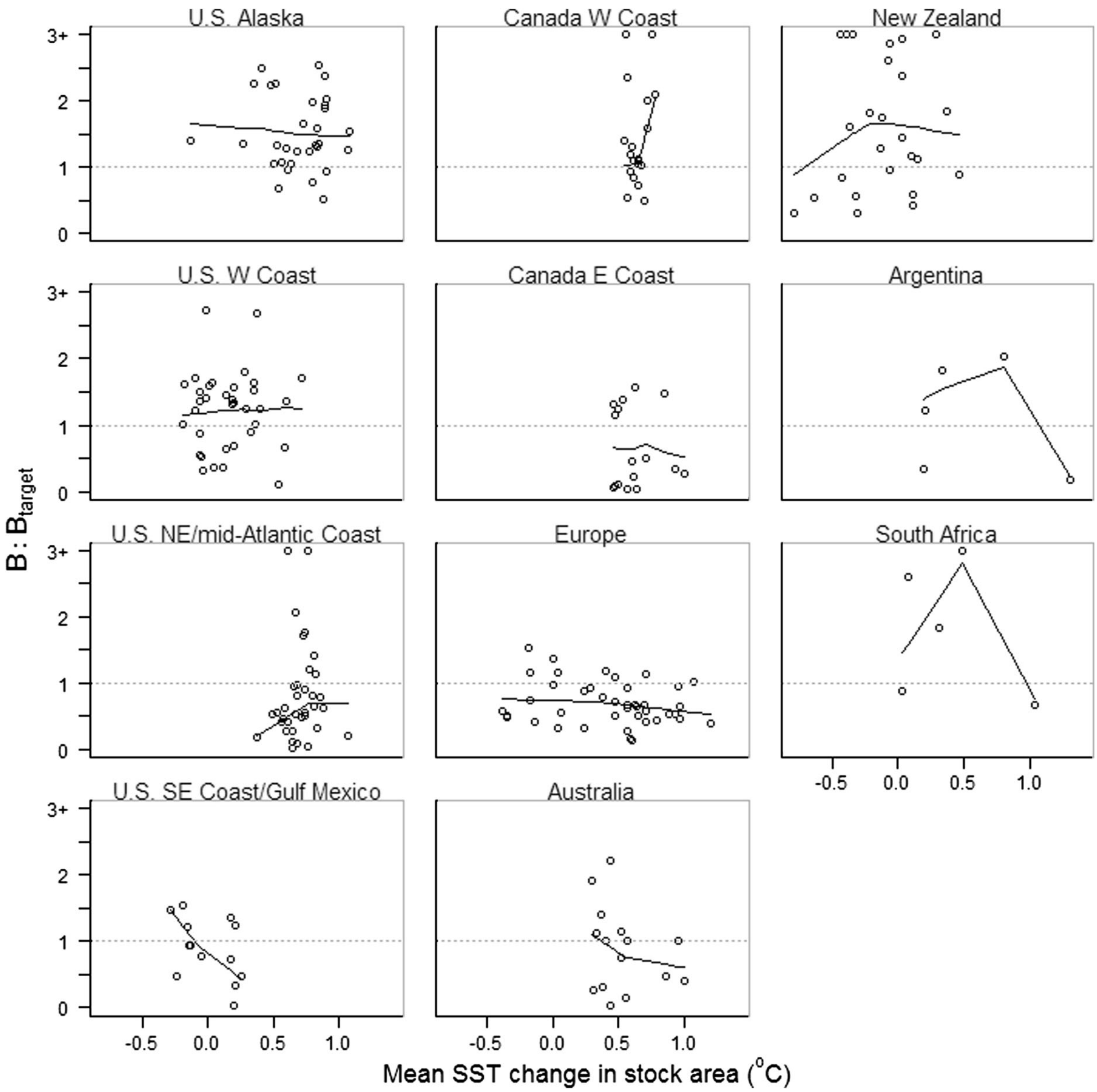

Fig. 8 Ratio of current stock biomass to target biomass in relation to mean temperature change from 1950 to 2005. Stocks are separated by region. Values greater than 3 are shown as 3. *Dotted gray line* shows management target. *Solid black line* shows a Lowess fit for each region with a smoothing parameter value of 1

biomass (Fulton 2011). However, biomass depletions from fishing, of 50 % or more relative to target levels, are also common around the world (Worm et al. 2009), so at the least the predicted climate-driven abundance changes are not outside the range of our experience from overfishing. Once fishing pressure is relaxed, stocks often recover (Worm et al. 2009; Murawski 2010). This suggests that existing harvest control rules will likely be able to deal adequately with climate-driven species changes so long as reduced fishing pressure compensates for climate-driven declines.

Biological reference points like the biomass level and exploitation rate expected to generate long-term maximum sustainable yield (or similarly, a population's carrying capacity and productivity), may change under climate change (Kell et al. 2005). Non-stationarity in production and reference points has long been recognized as a potential pitfall in stock assessment

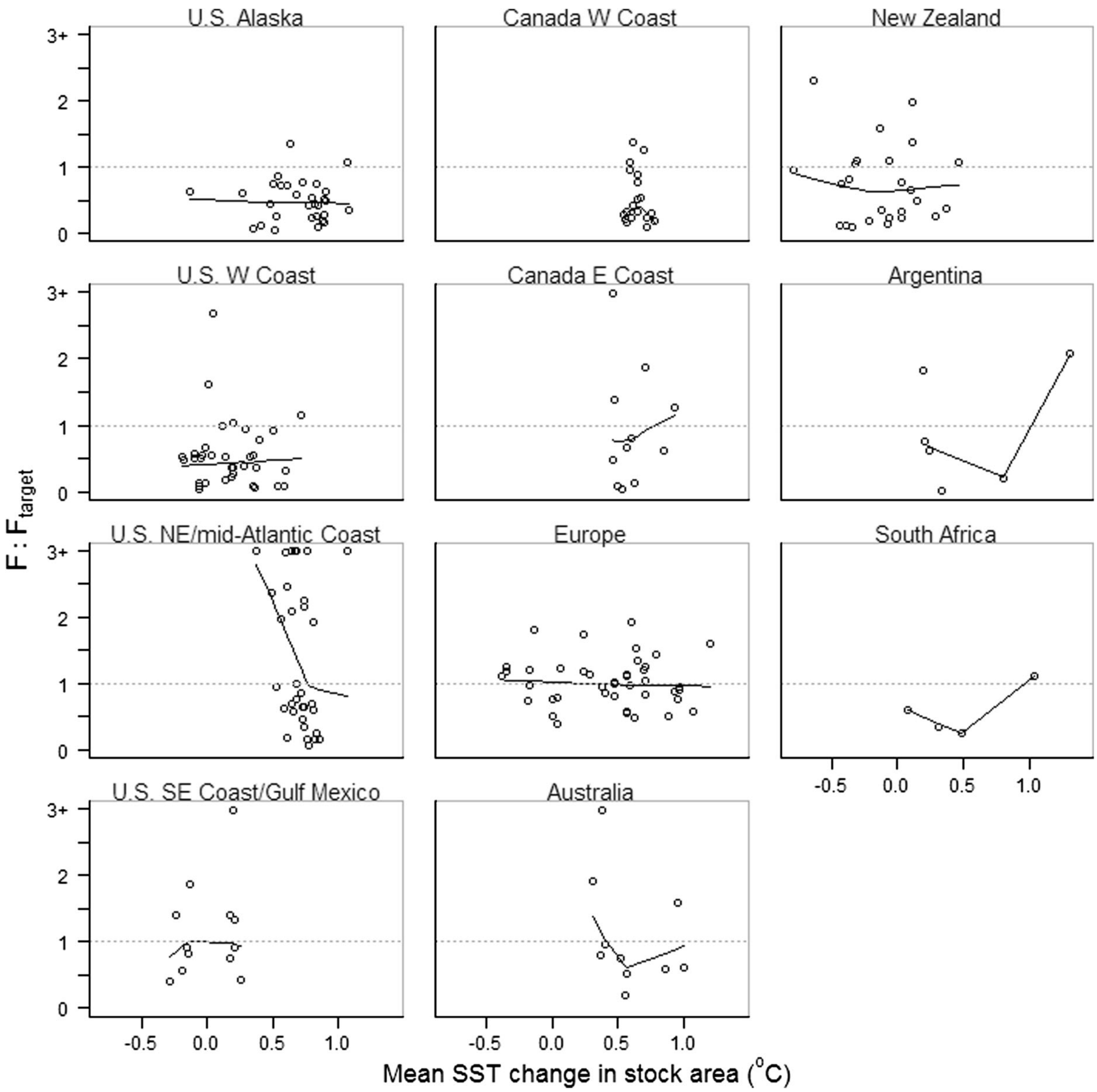

Fig. 9 Ratio of current exploitation rate to target exploitation rate in relation to mean temperature change from 1950 to 2005. Stocks are separated by region. Values greater than 3 are shown as 3. *Dotted gray line* shows management target. *Solid black line* shows a Lowess fit for each region with a smoothing parameter value of 1

(Walters 1987; Walters et al. 2008), and this may become increasingly common under changes in regional climate patterns. Across several regions of the world, multispecies exploitation rate reference points, F_{MMSY}, are expected to decrease by >10 %, with decreases of >20–30 % for some regions (i.e., a predicted decrease in the productivity of exploited populations; Fulton 2011). If reference points do change, it may be difficult to detect changes and to correctly attribute any observed changes to particular causes like climate factors (Punt 2011), as non-stationarity can also arise from other causes. Reference points are often estimated in stock assessments simultaneously with estimating time series of biomass and exploitation rates, so usually there is at least the potential for detecting non-stationarity. Thus, there is also the potential to maintain a stock at its most productive biomass under a given set of environmental conditions, even if that most productive level in the future differs from what it is today. Changes in estimated reference points would then feed into the usage of harvest control rules which are based on those reference points.

Impacts of climate change on exploited populations may be more severe for stocks caught in multi-species fisheries than for stocks caught in single-species fisheries because of bycatch limits. While bycatch may in general lead to overexploiting some stocks (Crowder and Murawski 1998), limits on the bycatch of sensitive stocks may lead to underexploiting some targeted stocks through severe catch constraints (Crowder and Murawski 1998; Hilborn et al. 2012; Melnychuk et al. 2013). Thus, climate-induced abundance declines of a few species may indirectly affect the catch (and therefore landed value and food security potential) of several other species, through bycatch limits in multispecies fisheries. In other words, socioeconomic consequences of climate warming may be greater overall than those directly ascribed to climate-sensitive species. No differences were observed between single and multi-species fisheries in either the mean sea surface temperature change or the proportion of overlap between stock distribution and hotspot areas (data not shown), but multispecies groundfish fisheries predominate in several regions that have experienced high warming rates including the US Northeast Coast and the North Sea. Managers of multi-species fisheries may be faced in years to come with difficult trade-offs of reducing overall fishing pressure to protect weaker stocks or maintaining sustainable harvest of target species, at risk of further depleting sensitive stocks. Efforts to selectively target certain species (Branch and Hilborn 2008) will aid with negotiating this trade-off.

Management systems with flexible opening and closing dates of fishing seasons, typically using some form of in-season monitoring to determine appropriate dates, are more likely to detect shifts in the timing of life history events like spawning that may arise through climate change. Flexible opening dates were relatively more common in small pelagic species like herring, when the value of the catch can vary substantially depending on when roe is harvested. Many groundfish fisheries on the other hand use fixed opening dates year to year; without adequate sampling, phenological shifts in species may go undetected, with closure times becoming increasingly sub-optimal (Loher 2011). Flexible openings were, at least, most common in areas of greatest sea surface warming (or with greater overlap with hotspot areas) after accounting for habitat associations, although a substantial number of demersal fish and invertebrate stocks were managed under fixed-date closures in areas with the greatest warming rates and overlap with hotspot areas. As mentioned previously, flexible openings are not necessarily optimal in all cases. Many successful fisheries do not use any form of temporal closure, as catches are effectively regulated with individual quotas (Turris 2000) or other means, and fishermen may voluntarily avoid fishing during sensitive times like spawning or periods of high bycatch (Griffith 2008) even if such 'closures' are not official.

Marine populations respond to both fishing and environmental factors, and the adaptive capacity of management systems to successfully respond to species changes will be enhanced if scientists can distinguish climate-driven changes from those due to fishing. In terms of harvest control rules, climate-driven changes to the productivity or carrying capacity of a population will affect biological reference points. Thus the ratio of current biomass to reference biomass, for example, will change even if estimated biomass (the numerator) is stationary for several years. Correctly identifying changes in reference points as they occur, whether increasing or decreasing as a result of environmental factors, will aid in maintaining stocks at productive levels. Our study suggests that oceanic temperature changes from 1950 to 2005 have not had a consistent impact on the biomass or exploitation rate of assessed stocks relative to management targets, but further warming within stock distribution areas may result in more apparent changes in population abundances or species ranges. Harvest strategies based on reference points estimated from stocks assessments could benefit from more explicit consideration of climate effects, especially in coming years.

Strong regional differences were observed in mean sea surface temperature changes, the proportion of overlap between stock areas and hotspot areas, the use of harvest control rules, and use of seasonal closures. Observed results were generally consistent between the two metrics of temperature change, but these results should not be generalized to represent management systems outside of industrialized commercial fisheries. In management systems of the developing world, the lack of stock assessments and in-season monitoring programs in many cases limit the use of harvest control rules and seasonal closures, respectively. In these regions other problems of fisheries management are paramount, and climate driven changes may exacerbate these (Sumaila et al. 2011). Biological changes driven by climate are likely to occur for marine populations around the world across a wide variety of fishery management systems and socioeconomic climates, and these will largely be unpredictable. Whatever particular strategies and tactics make up a given fishery management system, flexibility in these attributes will likely be beneficial for confronting possible climate impacts on populations.

Acknowledgments We thank many fishery scientists and managers for proving information about the use of harvest control rules and seasonal closures through interviews, including: Jane DiCosimo, Diana Stram, Mary Furuness, Edward Poulsen, Scott Kelley, Gretchen Bishop, Dave Harris, Tim Sands, Mark Stichert, Joe Stratman, and Jeff Wadle (US Alaska); John Devore, Kerry Griffin, Kristine Barsky, Kelly Corbett, Scott Groth, Bob Hannah, Peter Kalvass, Heather Reed, Bob Sizemore, Mike Ulrich, and Lorna Wargo (US West Coast); Tom Nies, Andy Applegate, Jason Didden, Toni Kerns, Danielle Chesky, Peter Christopher, Phil Haring, Tom Hoff, José Montañez, and Lori Steele (US East Coast); Tamee Karim, Rob Tadey, Dan Clark, Laurie Convey, Michelle James, Lisa Mijacika, Pauline Ridings, Bryan Rusch, Brenda Spence, and Erin Wylie (Canada West Coast); Analia Giussi, Jorge Hansen, and Marta Renzi (Argentina); Doug Butterworth, Carryn de Moor, Susan Halloway, and Rebecca Rademeyer (South Africa). We thank Alistair Hobday for providing the map shown in Fig. 1. We thank two anonymous reviewers for helpful comments. We thank William Cheung for helpful discussions. We thank the Global Marine Hotspots Network for the invitation to participate in the World Fisheries Congress session and this special issue. Funding for this study was provided by a Comparative Analysis Of Marine Ecosystem Organization (CAMEO) grant through the National Science Foundation and NOAA, by the Walton Family Foundation, and by a Banting Fellowship from the Natural Sciences and Engineering Research Council of Canada.

References

Branch TA, Hilborn R (2008) Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. Can J Fish Aquat Sci 65(7):1435–1446. doi:10.1139/f08-065

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob Change Biol 16(1):24–35. doi:10.1111/j.1365-2486.2009.01995.x

Cheung WWL, Pinnegar J, Merino G, Jones MC, Barange M (2012) Review of climate change impacts on marine fisheries in the UK and Ireland. Aquat Conserv Mar Freshw Ecosyst. doi:10.1002/aqc.2248

Christensen RHB (2012) ordinal: regression models for ordinal data. Version 2012.01-19

Crowder LB, Murawski SA (1998) Fisheries bycatch: implications for management. Fisheries 23(6):8–17. doi:10.1577/1548-8446(1998)023<0008:fbifm>2.0.co;2

Drinkwater KF (2005) The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES J Mar Sci 62(7):1327–1337. doi:10.1016/j.icejms.2005.05.015

Essington TE, Melnychuk MC, Branch TA, Heppell SS, Jensen OP, Link JS, Martell SJD, Parma AM, Pope JG, Smith ADM (2012) Catch shares, fisheries, and ecological stewardship: a comparative analysis of resource responses to a rights-based policy instrument. Conserv Lett 5(3):186–195. doi:10.1111/j.1755-263X.2012.00226.x

Fulton EA (2011) Interesting times: winners, losers, and system shifts under climate change around Australia. ICES J Mar Sci 68(6):1329–1342. doi:10.1093/icesjms/fsr032

Griffith DR (2008) The ecological implications of individual fishing quotas and harvest cooperatives. Front Ecol Environ 6(4):191–198. doi:10.1890/050060

Hilborn R, Walters CJ (1992) Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York

Hilborn R, Stewart IJ, Branch TA, Jensen OP (2012) Defining trade-offs among conservation, profitability, and food security in the California current bottom-trawl fishery. Conserv Biol J Soc Conserv Biol 26(2):257–266. doi:10.1111/j.1523-1739.2011.01800.x

Hutchings JA, Myers RA (1994) Timing of cod reproduction: interannual variability and the influence of temperature. Mar Ecol-Prog Ser 108(1–2):21–31. doi:10.3354/meps108021

Jennings S, Brander K (2010) Predicting the effects of climate change on marine communities and the consequences for fisheries. J Mar Syst 79(3–4):418–426. doi:10.1016/j.jmarsys.2008.12.016

Kell LT, Pilling GM, O'Brien CA (2005) Implications of climate change for the management of North Sea cod (*Gadus morhua*). ICES J Mar Sci 62(7):1483–1491. doi:10.1016/j.icesjms.2005.05.006

Loher T (2011) Analysis of match-mismatch between commercial fishing periods and spawning ecology of Pacific halibut (*Hippoglossus stenolepis*), based on winter surveys and behavioural data from electronic archival tags. ICES J Mar Sci 68(10):2240–2251. doi:10.1093/icesjms/fsr152

Mace PM (2001) A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish Fish 2(1):2–32. doi:10.1046/j.1467-2979.2001.00033.x

Melnychuk MC, Banobi JA, Hilborn R (2013) Effects of management tactics on meeting conservation objectives for western North American groundfish fisheries. PLoS ONE 8(2):e56684. doi:10.1371/journal.pone.0056684

Melnychuk MC, Essington TE, Branch TA, Heppell SS, Jensen OP, Link JS, Martell SJD, Parma AM, Pope JG, Smith ADM (2012) Can catch share fisheries better track

management targets? Fish Fish 13(3):267–290. doi:10.1111/j.1467-2979.2011.00429.x
Murawski SA (2010) Rebuilding depleted fish stocks: the good, the bad, and, mostly, the ugly. ICES J Mar Sci J du Conseil 67(9):1830–1840. doi:10.1093/icesjms/fsq125
Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. Science 308(5730):1912–1915. doi:10.1126/science.1111322
Portner HO, Knust R (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315(5808):95–97. doi:10.1126/science.1135471
Punt AE (2011) The impact of climate change on the performance of rebuilding strategies for overfished groundfish species of the U.S. west coast. Fish Res 109(2–3):320–329. doi:10.1016/j.fishres.2011.02.019
R Development Core Team (2012) R: a language and environment for statistical computing, 2.14.1 edn. R Foundation for Statistical Computing, Vienna
Restrepo VR, Thompson GG, Mace PM, Gabriel WL, Low LL, MacCall AD, Methot RD, Powers JE, Taylor BL, Wade PR, Witzig JF (1998) Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson–Stevens Fishery Conservation and Management Act. National Oceanic and Atmospheric Administration (US) Technical Memorandum NMFS-F/SPO-31
Ricard D, Minto C, Jensen OP, Baum JK (2012) Examining the knowledge base and status of commercially exploited marine species with the RAM legacy stock assessment database. Fish Fish 13(4):380–398. doi:10.1111/j.1467-2979.2011.00435.x
Rosenberg AA, Restrepo VR (1994) Uncertainty and risk evaluation in stock assessment advice for U.S. maine fisheries. Can J Fish Aquat Sci 51:2715–2720
Schaefer MB (1954) Some aspects of the dynamics of populations, important for the management of the commercial fisheries. Bull Inter-Am Trop Tuna Comm 1(2):25–56
Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of image analysis. Nat Methods 9:671–675
Sims DW, Wearmouth VJ, Genner MJ, Southward AJ, Hawkins SJ (2004) Low-temperature-driven early spawning migration of a temperate marine fish. J Anim Ecol 73(2): 333–341. doi:10.1111/j.0021-8790.2004.00810.x
Stock CA, Alexander MA, Bond NA, Brander KM, Cheung WWL, Curchitser EN, Delworth TL, Dunne JP, Griffies SM, Haltuch MA, Hare JA, Hollowed AB, Lehodey P, Levin SA, Link JS, Rose KA, Rykaczewski RR, Sarmiento JL, Stouffer RJ, Schwing FB, Vecchi GA, Werner FE (2011) On the use of IPCC-class models to assess the impact of climate on living marine resources. Prog Oceanogr 88(1–4):1–27. doi:10.1016/j.pocean.2010.09.001
Sumaila UR, Cheung WWL, Lam VWY, Pauly D, Herrick S (2011) Climate change impacts on the biophysics and economics of world fisheries. Nat Clim Chang 1(9): 449–456. doi:10.1038/nclimate1301
Turris BR (2000) A comparison of British Columbia's ITQ fisheries for groundfish trawl and sablefish: similar results from programmes with differing objectives, designs and processes. In: Shotton R (ed) Use of property rights in fisheries management. FAO Fisheries Technical Paper 404/1. FishRights 99 Conference, vol 404/1. FAO, Fremantle, pp 254–261
Walters C (1986) Adaptive management of renewable resources. Macmillan Publishing, New York, NY
Walters CJ (1987) Nonstationarity of production relationships in exploited populations. Can J Fish Aquat Sci 44:156–165
Walters CJ, Martell SJD (2004) Fisheries ecology and management. Princeton University Press, Princeton, NJ
Walters CJ, Hilborn R, Christensen V (2008) Surplus production dynamics in declining and recovering fish populations. Can J Fish Aquat Sci 65(11):2536–2551. doi:10.1139/f08-170
Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, Costello C, Fogarty MJ, Fulton EA, Hutchings JA, Jennings S, Jensen OP, Lotze HK, Mace PM, McClanahan TR, Minto C, Palumbi SR, Parma AM, Ricard D, Rosenberg AA, Watson R, Zeller D (2009) Rebuilding global fisheries. Science 325(5940):578–585. doi:10.1126/science.1173146