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Unintended consequences of climate-adaptive fisheries management targets

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Abstract
Climate change is projected to affect the productivity of global fisheries. Management based on maximum sustainable yield (MSY) has been effective at eliminating overfishing in many regions. However, continuing to use yield-maximizing targets under climate-driven changes in productivity can result in higher anthropogenic pressure on populations subject to climate-related stress than maintaining *status quo* management targets. We demonstrate this effect using a theoretical example and case studies from snow crab in the eastern Bering Sea and a global marine fisheries database. In these examples, the conservation gain (i.e. biomass in the ocean) of maintaining *status quo* management targets is larger than the small gain in harvest made through climate adaptation in MSY-based management. The aggregate conservation gain of maintaining management targets increases as the harmful impacts of climate change on productivity worsen. Instead of climate-adaptive MSY-based targets, new management tools are needed to balance conservation and food production in ecosystems of populations displaying non-stationary productivity.

KEYWORDS
climate change, fisheries management targets, maximum sustainable yield

1 | CLIMATE CHANGE AND FISHERIES MANAGEMENT

Harvested living marine resources support ecosystem function, economic development, and food/nutritional security on a global scale. Wild inland and marine capture fisheries produced 96.4 million tonnes of seafood, and fisheries trade had an export value of $164 billion worldwide in 2018 (FAO, 2020). Globally, food from the sea constitutes 17% of the animal protein consumed but can exceed 50% in some areas (FAO, 2020). Marine resources must be sustainably managed so that society can continue to benefit from the ecosystem services they produce. Sustainable harvests of fished species are determined by the productivity of the resource, which is determined by ecological and biological processes such as somatic growth, natural mortality, reproduction, competition, and resource limitation.

Climate change is already influencing the productivity of harvested marine populations. Warming temperatures are influencing the somatic growth rates and the reproductive capacity of fishes (Britten et al., 2016; Huang et al., 2021). Spatial distributions of species are changing, which may have consequences for processes ranging from nutrient cycling to predation and competition (Pinsky et al., 2013). Diseases and infestations will vary as environmental conditions change and stressors mount (Tracy et al., 2019). The increasing intensity of marine heat waves will affect the availability of suitable habitat, and may induce reinforcing cycles of decline, further impacting productivity (Frolicher et al., 2018, Holbrook et al., 2019). Ocean acidification is altering various aspects of the physiology of marine organisms (Fabry et al., 2008). These stressors will act in concert to influence the productivity of many harvested populations, and by extension potential sustainable harvest rates.

Harvested natural resources are often managed using targets for population sizes and harvest rates based on the concept of maximum sustainable yield (MSY; Schaefer, 1957). MSY management targets reflect the productivity of a population, and highly productive populations can be harvested more intensely than populations with lower productivity. The median assessed fishery in the RAM Legacy Stock Assessment Database (RAMLDB) during 1995 was fishing at a level ~25% higher than the exploitation rates that would produce MSY (U_{MSY}); in 2010, the median exploitation rate was ~25% less than U_{MSY} (Hilborn et al., 2020). Europe and the United States saw some of the largest improvements in the status of marine fisheries over this period and their fisheries policies (the Common Fisheries Policy and the Magnuson Stevens Act, respectively) are explicitly based on the MSY paradigm. The stocks in RAMLDB used to calculate changes in exploitation rates represent roughly 50% of global fisheries catch; the status of the other half of global fisheries is likely poorer (Costello et al., 2016) and implementation of management measures including target and limit reference points would likely improve fishery status (Melnychuk et al., 2021).

Many MSY-based management frameworks specify that targets should reflect the productivity determined by current environmental conditions. One such specification in the U.S. Magnuson Stevens Act directs that 'optimum yield' shall be achieved by specifying 'the present and probable future condition of, and the MSY' from a fishery in the United States (MSA, 2007). Consequently, determining the period to serve as a reference for productivity is a central part of the decision-making process in U.S. fisheries management. For example, groundfish stocks reviewed by the North Pacific Fisheries Management Council use recruitment time series from 1977 to the most recent year of reliably estimated recruitment to estimate MSY-proxy reference points. This decision is based on a perceived ecological regime shift in the late 1970s and consistent data availability after this time period (see assessment documents at NOAA Fisheries, 2021).

Given this regulatory background, widespread climate change-induced shifts in productivity may imply that the frames of reference for MSY-based management targets will need to change. Here, we demonstrate counter-intuitive changes to harvest rates resulting from the application of climate-adaptive management targets (i.e. those that 'adapt' to new productivity using only recent data in management targets) compared to holding targets at a *status quo* level. We show this pattern to be consistent using a simulated population, a fished population of snow crab (*Chionoecetes opilio*; Oregoniidae) in the eastern Bering Sea, and a database of output from global fisheries assessments. We conclude with a discussion of the potential solutions to the unintended consequences of climate-adaptive MSY-based management.

2 | CLIMATE-ADAPTIVE MANAGEMENT TARGETS IN SIMULATION

Harvested populations can be modelled with logistic population (or biomass dynamics) models that depend on an intrinsic growth rate, *r*, and a resource-carrying capacity, *K* (Schaefer, 1957). Under the logistic model, populations are most productive and thus can sustain the greatest annual harvest at intermediate levels of biomass. The value of biomass and harvest rate that produce MSY (B_{MSY} and U_{MSY}, respectively) can be derived from these models and incorporated into harvest control rules to calculate allowable harvests (Figure 1). The 'sloped' harvest control rule is one of the most powerful conservation tools at the disposal of managers (Hilborn et al., 2020). It dictates that harvest rates, and hence human impacts, decline from a target harvest rate as the biomass of a resource declines below a threshold. The decline in harvest rate serves both to accelerate the rebuilding of the population to levels thought to maximize long-term yield and to protect the population from declining to low levels.

To demonstrate the impacts of changing management targets, we simulated a harvested resource with a logistic population model for 100 years in which the carrying capacity was halved at year 50 (from K^A to K^B in Figure 1) but the intrinsic rate of growth remained unchanged, reducing the MSY of the resource. A step change in productivity is somewhat dramatic, though not uncommon – tipping points and regime shifts are widely described in the fisheries literature (e.g. Britten et al., 2016; Szuwalski et al., 2015). While there may be other trajectories for productivity change, the choice of a step change illustrates the problem we are describing most clearly.

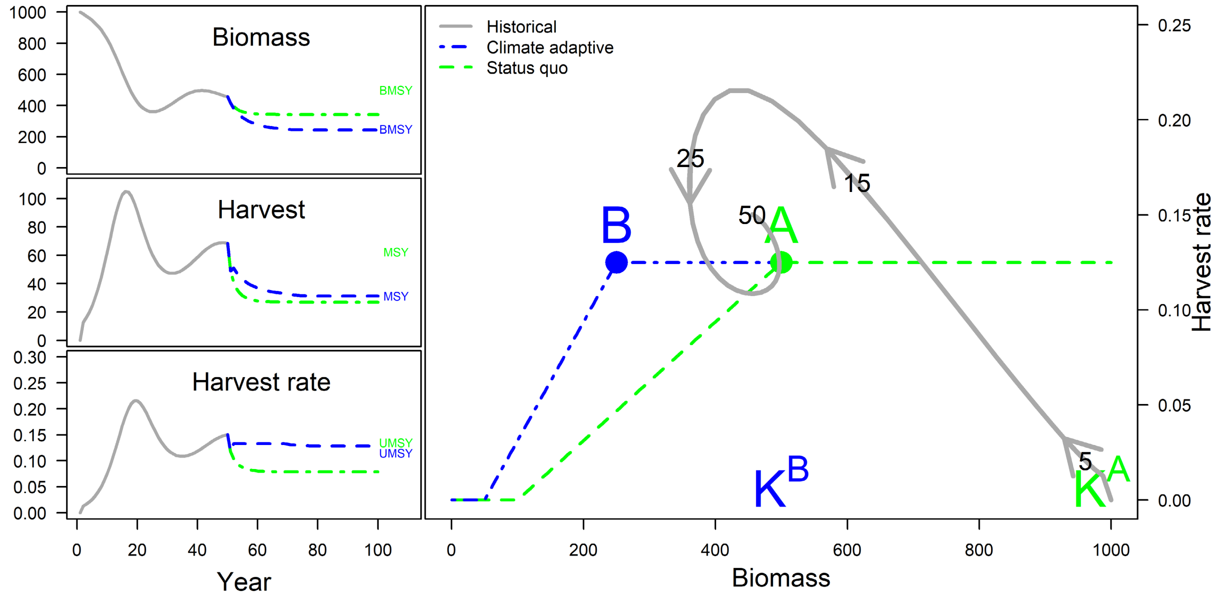

FIGURE 1 Management challenges in a simulated population undergoing changes in productivity. Trajectories of biomass, harvest, and harvest rates (left panels) under adaptive (blue dash) and *status quo* (green dot-dash) management targets. The value of the management targets (B_{MSY}, MSY, and U_{MSY}) for each harvest control rule is noted by the position of the text at the right of each figure. Biomass vs. harvest rate phase space (right panel) maps the population (grey line) through time relative to management targets (numbers correspond to simulation year); during these first 50 years the biomass target was A. In year 50, B_{MSY} changes to B, reflecting an instantaneous decrease in carrying capacity from K^A to K^B. The harvest control rules resulting from either maintaining *status quo* management targets or adapting to climate change specify the harvest rate applied at a given biomass.

The initial trajectory of simulated harvest rates progressed from low levels to rates beyond the management target, and finally declined, returning to near the management target (Figure 1). When a productivity change occurs (the halving of K in year 50), the manager of this population is faced with a decision: should the management targets be maintained at *status quo* levels (point A) or changed to reflect the decrease in productivity (point B)?

We can look at the estimated position of the population relative to the management targets to understand the decision the manager faces. Within the frame of reference of the *status quo* management targets, the year-50 biomass is less than the target biomass set based on K^A. Consequently, the harvest control rule dictates that harvest rates should decrease to allow the resource to rebound (Figure 1). However, if 'climate-adaptive' management targets are used, the year-50 biomass is instead above the new target biomass based on the lower K^B. This, in contrast, implies that harvest rates should be maintained to reduce the population to the new biomass target. If the productivity of a resource decreases and management adjusts to the new productivity regime, harvest rates can increase or be maintained compared to a *status quo* control rule. Conversely, if productivity increases and management adjusts, harvest rates can be lower than those under a *status quo* rule. The differences in the trajectory of the stock are derived from different assumptions about the productivity of the stock, which influence the inferred 'status' of the stock, its position on the harvest control rule, and ultimately the exploitation rates applied. The resulting changes in exploitation rates – increased if productivity decreases, and decreased if productivity increases – are opposite to what one might expect from managers when managing populations experiencing stress or flourishing under new environmental conditions.

The logistic population model oversimplifies reality and is rarely used in management because of its shortcomings. We developed a more realistic population model to explore the impact of climate-adaptive management targets for snow crab in the eastern Bering Sea to compare to the conclusions drawn from the logistic model.

3 | A CASE STUDY FOR THE EASTERN BERING SEA SNOW CRAB

Snow crab have been commercially fished in the eastern Bering Sea since the mid-1970s and the fishery only harvests large males. Snow crab reproductive dynamics appear to be influenced by environmental conditions, particularly sea ice, and through mechanisms quantified by the Arctic Oscillation (Szuwalski, Cheng, et al., 2020; Szuwalski, Jin, et al., 2020). Projections of environmental indices from global climate models coupled with models of historical recruitment (i.e. young crab entering the population) suggest that the recruitment of snow crab will decrease as sea ice disappears from the eastern Bering Sea and the cold pool shrinks (Figure 2). These changes in predicted recruitment affect forecasts for biomass, and in turn, sustainable yield (see 'In depth methods' below for details).

For snow crab, climate-adaptive management targets dictate higher harvest rates than *status quo* rules in response to a decrease in productivity (Figure 2). Yields increase initially as harvest rates are maintained at high levels under the climate-adaptive targets, but eventually decline below the yields achieved under the *status quo* harvest control rule. The projected average catch from 2030 to 2040 is 19% higher under climate-adaptive management targets, but starting in 2050, maintaining *status quo* management targets provides 10% higher yields and leaves 28% more biomass in the ocean.

The influence of a changing climate on snow crab outlined here operated through reproductive dynamics, but climate change may also affect other population processes, such as natural mortality or growth. Changes in recruitment primarily influence the target biomass (Szuwalski & Punt, 2013), but a change in growth or natural mortality would change the both target harvest rate and target biomass (Legault & Palmer, 2016). An increase in natural mortality or a decrease in growth (i.e. declines in productivity) resulted in higher target harvest rates and lower target biomasses under climate-adaptive management for snow crab, increasing the potential harm from adaptation (Figures 3 and 4).

4 | BEYOND THEORY

The problems presented by changing productivity are not simply a theoretical idea that managers may have to grapple with in the future. Decisions to maintain or change reference points under changes in productivity are already occurring. For example, Tanner crab (*Chionoecetes bairdi*; Oredoniidae) in the eastern Bering Sea had management targets redefined in 2013 that allowed higher harvest rates than would have been implemented under the *status quo* (Stockhausen, 2019; part of this was also a result of changing the assessment framework). Jackass morwong (*Nemadactylus macropterus*; Cheilodactylidae) in southeastern Australia underwent a revision of management targets in 2018 after an apparent shift in recruitment, which resulted in higher harvest rates on a stock with a lower maximum production (leading to heated debates; Edgar et al., 2018; Little et al., 2019). The heavily depleted Jack mackerel (*Trachurus murphyi*; Carangidae) stock in the Southwest Pacific has recently come under international management by the South Pacific Regional Fisheries Management Organization (SPRFMO, 2022). Instead of 'adapting' to what appears to be a new regime of lower than average recruitment, managers selected target reference points similar to the status quo defined within this paper to improve the chance of stock rebuilding.

In addition to the specific management decisions above, analyses exist in the literature that evaluate management strategies under both gradual and regime-like shifts in productivity. A'mar et al. (2009) developed full-feedback analyses that simulated

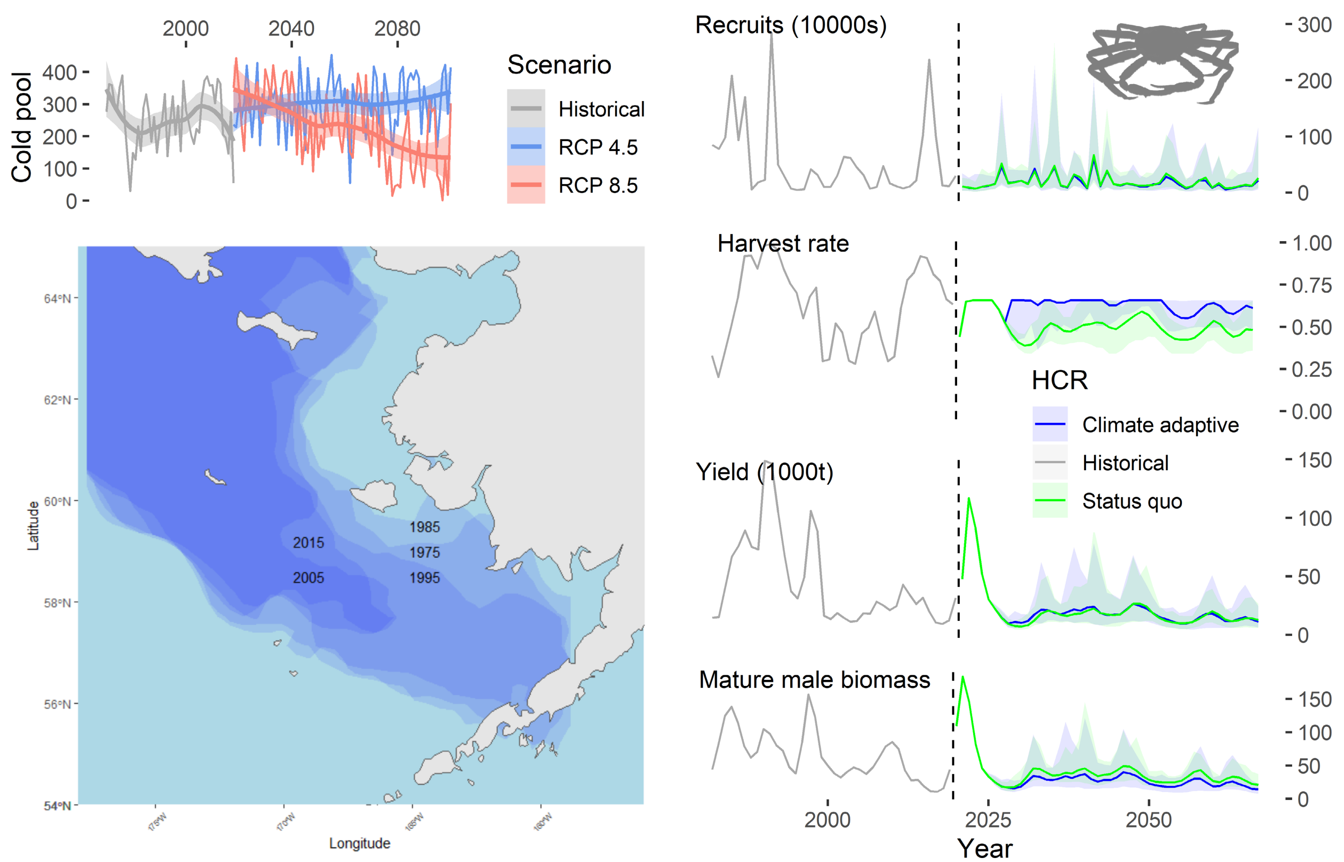

FIGURE 2 Climate-adaptive vs. status quo projections for snow crab in the eastern Bering Sea. Snow crab recruitment (top right) is projected to decrease as the cold pool shrinks in the Bering Sea. The historical cold pool, which is highly correlated with sea ice extent, is at the left bottom. The projected cold pool at the left top in terms of the number of survey stations with bottom temperature below 2 C. Population projections were performed under RCP 8.5.

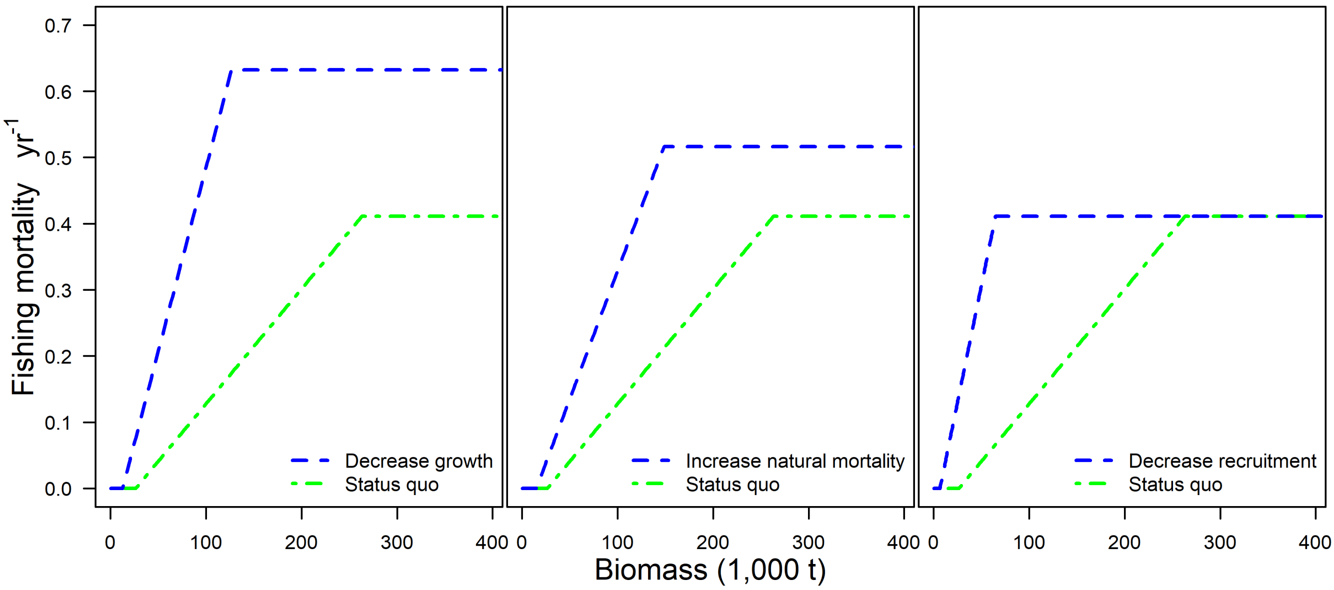

FIGURE 3 Sloped harvest control rules for a population similar to snow crab in the Bering Sea under shifts in natural mortality, growth, and recruitment.

every aspect of the management system for walleye pollock (*Gadus chalcogrammus*; Gadidae) in the Gulf of Alaska (i.e. scientific surveys, stock assessment, fishery dynamics, population dynamics, and management decisions) to evaluate control rules given shifts in productivity. They found that management performance did not markedly improve under climate-adaptive management targets. Other published management strategy evaluations produced similar outcomes (Klaer et al., 2015; Punt et al., 2014), but were based on single-species evaluations. Changing productivity will likely affect interacting species in unique ways (Szuwalski & Hollowed, 2016), so examining aggregate outcomes for managed populations with different responses to climate changes may provide insight for management.

5 | POTENTIAL IMPACTS OF CLIMATE-ADAPTIVE MANAGEMENT TARGETS ON GLOBAL FISHERIES

The RAM Legacy Stock Assessment Database is a collection of estimates of the harvest history, biomass, and status for over 590 harvested marine populations that account for roughly one-half of global marine fisheries production through the year 2010 (RAM, 2020). We fit logistic models to the fishery data individually for each population to parameterize models to project forward, and then performed 100 simulations projecting the populations for 50 years. The carrying capacity for each population was multiplied by a normal random variable with a mean of 0.5 or 1.5 and a standard deviation of 0.1 in the year 2040. We then compared the trajectories of biomass and yield achieved by applying HCRs with climate-adaptive or *status quo* management targets over the projection (see methods for details).

Projected total biomass was 8% higher under *status quo* targets than climate-adaptive targets, yet total projected yield increased by only 3% under adaptation (Figure 5). The relatively small changes in yield but larger changes in biomass can be understood by comparing the results for declining stocks with those for increasing populations. The biomass for increasing populations equilibrated at the same levels over time and produced similar yields under both harvest control rules. The most notable difference in contribution to total biomass and yield arose from the declining populations. The climate-adaptive management targets depleted these populations to levels 34% lower than those under the *status quo* targets, but only increased yield by 10%.

The above results came from scenarios in which the increases in MSY were balanced by the decreases in MSY. However, if climate change influences more populations negatively than positively, the conservation benefits of maintaining *status quo* targets would become larger as the projected biomass sums between approaches diverge (Figure 6). Aggregate yield trended downward with more populations negatively influenced by climate change for both strategies, but the difference between the strategies for a given proportion was small. Changing productivity can also influence target harvest rates (Figure 3), so the impact on vulnerable populations of using climate-adaptive management targets is likely larger than reported here.

6 | LOOKING FORWARD

Climate-adaptive management targets resulted in slightly higher aggregate yields for our global fisheries case study, but losses in biomass disproportionately incurred by populations under stress overshadowed the small gains in yield. Slightly higher aggregate yields could

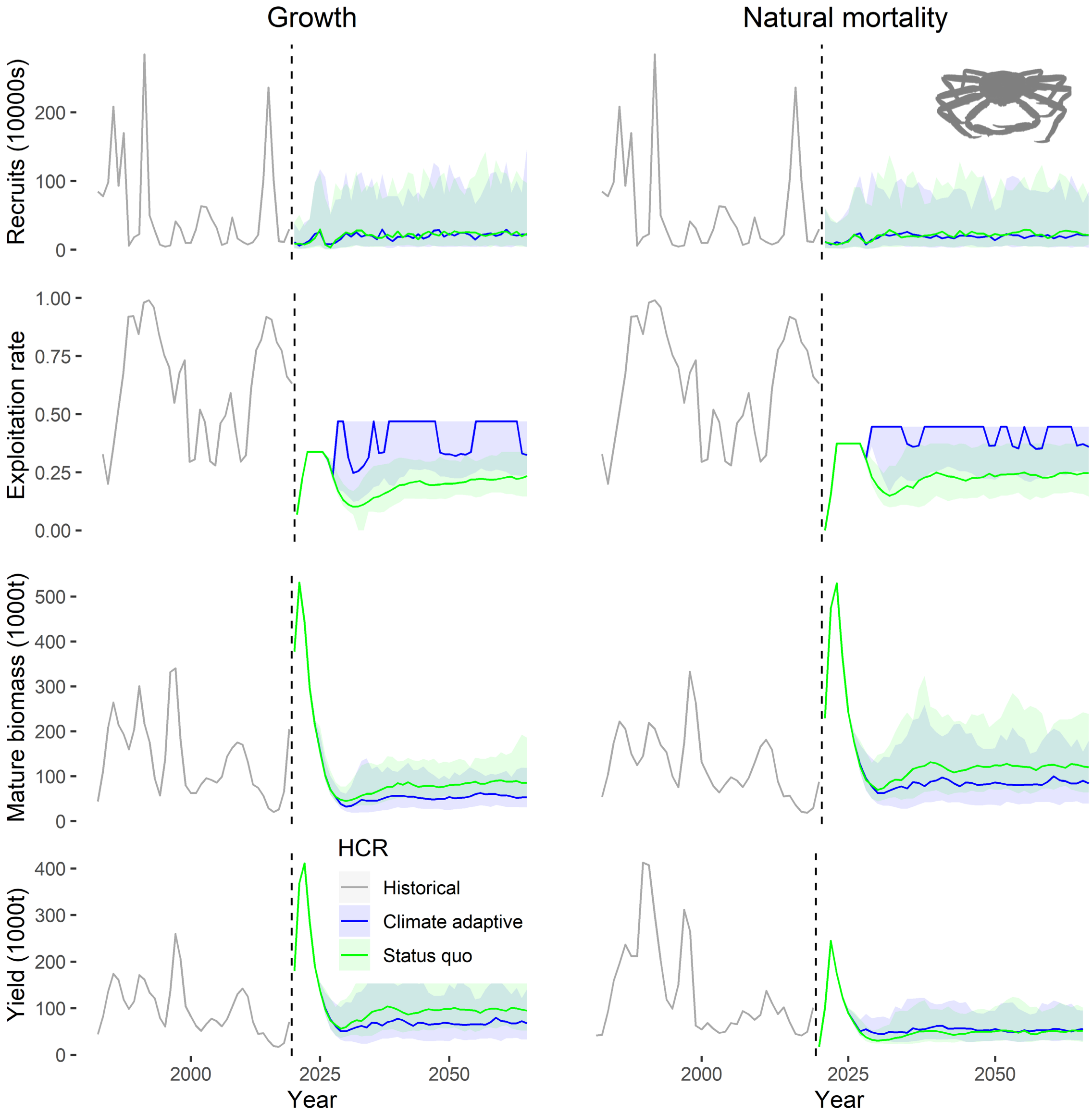

FIGURE 4 Management projections for snow crab in the eastern Bering Sea under changes in natural mortality and growth. Shading represents the 95% quantile from the Monte Carlo simulation performed over recruitment variability.

be expected because the key goal of MSY is to maximize yield. It may also not be surprising that lower exploitation rates under *status quo* management can provide similar yields (see Hilborn's 'pretty good yield'; 2010). However, for many managers and stakeholders, MSY-based management has become synonymous with 'good' management. Conservation benefits were a desired but not fundamental side effect of attempting to maximize yields in populations that had a history of over-exploitation, and MSY-based management has eliminated overfishing in many regions. However, it may be necessary to reconsider the use of yield-maximizing strategies to accommodate both conservation goals and food production under widespread changes in productivity.

Maintaining *status quo* management targets may be an acceptable initial default management approach under changing productivity because it preserves the conservation intent of management (i.e. to lessen anthropogenic impacts on populations under stress) while still providing aggregate yields that are not markedly lower than can be achieved by changing management targets. Maintaining *status quo* targets also builds in precaution by acknowledging that populations have evolved survival strategies that may be fundamentally altered under climate change, with insufficient time to adapt alternatives. However, choosing this path can sever the link between the current productivity of the population and management targets. A portion of this decision hinges on a manager's expectation of the likelihood of mitigating climate change impacts. If climate change impacts are successfully mitigated, acknowledging a change in productivity as an additional source of anthropogenic mortality and managing under the expectation that the additional mortality may eventually be removed may be appropriate.

Although maintaining *status quo* management targets may be an acceptable initial default, other factors may influence the decision to change or maintain targets. Economic incentives exist for

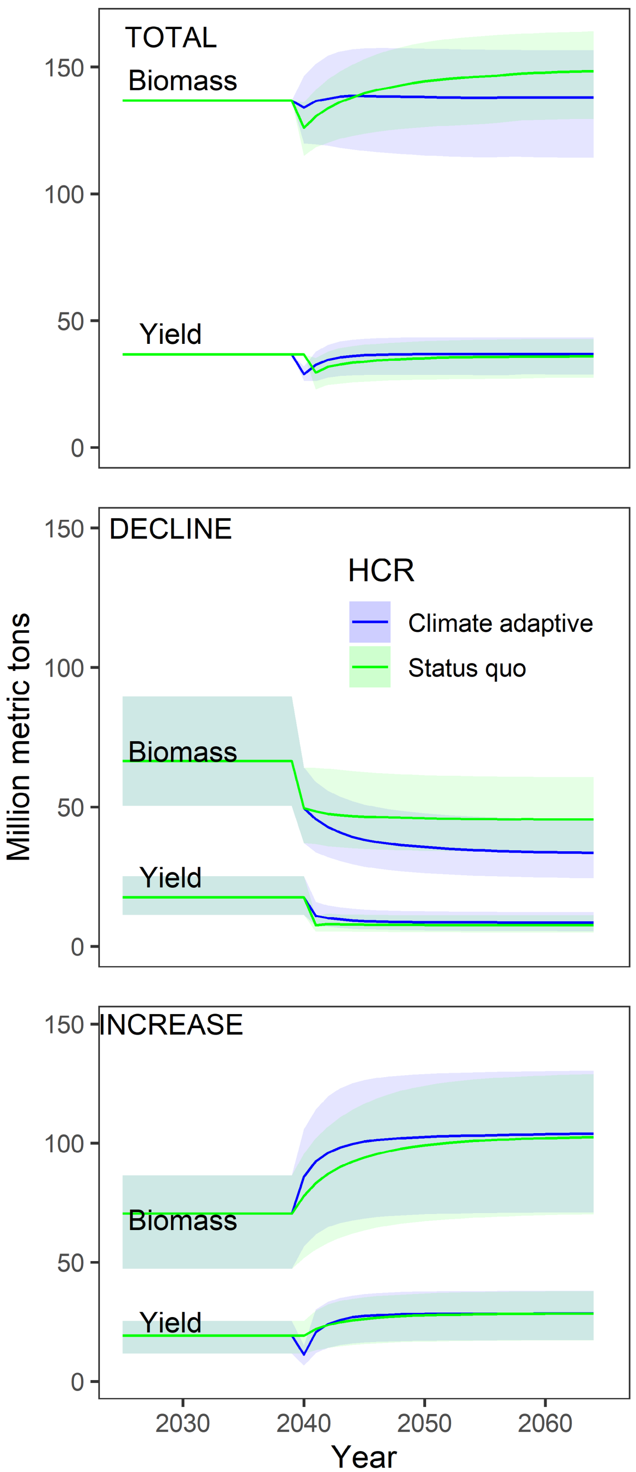

FIGURE 5 Projected aggregate biomasses and yields in millions of metric tonnes for 539 populations in the RAM Legacy Stock Assessment Database under climate-adaptive and *status quo* management targets. For each Monte Carlo simulation, populations were randomly assigned to either 'increasing' or 'decreasing' groups with a 50% probability. Totals are at the top; populations that experienced a decrease in productivity in the middle, and populations undergoing an increase in productivity are at the bottom. Solid lines represent the median value over the Monte Carlo simulations and shaded areas represent the 95% simulation interval.

maintaining yield from high-value resources. Higher levels of biomass in ecosystems may decrease the costs to fishers of finding and capturing fish. Ecosystem interactions also provide management incentives: for example, if a prey species experiences a drop in productivity, but supports an array of harvested predator species, maintaining higher biomass management targets for the prey species may be warranted (Pikitch et al., 2014). Methods of harvesting resources can interact (e.g. fishing in one area with one gear may result in the harvest of many species). If co-harvested species respond differently to shifting climate, species with declining productivity may impede the utilization of co-harvested species with increasing productivity (Burgess et al., 2013).

Societies value ecosystem services differently and might, for example, place a larger emphasis on food production compared to ecosystem structure (Szuwalski et al., 2017). The winners and losers of climate change will not be randomly scattered around the globe – there will likely be hotspots of productivity loss and gain, and the difference between local and global outcomes may strongly affect management decisions, particularly in developing countries (Oremus et al., 2020). The uncertainty and risk surrounding projected resource response and market conditions will further complicate managing resources under climate change. For example, aquaculture provides an increasingly large fraction of global seafood and may be able to supplant wild-capture seafood over time (as seen in China; Szuwalski, Cheng, et al., 2020; Szuwalski, Jin, et al., 2020). Increased seafood supply via aquaculture may offer further support for managing declining wild resources conservatively and maintaining *status quo* targets.

There will likely be no one-size-fits-all solution for managing fisheries under a changing climate and, although *status quo* management may be a useful initial default, this does not mean improvements cannot be made (Holsman et al., 2019). Large-scale efforts are underway attempting to predict the impact of climate change on natural resources (e.g. Hollowed et al., 2020; Holsman et al., 2020; Peck et al., 2020). Our results do not negate the importance of these studies and we stress the need to consider economic, ecological, and social consequences in management decisions. Furthermore, our analyses concern already-managed fisheries – fisheries that produce nearly half of the world's catch are still minimally managed and would benefit from basic fisheries management (Costello et al., 2016; Melnychuk et al., 2021).

Ecosystem-based fisheries management (EBFM) has been long proposed to attempt to reconcile some of the competing issues outlined above (e.g. Link, 2002). Clearly defining EBFM can be difficult, but attempts have been made at implementing systems that incorporate considerations other than aiming to maximize sustainable yield. For example, in the eastern Bering Sea, yearly total removals are capped at 2 million tonnes and forage species are not fished in federal fisheries. Alaskan fisheries are among the most conservatively managed relative to MSY-based reference points of the fisheries represented in RAMLDB (Hilborn et al., 2020) as a result of these actions. However, in spite of this strong ecosystem focus, MSY-based reference points are still at the core of the management

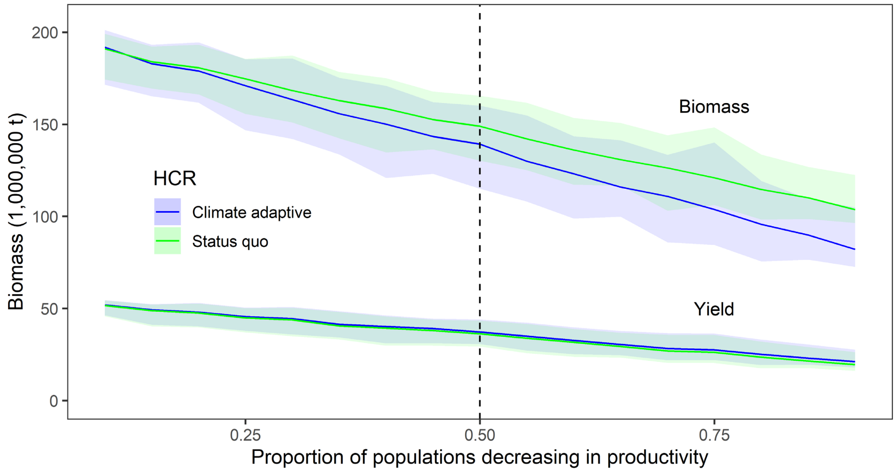

FIGURE 6 Aggregate equilibrium yield and biomass from RAM database populations for harvest control rules in which the management targets change or are maintained at *status quo* for a range of proportions of populations undergoing increases in carrying capacity vs. decreases. The vertical dashed line corresponds to the scenario in Figure 5.

system. Considerable effort goes into producing stock assessments to calculate reference points yearly and discussions about the most appropriate period to serve as a reference for management targets often occur at management meetings for Alaskan fisheries. These MSY-based reference points provide the starting point for determining acceptable biological catches for the largest and most valuable stocks in the eastern Bering Sea under the 2 million tonnes cap. Discussions in management bodies around appropriate periods to use for estimating reference points of stocks facing productivity shifts under climate change spurred the writing of this paper.

MSY-based management is the dominant paradigm in fisheries at least partially because the concept of MSY is easy to understand and MSY management targets are (somewhat) easily calculated. The same cannot be said for EBFM targets that attempt to balance the competing issues outlined above and this is likely why the widespread adoption of EBFM has been slow and practices widely vary across the globe (compare the 'EBFM' in Alaska to that implemented in Australia; Fulton et al., 2020; Ogier et al., 2016). The counter-intuitive consequences of applying existing MSY-based management principles to resources undergoing changes in productivity that we have outlined here should emphasize the need to develop more easily implemented EBFM management targets that can quantify the trade-offs between competing priorities.

Moving forward, the repercussions of single instances of climate-adaptive MSY-based management may not have large ecological or economic impacts. However, multiple interacting resources responding to a rapidly changing climate could result in the destabilization of both ecosystems and markets. The net effect of seemingly small, well-intentioned decisions by managers around the globe may translate to large changes in both the biomass of harvested populations remaining in the ocean and harvest levels. Concerted international planning among managers is needed to confront the potential problems introduced by climate-induced changes in productivity. This planning will require explicitly identifying trade-offs and agreeing upon preferences, which will necessitate honest discussions about the goals of management, data sharing, and collaborative analysis. In particular, managers may be faced with a choice of pursuing biomass levels similar to a pre-warming past, or yields reflective of a post-warming future.

There are many ways to model changes in productivity and management response to them. Our goal with this paper was not to exhaustively explore this space, but rather to emphasize that managers will increasingly face decisions about how to manage changing resources. 'Climate-adaptive' management is often presented as the gold standard to improve management outcomes (Bahri et al., 2021), and although 'climate-adaptive' can refer to strategies other than defining biomass and exploitation rate targets, many management bodies focus primarily on appropriately defining and implementing these management targets. We reinforce previous literature which showed that following the MSY paradigm may produce undesirable conservation outcomes for single populations and add that, when considered in aggregate, populations under climate stress would receive the brunt of the harm from MSY-based adaptation. Larkin published 'An epitaph for maximum sustainable yield' in 1977 decrying the shortcomings of MSY (Larkin, 1997). In spite of the problems he identified, MSY-based management has played a critical role in rebuilding global fisheries (Hilborn et al., 2020). The successes of MSY-based management should be celebrated, but the looming problem of changing productivity requires renewed scrutiny by the scientific community to safeguard marine resources for future generations.

7 | IN-DEPTH METHODS

7.1 | Simulated harvested population dynamics

We first demonstrate problems associated with managing a population undergoing changes in productivity using a logistic population dynamics (or biomass dynamics) model. We simulated a population with a harvest history in which 'effort dynamics' determined the harvest rate (Thorson et al., 2013). This simple model can be used to simulate the change in biomass, B, of a harvested natural living resource. Population dynamics are a function of an intrinsic rate of growth, r, the carrying capacity of the resource, K, and removals, C. The carrying capacity was specified to change halfway through the 100-year modelled time series from 1000 to 500, to mimic a change in productivity.

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K_t}\right) - C_t$$

where B_t is the Biomass at time t; r is the Intrinsic rate of population growth (set to 0.25); K is the Carrying capacity (initially set to 1000) and C_t is the Harvest from the resource at time t.

The catch for years 1–3 is determined using an effort dynamics model

$$C_{t+1} = \frac{C_t}{B_t}\left(\frac{B_t}{aB_0/2}\right)^x B_{t+1}$$

where a is the Indicates what fraction of B_{MSY} bio-economic equilibrium occurs (set to 0.9); B_0 is the Unexploited biomass and x is the Adjusts the fraction of last year's harvest applied based on the relationship of current biomass to the biomass at equilibrium (set to 0.2).

The effort dynamics model is useful because it captures the oft-seen dynamics of the harvest of a resource overshooting appropriate levels, then being modified to reach management targets (Hilborn et al., 2020). It was used here to determine catches until year 50, when carrying capacity, and hence maximum production, changed, after which two alternative harvest control rules were compared.

A harvest control rule (HCR) using 'climate-adaptive' management targets was compared to a *status quo* HCR. Each HCR requires targets for harvest rates and biomass and a parameter that determines the slope of the descending leg of the HCR. The equilibrium biomass at which MSY (B_{MSY}) occurs was half the carrying capacity in the simulation; the difference between the HCRs was the carrying capacity used to calculate the target biomass. The HCRs are 'sloped', which implies that, as biomass declines below a target, the realized harvest rate was decreased from the target harvest rate. At biomass below 0.2 B_{MSY}, all fishing ceases.

$$U_t = \begin{cases} 0 & \text{if } \frac{B_t}{B_T} \le 0.2 \\ \frac{U_T\left(\frac{B_t}{B_T} - \alpha\right)}{1-\alpha} & \text{if } 0.2 < \frac{B_t}{B_T} < 1 \\ U_T & \text{if } \frac{B_t}{B_T} > 1 \end{cases}$$

where U_t is the Harvest rate at time t; U_T is the Target harvest rate; B_t is the Biomass at time t; B_T is the Target biomass (B_{MSY}) and α is the Determines the slope of the descending limb of the sloped control rule (set to 0.2).

7.2 | Snow crab in the eastern Bering Sea

Snow crab in the eastern Bering Sea have been harvested since the mid-1970s. The fishery is male-only and this is relatively easily enforced given strong sexual dimorphism. The snow crab fishery in the Bering Sea protects a large part of the mature male population through size restrictions, which allows for high target fishing mortality rates on the fraction of the population that is exploitable. The maximum age for snow crab is likely no more than 20 years, but natural mortality is not precisely known. Snow crab molt annually, until a final molt to maturity, after which they do not grow. The reproductive dynamics appear to be strongly influenced by environmental conditions, particularly sea ice and the Arctic Oscillation (Szuwalski, Cheng, et al., 2020; Szuwalski, Jin, et al., 2020). The population dynamics model used here to project the snow crab population in the eastern Bering Sea under climate change and different harvest control rules is a simplification of the model on which the current assessment is based but nevertheless captures the above-mentioned characteristics of the fishery (44; see GitHub repository for code). The basic dynamics can be represented by:

$$N_{t+1,l,m} = \begin{cases} (1-T_l)X_{l,l'}N_{t,l,m=1}S_{t,l,m} + R_tP_l & \text{if(immature)} \\ T_lX_{l,l'}N_{t,l,m=1}S_{t,l,m} + N_{t,l,m=2}S_{t,l,m} & \text{if(mature)} \end{cases}$$

where $N_{t,l,m}$ is the numbers at the start of time-step t (there are three time steps in a year, summer survey, winter fishery, and mating season) of length-class l and maturity state m ($m = 1$ immature; $2 =$ mature), T_l is the probability of molting to maturity, $X_{l,l'}$ is a size-transition matrix that determines the how much a crab in length-class l grows when it molts, $S_{t,l,m}$ is the survival during time-step t for animals in length-class l of maturity state m, R_t is the number of recruiting crab at the end of time-step t, and P_l is the proportion of recruiting crab distributed to length bin l. The start of the model year is July 1. Parameters associated with these processes are estimated within the stock assessment and specified in the projection model used here (see github repo; Figure 7). The size-transition matrix, the probability of terminal molt, the number of recruiting crab, and the proportion of recruiting crab are all directly input into the projection model. Other processes are derived from inputs as described below.

Survival is a function of natural mortality, M, during time-step t by maturity state m, fully selected fishing mortality (F_t), and fishery selectivity at length, V_l. Natural mortality and fishing mortality are inputs in the projection model.

$$S_{t,l,m} = e^{-(M_{t,m} + F_tV_l)}$$

Fishery selectivity is a logistic function of size with a maximum of 1 and a probability of 50% capture (V_{50}) of approximately 95 mm carapace width.

$$V_l = \frac{1}{1 + e^{(-b(l - V_{50}))}}$$

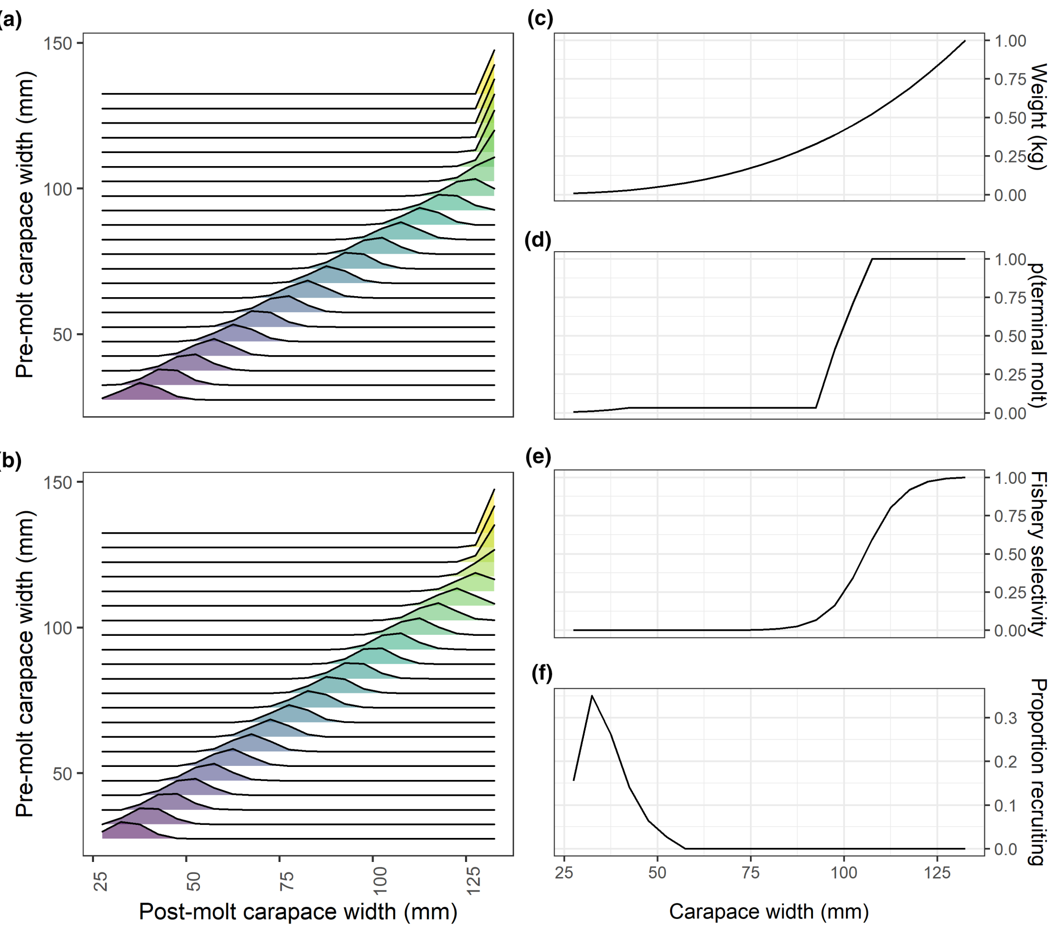

FIGURE 7 Population specifications for the snow crab models projected under a changing climate. The size-transition matrices are at the left; (a) is the variant used to test the impact of changes in growth and (b) is the matrix based on available growth increment data. Weight-at-size, probability of maturing at size, fishery selectivity-at-size, and the size at recruitment (top to bottom, respectively) are at the right.

Growth per molt is specified by a linear relationship between expected growth increment and length. The variability around expected growth is specified by a discretized normal distribution, $Y_{l,l'}$. These two pieces are combined to produce the entries of the size-transition matrix $X_{l,l'}$, used to determine the procession of crab from size l to size l' in the population dynamics model over time. Immature crab are assumed to molt every year.

$$X_{l,l'} = \frac{Y_{l,l'}}{\sum_{l'} Y_{l,l'}}$$

$$Y_{l,l'} = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(l-l')^2}{2\sigma^2}}$$

$$l' = \alpha_g + \beta_g l$$

Yields during time-step t (fishing occurs 6 months after recruitment and the fishery is modelled as a pulse fishery) are a function of fishing mortality, weight-at-length, and numbers-at-length.

$$Y_t = \sum_{l,m} w_l N_{t,l,m} \left(1 - e^{-F_t V_l}\right)$$

Mature male biomass during time-step t is calculated as the sum of the product of weight-at-length and the numbers by length-class of mature individuals in a given time step. The mature male biomass that determines recruitment is calculated immediately after the fishery.

$$\mathrm{MMB}_t = \sum_l w_l N_{t,l,m=2}$$

Only males are harvested in this fishery so only males are modelled and mature male biomass is used as a proxy for reproductive potential (both in this analysis and in management; 44).

7.2.1 | Estimates of recruitment, spawning biomass, and historical environmental data

Szuwalski, Cheng, et al. (2020), Szuwalski, Jin, et al. (2020) developed a model to project snow crab recruitment under climate change using historical estimates of recruitment and mature female biomass, historical local and large-scale indices of environmental variation, and projected indices of local and large-scale indices of environmental variation. Here, that model is updated to use additional data and to incorporate mature male biomass (because only male biomass is modelled above). Estimates of recruitment and mature male biomass were taken from the most recent stock assessment for snow crab, which included both sexes (Szuwalski, 2019). Estimates of recruitment were lagged 5 years to the year of fertilization (Szuwalski, Cheng, et al., 2020; Szuwalski, Jin, et al., 2020).

The natural logarithm of the ratio of estimated recruits, *R*, to mature male biomass, *S*, was modelled as a linear function of mature male biomass, *S*, and other environmental variables, *I*, in the form of a linearized Ricker curve. A Ricker curve was chosen to accommodate the estimated large recruitments at intermediate values of mature male biomass observed in snow crab (Ricker, 1954).

$$\log\left(\frac{R}{S}\right) = \alpha + \beta_1 S + \beta_2 I + \varepsilon; \varepsilon \sim N(0, \sigma)$$

The Arctic Oscillation and ice extent were significant predictors of snow crab recruitment in Szuwalski, Cheng, et al. (2020), Szuwalski, Jin, et al. (2020) and they remained so after using mature male biomass in place of mature female biomass. Data for these environmental variables were collated from the National Oceanic and Atmospheric Administration's 'Bering Climate' data portal (NOAA, 2018).

7.2.2 | Projections of productivity

The Alaska Climate Change Integrated Modeling project (ACLIM; Hollowed et al., 2020) recently produced high-resolution downscaled projections of oceanographic conditions in the Bering Sea using the Regional Ocean Modeling System and the global climate model GFDL-ESM2M. CMIP5 representative concentration pathways (RCP) 8.5 (high baseline carbon emissions) was used to drive the boundary and atmospheric conditions of the regional model (Hermann et al., 2016, 2019). For each projection, the National Marine Fisheries Service Alaska Fisheries Science Center annual summer bottom-trawl survey was replicated in time and space (using historical mean survey date at each latitude and longitude of each gridded survey station) to derive estimates of bottom temperatures.

Projections of the Arctic Oscillation (AO, also known as the Northern Annular Mode; NAM) were obtained from the global climate model GFDL-ESM2M to remain consistent with the model above (Dunne et al., 2012). In particular, the 2020–2100 period of the RCP 8.5 simulations were applied in this study to obtain the AO indices to establish a scenario concerning warming for the Bering Sea. The first EOFs of SST and sea level pressure, were obtained over the Northern Pacific Ocean and Northern Hemisphere from reanalysis datasets (HadISSTv1.1 [Rayner et al., 2003] and NOAA-CIRES 20CR [Compo et al., 2011], respectively) for a historical period (1900–2005), were projected to future projection simulations to obtain the associated principal component (PC) time series, which were then used as the future projections of the AO indices in this study. A detailed description of the methodology can be found in Lee et al. (2019).

7.2.3 | Management targets and projections for snow crab

Proxies for biomass and fishing mortality management targets were calculated for snow crab using spawner-per-recruit methods (sensu Clark, 1993). $B_{35\%}$ is the biomass at which spawning biomass (i.e. mature male biomass) per recruit is 35% of unfished levels and has been shown to provide close to MSY for a range of steepness (i.e. the fraction of unfished recruitment achieved at 20% of unfished spawning biomass; Clark, 1993) values. Consequently, it is an often-used target when stock-recruitment relationships are poorly defined (as is the case for snow crab and many marine stocks globally). To calculate management targets, the snow crab population dynamics model was projected forward 100 years using the specified parameters under no harvest to determine 'unfished' mature male biomass-per-recruit. Projections were repeated in which fishing mortality that reduced the mature male biomass-per-recruit to 35% of the unfished level was calculated (i.e. $F_{35\%}$). $B_{35\%}$ was calculated by multiplying the mature male biomass-per-recruit by the average recruitment over a defined period of time. The *status quo* harvest control rule used the entire time period of recruitment since 1982 (updated each time the projection moved forward a year). The adaptive harvest control rule used the average recruitment from the year 2025 once the projection moved beyond the year 2030; before that the same recruitment calculated for the *status quo* rule was used.

7.2.4 | Changes in other population processes

In addition to changes in recruitment, changes in processes such as natural mortality or growth will also affect estimated population status and dynamics, and will result in changes in management targets incorporated into harvest control rules. We demonstrated the effects of a change in natural mortality and growth on management targets by projecting the snow crab model described above forward to the year 2060 with small changes. First, rather than changing projected recruitment functions, we changed natural mortality or growth in the year 2030 (Figure 7). The selectivity and probability of terminal molt were also adjusted to reflect a fishery in which a larger fraction of the mature biomass is vulnerable to capture to allow for better differentiation between the scenarios. Spawning biomass-per-recruit proxies for target biomasses and fishing mortalities were calculated for each value of natural mortality or growth (i.e. the pre- and post-change natural mortalities; 0.3 and 0.4 yr^{-1}, respectively) and the resulting harvest control rules (Figure 3) were used to project the population forward after the shift in productivity (Figure 4).

Both management targets changed when natural mortality or growth changed, which is an important difference between the scenario in which recruitment changed and only the target biomass changed. When natural mortality increases or growth decreases, the population is less 'productive'. For a given number of new recruits to the population, the mature biomass produced decreases when natural mortality increases or growth decreases. The overall 'scale' of the population decreases and the crab die at a smaller size on average. Consequently, the optimal age/size at harvest decreases to balance the trade-off between growth and natural mortality. This translates to higher target harvest rates and lower target biomasses. This implies a 'double-threat' because, as the population is stressed (displayed as increases in natural mortality or decreases in growth in response to environmental change), adapting the harvest control rule to changing environmental conditions would result in both lower biomass targets and higher harvest rates.

7.3 | Global fisheries

7.3.1 | RAM legacy stock assessment database

The RAMLDB is the most extensive and in-depth database available describing the dynamics of harvested marine populations (RAM, 2020). It is a collection of the output of over 590 stock assessments, representing populations that account for 34%–49% of global catch (depending on the year of comparison – some of these assessments are only up-to-date through the end of the 2000s). Stock assessments generally incorporate all available data and model the idiosyncrasies of life history and harvest patterns specific to each fishery (the eastern Bering Sea snow crab fishery described above is one such population and is included in the RAMLDB). Consequently, the output of these models represents the best available scientific information available for each population.

It is not possible to recreate every stock assessment that produced the output in the RAMLDB in a single, inclusive model to test HCRs in a projection. However, it is possible to fit simpler models to the output contained in RAMLDB and use those for projections. Simpler models lose much of the details of a fishery, but approximately preserve the scale and biomass dynamics. We fit Pella–Tomlinson surplus production models (Pella & Tomlinson, 1969) to total biomass (B) and catch (C) reported in the RAMDLB:

$$B_{t+1} = B_t + B_t \frac{\varphi}{\varphi - 1} u_{\text{MSY}} - \frac{u_{\text{MSY}} B_t^{\varphi}}{(\varphi - 1)\left(B_{\text{MSY}}^{\varphi-1}\right)} - C_t$$

where u_{MSY} is the Harvest rate at which maximum sustainable yield occurs; B_{MSY} is the Biomass at which maximum sustainable yield occurs and φ is the Determines the shape of the production function.

Fits to the data by production models were subject to checks related to time series length, the convergence of the optimization algorithm, and reasonable estimates of target exploitation rates and biomasses (see Melnychuk et al. (2020) for a complete description of the criteria). This analysis includes 529 populations that met these criteria (Figure 8). The overarching goal of the fitting was to produce populations to project that were of the approximate scale of those represented in the RAMLDB, and the modelled populations achieve this objective. Models were projected for 50 years (starting in 2015), during which all populations experienced a shift in carrying capacity after 25 years. The performance of a climate-adaptive rule and a *status quo* rule (similar to the rules described above for the simulated population) were compared in terms of projected yield and biomass in the water.

Biomass dynamic models do not provide a good basis for managing natural resources. They miss important details in population and harvest dynamics (e.g. gear selectivity is important and not all individuals are equal in reproduction) and estimated management targets compared poorly with those from more complex assessment models (Lee et al., 2020; Punt & Szuwalski, 2012). Within the RAMLDB, the correlation between B_{MSY} from the assessment and B_{MSY} estimated from production models was 0.55; the correlation between U_{MSY} from the assessment and U_{MSY} estimated from production models was 0.58. Production models are even worse tools to try to identify drivers of changes in productivity because inherent changes in productivity occur as a result of transient effects of changing age structures unrelated to external drivers (Szuwalski, 2016, 2020). Despite their limitations, production models are useful for comparisons of HCRs, which do not require a model to fully capture the dynamics of a population. Our use of production models here is not an endorsement of their use for management, only a useful simplification with which to test harvest control rules that captures the approximate scale of managed fisheries at the global scale.

7.3.2 | Projected impacts of climate change

The impact at the global scale of climate change on fisheries is uncertain, in spite of many attempts to quantify the impact of climate change on future fisheries in the scientific literature. It is difficult to understand how multiple interacting stressors and the potential for adaptation will influence the future productivity of populations. So, rather than attempting to predict the impact of climate change on resources, our focus is on understanding the impact of management decisions on the trajectory of changing resources. To accomplish this, we performed 100 Monte Carlo simulations in which the carrying capacities of populations were multiplied by a randomly distributed normal variable with a mean of either 0.5 or 1.5 and a standard deviation of 0.1. Populations were assigned to the 'increasing productivity' group with a probability of 50% for the first analysis. Assignment of a stock to an increasing or decreasing productivity group was also random across the simulations so that over the simulations, a given stock increased half of the time and decreased half of the time on average. This guard against the potential of a single large stock influencing the results.

Changing the productivity in the above manner ensures that the future aggregate productivity of fisheries remains roughly the same

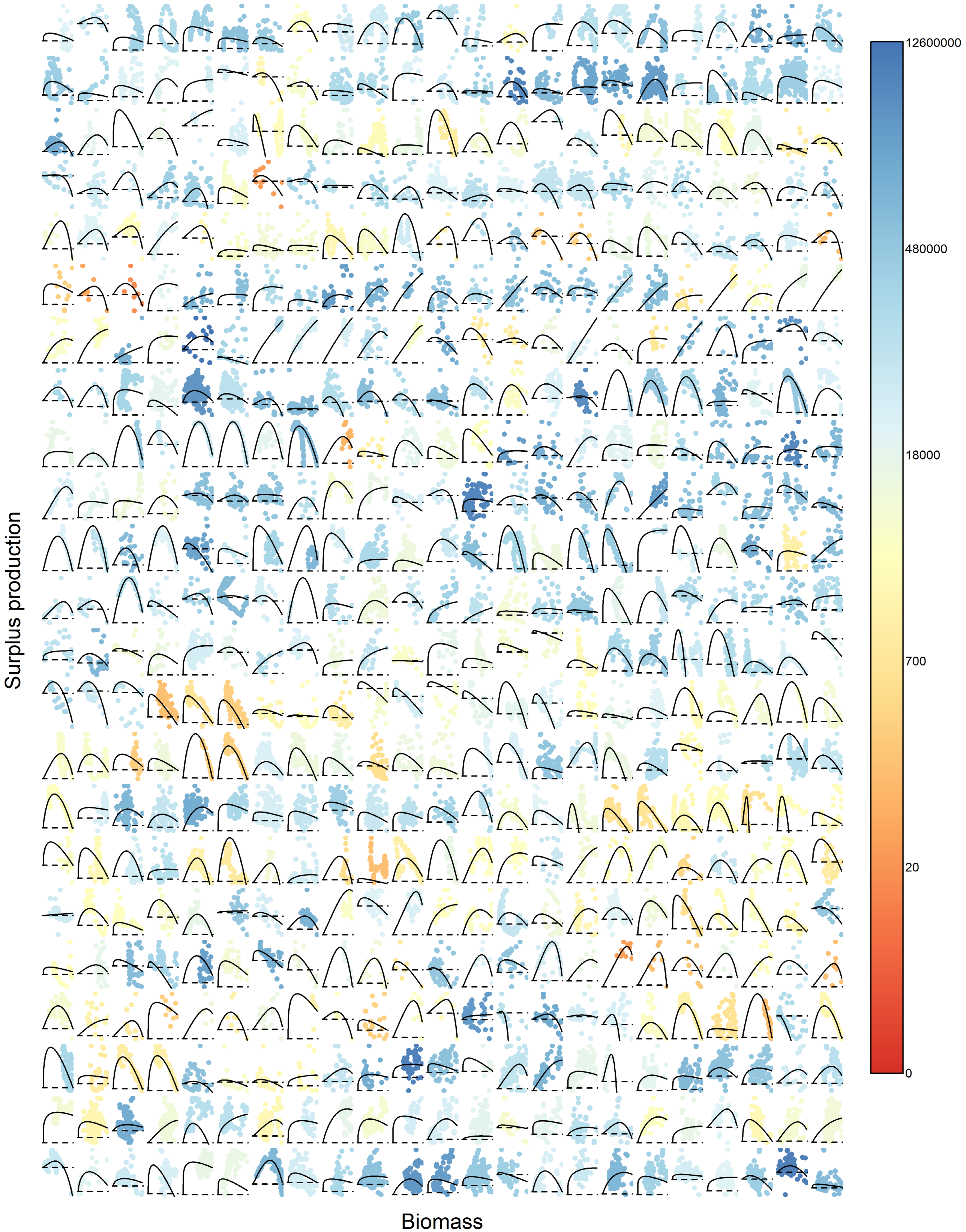

FIGURE 8 Model fits to surplus production for populations from RAMLDB used in the analysis (n = 539). Colour of data points for each population represents the magnitude of the estimated B_{MSY} for the population in tonnes (either from the assessment or from the surplus production model fit to assessment outputs). Horizontal dashed lines show surplus production values of 0.

and provides a stable basis for initial comparison of the harvest control rules. However, it is possible (or even likely) that the distributions of increases and decreases in productivity will not be equal. We therefore examined a range of probabilities (5%–95%) for being assigned to the 'increasing productivity' group.

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DATA AVAILABILITY STATEMENT

All code and data used to perform this analysis can be found at: https://github.com/szuwalski/productivity_problem.

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