

Persistence of marine populations under climate and fishing

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1 Abstract

When the climate changes, so does the location of habitats suitable for an organism's survival and reproduction. This change does not occur in isolation but rather appears on a background of other disturbances, making the study of interactions between stressors important. In order to understand how two disturbances, range shift and harvesting, interact and affect population persistence, we analyzed an integrodifference model that explicitly included the mechanisms of dispersal and reproduction. We found how the critical rates of harvesting and climate velocity that suffice to drive the population extinct depend on the growth rate and dispersal kernel of the population. We measured the interaction between the stressors and found that the disturbances interact nearly additively, with low positive synergy only at the greatest harvest rates and climate velocity that almost drive the population extinct. We also introduced two conservation techniques into simulations of the population model, threshold harvest rules and marine protected areas (MPAs), and found that under some circumstances these approaches could be effective management tools as they mitigate the interaction between the two stressors.

Keywords: Climate change, fishing, integrodifference model, synergy, multiple disturbances

2 Introduction

Many stressors can disturb an ecosystem, and ecologists have quantified the consequences of many of these perturbations [Wilcove et al., 1998, Crain et al., 2008, Darling and Côté, 2008]. Less work, however, has been done to measure the effects of multiple stressors and the interactions between them. If disturbances interact synergistically, a perturbation that has

little effect when it occurs individually may amplify the disturbance caused by a coincident perturbation [Crain et al., 2008, Darling and Côté, 2008, Nye et al., 2013, Gurevitch et al., 2000]. In the most extreme (and worrying) cases, synergistic interactions between multiple stressors will drive a population extinct even though it could persist in the face of any single stressor (e.g. Pelletier et al. [2006]). If disturbances interact antagonistically, on the other hand, the effects of multiple stressors may be less than that predicted by the individual effects of the stressors. Since disturbances rarely occur in isolation, measuring the effects of multiple disturbances gives a better understanding of the likely impacts to the system [Doak and Morris, 2010, Fordham et al., 2013, Folt et al., 1999].

Climate change and fishing, two of the largest human impacts on the ocean [Halpern et al., 2008], provide an important case study of how disturbances interact in their effects on biological populations. Marine fish are already moving in response to climate change [Perry et al., 2005, Hiddink and ter Hofstede, 2008, Rijnsdorp et al., 2009, Dulvy et al., 2008, Simpson et al., 2011] and are projected to continue in the future [Kell et al., 2005, Mackenzie et al., 2007]. These shifting species, and those likely to move in the future, are also subject to harvesting, among other disturbances including pollution, ocean acidification, habitat fragmentation, and invasive species [Wilcove et al., 1998, Sala, 2000, Assessment, 2005, Pinsky et al., 2013, Barry et al., 1995, Nye et al., 2009]. Previous empirical work has found synergistic interactions between overfishing and temperature-driven range shifts [Ling et al., 2009] and synergistic interactions between warming temperatures, harvesting and connectivity have been identified in microcosm experiments [Mora et al., 2007]. This empirical work underscores the importance of understanding how range shifts and harvesting interact.

A common approach to predicting future population distributions has been to use

bioclimatic-envelope models (also known as species distribution models – SDMs). These
 statistical models typically correlate presence-absence data with biophysical characteristics
 such as mean or maximum temperature, rainfall, or salinity, to predict how species ranges’
 will differ under climate change [Elith et al., 2006, Guisan and Thuiller, 2005, Guisan and
 Zimmermann, 2000]. Despite these models’ widespread adoption, many papers have
 criticized SDMs as oversimplified as they lack species interactions, dispersal and
 reproductive processes [Kearney and Porter, 2009, Zarnetske et al., 2012, Robinson et al.,
 2011]. Recent work on range shifts has addressed some of these gaps by explicitly including
 dispersal and reproduction [Berestycki et al., 2009, Zhou and Kot, 2011]. However these
 models only address one disturbance, climate-driven range shifts.

Work on the joint impacts of climate and fishing often considers climate fluctuations (large
 anomalies around the mean) rather than directional changes in climate [Walters and Parma,
 1996, King and McFarlane, 2006]. When studies consider the effects of climate-driven range
 shifts on fishing, the models are typically case-specific and detailed, integrating multiple
 drivers and disturbances [Cheung et al., 2010, Lindegren et al., 2010, Brown et al., 2010,
 Merino et al., 2010a,b, Plaganyi et al., 2011, Ainsworth et al., 2011, Zhang et al., 2011,
 Barange et al., 2011, Howard et al., 2013]. These predicted impacts are important for
 management and conservation planning [Allison et al., 2009], however these models are so
 complex that it makes understanding the relative importance of particular drivers,
 disturbances, and interactions difficult (but see Nye et al. [2013] for an approach using
 ecosystem-level models to discern relative importance of disturbances).

Here we extended a previously studied model of a fish population subject to climate-driven
 range shift by also considering harvesting pressure. The model explicitly included
 reproduction and dispersal, two mechanistic processes central to species’ responses to

climate and fishing. Previous work has highlighted the importance of these two processes and their vulnerability to climate change [Fordham et al., 2013, Hastings et al., 2005]. We found the critical harvesting rate and climate velocity that drive the population extinct and how these critical rates depend on one another. We also found that climate-driven range shifts and fishing interact nearly additively, with low positive synergy at more extreme levels of the stressors.

We also examined the efficacy of two different types of management strategies: threshold harvesting rules and marine protected areas (MPAs). MPAs are frequently recommended for conservation of biodiversity and improved fisheries yield [Gaines et al., 2010a], and we evaluate whether MPAs established for those purposes could improve species persistence when habitat shifts rapidly. Previous work has suggested protected areas can be a key form of climate insurance and can provide stepping stones to help species keep up with a changing environment [Thomas et al., 2012, Hannah et al., 2007]. We found that threshold harvesting rules remove the interaction between harvesting rates and climate velocity and that MPAs can help a species persist with higher harvesting pressure and slightly increase the maximum climate velocity with which a species can keep up.

3 Methods

We studied a model of the dynamics of a fish population constrained to a single, one-dimensional habitat patch by their inability to reproduce outside of that area, as introduced by Zhou and Kot [2011]. This viable habitat patch (here after ‘patch’) shifts at a fixed velocity and harvest occurs at each point in space along the entire one-dimensional world. We first determined the harvesting rate climate velocity that would drive the

population extinct (hereafter the critical harvesting rate and critical climate velocity), and then measured synergy by calculating the drop in biomass caused by each stressor both individually and together. We finally added threshold harvesting rules and marine protected areas (MPAs) in numerical simulations of the model to determine how these management strategies affect population persistence.

3.1 The Model In the model of Zhou and Kot [2011], the adults from the current year produce offspring according to a recruitment function and these offspring disperse across the one-dimensional world according to a dispersal kernel to become the next generation's adults. We extend this model by additionally subjecting the adults to harvesting before they produce offspring so that only a proportion of the fish survive to reproduce. These processes—recruitment, harvesting, and dispersal—are incorporated into an integrodifference model to describe how the population changes over time. If $n_t(x)$ is the density of fish at position x at time t , then the density of fish at the next generation is given by

$$n_{t+1}(x) = \int_{-\frac{L}{2}+ct}^{\frac{L}{2}+ct} k(x-y)f((1-h)n_t(y))dy,$$

where h is the proportion of adults harvested, $f(n)$ is the recruitment function giving the number of offspring produced by a population of size n (accounting for density dependence), $k(x-y)$ is the dispersal kernel giving the probability of a larva traveling from position y to position x , L is the length of the patch, and c is the rate at which it shifts across space. We provide a list of variables and functions in Table 1. We used a Beverton-Holt recruitment function,

$$f(n_t) = \frac{R_0 n_t}{1 + \left(\frac{R_0-1}{K}\right) n_t}.$$

121 Analyzing this kind of model becomes easier if the dispersal kernel is separable into its
 122 dependence on the source of larvae and its dependence on the destination of the larvae, i.e. if
 123 there are functions a_i, b_i such that $k(x - y) = \sum_{i=1}^{\infty} a_i(x)b_i(y)$. In our analyses, as in Latore
 124 et al. [1998], we used the separable Gaussian kernel given by

$$k(x - y) = \frac{1}{2\sqrt{D\pi}} e^{\frac{-(x-y)^2}{4D}}.$$

125 To derive analytical expressions, we approximated the kernel, as described Appendix A.3.
 126 Analytical results for a separable sinusoidal kernel are also described in Appendix A.4. We
 127 used simulations to analyze a Laplace dispersal kernel that is not amenable to this method,
 128 as described below.

129 At equilibrium, the population will move in a traveling wave, where the density of fish at a
 130 given point in space will change but the density of fish at a location relative to the shifting
 131 patch will not. The traveling wave n^* must satisfy

$$n^*(\bar{x}) = \int_{-\frac{L}{2}}^{\frac{L}{2}} k(\bar{x} + c - \bar{y}) f((1 - h)n^*(\bar{y})) d\bar{y}, \quad (1)$$

132 where $\bar{x} \in \left[-\frac{L}{2}, \frac{L}{2}\right]$ describes the position within the patch [Zhou and Kot, 2011]. For a
 133 separable kernel, the equilibrium traveling pulse $n^*(x)$ must satisfy

$$n^*(x) = \sum_{i=1}^{\infty} a_i(x) \int_{-\frac{L}{2}}^{\frac{L}{2}} b_i(y - c) f((1 - h)n^*(y)) dy = \sum_{i=1}^{\infty} m_i a_i(x), \quad (2)$$

134 where the m_i satisfy the recursive equations

$$m_i = \int_{-\frac{L}{2}}^{\frac{L}{2}} b_i(y - c) f\left((1 - h) \sum_{j=1}^{\infty} m_j a_j(x)\right) dy. \quad (3)$$

135 [Latore et al., 1998].

136 **3.2 Persistence** If the population is harvested at low enough levels and the climate
137 velocity is slow enough, the population will be able to persist. There are threshold values of
138 the harvesting rate h and the climate velocity c such that if we increase the parameters
139 beyond these values, the population will be driven extinct. When the population is extinct,
140 the system is in equilibrium, i.e. there is a ‘trivial’ traveling pulse, $n^*(\bar{x}) = 0$ for all
141 $x \in \left[-\frac{L}{2}, \frac{L}{2}\right]$, which satisfies Equation (1). If a population persists, it must be able to avoid
142 extinction and grow even when small. If the trivial pulse is stable, the system will return to
143 extinction even after the introduction of a small population. If the trivial pulse is unstable, a
144 small population may increase and form a persistent population. Population persistence is
145 therefore equivalent to the trivial traveling pulse being an unstable equilibrium. We found
146 the critical parameters, h^* and c^* , by finding the parameters that make the trivial pulse
147 unstable. See Appendix A.1 for details.

148 Regardless of the exact functional form of the recruitment function, the critical parameter in
149 determining population persistence is how quickly recruitment increases when the population
150 size is near (but above) 0, which is equivalent to the intrinsic growth rate $R_0 = f'(0)$. For
151 each kernel, the population’s ability to persist depends on properties of the population itself–
152 the expected distance a larva disperses $\langle d \rangle$ and the intrinsic growth rate R_0 ; properties of the
153 environment– the length of the viable patch L and how quickly the environment shifts c ; and
154 the harvesting rate h . For a Gaussian kernel, the critical rates c^* and h^* are those values of c
155 and h such that

$$R_0(1 - h)2\sqrt{2} \exp\left(\frac{-c^2}{8D}\right) \left[\operatorname{erf}\left(\frac{L - c}{2\sqrt{2D}}\right) - \operatorname{erf}\left(\frac{-L - c}{2\sqrt{2D}}\right) \right] = 1.$$

We derive a similar expression for a sinusoidal kernel in the Appendix A.4. For both kernels, we can approximate the critical harvesting proportion by a function that looks like

$$h^* \sim 1 - \frac{1}{R_0} \cdot C(L, R_0) f(\langle d \rangle, c^2, L^2 + 3c^2),$$

where $C(L, R_0)$ is a decreasing function of the length of the viable patch and the intrinsic growth rate.

3.3 Calculating synergy Zhou and Kot [2011] only considered whether a shifting environment will drive a population extinct. In order to quantify whether the two stressors interact additively, synergistically, or antagonistically, we found the total biomass of the population when it reached an equilibrium traveling pulse and compared this equilibrium biomass in the presence and absence of each stressor individually or the two stressors together. Equations (3) and (2) allowed us to numerically find the total biomass in the equilibrium traveling pulse.

We used B_0 to denote the equilibrium biomass without either stressor, B_h the equilibrium biomass with harvesting but a constant environment, B_c the equilibrium biomass with a shifting environment but no harvesting, and B_{hc} the equilibrium biomass with both stressors. For each stressor or combination of stressors, we found the drop in biomass caused by stressor s ,

$$E_s = B_0 - B_s.$$

If the stressors do not interact, the drop caused by both stressors would be the sum of the drops caused by either individually. The synergy is therefore defined as

$$S = E_{\text{hc}} - (E_{\text{h}} + E_{\text{c}}).$$

If the stressors aggravate each other, the effect of both stressors is greater than we would expect from considering either stressor individually and synergy is positive. If the stressors alleviate each other, the effect of both stressors is less than we would expect from considering either stressor individually and synergy is negative. If the effect of both stressors is exactly as expected from considering either stressor individually, there is no interaction and no synergy.

3.4 Simulations We used simulations to extend the basic integrodifference model in two ways that make it analytically intractable. First, we examined the sensitivity of the model to choice of dispersal kernel by using the Laplace dispersal kernel,

$$k(x - y) = \frac{1}{2}be^{-b|x-y|},$$

a commonly used model of larval dispersal [Pinsky, 2011]. Second, we implemented two management strategies, threshold rules and MPAs, to understand their effect on population persistence and on the synergistic interactions between stressors. For every simulation, in the first generation, we seeded the world with 50 individuals at a single point, as in Zhou and Kot [2011]. We first ran through 150 generations in order for the population to reach equilibrium without harvesting or climate shift. We then added harvesting pressure, allowed the population to again reach equilibrium (150 generations), and finally added climate change by moving the viable patch. We calculated equilibrium biomass as the mean biomass of 300 time steps once the difference in biomass between successive generations was no greater than 0.1.

Under the two management strategies, harvesting pressure was implemented differently.

With a threshold rule, we evaluated the population at each point in space to determine how much harvesting should occur. If the population abundance was below the designated threshold, no harvesting occurred. If the population exceeded the threshold, then we harvested all the ‘surplus’ individuals.

We introduce networks of MPAs into our simulations by designating segments of space where the harvesting rate was equal to 0. MPAs are typically designed to meet either fishery management or conservation goals [Agardy, 1994, Holland and Brazee, 1996, Gaines et al., 2010b]. Fisheries-oriented MPAs are often designed such that they maximize adult spillover into fishable areas by creating many small reserves closely spaced [Hastings and Botsford, 2003, Gaylord et al., 2005, Gaines et al., 2010b]. To mimic this management scheme, we implemented MPAs with a length of $\frac{1}{3}$ of the average dispersal distance and a distance of $\frac{2}{3}$ of the average dispersal distance between them. Conservation-oriented MPAs seek to reduce adult spillover by creating fewer larger protected areas [Hastings and Botsford, 2006, Gaines et al., 2010b]. To mimic this scheme, we implemented MPAs with a length of 4 times the average dispersal distance and a distance of 8 times the average dispersal distance between them [Lockwood et al., 2002].

4 Results

4.1 Interactions Between Stressors The critical climate velocity and harvest rate are inversely related. As the climate velocity shift c increases, the critical harvesting rate h^* decreases (Figure 1). This means that a harvesting rate that is sustainable in the absence of environmental shift may no longer be sustainable if the environment starts changing.

212 Conversely, as the harvesting rate h increases, the critical climate velocity c^* decreases
 213 (Figure 1). This means that as harvesting pressure increases, it becomes increasingly easy
 214 for a shifting environment to drive the population extinct.
 215 When the climate velocity or harvesting pressure exceed their critical rates (c^*, h^*
 216 respectively), the biomass of the population at equilibrium will be equal to 0. Before the
 217 stressors reaches those thresholds, the equilibrium biomass of the population decreases as
 218 either the harvesting pressure increases or the environmental shifts more quickly (Figure 1).
 219 Our simulations confirm the analytical results with the critical speed c^* declining as the
 220 critical harvest rate h^* increases and vice versa (Figure 3a).
 221 It is always the case that increasing the intrinsic growth rate, R_0 , increases the critical
 222 climate velocity c^* and the critical harvesting rate h^* , since a population that grows more
 223 quickly can recover more quickly from losses caused by these disturbances. However,
 224 whether or not dispersing farther is better depends on how quickly the environment is
 225 shifting (Figure 1). When the environment is shifting slowly, dispersing farther is
 226 detrimental since many larvae will disperse too far away from the viable patch. When the
 227 environment is shifting quickly, on the other hand, dispersing farther can help the
 228 population persist because some larvae will disperse into the space that will become viable
 229 shortly in the future. This affects the critical harvesting rate: at a low climate velocity, we
 230 can more severely harvest populations that have a shorter dispersal distance than those that
 231 disperse farther, whereas at a high climate velocity, we can more aggressively harvest
 232 populations that disperse farther.
 233 We found low levels of positive synergy between the two stressors in our analysis of the
 234 Gaussian kernel (Figure 2). Where positive synergy exists, a doubly stressed population
 235 loses more biomass than we would predict from either stressor individually. The stressors

interact most strongly at high values, shortly before they drive the population extinct. However, the excess loss in biomass is very low, meaning the stressors interact more or less additively. We found similar analytical results for a sinusoidal dispersal kernel, which indicates that this result is robust to changes in the dispersal kernel.

4.2 Management strategies Without any management strategies, we found that the more severely we harvest the population, a slower climate velocity will suffice to drive the population extinct. However, when we put thresholds in place, a small population can always escape harvesting pressure and the critical climate velocity c^* no longer depends on the harvesting rate (Figure 3). In other words, as long as there is some threshold below which harvesting is not allowed, there is a constant critical climate velocity that only depends on the growth rate, length of the viable patch, and average dispersal distance. With either type of MPA strategies examined (many small versus few large), the population withstood combinations of higher climate velocities and harvesting rates (Figure 3). At lower climate velocities, MPAs spaced more than one average dispersal distance apart resulted in larger fluctuations of population biomass relative to small, closely spaced, MPAs. As climate velocities increase, for both MPA strategies, the mean population abundance declines but the population experiences less extreme oscillations in abundance. Since minimum population biomass is increased, the population would be more buffered from possible extinction in a stochastic environment.

5 Discussion

Understanding interactions among disturbances will help to design management for populations subjected to these disturbances. The co-occurrence of climate change-driven

range shifts and fishing mean that there is the potential for synergistic interactions, which have been largely unexamined. Here we have built a general model to examine how climate and harvesting interact to affect species persistence by incorporating dispersal and reproduction.

For each kernel we studied, we found that the higher the growth rate and the better the mean dispersal distance matches the climate velocity, the better a population can adjust to harvest and climate change. More interestingly, we found a negative relationship between the critical harvesting rate and the climate velocity. That is, the more quickly the environment shifts the less harvesting it takes to drive the population extinct. This is an indication of an interaction between the stressors.

To quantify the interaction between the stressors, we measured the synergy between their effects on population biomass. We found positive synergy between the stressors and that the synergy is greatest in the region of parameter space where the equilibrium biomass is smallest. We found similar results from the analytically derived biomass and the simulation derived biomass. This indicates that this result is robust to changes in the dispersal kernel. We chose to measure the effect of each stressor by the absolute drop in biomass caused by the stressor, and we used the sum of the individual effects for our null prediction of the effect of both stressors, as in Crain et al. [2008], Darling and Côté [2008], Nye et al. [2013]. We could also have measured the effect by the percentage drop caused by the stressor(s) and used a multiplicative null prediction for the effect of both stressors. In general, measuring synergy against an additive null prediction is more conservative than measuring synergy multiplicatively: the presence of additive synergy implies multiplicative synergy, but not vice versa [Crain et al., 2008, Folt et al., 1999]. Since we found small levels of positive additive synergy between the two stressors, other measures of synergy might show even higher levels

282 of interaction.

283 Worryingly, we find the highest synergy in those populations whose persistence is most
284 tenuous. This means that harvesting levels or climate velocity that are sustainable
285 individually together can drive a population to extinction. However the drop in biomass
286 caused by both stressors was never much higher than the null prediction, i.e. synergistic
287 effects were quite small. Synergy between harvesting and the effects of climate change has
288 been identified in experimental populations [Mora et al., 2007], in specific populations
289 [Planque et al., 2010a], and at the ecosystem level [Kirby et al., 2009, Planque et al., 2010a].
290 In the experimental populations, synergy was identified between warming and harvesting but
291 not between habitat fragmentation [Mora et al., 2007]. While we did find (very) low levels of
292 positive synergy, we did not find as much as predicted from these empirical studies.
293 However, these previous results are not directly comparable to ours because they focus on
294 different aspects of climate change, e.g. warming temperature [Mora et al., 2007, Kirby
295 et al., 2009] or a more variable climate [Planque et al., 2010a]. Additionally, while we can
296 isolate the affects of climate shift and harvesting in our simple analytical model, there are
297 other forces acting on real populations that may produce the observed synergistic effects.
298 Our results suggest that particular combinations of harvesting and climate velocity will affect
299 some species more than others. As shown in Figure 1, species with a higher reproductive
300 rate and a longer average dispersal distance will better track a high climate velocity relative
301 to a species that has a low reproductive rate and short dispersal distance. The finding that a
302 higher reproductive rate can sustain higher climate velocities and harvesting rates is
303 intuitive, especially because harvesting rate and reproductive rate cancel each other out.
304 However it is worth pointing out that a higher reproductive rate can be generated either by
305 shorter generation times or higher fecundity. Finding that species with shorter generation

times can better keep up with shifts in climate is in agreement with empirical work which has found that fish which shifted in response to warming in North Sea had faster life histories than non shifting species [Perry et al., 2005]. While higher reproductive rates improved a population's ability to persist, there was a tradeoff in increasing dispersal distances. At low speeds, we found that a short dispersal distance improved the maximum harvesting rate a population could sustain while at higher speeds a longer dispersal distance improved the maximum climate velocity in which the population could persist (Figure 1). This tradeoff is due to the proportion of dispersing offspring at time step t which lands within the patch at time step $t + 1$. When climate is shifting slowly, a large dispersal distance sends most offspring ahead of the patch, while with faster climate velocities a long dispersal distance allows the population to make it to the new patch (Figure 1). Thus climate velocity will selectively favor species with dispersal distances best matched to the rate of shift. We also examined whether frequently recommended management approaches, MPAs and harvest control rules, ensure species persistence. With these management strategies we found increases in the population's biomass at equilibrium and an improved ability to persist. We found that a threshold harvesting rule alleviates interactions between the two stressors. Thresholds have this effect as the management approach effectively prevents harvesting of the leading edge, which allows colonization to occur as if these individuals were moving into un-fished areas. It's interesting to note that novel, low abundance species are commonly unregulated in fisheries systems; so in order to decouple the additive effects of harvest and climate change, management would have to reverse this paradigm by allowing no harvest of new species until they had become established. Unlike thresholds, MPAs are explicitly spatial. Previous work has advanced protected areas as a way to help organisms keep pace with range shifts, as well as to ameliorate

anthropogenic disturbances like harvesting and habitat fragmentation [Lawler et al., 2010,
Hannah et al., 2007, Botsford et al., 2001, Gaylord et al., 2005, Hastings and Botsford, 2003,
Thomas et al., 2012]. Our results show that both threshold and MPAs increase the
equilibrium biomass at a given climate velocity, which support their use as a tool to
ameliorate the effect of climate velocity. However, for MPAs, the details matter: few, large
MPAs caused increased variability at low climate velocities while many smaller MPAs
maintained a population bounded farther from extinction. Finally, with sufficiently high
harvesting pressure, few, large MPAs rescued populations at intermediate speeds. With
intermediate speeds, the population was able to reach a protected area fast enough to avoid
extinction, and the protected area was large enough to allow a partial rebuilding of the
population before it moved out the other side. However this effect disappears as speed
continues to increase, suggesting that understanding the relationship between climate
velocity, dispersal distance and reproductive rate are important parameters in designing
management strategies effective under both climate change and harvesting pressure.
While the management strategies only change harvesting practices and do not directly
address the effects of climate change, understanding how they ameliorate synergistic effects
between harvesting and range shifts will help to better implement harvesting rules and place
protected areas. This is encouraging evidence that a single set of management practices
may help to protect marine populations from both harvesting and climate change.
The advantage of a simple model like ours is that it is general enough to be applied to a
number of systems. However, this simplistic approach requires that we ignore complexities
known to be present in marine fisheries. For example, we do not include Allee effects, so that
even if the population shrank to low levels it was possible for it to persist over time.
However, with Allee effects we expect qualitatively similar results. An Allee effect would

354 make it harder for populations to colonize new areas and add a threshold below which
355 fishing drives the population to extinction. Thus an Allee effect would change lower the
356 critical harvest rates and climate velocity, but we do not expect the additive nature of the
357 interaction between climate and harvesting to change. We also did not include age structure
358 in our model. The effects of both harvesting and climate change may be different across
359 different age classes and may destabilize the system in complicated ways, including
360 resonance [Botsford et al., 2011, Planque et al., 2010b]; and we leave this additional
361 complexity for future work. Similarly, we did not include any mechanisms aside from larval
362 dispersal by which the population could keep up with a shifting climate. Besides these
363 species-specific extensions, this modeling framework could be extended to consider species
364 interactions, especially predator-prey pairs. By introducing a predatory species, we would be
365 imposing yet another stressor on the focus species [Ling et al., 2009, Gurevitch et al., 2000]
366 and we are interested in measuring the interaction between the effects of this stressor and
367 the two we consider here.

368 Using a simple mechanistic model like the one we present here provides a useful framework
369 for incorporating additional ecological complexities which can mediate species persistence
370 under multiple disturbances. Using this modeling framework as a starting point, we believe
371 exploring how species interactions, age structure, and additional disturbances (e.g.
372 physiological response to temperature) affect population viability will improve our
373 predictions and help us to understand whether species will persist under predicted climate
374 and harvesting regimes. Finally, this work can help make general predictions as to whether
375 specific life histories offer selective advantages over others as harvesting and range shifts
376 increase and highlights the importance of considering stressors in combination as outcomes
377 can deviate from what we would predict in isolation. This is especially true for management

strategies which may result in unanticipated effects such as large fluctuations associated with big, distant MPAs shown here.

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Figure Legends

Figure 1: (a) The critical harvesting rate on the y-axis as a function of the climate velocity on the x-axis. Black lines correspond to a growth rate of $R_0 = 3$, red to $R_0 = 7$, and blue to $R_0 = 10$. Solid lines correspond to an average dispersal distance $\langle d \rangle = 0.1$ and dashed lines correspond to an average dispersal distance $\langle d \rangle = 0.25$. These results are from an approximated Gaussian dispersal kernel with $L = 1$. (b) The equilibrium biomass of the population as a function of the climate velocity on the x-axis and the harvesting rate on the y-axis. These results are from a Gaussian dispersal kernel with parameters $L = 1$, $R_0 = 5$, $\langle d \rangle = 0.399$.

Figure 2: Positive synergy between the two stressors. The x-axis shows the climate velocity, the y-axis shows the harvesting rate, and the color indicates the loss in biomass in the doubly stressed population in excess of the sum of the losses caused by each stressor individually, $E_{hc} - E_h - E_c$. This excess loss, on the order of .001, is small in comparison to the total biomass, which can be as large as 20. These results are from an approximated Gaussian dispersal kernel with parameters $L = 1$, $R_0 = 5$, $\langle d \rangle = 0.399$.

Figure 3: The equilibrium biomass of the population as a function of the climate velocity on the x-axis and the harvesting rate on the y-axis with and without management strategies. (a) No management. (b) Threshold harvesting levels. (c) MPAs. These results are from a simulation with a Laplacian dispersal kernel with parameters $L = 1$, $R_0 = 5$, $K = 100$, and $\langle d \rangle = 2$.

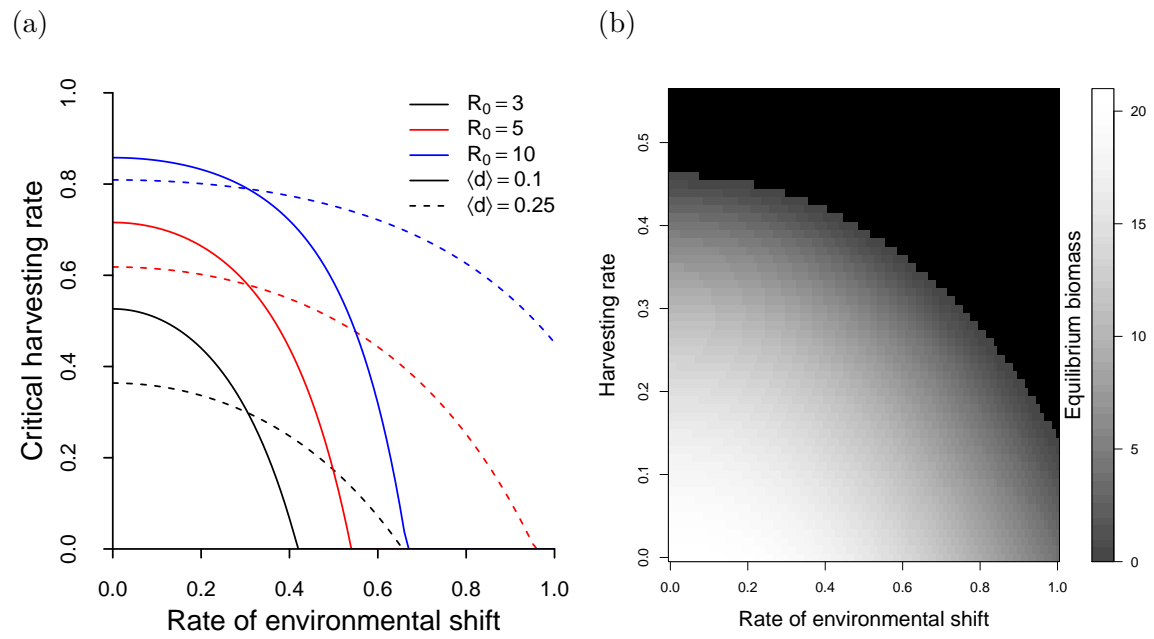


Figure 1

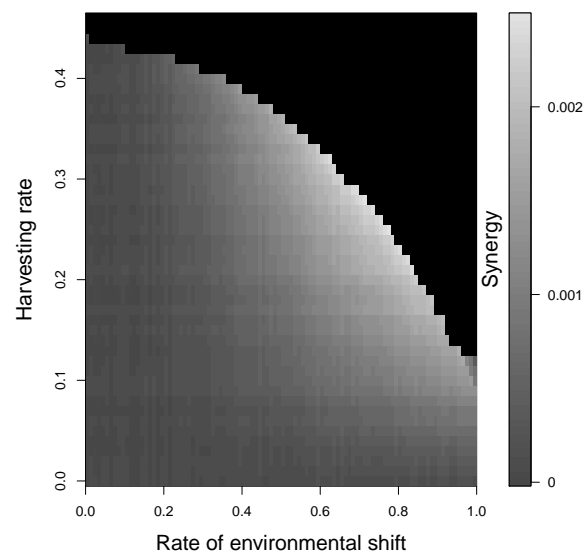
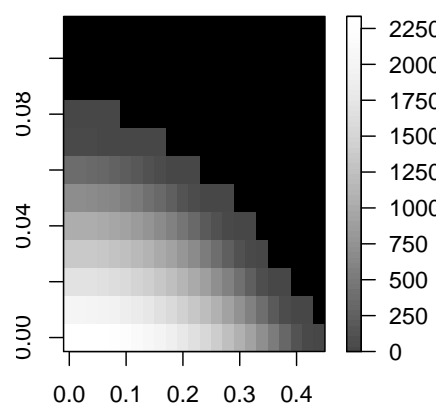
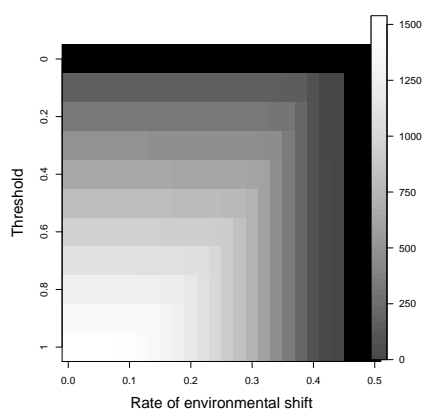


Figure 2

(a)



(b)



(c)

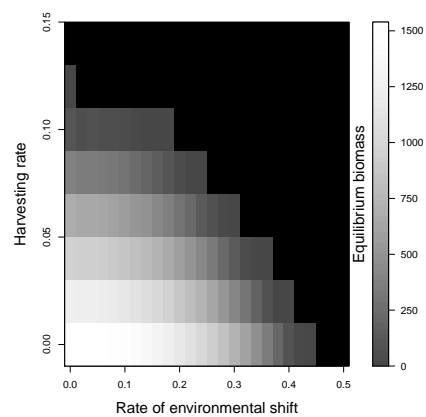


Figure 3

7 Tables

Table 1: Table of variables used in the text

Variable	Definition
$n_t(x)$	density of fish at position x at time t
$n^*(\bar{x})$	density of fish at equilibrium at position \bar{x} relative to the patch
$k(x - y)$	dispersal kernel, the probability of larva traveling from position y to position x
$\langle d \rangle$	expected distance traveled by larva
$f(n)$	recruitment function, the number of offspring produced by a population of size n
R_0	intrinsic growth rate, $R_0 = f'(0)$
h	proportion of adults harvested
L	patch length
c	climate velocity