Appendix B: Canaries of the Arctic: the collapse of eastern Bering Sea snow crab

Cody Szuwalski (and others to come)

Snow crab are an iconic species the Bering Sea that support an economically important fishery and undergo extensive monitoring and management. However, since 2018 more than 10 billion snow crab have disappeared from the Bering Sea shelf and the population collapsed to historical lows in 2021. We link this collapse to a marine heatwave that occurred in the Bering Sea during 2018 and 2019. Calculated caloric requirements and observed body condition suggests that starvation may have played a role in the collapse. Fisheries disaster funds were requested in 2022 after allowable catches in the fisheries were slashed by ~90% in 2021 and short-term prospects for snow crab in the Bering Sea are grim. The collapse of snow crab foreshadows climate-related fisheries management problems that will be more frequently faced around the globe. Losing a frame of reference for future ecosystems as environmental conditions move beyond historical observations shifts our management paradigm from predictive to reactive. New managements paradigms will be needed to face this challenge.

THIS IS A DRAFT MANUSCRIPT INTENDED FOR SUBMISSION TO A PEER-REVIEWED JOURNAL

ALL CONCLUSIONS ARE PRELIMINARY

Introduction

Snow crab are one of the most abundant species in the benthic ecosystem of the eastern Bering Sea and have supported an iconic fishery valued at over US$250 million that is the focus of "Deadliest catch', a widely viewed reality television show. The implementation of quota-based fisheries management in 2005 has made the fishery less 'deadly' (NPFMC, 2010) and fisheries management in Alaska is considered to be some of the most effective in the world (Hilborn et al., 2021). Snow crab are distributed widely over the Bering Sea shelf (Figure 1a) and yearly bottom trawl surveys monitor the size and number of crab in the ocean. Myriad field and laboratory studies aimed at understanding population processes like growth and maturity have been performed (e.g. Copeman et al., 2021), but in spite of this attention and effort, the stock collapsed unexpectedly in 2021.

The collapse in 2021 occurred three years after the observed abundance of snow crab was at historical highs (Figure 1c). Groups of crab of similar sizes are called 'pseudocohorts' because true cohorts cannot be identified as a result of difficulties in aging crab associated with the loss of the hard body parts during the molting process. The largest pseudocohort on record was observed in the summer survey beginning in 2015 and unexpectedly declined by roughly half from 2018 to 2019 (Figure 1d). The survey was cancelled in 2020 because of the coronavirus pandemic, but the 2021 survey found the fewest snow crab on the eastern Bering Sea shelf since the survey began in 1975. More than 10 billion crab went missing from the eastern Bering Sea shelf from 2018 to 2021 (Szuwalski, 2021).

Hypotheses to explain the disappearance of these crab fall under two categories: either the crab are still alive but the survey did not see them or the crab have died. It is possible the crab are in the eastern Bering Sea, but were poorly captured by the most recent surveys. If this were the case, one would expect estimates for other similar species like Tanner crab to have declined unexpectedly, but the population trends for Tanner crab increased (figures S1). Movement to the northern Bering Sea could account for declines in the eastern Bering Sea, but surveys in the northern Bering Sea did not find crab in the quantities or of the correct sizes to explain declines in the south (Figure 1a). Movement west into Russian waters is another possibility, but Russian scientists reported declines in catch per unit effort in 2020 (Chernienko, 2021), which one might not expect if crab from Alaska emigrated. Finally, it is possible that the crab moved into deeper waters on the Bering Sea slope. High fishery catch per unit effort in deeper waters during the 2021 fishery supports this possibility to some extent, but the amount of available habitat is less than 10% that on the shelf (figures S2) and fishery catch per unit effort from 2022 were the lowest on record (figure S3). Consequently, it is unlikely that all of the missing crab from the shelf are on the slope. Given these observations, although movement off of the shelf could have played some role in the decline, mortality is a likely culprit for the bulk of the collapse.

Mortality could be affected via several pathways. Snow crab are generally cold-water loving, but they can function in waters up to 12 degrees in the laboratory (Foyle et al., 1989). An intense marine heatwave occurred in the Bering Sea during 2018 and 2019 and the 'cold pool' (a mass of water <2 degrees C on the sea floor with which juvenile snow crab are associated) disappeared during this period (Figure 1b). While not fatal, the resulting bottom temperatures could affect metabolic costs and alter intra- and inter-specific interactions. Smaller crab are a main component of the diet of Pacific cod in the Bering Sea (Lang and Livingston, 1996) and recent changes in the distribution and abundance of cod and crab has resulted in increased consumption. Removals from the snow crab fishery and incidental mortality in fisheries for other species in the Bering Sea also may also impact the dynamics of snow crab. Larger snow crab are known to cannibalize smaller snow crab and cannibalism has been suggested as an important driver of population dynamics in eastern Canadian populations (Lovrich et al., 1997). Finally, bitter crab syndrome, a fatal disease resulting from infection by a dinoflagellate (Meyers et al. 1996), has been observed more frequently in the summer survey in the last several years and is generally associated with warmer conditions and high densities of immature crab.

To understand the recent collapse, we first attempt to understand the historical variability in mortality. We fit a population dynamics model to the abundance and size composition data for male crab and estimated recruitment (small crab entering the population) and a maturity- and year-specific total mortality. 'Total mortality' represents the fraction of crab dying in a given year due to any cause. We then collated maturityspecific time series of potential stressors from 1991 to 2019 and used them in generalized additive models (GAMs; Woods, 2011) to predict total mortality estimated from the population dynamics models (see SI for detailed methodology, sensitivities, and simulation testing).

The population dynamics model fit the indices of abundance and size composition data from the survey well, which is not unexpected, given the flexibility of the model (Figure 2a & b). Estimated mortality was higher and more varied for mature crab than for immature crab and estimated mortalities in 2018 and 2019 were the some of the highest for both immature and mature crab in the time series. We simulated snow crab populations with time-variation in mortality to understand the ability of our population dynamics model to estimate these quantities with the available data. The correlation between estimated mortality and simulated mortality were high which suggests that analyses relating estimates of mortality and environmental covariates are justifiable (see SI for details). GAMs fit to estimated immature and mature mortality both returned at least one significant relationship with environmental stressors and explained ~72% and ~66% of the variability, respectively (Figure 2c). Higher temperatures and higher densities of mature crab were associated with higher mortality for both immature and mature crab. These relationships were robust to leave-one-out-cross validation and the deviance explained was 'significant' under randomization trials (see SI).

Assessing the predictive skill of a model is an important check on over-fitting and relevant to providing management advice. After an ecologically damaging and economically costly collapse, it is natural to ask if we could have foreseen the collapse. To explore this question, we excluded 1, 2, and 3 years of data from the end of the time series, refit the models, then tried to predict the last years of mortality with the covariates from those years. The model for immature mortality contained enough information in 2016 to forecast an increase in mortality, but never was able to reach the magnitude of the estimated mortality in 2019 (Figure 2c). The model for mature mortality performed similarly, forecasting an increase in mortality over the projection period, but was not able to reach the estimated mortalities until the most recent data was in the model. This suggests that the circumstances underpinning the recent collapse were unprecedented in the Bering Sea in recent history.

The collapse of eastern Bering Sea snow crab appears to be one of the largest reported losses of marine macrofauna to marine heatwaves globally, exacerbated by the record number of snow crab in the system. Temperatures and density of mature crab were the most extreme covariates in 2018 and 2019. However, temperature and density alone are not a very satisfying explanation for what happened to the crab because the physiological thermal limits for snow crab far exceed the observed temperatures (Foyle et al., 1998). Temperature dependent caloric requirements are a potential explanation to relate temperature to mortality. Foyle et al. (1998) showed the caloric requirements for snow crab in the lab nearly double from 0 degrees to 3 degrees, which is roughly the change experienced by immature crab from 2017 to 2018 (Figure 3). Extrapolating the caloric requirements based on temperature occupied, abundance of crab at size, and weight at size suggests that the caloric requirements for snow crab in the eastern Bering Sea during 2018 quadrupled from 2017 and were double the previous maximum value in 1998. The impact of increased caloric demands can also be seen in the observed weight at size. A 75 mm carapace width crab in 2018 weighed on average 156 grams and was ~25 grams lighter (~15% of its bodyweight) than a crab in 2017 of the same size in the same temperature waters (Figure 3). Given this information, starvation likely played a role in the disappearance of the ~10 billion snow crab, similar to the marine-heatwave related collapse of Pacific cod in the Gulf of Alaska in 2016 (Barbeaux et al., 2020).

Snow crab previously collapsed in the late 1990s, but the collapse arose from a lack of recruitment, not a sudden mortality event. Snow crab recruitment has been linked to changes in the Arctic Oscillation and sea ice (Szuwalski et al., 2020). Recent projections of recruitment suggest snow crab abundances will decline in the future as sea ice disappears from the eastern Bering Sea (Szuwalski et al., 2021). However, these declines were projected for at least twenty years from now. Given the recent collapse, the short-term future of snow crab in the eastern Bering Sea is precariously uncertain. Long-term the northern Bering Sea is a prospective climate refugia for snow crab (and potentially a fishery; Mullowney, in review), but the possibility of a fishery rests on the uncertain probability of crab growing to a larger size in the north and the currents retaining pelagic larvae released in the northern Bering Sea.

In 2021, 59 boats fished for snow crab and brought $219 million (ex-vessel) into fishing communities (Garber-

Yonts, 2022). The disappearance of snow crab will be a staggering blow to the functioning of some communities in rural Alaska like St. Paul, which relies strongly on the revenue derived from the capture and processing of snow crab to support the functioning of local communities. The Magnuson-Stevens Act includes provisions for fisheries disaster assistance which were designed to provide economic support for communities facing hardship as a result of collapsed fisheries. The number of applications in the U.S. has been increasing in recent years (Bellquist et al., 2021) and an application for snow crab was received in early 2022. These funds are a boon in the medium-term, but can take years from disaster to dispersal. Consequently, Alaskan crabbers face an uncertain short-term future as the disaster funds may not arrive in time to forestall the bankruptcy of long-standing family businesses.

Beyond the fishery for snow crab, Alaskan fisheries are some of the most productive in the world, producing 5.27 billion tons of seafood in 2021 valued at $1.9 billion (NOAA FOSS, 2022). When snow crab populations declined in 1999, the Bering Sea walleye pollock population (which supports the largest fishery in the Bering Sea and one of the largest in the world, FAO, 2022) also declined shortly after (Figure 4). This relationship is captured by the significant correlation between the time series of pollock and snow crab abundance at a lag of 1 year (Figure 4d). While this correlation is suggestive, it is ultimately uncertain how the massive loss of crab will affect the benthic ecosystem and the fisheries dependent upon it. However, it is virtually certain that the benthic community in the eastern Bering Sea during not-too-distant future will look different than today's given the rapid pace of warming (Rantanen et al., 2022).

Overfishing has historically been the largest threat to global fisheries, but, in many parts of the world, this problem has been solved (Hilborn et al., 2022). Climate change is the next existential crisis for fisheries, and snow crab is a prime example for how quickly the outlook can change for a population. In 2018, catches were projected to increase to levels not seen in decades. Three years later, the population had collapsed. Our current management tools base projected sustainable yields on the historical dynamics of a population. However, projections based on assumptions relying on historical dynamics are not reliable when the future of a region will not resemble the past. Beyond reconsidering how allowable catches are calculated, the practical matters of efficient disaster response, implementing management institutions that allow fishers to pursue diverse portfolios of species, and support for the development of alternative marine-based livelihoods (e.g. mariculture) need close attention from management and stakeholders. The Bering Sea is on the front lines of climate-driven ecosystem change and the problems currently faced in the Bering Sea foreshadow the problems that will need to be confronted globally.

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Supplementary materials

The github repository including the code used to perform the analysis can be found at: https://github.com/szuwalski/snow_down.

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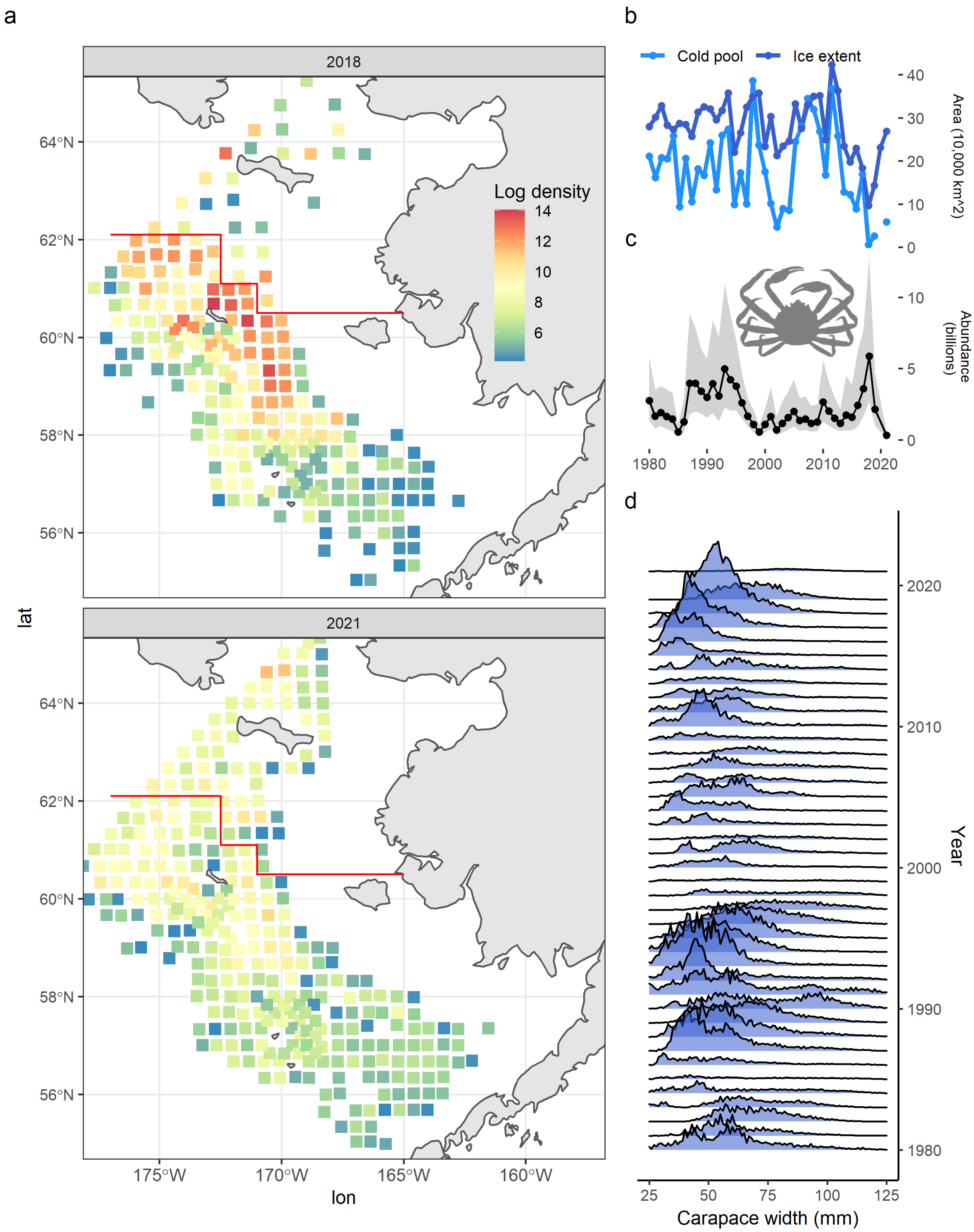

Figure 1: The collapse of snow crab in the eastern Bering Sea. Snow crab are widely distributed on the eastern Bering Sea shelf (a, each square represents a survey tow with snow crab present) and densities of crab were an order of magnitude lower in 2021 compared to 2018 (a). Changes in ice extent and the resulting cold pool (b) influence the population dynamics (c) of snow crab (only male abundance is plotted). The collapse of crab was not size dependent; crab of all sizes disappeared from 2018 to 2021 (d shows the relative numbers at size at crab observed in the NMFS survey over time).

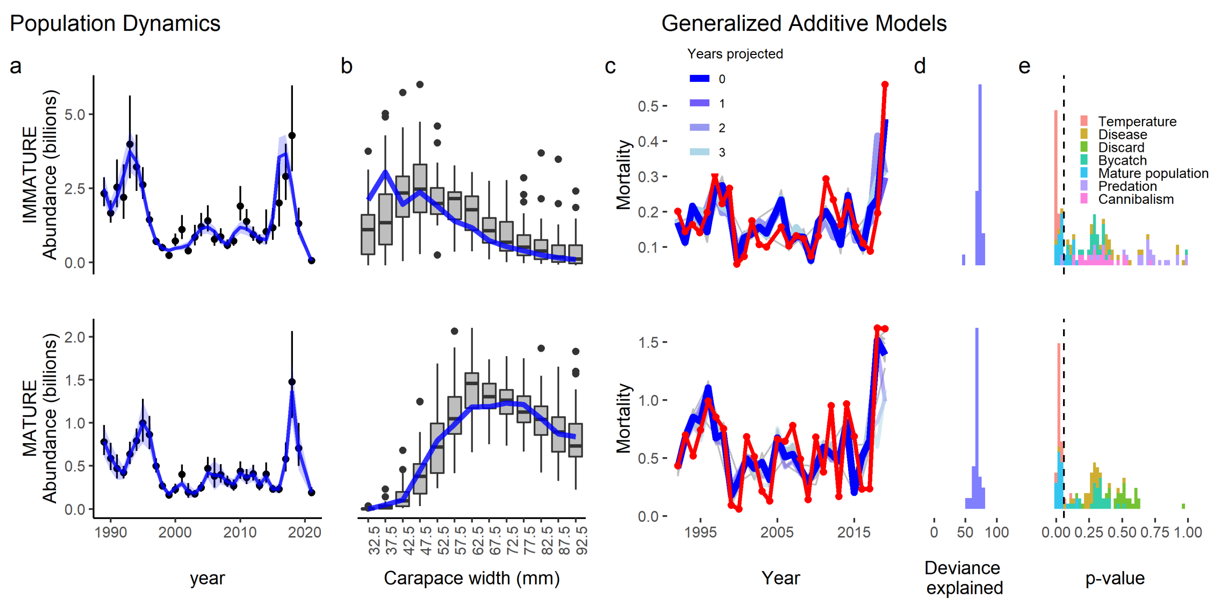

Figure 2: Population dynamics model fits to the data (abundance and confidence intervals (a), size composition data (b)). Fits (c; in blue) to estimated mortality (c; in red) from GAMs with the deviance explained (d) and the significance of covariates (e) resulting from replicates over leave-one out cross validation.

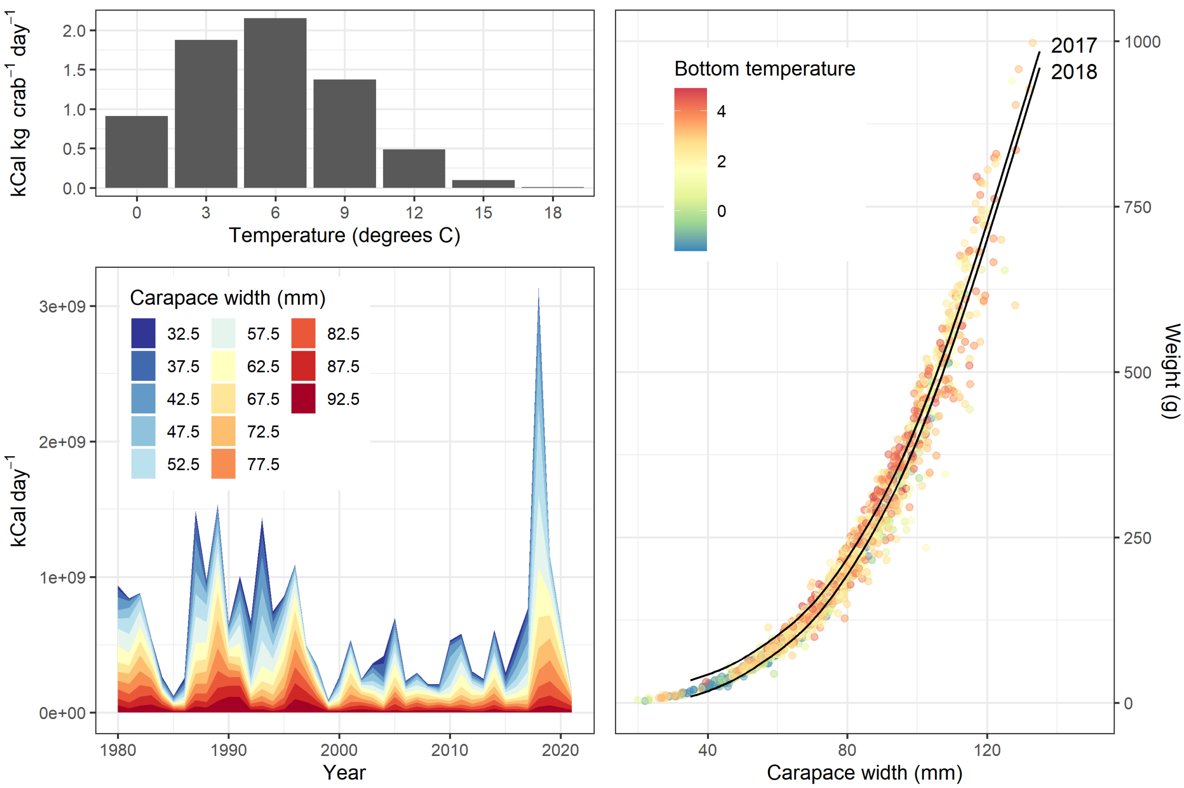

Figure 3: Impact of temperature on caloric requirements for snow crab in the lab (a; reproduced from Foyle et al., 1998), the extrapolated caloric requirements for crab in the eastern Bering Sea based on temperature, abundance at size, and weight at size (b), and the observed weight at size colored by the temperature at which the crab was collected (c). The lines represent the relationship between weight at size in 2017 and 2018 while holding temperature at 1 degree.

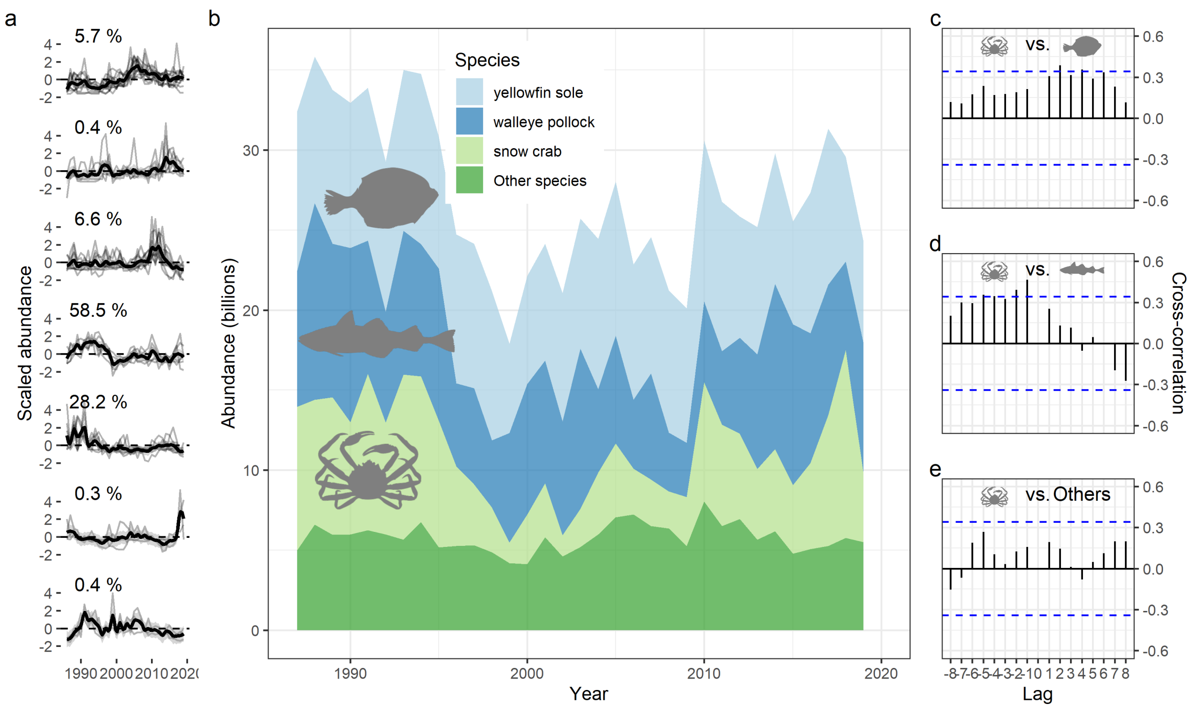

Figure 4: Time-series of scaled abundances of animals captured in the NMFS summer bottom trawl survey clustered using hierarchical clustering (a; 55 species represented, percentage in the top left of the panel represents the average proportion of the total abundance in that cluster) and total abundances over time for the three most abundance species in the bottom trawl survey and all 'other species' combined (b). Panels c-e are the cross-correlation between the time series of abundance for snow crab against yellowfin sole, walleye pollock, and other species, respectively.