Thresholds in a changing ocean environment: bioeconomic implications to inform adaptation decisions for Alaska's salmon fisheries

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Alaska is expected to experience ocean acidification (OA) faster and more intensely than other parts of the globe, primarily due to its cold water which has a higher capacity to absorb CO_2. Yet, little is known about the way species in Alaska may respond to OA. Peer reviewed research has been conducted on only 14 of Alaska's marine species, and while this body of literature is growing, most commercial fish species have not been studied. With a $5.8 million seafood industry and a population reliant on healthy oceans for subsistence, nutrition, and livelihoods, OA is expected to have serious implications for the state.

Among the concerns relating to OA, the potential impact to salmon has emerged as one of the top priorities, as identified during a 2016 statewide OA workshop and a recent OA stakeholder survey on information needs. The wholesale value of commercially caught Alaska salmon exceeded $1.2 billion since 2010 and Alaskans harvest over 12 million pounds for their own consumption annually. This is equal to one third of all wild foods they consume. However, despite salmon being the backbone of Alaska's fisheries, there are only two studies that have looked at salmon response to OA, both conducted outside of Alaska. Research shows that OA impairs coho salmon's olfactory senses and their ability to detect prey and negatively affects pink salmon growth rates. Other potential impacts to growth, metabolism, behavior and changes to prey quality and availability, remain unknown.

For Alaskans dependent on salmon, understanding how they may fare in a higher-acidity environment, and the cultural and economic implications of their response, is critical. Formally evaluating the risks of OA and related thresholds to salmon fisheries, and assessing the benefits of pre-emptive human responses is needed for adaptation planning and decision making. This is particularly important in Alaska, as the state's constitution mandates salmon populations to be managed according to maximum sustainable yield, thereby providing less room for adaptive ecosystem-based management approaches such as the response to, or avoidance of, regime shifts. Therefore, understanding the legal and institutional barriers to implementing OA adaptation strategies is critical for a management transition.

The project's objectives are to: A) leverage ongoing salmon data synthesis to identify critical ecosystem and socio-economic indicators, their current status and synergistic thresholds resulting in system-wide regime shifts; B) develop a dynamic ecological-economic model to simulate management scenarios with human-ecological feedbacks; C) reduce model uncertainty by conducting a laboratory study investigating the combined direct and indirect OA response in chum salmon as a case study; D) identify barriers to implementing adaptation and management transition plans; E) engage affected stakeholders and managers to guide the science and co-produce the plans; and F) communicate the project's scientific and planning results to legislative decision makers, fishermen, salmon-dependent communities, and wider scientific circles.

PROJECT DESCRIPTION

TOPIC AND REGION

This proposal addresses the need for integrated multi-disciplinary research on the impacts of OA and the influence of tipping points on Alaska's fisheries. We use the test case of Alaska salmon fisheries and their management to examine what scientific information is critical for minimizing the risk of ocean acidification (OA). We focus our investigation on the response of salmon, particularly chum (*Oncorhynchus keta*) in the Gulf of Alaska (GOA). The majority of commercially caught chum are harvested in the GOA (ADFG, 2018). Even though chum are the least valuable salmon species harvested by Alaska's commercial salmon fisheries, they have ranked second to pink (*O. gorbuscha*) in average annual harvest volume since statehood. Chum are also one of the most important subsistence foods in Arctic, Western, and Interior Alaska. Due to the broad geographic distribution of chum across Alaska, their importance to various fishing stakeholders, and the size of harvested biomass, chum salmon are a good indicator species to investigate potential synergistic thresholds synthesizing statistical patterns across large numbers of ecosystem and socio-economic indicators. Some of the indicators we will be investigating range from permit prices and ex-vessel prices to harvest volume and average fish size. Besides the analysis of regime shifts, we will use the results from a dynamic stochastic bioeconomic model to create decision tools for salmon managers. This bioeconomic risk analysis will also inform fisheries OA adaptation strategies across Alaska and elsewhere.

OBJECTIVES AND PRESENT STATE OF KNOWLEDGE

Alaska's coastal waters are particularly vulnerable due to high CO_2 solubility at cold seawater temperatures and naturally high seawater CO_2 (Fabry et al., 2009). While the literature on OA and its effects on fish is quickly expanding, there is little research focusing on Pacific salmon (Williams, unpublished, Hamilton et al., 2014). Direct effects on fish behavior can lead to higher mortality due to increased predation (Dixson et al., 2010; Munday, 2015). Other behavioral effects include increased fish anxiety in juveniles (Hamilton et al., 2014), and increased migration intensity (Hellström et al., 2016). Particularly, early life stages show behavioral impacts combined with a reduction in growth and oxygen uptake capacity (Ou et al., 2015). Although these effects are reversible in some fish (Hamilton et al., 2014), observed direct effects on juvenile coho (*O. kisutch*) seem to be irreversible (Munday, 2015). Similar results were found for other fish species (Busch and McElhany, 2016; Marshall et al., 2017).

Indirect effects of OA—alterations of tropic interactions—are key factors determining Pacific salmon survival, their abundance and productivity. While the diets of salmon are diverse, certain prey items show consistent and quantitatively important patterns including copepods, euphasids, hyperiids, and pteropods (Armstrong et al., 2008; Aydin et al., 2005; Karpenko et al., 2007). Pteropods, copepods and hyperiids are predicted to face adverse but varying effects under future OA conditions (Almén et al., 2016; Bednaršek et al., 2017; Cripps et al., 2014; Passarelli et al., 2017). In years when pteropods and other non-crustacean prey were dominant components in the diet during critical growth periods, pink salmon feeding, growth and survival were significantly higher than when a copepod-based food web prevailed in GOA (Beauchamp et al., 2007; Cross et al., 2009). It is likely that reduced prey availability will represent negative direct effects on salmon by reducing consumption and growth and thus survival via size-selective mortality. Experiments measuring the energetic response of fish exposed to future OA conditions showed reduced ability to respond to rapid fluctuations in food availability (Cripps et al., 2014). Ultimately, the direct and indirect effects could reduce recruitment success and have far-reaching consequences for the sustainability of fish populations and fisheries (Munday et al., 2010).

A recent review of economic studies related to OA found that almost all studies predict negative economic effects consistent across taxa and ecosystem services (Falkenberg and Tubb, 2017). Colt and Knapp (2016) conclude that under a scientifically plausible level of OA, a complete collapse of marine capture fisheries by 2200 is plausible. While there is a growing literature discussing the topic, bioeconomic assessments that explicitly link environmental change to changes in the economy and vice versa are few. The key challenge for more detailed risk analyses are associated with the complexity and the multi-disciplinary nature of integrating biology with economics (Armstrong et al., 2012). In order to inform current and future decision making on human adaptation, analysis of the direction, magnitude, and probability of economic change is needed (Yates et al., 2015). This project will fill this gap for Alaska's salmon fisheries by incentivize preemptive changes in management and inform adaptation for the world's most valuable wild salmon fisheries, by aiming to achieve the following objectives:

A. Identify and then synthesize knowledge on critical ecosystem and socio-economic indicators, their current status and synergistic thresholds resulting in potential system-wide regime shifts.
B. Develop a dynamic ecological-economic model to simulate salmon management scenarios with human-ecological feedbacks.
C. Address key uncertainties identified in A. and B. by conducting small-scale laboratory experiments and use the results to validate and further refine the developed model in B.
D. Identify barriers to implementation throughout existing fisheries governance structure.
E. Engage affected fisheries stakeholders and ADFG salmon management in the project early on to guide relevant research outcomes that inform a management transition plan and fisheries adaptation plan for affected stakeholders.
F. Communicate scientific results to wider scientific communities and OA researchers and distribute co-produced OA adaptation plan to wider fishing communities.

RESEARCH ACTIVITIES AND EXPERTISE

Below we outline the methods for accomplishing each of the objectives in chronological order.

A. Identify and then synthesize knowledge on critical ecosystem and socio-economic indicators, their current status and synergistic thresholds resulting in system-wide regime shifts.

We propose to use statistical methods for identifying non-linearities and driver-response mechanisms for regime shifts in the GOA. Biophysical examples of currently known regime shifts include kelp forests and reefs along the Aleutian Chain and the pelagic zone in the GOA. Further, dissolution of pteropod shells observed in the GOA can serve as biophysical early warning indicators for OA as well as other key ecosystem attributes (e.g. freshwater input, water temperature, etc.). Examples of socio-economic shifts include local and global drivers such as social change, access to capital and the onset of salmon farming resulting in permit ownership decline in rural coastal communities and price declines respectively. The Co-PIs will use their ongoing and soon to be completed multi-disciplinary synthesis of existing historical salmon data

(NCEAS Exxon Valdez portfolio effects working group, SASAP) and leverage spatially-specific research on OA sensitivities of zooplankton in the GOA and other high-latitudes.

Tipping points and thresholds. To identify tipping points and thresholds, we will implement standard metrics for time series analyses of critical slowing down periods, including changes in autocorrelation or variance (Litzow and Hunsicker 2016). This previous work has suggested that decreases in autocorrelation or increases in variance may be indicators of critical tipping points. We propose to apply each of these metrics in a temporal setting (or spatio-temporal for spatially referenced data) to identify data support for tipping points or thresholds. As a second phase of this analysis, we will implement statistical models that have been previously used to identify the shapes of non-linearities, as well as thresholds associated with these (Samhouri et al. 2017). These approaches include segmented regression, generalized additive models (GAMs) and gradient forests. Output from this analysis will be used to identify which driver – response relationships may be most sensitive to perturbations.

Identification of shared regimes across taxa. One of the challenges in synthesizing patterns across large numbers of ecosystem or socio-economic indicators is that (1) data collected from different sources has different levels of precision, including variable amounts of observation or measurement error, and (2) identifying common trends or drivers may be complicated, particularly when datasets are combined across spatial scales. Examples of these challenges include identifying common trends across salmon species in Alaska (spanning different populations, life history types, geographic regions) or across different fisheries (hundreds of different types of permits in state and federal fisheries, including many individuals who have multiple permits; Anderson et al. 2017).

We propose to use a statistical tool known as Dynamic Factor Analysis (DFA) that is similar to Principal Components Analysis (PCA) but designed for time series data (Molenaar 1985; Harvey 1989). This approach has been recently used in fisheries (Zuur et al. 2003) including applications to Alaska salmon data (Stachura et al. 2014; Ohlberger et al. in press). For a collection of time series, the number of estimated 'trends' is specified a priori, and DFA estimates these latent trends as independent random walks. In mathematical form, this is expressed as

$$\mathbf{X}_t = \mathbf{X}_{t-1} + \epsilon_{t-1}$$

Where $\mathbf{X}_t$ represents the value of *m* latent (unobserved) trends at time *t*, and the process error deviations ϵ_{t-1} are assumed to have arisen from some distribution (In traditional maximum likelihood implementations, these are assumed to be normally distributed with variance fixed at 1 for identifiability). The latent trends are mapped to the observed data **Y** through a loadings matrix **Z** and residual error δ_t,

$$\mathbf{Y}_t = \mathbf{Z}\mathbf{X}_{t-1} + \delta_{t-1}$$

The residual error variance is assumed to be drawn from a univariate or multivariate normal distribution, where variances may be shared or not across time series, as well as correlated or not. Our implementation of the DFA model has been done in a maximum likelihood framework (Holmes et al. 2012) and more recently in a Bayesian setting. The Bayesian framework is more flexible, allowing for different modeling of extreme values, and incorporation of autoregressive and moving average model components.

Hidden Markov Models to detect regime shifts. We propose to use Hidden Markov Models (HMMs; Elliott et al. 1995) to identify regime shifts, both in the raw datasets, and in the output from the Bayesian DFA model described above. HMMs (also referred to as state-space switching models) describe a statistical approach for modeling a latent, unobserved state of nature. For a sequence of observations Y_t , the HMM evaluates $P(Y_t|S_i)$ where S_i is a discrete and unobserved state. Because the latent transitions between states are modeled as a Markov Process, this framework also allows for estimation of derived quantities. Examples include the probabilities of transitioning between states (e.g. $P(S_i|S_j)$ or the transition from j to i), and the expected time duration spent in each state. More complex extensions of these basic models include allowing for static or time-varying covariates to affect the state transitions, or observation model, and these extensions will be considered in our modeling. Estimation of HMMs will be done using the R packages *depmixS4* (Visser and Speekenbrink 2010) and *bayesdfa* (co-authored by PI Ward).

Forecasting regime switching. Our combined analysis of DFA with HMMs will allow us to identify the latent regimes in a large number of bioeconomic and ecological time series. Results from these models will allow us to identify current states of nature, and also develop models for forecasting. Our work predicting future regime states and transitions will rely on models where there is data support for the inclusion of predictors in HMMs (particularly in the transition matrices). For example, if the effect of sea surface temperature (SST) is found to affect the transition matrices of the HMM models of ecological indicators, downscaled global forecasts of SST change can be used to make predictions of SST on a fine spatiotemporal scale, and consequently predict the probability of switching to alternate regimes in the HMM framework. Forecast lengths will be dependent on the timescale that predictions are provided for (e.g. SST may be predicted several years in advance, PDO may be predicted on a shorter time scale).

B. Develop a dynamic ecological-economic model to simulate salmon management scenarios with human-ecological feedbacks.

Due to a lack of available data and the forward-looking nature of the analysis, we propose the development of nested bioeconomic models that incorporate the estimation of thresholds in part A to examine the implications of (OA) and its associated uncertainties, for fisheries management of GOA salmon. Bioeconomic models have been used in the past to evaluate the affects of OA on crab fisheries (Seung and Dalton, 2015) and to evaluate fishery efficiency in Alaska (A'mar et al., 2009; Carney and Adkison, 2014). Bioeconomic models have also been used in Alaskan marine ecosystems to estimate the sensitivity of fish and nonfish species, including Stellar sea lions, to fishery management in Alaska (Finnoff and Tschirhart 2003a; Finnoff and Tschirhart 2003b).

The modelling framework builds on a presumption that CO_2 levels may cross a threshold at some date T in the future leading to significant impacts on the GOA ecosystem. This time T will be calibrated to incorporate results of the combined DFA and HMMs analysis, including our forecast transition times based on current GOA conditons. Dividing time into the ex ante, pre-OA interval $t < T$, and the ex post, post-OA interval $t \geq T$, allows us to focus on how pre-OA management influences the initial states of nature in the post-OA management problem. As demonstrated by Finnoff et al. (2016) and Horan et al. (2018) the framework brings into ex ante management a consideration of ex post impacts of ex ante decisions. The initial conditions of the ex post problem (when the impacts of OA are felt) are determined by ex ante escapement and hatchery release rules.

The OA impacts we propose to consider include pteropod (salmon prey) growth (McLaskey et al., 2016), salmon predator response (Williams unpublished, other fish species Dixson et al., 2010), salmon growth rates, and salmon predation efficiency (Ou et al., 2015; Fivelstad et al. 2018), all of which present fundamental changes to current state of the art salmon management models (see Fleischman et al 2013). Previous ecosystem models highlight the coupled nature of the ecological and economic systems (Finnoff and Tschirhart 2008; Brock et al. 2009). The potential for feedbacks in these types of ecological-economic models is well documented in the literature (Finnoff and Tschirhart 2005). The ecological and economic response to these consequences have serious implications for salmon fishery management. Sensitivity analysis related to the bioeconomic model will uncover key parameters and consequences.

The uncertainty related to the timing of crossing a threshold is commonly modelled as a Poisson-distributed shock to either resource dynamics or the resource stock (Polasky et al., 2011; Reed and Heras, 1992). The existence of tipping points can lead to either precautionary management to protect valuable resources, or to more aggressive harvest due to the higher risk of losing the resource (Polasky et al., 2011; Berry and Finnoff 2016). These competing effects depend on the context of the problem, and can lead to different qualitative prescriptions for the optimal management policy (Berry et al. 2015). Typically, when the risk of crossing the threshold is beyond the control of managers haste trumps precaution. Recent work has also shown how the existence of these tipping points can impact the value of "natural insurance", or forgone harvest which increases the probability of being in a good post-threshold world (Finnoff et al., 2016).

Our proposed work will examine how the existence of natural insurance in the form of increased salmon escapement or hatchery release changes management incentives in response to foodweb interactions and OA tipping point risk. We hypothesize that tipping points in the context of natural insurance can lead to precautionary behavior even when risk is exogenous. Salmon fisheries responding to OA risk do not have a one size all policy solution, instead the best response will be context dependent. Our goal is to highlight which parts of this context provide the greatest information.

Predator-prey model. We propose to construct a model of the system after an OA threshold has been crossed. This threshold can include various effects on either salmon or their primary prey, pteropods. It is vital that the model be flexible to the results of the lab experiments included in this proposal. We will model the ex post scenario in discrete time to incorporate key characteristics of salmon populations, namely the methodology of existing stock assessments that are employed in estimating the number of spawning salmon in a given period (Fleischman et al 2013).

This model will include predator prey interactions between salmon (S) and prey (P). The evolution of Salmon populations overtime can be captured through a basic stock-recruitment model (Fleischman et al 2013), and prey through density and OA dependent growth. Adult salmon (S_t), where subscripts denote time, spawn once at rate $F(S_t)$ creating recruits (R_t) and are harvested (H_t). The stock-recruitment relation includes hatchery releases (r_t) the predation of prey (P_t) and incorporates the potential of OA affecting the efficiency of salmon predation and growth ($G(P_t, S_t; OA)$, in an additively separable fashion:

(1) $R_{t+1} = r_t + F(S_t) + G(P_t, R_t; OA) - M\big(R_t, K(P_t, S_t; OA)\big)$

Immature salmon mature at a rate $M(.)$ which depends on the amount of recruits, available prey and predation efficiency of adults $K(P_t, S_t; OA)$ which also depends on OA state of the world. Some fraction of salmon are harvested before they are able to spawn (H_t), so that the dynamics of adult salmon are given by

(2) $S_{t+1} = M\big(R_t, K(P_t, S_t; OA)\big) - H_t$
and dynamics of salmon prey by

(3) $P_{t+1} = J(P_t, OA) - G(P_t, R_t; OA) - K(P_t, S_t; OA)$
where $J(P_t; OA)$ reflects density dependent growth of prey including the affects of OA. OA may effect the growth rates or carrying capacity of salmon prey directly, or indirectly through the predation efficiency of salmon recruits ($G(P_t, R_t; OA)$) and adults ($K(P_t, S_t; OA)$). The influence of either effect on $J(P_t, OA)$ and $G(P_t, S_t; OA)$will be estimated in our lab experiments. The predation functions $G(P_t, S_t; OA)$ and $K(P_t, S_t; OA)$ will include impacts from OA on salmon behavior that impact their effectiveness as predators, including impacts on their senses and behavior.

Incorporating this model in a standard bioeconomic model of optimal harvesting will allow us to characterize optimal policy after crossing a threshold by choosing harvests H_t and hatchery release r_t levels. We will follow Horan et al (2018) to estimate the value function for the ex post problem using the optimality conditions for the dynamic programming problem to simulate optimal policy and welfare after an OA regime shift. By incorporating non-convexities due to predator prey interactions, there is a potential for multistability where initial conditions determine the movement of the system into one of several different basins of attraction. Once we have an estimate of the value function we will also know the expected value of the system from any initial condition.

Poisson model – quantifying uncertainty. The next step of this analysis is to incorporate uncertainty about the transition from a low OA world to a high OA world using a hazard rate to represent the uncertain timing of crossing some threshold where the ecosystem is first negatively impacted (Polasky et al., 2011; Reed and Heras, 1992). This hazard rate can be defined as the probability of time t being t = Ʈ, where Ʈ is the moment the system crosses some OA threshold, given that it has not yet occurred. There is a possibility of multiple impacts of OA occurring at different times and levels of OA, however this model is flexible to the inclusion of multiple hazards.

We will follow the literature on tipping points to transform this problem into one of deterministic optimal control (Reed and Heras, 1992) and examine how the existence of a threshold impacts management before it is crossed. The expected value of the ex post problem, or the value of a set of initial salmon stock and prey stock given optimal control, is the value function $V(p_T, S_T, e)$ which includes the uncertain impacts of OA, represented by e, that includes impacts on salmon and pteropod growth rates, the predation rate, or other effects identified by our experiments. We assume that this ex post value function has the potential for multistability which depend on initial salmon and pteropod populations, and the uncertain impacts of crossing the OA threshold. Following Horan et al. (2018) we will define a probability density function $\phi(e)$ and managers will weigh the potential impacts of OA in their ex ante decisions. We will assume multistability where conditional on the impact of OA the system falls into either a superior or inferior basin of attraction in the ex-post. The probability of being in one basin of attraction or another depends on the stocks of pteropods and salmon and the actual impacts of OA. We can estimate the value of any initial level of salmon and prey, conditional on OA damages, in the ex post as

$$W(s_T) = \int_0^{s_T} V(p_T, S_T, e)\phi(e)\, de.$$

Previous work has shown that there is a potential for multistability in the post threshold world to create multistability in the pre-threshold world as managers invest in natural insurance (Finnoff et al., 2016). In our model, investing in natural insurance involves adjusting escapement and hatchery release levels. It is not clear, based on the predator-prey relationships and the uncertainty related to the specific implications of OA whether risk should increase or reduce the optimal hatchery releases and escapement levels. Higher salmon populations will put more pressure on potentially less productive prey populations. Lower salmon populations that return to reproduce at a lower rate could additionally lead to extirpation.

Social Goals. Additionally, we will incorporate various social goals including minimum requirements to maintain a commercial fishery and minimum subsistence harvests for community viability. Commercial fisheries depend on some minimum financial return to justify large capital investments. Similarly, the ability of individuals to maintain a subsistence lifestyle depends on some minimal productivity, even in low return years. Both act as constraints for managers concerned with the sustainability of the fishery and the communities that depend upon it. By constraining management options, we increase the probability of multistability and complicate the ability of managers to optimally manage the resource (Fenichel and Horan, 2016). The uncertain nature of the consequences of OA for the pteropod-salmon relationship and social constraints on managers can have non-monotonic impacts on the value of (in situ) salmon. Changes in this value will influence whether the marginal salmon is a "good" or a "bad" and whether managers should invest or divest in the resource to ensure not only ecological, but also social sustainability.

C. ***Address key uncertainties identified in A. and B. by conducting small-scale laboratory experiments.***

OA Lab study. The physiological and behavioral effects of OA on early stages of marine fish have been broadly examined through laboratory controlled studies (e.g., Hurst et al. 2013, Ou et al. 2015, Fivelstad et al. 2018), however no known studies have examined potential indirect and interactive effects of reduced prey quality and quantity with varying levels of OA. Increasing pCO_2 has shown to negatively affect zooplankton growth (Pedersen et al. 2014), reproduction (Kurihara et al. 2004, Zervoudaki et al. 2013), survival (Mayor et al. 2007, Zervoudaki et al. 2013, Cripps et al. 2015) and fatty acid content (Rossoll et al. 2012, Bermúdez et al. 2016). Incorporation of indirect effects through food limitation as a factor within levels of pCO_2 on measures of growth would address a significant gap in knowledge while the results can furthermore be scaled-up to populations by incorporation into existing stock assessment models for chum Salmon in the GOA.

For the wet laboratory component of this proposal, we will compare growth indices in juvenile (fry) chum salmon cultured across different pCO_2 and ration treatments that incorporate current and future OA conditions. This study will be carried out at the Aleutiiq Pride Shellfish Hatchery with supporting staff from the Alaska Sea Life Center in Seward. As fish holding/culture tanks and continuous OA monitoring using a "Burk-o-lator" are already set up and functional in the facility's OA wetlab, we will require funding to build an OA system for maintaining and monitoring pCO_2 levels across tanks. The goals of the wet lab study are: to generate a growth-based predictive model, provide updated growth and condition inputs as indicators for current stock assessment models, and to get an initial mechanistic understanding of underlying physiological changes that determine how and why juvenile chum salmon are affected by OA conditions in terms of food limitation and pCO_2. Fish for the laboratory study will be obtained from the Ester Island Hatchery (Prince William Sound Aquaculture Corporation), Alaska. To compare the effect of pCO_2 and food limitation on growth of juvenile chum, we will culture fish across three pCO_2 treatments with each having a growth-based and reduced ration. In addition to providing pCO_2 and ration dependent growth model inputs for the stock assessment, this wet lab component will inform our understanding of how juvenile chum salmon can be affected directly by OA conditions and indirectly by food limitation.

Laboratory Experimental Design: Fish will be cultured at four pCO_2 treatments. In each pCO_2 treatment, fish will be fed two different rations of a pellet-based diet, with triplicate culture tanks for each (n = 3 tanks/ pCO_2 treatment + 2 rations; 24 tanks total). The pCO_2 treatments will include an ambient pCO_2 level based on levels off Seward Alaska (~400 ppm), below ambient (100ppm), and a mid-level (700 ppm) and high level treatment (1,000 ppm) above ambient based on projected levels by Mathis et al. (2015) for the Pacific-Arctic region. Ration treatments will be at two levels, one growth level of 2.5% body weight/day, and a reduced level of 50% of the growth ration. Rations for all treatments will be adjusted for each tank in terms of the mean biomass of fish through time as they grow. We will utilize formulated food in order to avoid potential issues with food digestibility and changing energy content as might happen if we use wild prey items as feed. Upon delivery of fish from the hatchery, fish will first be allowed to acclimate for 1 week at ambient pCO_2 levels and feeding at the growth ration (2.5% BW/day), then subsequently switched to their respected pCO_2 and ration treatments for a total of 13 weeks. Each tank is 100L and will hold 250 chum fry at the start of the study (n = 6,000 fish total). A total of 8 fish/tank will be sacrificially sampled every week (n=192), with individuals measured for fork length (±1.0mm), blotted wet weight (±0.01 g), and then dried in a drying oven (50^{0}C) for 36hrs and reweighed for dry weight (±0.01g). Tracking these growth and condition indices and how they change over the study period will allow us to better understand physiological responses to different food and pCO_2 treatments.
pCO_2 generation system and monitoring. The system to generate pCO_2 treatments will follow a modified version developed by Fangue et al. (2010). The system consists of a series of mass flow controllers to produce and maintain desired pCO_2 levels which are bubbled into gas-mixing reservoirs for equilibration with filtered seawater. This seawater is then delivered to fish culturing tanks thus providing study organisms with a continuous supply of clean seawater consistent with optimal culturing methodologies. Monitoring of pCO_2 levels will be performed by a monitoring system (termed "Burk-O-Lator", developed by Burke Hales, Oregon State University) that uses pCO_2/TCO_2 analyzers to take highly accurate continuous measures of seawater pCO_2, total dissolved inorganic carbon (TCO_2), temperature, and salinity. Using these four parameters, the saturation state of aragonite (Ω_{arag}) and pH can be tracked in real-time. The wetlab and monitoring system will be operated by staff from the Alutiiq Pride Shellfish Hatchery.

Bioenergetic modeling. We will use the laboratory studies of captive fish to parameterize bioenergetics models that describe the growth and condition of juvenile chum Salmon during their first year of life in response to variable OA conditions. These models will be based on components of the traditional Wisconsin bioenergetics model which incorporates temperature-dependent responses in physiological processes (Kitchell et al. 1977). However, in lieu of temperature response, we will evaluate pCO_2-dependent response in growth, consumption, and conversion efficiency for juvenile chum Salmon. The pCO_2 model will be used to evaluate growth performance of chum Salmon over their first year of life under a range of habitat conditions. We will model growth and condition of age-0 chum Salmon across a range of scenarios representing different combinations of pCO_2 conditions (based on observed seasonal pCO_2 from data collected by the Alutiiq Pride Shellfish Hatchery; personal communication Hetrick 2018), and prey quantity (high and low ration size). Size and condition of modeled fish will be compared to observations of wild caught Chum Salmon to corroborate model outputs and to inform aspects of the model which need further refinement.

Historic and projected pCO_2 levels from Seward and GOA will be used to develop hindcast and forecast models of juvenile chum growth and condition through time. Outputs from our hindcast model will be compared to measurements of surveyed wild caught fish to assess the ability of our model to accurately describe the size and condition of chum Salmon under variable OA conditions. This will allow us to develop forecast scenarios utilizing a plausible range of habitat conditions that would lead to different growth and nutritional outcomes for juvenile chum Salmon. Model outputs from a range of seasonal pCO_2 and prey quantity scenarios will be used to develop indicators of juvenile condition and growth that can be used to better estimate the recruitment deviations estimated in the chum Salmon stock assessment. These indicators may be used to better predict future recruitments impacted by rising OA levels, thus influencing future management and harvest allocation strategies and allotments. Engage affected stakeholders, communities, and state salmon management in OA adaptation planning and research processes; and better understand how information on ecological and economic tipping points informs decision making.

D. Identify barriers to implementation throughout existing fisheries governance structure.

Co-PI's previous work. Dr. Marie Lowe, an Associate Professor of Public Policy and Anthropologist at the University of Alaska Anchorage's Institute of Social and Economic Research has past research experience on Alaska policy topics relevant to the proposed study including: community impacts of fisheries restructuring and coastal community viability; institutional study of land tenure arrangements and salmon habitat management; and local and scientific knowledge of salmon ecology in Alaska.

Fisheries governance. In leading this objective, Dr. Lowe will begin by defining the GOA fisheries governance structure. "Governance" is a term of art; more inclusive than its cognate, "government," in that it implies broader stakeholder involvement in decision-making than traditional command and control management and regulatory regimes. As applied to fisheries management, in most contexts the governance concept can encompass three modes: (1) the hierarchical mode; (2) the market mode; and (3) the participatory mode (Vliet and Dubbink 1999; Gray 2005). The hierarchical mode refers to state directed, administrative management and decision-making; informed by science and guided by the rule of law. The market mode refers to forces of supply and demand and private property regimes. The participatory mode refers to various types of stakeholder participation such as self-regulation and co-management models as well as participation by a range of non-governmental entities from industry participants to tribes and conservation groups.

Identifying barriers to implementation. Although most fisheries governance regimes are a mix of these three ideal types (Gray 2005), like many other areas of the world, Alaska is primarily characterized by the hierarchical and market-based modes with the participatory mode oftentimes remaining the ideal rather than the reality. However, the term "governance" implies decentralization and devolution processes—arguably critical in addressing complex environmental problems like OA that are globally sourced but locally experienced (Ekstrom and Crona 2017). Participatory stakeholders can lend an intimate perspective on environmental change valuable to the governance process. Moreover, Mumby et al. (2017) argue climate change could result in management agencies experiencing reduced budgets and therefore reduced ability to adequately monitor resource use and changes as well as enforce regulations. This scenario could emerge at a time when there is in fact a greater need for management, i.e. both ecosystem-based and adaptive management. These issues speak to a possible lack of fit between environmental threats and governing institutions, i.e. “institutional gaps” (Ekstrom and Crona 2017) which could contribute to the range of potential barriers to implementation of the Alaska Salmon Fisheries OA Adaptation Plan.

Methodology. The study of governance structures will use institutions as the unit of analysis. Institutions are defined as “systems of agreements, rules, rights, laws, norms, beliefs, roles, procedures and organizations” (Kooiman and Bavinck, 2005:17). PI Lowe will adapt the analytical framework developed by Ekstrom and Crona (2017) for understanding the “ecological-institutional fit” in the Alaska context for response to OA and impacts to salmon populations. This framework entails a three-step process: (1) As informed by products of the proposed research, build a model of the GOA social-ecological system (SES) affected by OA; (2) identify policy/institutional gaps associated with OA in Alaska; and (3) map which organizations are responsible for the needed regulatory structure identified in step (2). This analysis and policy recommendations will then be presented for feedback at the stakeholder workshops and refined prior to development of the Alaska Salmon Fisheries OA Adaptation Plan for inclusion within the plan.

E. ***Engage affected fisheries stakeholders and ADFG salmon management in the project early on to guide relevant research outcomes that inform a management transition plan and fisheries adaptation plan for affected stakeholders.***

This project will go beyond communicating and disseminating research by engaging stakeholders directly in the research process and outcomes from the start of the project. Meridian Institute, a national not-for-profit organization specializing in facilitating consensus-based ocean planning will facilitate a project kick-off-meeting and four workshops aimed at developing the Alaska Salmon Fisheries OA Adaptation Plan (OA Adaptation Plan) with Management Transition Plan.

We will structure the engagement of Alaska’s salmon users through a nine-member strong fisheries participatory group (FPG) that’s overseen by a three-person steering committee (SC). The project’s Advisory Committee (AC) will include scientists who are experts in the proposed science and two representatives from the Alaska Department of Fish and Game (ADFG) responsible for Alaska salmon management. While the SC will approve the OA Adaptation Plan, the AC will be responsible for developing and implementing the Management Transition Plan

Steering Committee Coordination. A Steering Committee (SC) will be established to work with the facilitator and PIs to collaboratively design and guide the stakeholder engagement process. The SC members will participate in all planning activities and review, approve, and aim to implement the final OA Adaptation Plan. The SC will consist of about three Alaska salmon users in leadership positions representing subsistence, commercial, and sport salmon fishing interests. Meridian will recruit the three SC members. A project kick-off meeting including the SC, AC, and the PIs will take place at the outset of the project to co-design planning activities and align sequencing of workshops with research activities. A stakeholder engagement work plan will be refined, including objectives, outcomes, timeline for implementation, and scoping activities.

Fisheries Participatory Group. A nine-member Fisheries Participatory Group (FPG) consisting of Alaska commercial and subsistence salmon permit holders will be recruited by Meridian and participate in four facilitated planning workshops. Meridian and the PIs will work with the SC to consider a range of factors in selecting FPG members to be representative of Alaska's salmon regions, type of fisheries, diverse attitudes towards climate change, backgrounds, and socio-economic characteristics. Particular emphasis will be given to recruiting influential people willing and able to implement change related to a fisheries adaptation plan. Relevant salmon fisheries in Alaska may include Western Alaska (Yukon, Kuskokwim, Kobuk Rivers), Prince William Sound, Southeast Alaska, and/or Kodiak. The SC will approve final participants to the FPG and ensure adequate representation across interest groups. The FPG will work with select members of the project team to ensure that the research remains relevant for stakeholders and will inform adaptation planning.

Stakeholder Scoping. Meridian will conduct scoping of existing information and use key informant interviews to inform and recruit participants in the FPB and SC. Specific activities include:

- Integrate the scientific research results from other objectives into the scoping and planning process and vice-versa collect stakeholder perspectives on ocean changes that can be used to guide model assumptions and validation.
- Conduct targeted interviews of a sample of stakeholders representative of various salmon fisheries and geographies in Alaska to better understand adaptation capacities and issues.
- Develop a summary of recent scoping efforts including recent OA outreach surveys conducted by United Fishermen of Alaska and the Alaska OA Network.

Workshops. Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) participatory modeling will be used to structure a deliberative learning-based process that integrates local knowledge with project's scientific information (Webler et al., 2016). The timing and goals of the four workshops are proposed to coincide with anticipated research outputs from Objectives A-D to identify adaptation actions, strategies, and capacity needs.

The planning process will follow five guiding principles for dealing with uncertainty in fisheries affected by climate change established by AC member Dr. Knapp: 1) assemble and integrate the best available information about how fisheries resources may change; 2) allocate in ways that reduce risk from resource change; 3) geographic changes in fish distributions require mobile fishing and processing capacity; 4) facilitate responsible use of new fishing opportunities; 5) plan for resource decline and understand assistance and compensation schemes (Knapp and Livingston, 1998; McIlgorm et al., 2010). AC member Dr. Knapp will provide insights from his decades of research related to Alaska's salmon fisheries and Dr. Lowe will inform planning efforts about institutional barriers to implementing the OA Adaptation Plan (Obj. E).

The schedule will be adjusted in consultation with the SC and PIs to make the best use of stakeholder time. Anticipated locations of the workshops include: Kodiak, Juneau Anchorage and a location in western Alaska (e.g. Bethel, Kotzebue, or Nome).

F. ***Communicate scientific results to stakeholder communities, including fishermen, resource managers, coastal residents and scientists.***

This objective will be led by Darcy Dugan, Director of the Alaska OA Network. The Alaska OA Network was established in 2016 to engage with scientists and stakeholders to expand knowledge on OA processes, consequences, and adaptation strategies. Network members range from academic and agency scientists to fishermen, shellfish growers, Tribes, educators, and coastal residents. The network facilitates six topic-specific working groups and provides the ability to leverage existing pathways of communication and information sharing. The Alaska OA Network will collaborate with the project scientists to perform the following outreach activities:

1. **Develop project webpage**. AOOS will construct a project website nested within the Alaska OA Network domain, providing a project overview, list of key participants, research activities, findings, and appropriate links.
2. **Collaborate with PIs to distill scientific information for a lay audience**. AOOS will work with PIs to develop content using terms and examples that convey scientific results in an understandable manner to a lay audience. This content will then be used for outreach materials and presentations, and circulated to the Alaska OA Network's working groups for further distribution to relevant stakeholders, including the United Fishermen of Alaska's routine correspondence to salmon permit holders. Over the course of the project, outreach materials will include 1-pagers, web content, stories for newsletters, and an overview poster.
3. **Circulate project news through various communication channels.** Project activities and findings will be shared through the Alaska OA Network's monthly e-News which goes to over 1,100 people, as well as the network's website and Facebook page. AOOS and PIs will also contribute to the new OA Information Exchange (OAIE) hosted by NOAA's OA Program to ensure wide-reaching information exchange.
4. **Present research results at relevant venues**. AOOS will work with the PIs to present research results at venues across the state and beyond targeting affected stakeholders at: Alaska Marine Science Symposium (Anchorage), Pacific Marine Expo (Seattle), CommFish (Kodiak), Young Fishermen Summit (Anchorage), Alaska Center for Climate Assessment and Policy monthly webinar series, and a United Fishermen of Alaska annual meeting. A briefing to the Alaska Legislature's Resources or Fisheries committees is also planned.
5. **Share research findings through local radio shows.** Because coastal Alaska communities rely heavily on local radio, AOOS will help organize a radio program in one or more salmon fishing communities such as Petersburg, Cordova, Homer, Kodiak, and Juneau where project PIs can explain their research and answer questions.
6. **Design OA exhibit at the Alaska SeaLife Center.** AOOS will work with Alaska SeaLife Center education staff to design an OA exhibit.

PROJECT SIGNIFICANCE FOR ACHIEVING OAP PROGRAM PRIORITIES

The proposed research achieves OAP's primary goal of *understanding the exposure of marine resources to changing ocean chemistry* through Objectives A and C, *education and outreach* through Objective F, and *information for optimal adaptation* through Objectives B, D, and E. The outcome-based management goals are to first develop a fisheries management transition plan applying the research to management decision-making (Objectives A and B) and second co-produce the OA adaptation plan together with Alaska's salmon users (Objective D and E). These outcomes are also consistent with NOAA Fisheries Strategic Science Plan (Theme 2) to understand and forecast the effects of climate change on marine ecosystems.

Appropriate partnerships are in place between multi-disciplinary scientists from NOAA's Alaska Fisheries Science Center and academic institutions, ADFG fisheries managers, United Fishermen of Alaska (Alaska's largest fishing industry trade group), subsistence fishing interests, Alaska Ocean Observing System, hatcheries, the Alaska SeaLife Center, and Meridian Institute (a non-profit organization with extensive national and international experience facilitating ocean-related initiatives).

The proposed research will produce the three science products outlined on page 10 of the *Thresholds FFO.* These include: threshold detection and data synthesis, dynamic bioeconomic model simulating risk related to various management options, and guidance to fisheries managers about socio-economic and biophysical trade-offs related to their actions.

PROJECT PERSONNEL FUNCTIONS AND RESPONSIBILITIES

Dr. Finnoff—Associate Professor of Economics at the University of Wyoming in Laramie, WY—will serve as Lead-PI, responsible for the project in particular the development of the bioeconomic model (Obj. B) conditional on research results from Obj. A, C, D, and E. Dr. Finnoff will supervise one PhD student and communicate with the Federal Program Manager on all pertinent verbal and written information between the project team and funding agency.

Dr. Berry—Assistant Professor for Economics at the University of Alaska Anchorage (UAA) Institute of Social and Economic Research (ISER) in Anchorage, AK—will lead the implementation of the bioeconomic model and associated computer simulations (Obj. B).

Mrs. Dugan—Director of the Alaska Ocean Observing System's Alaska OA Network in Anchorage, AK—will lead various outreach activities throughout the project period (Obj. F).

Mr. Hetrick—Managing Director at the Alutiiq Pride Shellfish Hatchery in Seward, AK—will be responsible for modifying the current OA wetlab to suit the proposed experiments including proper pCO_2 dosing for experiments.

Dr. Horning—Science Director at the Alaska SeaLife Center(ASLC) in Seward, AK—will oversee the laboratory experiments conducted at the Alutiiq Pride Shellfish Hatchery's OA wetlab in Seward (Obj. C).

Dr. Krieger—Currently NRC Research Associate at the NOAA AFSC in Juneau and to be hired for this project as ASLC Fish Biologist will be responsible for bioenergetic modeling (Obj. C).

Dr. Lowe—Associate Professor for Public Policy at UAA's ISER in Anchorage, AK—will lead the investigation of institutional barriers to OA adaptation and implementation of policy changes related to project outcomes and recommendations (Obj. E).

Dr. Miller—Supervisory Fish Biologist with the Recruitment Energetics and Coastal Assessment (RECA) Research Program at the Auke Bay Laboratories, Ted Stevens Marine Research Institute in Juneau, AK—will be responsible for the experimental design of the lab study and supervise bioenergetic modeling (Obj. C).

Dr. Schwoerer—Senior Research Economist at UAA's ISER in Anchorage, AK—will provide overall management support for Lead-PI Finnoff by coordinating the project's predominately

Alaska-based collaborators. Dr. Schwoerer will also be the primary liaison to the Advisory and Steering Committees and lead stakeholder engagement facilitated by Meridian Institute (Obj. D).

Dr. Ward—Research fisheries biologist with the Northwest Fisheries Science Center Mathematical Biology and Systems Monitoring Program in Seattle, WA—will lead data synthesis and analysis of regime shifts and supervise a post-doc (Obj. A).

APPLICATIONS TO MANAGEMENT

Changing ocean environments are challenging the status quo of current salmon management in Alaska (See ADFG letter of commitment). Oceanographic studies show that OA may already affect important salmon prey species (i.e pteropod *Limacina helicina*) and their availability in the GOA (Manno et al., 2017). Alaska fishermen in recent years have had growing concerns about OA and its effects on their livelihoods with increased need for adaptation planning to avoid and minimize resource collapse (Dugan. forthcoming. Survey to inform future monitoring efforts in Alaska). Much is unknown about the magnitude and compounding effects of OA and other stressors on Alaska's fish populations. There is a potential for environmental thresholds, which, once crossed are difficult if not impossible to reverse. Further, there is a need to better understand the ramifications for humans from synergistic effects and the implications of human response or lack thereof with potential for additional policy thresholds. Preemptive management is often focused on ensuring society ends up in a preferably pre-threshold world by accounting for the potential post threshold consequences of their actions. Salmon fisheries managers may preemptively adapt to ensure they end up in a preferable post event world (e.g. through more flexible management regimes, changing escapement, or changing hatchery releases). The proposed research will simulate fisheries management scenarios to formally evaluate preemptive adaptation investments under post threshold multiple equilibria. In this way, we will investigate the optimal management responses given a range of uncertain outcomes. This approach will not only inform managers but also guide adaptation planning for industry and Alaskans whose livelihoods depend on salmon. Both end-user groups will be engaged in the research and co-production of management transition and adaptation plans from the beginning of the project.

Advisory committee. The primary responsibility of the advisory committee (AC) will be to develop a management transition plan that will outline how the scientific results of the research will be used in a management context, and expected timelines for that use. Implementation of such a plan is subject to identified legal and other barriers (Obj. E) and needs to account for affected fishing perspectives to OA adaptation in Objective E. Therefore, the AC will be engaged in most of the participatory planning. Second, AC members with science expertise will provide advice to the project team on integrating various interdisciplinary parts of the proposed project to the largest extent possible. In-person scientific advisory meetings (separate from OA adaptation planning workshops in Objective E) will occur once a year with an additional bi-annual teleconference. The project committed AC members (see letters of commitment) include:

- **Mr. Forrest Brower—**Deputy Director of ADFG's Division of Commercial Fisheries in Juneau, AK. Mr. Brower coordinates commercial fisheries regulations and management for salmon and other species throughout the state of Alaska. His expertise will be critical for implementing the management transition plan and for better understanding agency needs and existing capacity.
- **Dr. Richard Brenner—**Salmon stock assessment biologist with the Alaska Department of Fish and Game Division of Commercial Fisheries in Juneau, AK Division , Juneau,

AK. His duties include salmon forecasts and escapement goals and he has a background in biogeochemistry. Dr. Brenner will contribute his expertise in salmon research and salmon management to the team.

- **Dr. Gunnar Knapp—**University of Alaska Anchorage Professor of Economics, Anchorage, AK. Dr. Knapp is an internationally known expert on salmon markets with a publication record about implications of climate change on Alaska's fisheries that dates back decades. Dr. Knapp will advise the team on Objectives D and E.
- **Dr. Robert Foy—**NOAA Alaska Fisheries Science Center in Kodiak, AK. Dr. Foy is an expert on experimental research to assess the physiological response of OA on marine species. He will contribute his expertise to the lab study particularly the design of the pCO_2 generation system and monitoring (Objective C) and integration into Objective B.
- **Dr. Mike Litzow—**University of Alaska Fairbanks Adjunct Research Professor of fisheries ecology and oceanography, Kodiak, AK. Dr. Litzow has a research background in non-linearities and tipping points in marine ecosystem time series, climate effects on Alaska fisheries, particularly salmon fisheries. He will advise the team on model integration between Objectives A and B.
- **Dr. David A. Beauchamp**—Ecology Section Chief at the U.S. Geological Survey, Western Fisheries Research Center. Dr. Beauchamp is an expert on bioenergetics, food web ecology, and survival of salmon. Dr. Beauchamp will advise the team on Objective C, lab study and bioenergetic modeling (Objective C).