Final Report for Partnered CICOES Research Grant

Title: Is climate warming associated with elevated parasite burden for marine fishes in the Gulf of Alaska?

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Context

Lafferty et al. (2015) document 67 instances in which parasites reduced the growth, survivorship, or marketability of commercially important marine fish species. Among these examples are anisakid nematodes, which cause filets to appear "wormy" and therefore render them unsalable (Bao et al., 2017a; Bao et al., 2017b); copepod gill parasites, which can reduce growth and induce mortality, particularly in juvenile fish (Costello, 2006); trematode flatworms, which can induce mortality (Jacobson et al., 2008) and reduce marketability (Buchmann, 1986) of fish; monogenean flatworms, which reduce fish survival (Shirakashi et al., 2008); and tapeworms, which reduce fish growth (Saksvik et al., 2001). As consumers, parasites redirect energy that might otherwise flow to predators or fisheries, "stealing" fish biomass from commercial and subsistence stakeholders.

These parasitic threats may be on the rise as oceans warm (Harvell et al., 1999; Marcogliese, 2001; Harvell et al., 2002; Harvell et al., 2004). Climate change can influence parasite transmission by (1) increasing rates of parasite reproduction or the length of the reproductive season for parasite species (Marcogliese, 2001), (2) shifting the ranges of hosts and parasites such that hosts are exposed to new parasite species, or (3) eroding host immune defenses that would otherwise keep parasites at bay (Chubb, 1980; Esch and Hazen, 1980). A "rising tide" of disease may therefore be in store for warming oceans.

Alaska is experiencing much more rapid climate warming than the rest of the US (NOAA, 2013), and fishing is one of its most vital industries, bringing the state over $1 billion annually (NMFS, 2011). There is high potential for climate-driven impacts of parasitism on Alaskan fisheries, yet little research to suggest how parasitic threats might change with a changing Alaskan climate. Our project aims to fill this gap and **– as proposed – funding from CICOES has allowed us to collect pilot data toward Objective 1**; these pilot data will also support several larger proposals planned for the coming year (e.g., NPRB, NSF), which will allow us to complete the full suite of three objectives:

Objectives

1. Assess long-term (early 1900s–present day) trends in the abundance of parasites among 10 Gulf of Alaska fish species by performing parasitological dissection of fluid-preserved museum specimens held in the UW Burke Museum, UAF Museum of the North, and other natural history collections.
2. Use the resulting database of historical parasite abundance to identify the Gulf of Alaska regions experiencing the greatest and the least change over time in parasite abundance.
3. Assess the degree to which parasite abundance may be driven by climate warming for each parasite taxon detected, by regressing annual sea surface temperature against parasite abundance using existing climate reconstructions.

Methods

Quantifying the impacts of climate on parasite burden is challenging because climate changes gradually and in lockstep with many other pressures on marine ecosystems. It can be difficult to disentangle the influence of climate from collinear factors like coastal development, pollution, and changes in host density. **Alaska is the key to solving this problem.** Sub-regions of the Gulf of Alaska have warmed at different rates (**Figure 1**), and this variability offers a "natural experiment": if the trajectories of parasite populations differ systematically among these sub-regions, we can confidently attribute that variability to climate.
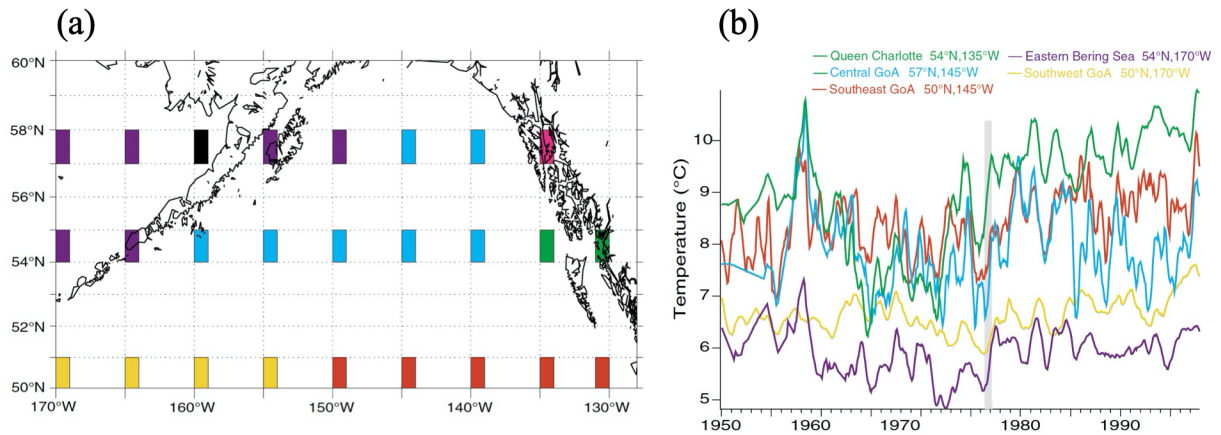

Figure 1. (a) Map showing regional differences in sea surface temperature (SST) variability across the Gulf of Alaska, where regions were grouped by cluster analysis of SST data. Colors correspond to (b), which shows reconstructed sea surface temperature values for five geographic regions in and around the Gulf of Alaska. Reproduced from Bograd et al. (2005).

We used parasitological dissection of fluid-preserved specimens to develop time profiles of parasite abundance encompassing more than 60 years and bracketing major turning points in the natural history of the Gulf of Alaska. We sourced fluid-preserved fish specimens from the University of Alaska Museum of the North (UAMN; with permission from Andrés López, who is PI of this project and Curator of Fishes and Marine Invertebrates at UAMN) and the University of Washington Fish Collection (UWFC; with permission from Curator of Fishes Luke Tornabene). In our original proposal, we suggested 10 suitable host species that spanned the Gulf of Alaska food web (trophic levels 3.1–4.2; Table 1). For each specimen that we examined, we recorded the location of collection from the paper tag included with the specimen and measured each fish's total length in centimeters. When the location of collection was described by name but not by latitude and longitude, we estimated the location in decimal degrees using Google Maps.

We subjected each fish to a thorough parasitological dissection (for methodological details, see Fiorenza et al. 2020). For each parasite taxon that we identified, we noted its broad taxonomic grouping (Subclass Copepoda, Subclass Hirudinea, Class Monogenea, Class Trematoda, Class Cestoda, Phylum Nematoda, and Class Acanthocephala). Every parasite was identified to the lowest possible taxonomic level, which we will further refine as we prepare a manuscript for publication (see **Products**, below). We classified each parasite taxon into one of two transmission strategies: directly transmitted (i.e., parasites that can be transmitted between conspecific hosts) or complex life cycle (i.e., parasites that are transmitted from one host species to another host species in an obligately required sequence).

Table 1. *Ten representative host species to be targeted for parasitological dissection in the full project (33% of which was to be supported by CICOES funding). TL = trophic level (from FishBase.org), # targeted = the number of specimens we aim to dissect from each species, # available at UWFC = # specimens originally collected in Alaskan waters and held at the UW Fish Collection, # available at UAF = # specimens originally collected within Alaskan waters and held at the University of Alaska Museum of the North, # available across all museums = # specimens originally collected within Alaskan waters and held at all natural history museums in North America. Years of collection of the oldest and most recent specimens are indicated in parentheses. Highlighted rows indicate the two species from this list that were sampled with CICOES support; note that another species (rougheye rockfish /* Sebastes aleutianus)*, not originally proposed or listed here, was also sampled with CICOES support.*

Host common name	Host Latin name	TL	# targeted	# available at UWFC (date range)	# available at UAF (date range)	# available across all museums (date range)
Coho salmon	*Oncorhynchus kisutch*	4.2	150	437 (1923–2003)	675 (1955–2013)	4504 (1877–2013)
Pacific cod	*Gadus macrocephalus*	4.2	150	710 (1931–2013)	102 (1957–2014)	1218 (1880–2014)
Arrowtooth flounder	*Atheresthes stomias*	4.2	150	165 (1928–2013)	410 (1957–2007)	1323 (1880–2013)
Flathead sole	*Hippoglossoides elassodon*	3.7	150	1758 (1928–2013)	281 (1956–2013)	2819 (1928–2013)
Walleye pollock	*Gadus chalcogrammus*	3.6	150	778 (1920–1989)	331 (1957–2015)	2368 (1880–2015)
Sockeye salmon	*Oncorhynchus nerka*	3.5	150	584 (1923–2009)	783 (1956–2013)	3897 (1877–2013)
Atka mackerel	*Pleurogrammus monopterygius*	3.4	150	311 (1930–2010)	21 (1962–2009)	446 (1930–2012)
Eulachon	*Thaleichthys pacificus*	3.3	150	204 (1934–2013)	190 (1957–2013)	618 (1879–2013)
Capelin	*Mallotus villosus*	3.2	150	1015 (1929–2013)	825 (1956–2015)	17,655 (1879–2015)
Pacific herring	*Clupea pallasii*	3.2	150	3379 (1923–2011)	1232 (1955–2016)	4986 (1880–2016)

Outcomes

Host species selected

With CICOES funding, we performed additional pre-analysis and decided to proceed with two of the proposed species (walleye pollock / *Gadus chalcogrammus* and capelin / *Mallotus villosus*) and an additional species that was not originally proposed (rougheye rockfish / *Sebastes aleutianus*). These selections were made to optimize replication across the various regions represented in Figure 1; that is, we selected those species where the availability of specimens in UAMN and UWFC would allow us to achieve a complete time profile (early 1900s–present day) within at least two regions where SST trajectory diverged. These choices were made because we wanted to select the "lowest hanging fruits" first – that is, we want our pilot data to have the greatest possible statistical power to detect associations between parasite burden and climate, so we selected the species likeliest to give us that power. When we secure funding for the larger project, we will complete the remaining (unhighlighted) species listed in **Table 1**.

We proposed to dissect 1,500 fish in total for the full project (across 10 host species), with 33% of this sampling to be supported by our CICOES Research Grant. In summer 2021, Research Technologist Katie Leslie travelled to UAMN in Fairbanks, Alaska to begin dissections and organize lots for shipping. With the dissections achieved during that one-month trip and in the subsequent months using fish shipped from UAMN, as well as lots from UWFC, we met our proposed level of sampling (**aim** = 33% * 10 fish species = 3 fish species; **actual** = 3 fish species; Table 2).

Table 2. *Ecological attributes of the three host species selected for study. Data from FishBase (Froese and Pauly 2000). Habitat indicates whether the species is primarily neritic (i.e., in the water column) or demersal (i.e., near or on the benthos). Vulnerability score given out of 100 points, with higher scores indicating higher vulnerability to fishing (Cheung et al. 2005) and climate (Jones and Cheung 2017) impacts. Highlighted rows indicate the two species from this list that we originally proposed to sample (i.e., these two species are also included in Table 1); another species (rougheye rockfish /* Sebastes aleutianus)*, not originally proposed, was also sampled with CICOES support.*

Host Latin name	Host common name	# sampled	Order	Trophic level	Habitat	Schooling	Fishing vulnerability	Climate vulnerability
Walleye pollock	*Gadus chalcogrammus*	117	Gadiformes	3.6	Demersal	During spawning	High (59)	High (55)
Capelin	*Mallotus villosus*	103	Osmeriformes	3.2	Neritic	Yes	Low (27)	Low (24)
Rough-eye rockfish	*Sebastes aleutianus*	57	Perciformes	4.1	Demersal	No	Moderate to high (49)	NA

Host individuals dissected

In total, we dissected 277 individuals across the three sampled fish species: 117 *Gadus chalcogrammus*, 103 *Mallotus villosus*, and 57 *Sebastes aleutianus*. Maximum sample sizes were limited by the availability of specimens in the collections, particularly for larger bodied species (e.g., *Sebastes aleutianus*), which tend to be less well-represented in collections because of storage space constraints. Of the 277 individuals we dissected, the oldest was collected in 1949 and the youngest was from 2013 (Table 3). By performing statistical analyses that pool across host species, we will be able to capitalize on the level of replication achieved in the Table 3 row marked "Total", which has high replication between the 1960s and 2000s – a period of time that saw significant change in SST in Alaskan waters (Figure 1).

Table 3. *Number of individuals of each species of fish dissected in each decade between 1949 and 2013. Cells are conditionally formatted such that more intense color indicates greater replication. Individuals with no date assigned were labeled with a paper tag that had no date listed; with additional research in museum archives, we will be able to assign a date to these specimens.*

	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2019	NA
Gadus chalcogrammus	1	2	32	15	41	4	17	4	0
Mallotus villosus	0	4	28	10	30	25	0	0	6
Sebastes aleutianus	0	0	4	11	4	14	20	4	0
Total	1	6	64	36	75	43	37	8	6

Parasites detected

Our team counted 18,091 individual parasites from 277 specimens of three host species. Of the 91 parasite taxa we detected, 47 were found at 5% or greater prevalence within their host species and across all years. Among all parasite taxa, 17.5% were directly transmitted (i.e., transmitted among conspecific hosts) and 78.0% were complex life cycle parasites with two or more obligately required host species in the life cycle. Among the common parasite taxa (i.e., those found at 5% or greater prevalence within their host species and across all years), 14.9% were directly transmitted and 78.7% were complex life cycle parasites. Additional taxonomic identification and literature searches will be needed to achieve the lowest possible taxonomic identification for each parasite and to determine the number of hosts obligately required by each complex life cycle parasite (see **Products**, below).

Products

1. One publication reporting change over time in the parasite burden of the 33% of fish species dissected with support of CICOES (in partial fulfillment of Objective 1)

We have already begun drafting a manuscript that will report the trajectory of change through time and the association with SST for parasites of the three host species we dissected. We expect to conduct the analysis between January and June of 2024, finish writing the manuscript in Summer of 2024, and to submit the paper to a peer-reviewed journal in Fall of 2024. We will acknowledge CICOES funding and send a pdf of the paper to CICOES upon publication.

> ***Next steps:***
> 1. ***Identifications*** – Refine taxonomic identifications for each parasite taxon by examining parasite vouchers under magnification, staining/mounting/clearing if necessary, and using dichotomous keys and host–parasite lists specific for the region. Extract from the literature natural history information for each parasite taxon (i.e., number of obligately required host species in the life cycle).
> 2. ***Extract data on environmental drivers*** – Extract sea surface temperature data for the time period of interest (1949–2013) and match each fish specimen to corresponding sea surface temperature reconstruction (i.e., assign each individual fish's collection location to the nearest 1° geographic pixel and its collection date to the closest month in the climate dataset and match it with the corresponding SST measurement; Hadley Centre for Climate Prediction and Research).
> 3. ***Analysis*** – Build statistical models to assess the correlation between parasite burden on one hand and climate on the other. We will model parasite abundance (# parasite individuals of a given species / host) in a mixed-effects, generalized linear model framework using the *glmer.nb()* function in the lme4 package in R. We will build a model with a fixed effect of temperature, life cycle complexity (i.e., number of obligately required host species) as a fixed effect, an interaction between year and life cycle complexity (to account for the possibility that the association between parasite burden and temperature might differ between parasites with different levels of life cycle complexity), and random intercepts of site nested within region (to account for the fact that samples from the same site/region are likely to be more similar than samples from different sites/regions) and year (to account for the fact that samples from similar years are likely to be more similar than are samples from different years). We will also include a temperature term with a random slope and a random intercept varying across parasite species nested within host species, to allow calculation of a unique estimate of the temperature effect for each parasite species. Finally, we will include a body size term (host total length in cm) with a random slope and a random intercept varying across parasite species nested within host species, to account for the effect of body size on parasite burden. The fixed effect of temperature will indicate whether parasite abundance in the ten focal host species tends to be positively related, negatively related, or unrelated to climate. The interaction will indicate whether the association with climate tends to vary across parasites with varying degrees of life cycle complexity.
> 4. ***Manuscript #1*** – Write a manuscript addressing whether the burden of parasitism is increasing for the three marine fishes evaluated *(Objective 1)* and – if possible given the current level of replication – assessing the likelihood of climate as a driver of this change *(Objective 3)*. This paper will focus on the big-picture: is climate change likely to drive shifts in parasite burden generally, within and beyond the Gulf of Alaska?

5. ***Manuscript #2*** – If possible given the current level of replication, write a manuscript addressing climate-driven change in the Gulf of Alaska specifically: which parasites have increased, which regions are the most heavily burdened, and which regions are experiencing the most rapid change *(Objective 2)*? This paper will also assess climate as a potential driver of the observed changes *(Objective 3)*.

2. At least two large (>$140K) grant proposals using CICOES-supported pilot data, which will support the fulfillment of Objectives 1–3

We applied for funding that would allow us to complete the proposed sampling: from **Washington Sea Grant** in May of 2021 (total budget = $417,115) and from **Alaska Sea Grant** in May of 2023 (total budget = $230,867). Both proposals were well-received by reviewers, but neither was funded. Although these two proposals were not successful, we believe that we can build on our existing proposal language and pilot data to successfully secure funding from the North Pacific Research Board (NPRB) or the NSF Biodiversity on a Changing Planet program (see below), and we are planning proposals to each of these funders.

Next steps:
1. Submit a proposal to **NPRB** in June 2024.
2. If NPRB is unsuccessful, submit a proposal to **NSF's Biodiversity on a Changing Planet** program in September of 2025.

Conclusion

Parasites pose a threat to the seafood industry, public health, and the ecosystems that support Alaska's economy, and they may be on the rise as climate warms. Our project will empirically test a suspicion held by many in the seafood industry: that climate warming is linked to increases in transmission of some types of parasites. This project will advance the sustainability and profitability of Alaska's seafood industry and quantify the magnitude of an emerging threat to marine ecosystems and public health – and it would not have been possible without support from CICOES.

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