Descriptors

Cycle Priorities

Fishes and Invertebrates

Species

Bathyraja interrupta, Mallotus villosus, Pacific cod (Gadus macrocephalus), Hippoglossoides elassodon, Sebastes aleutianus (rougheye rockfish), Ammodytes personatus, coho salmon (Oncorhynchus kisutch), Walleye pollock (Gadus chalcogrammus), Thaleicthys pacificus, Hemilepidotus jordani, Triglops pingelii, Gymnocanthus pistillinger

Large Marine Ecosystems

Gulf of Alaska, Bering Sea/Aleutian Islands

Research Approaches

Data Rescue -

Millions of jars of fish are preserved in natural history collections globally. For each of these specimens, the chemical fixation process preserves parasite tissue alongside host tissue, making each fish a time capsule of parasitological information from the time and place of its collection. Because there are few historical data on parasites, even simple questions - like, "are there more or fewer parasites than there used to be?" - are impossible to answer without using natural history collections to reconstruct parasite population trajectories through time.

Parasite data are currently locked inside of natural history specimens. In this proposal, we propose to rescue these parasite data, and thereby answer critical questions about whether the fisheries of the future will be wormier or not. PI Wood's lab makes all the data they collect publicly accessible in the Dryad Data Repository. We will do the same in the project proposed here, making previously inaccessible parasite information freely available to the public.

Cooperative Research with Industry -

This proposal was inspired by a list of research priorities generated by seafood industry participants, solicited and compiled by the Seafood Products Association (SPA). Our proposed research is therefore directly responsive to industry concerns. We will continue to ensure a two-way exchange of information between our research team and industry partners by forming an **industry advisory group: the Healthy Seafood Working Group**. The group will meet virtually twice per year, will be facilitated by our collaborators, Claudia Coles and Bruce Odegaard at SPA, and will include representatives from at least five Alaskan seafood operations. The goal of the meetings will be to facilitate information exchange: for industry to communicate their information needs, concerns, and observations to scientists, for scientists to report their findings back to industry, and for the entire group to collaboratively brainstorm creative solutions. We will also create **publicly available online videos** designed to provide rigorous, peer-reviewed scientific information on parasite biology and its intersection with seafood to interested members of the seafood industry and general public. Videos will include consumer-facing material (e.g., what’s this worm in my filet?) as well as industry-facing material (e.g., what processing/handling techniques minimize worm burdens in seafood products?), and will be co-produced with and disseminated by SPA, the Healthy Seafood Working Group, and the Alaska Seafood Marketing Institute (see *Letters of Collaboration*).

Keywords

climate change, fisheries, parasites, infectious disease

Proposal Resubmission

Since the last submission (in 2017), this proposal has evolved in three ways: (1) our team has established relationships with seafood producers and modified our science plan to better align with their concerns, (2) we received a pilot grant that allowed us to collect 30% of the total data targeted for this proposal, and (3) we have updated the outreach plan, including a new proposal for a physical museum exhibit on parasites at the University of Alaska Museum of the North.

(1) Over the past several years, our team has been working closely with the Seafood Products Association (SPA) to identify challenges facing seafood producers in the state of Alaska. One of the issues that SPA members consistently raise is their observation of a recent increase in parasites, particularly among Alaska salmon. The parasites (primarily "sushi worms", which are nematodes in the family Anisakidae) are problematic for producers because buyers often reject wormy filets, and some markets (e.g., the EU) restrict the import of filets with even a low burden of worms. As you'll see from the *Letters of Support* we've assembled, this issue is urgent for seafood producers.

(2) Another difference between this proposal and the last is that we have now completed a subset (30%) of the data collection we originally proposed, with a Pilot Research Grant from the Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES). We now seek funding from NPRB to support the remainder (70%) of the proposed data collection.

(3) Finally, in this proposal we present a new *Engagement Strategy*, totally overhauled in response to feedback on our last proposal. We propose to develop a physical museum exhibit on parasites that will be on display at the Museum of the North, as well as an online version of the exhibit and short videos.

Background

Parasites can reduce the growth, survivorship, and marketability of commercially important marine fish species. This is particularly true in Alaska, where, according to our industry partners at the Seafood Products Association (SPA), parasites are a growing concern. In addition to increasing processing costs and reducing quality of seafood products, parasites consume energy that might otherwise be harvested by fisheries, “stealing” fish biomass from commercial and subsistence stakeholders. We do not yet know what is causing the apparent increase in parasitism recently observed among Alaskan marine fishes, but many producers suspect a link to climate change.

Our team recently demonstrated that the past five decades have seen a global 283-fold increase in the number of anisakid worms (i.e., “sushi worms”, or nematodes in the family Anisakidae) among marine fishes (Figure 1a), and a corresponding rise in the abundance of worms in some Alaska salmon species (Figure 1b and 1c). This rising number of anisakid worms implies a rising risk of anisakidosis for people who eat raw or undercooked marine seafood products, rising costs for removing the worms, and increasing risk of rejection of seafood products by buyers.

In contrast, our team also recently finished assembling a 140-year time series of parasite burden for eight marine fish species and 85 parasite species of Puget Sound, Washington. Rather than increases in parasite abundance, we found declines (Wood et al. 2023). In fact, more than half of the parasite species we sampled tended to decline over time (Figure 1d), and these declines were strongly correlated with sea surface temperature, suggesting a connection to climate change (Figure 1e).

These contrasting findings suggest that a lot of change will happen among parasite populations as the world warms, and that we are currently unprepared to predict who the winners and losers will be among parasite species. It is critically important that we understand which parasite groups will tend to increase, so that we can anticipate and mitigate any potential industry and public health impacts. According to our industry partners at the Seafood Products Association, SPA members express a strong desire for research that will establish whether parasite prevalence in marine fish is higher in warmer years – a pattern that some members have noticed anecdotally, but which has yet to be formally tested (see *Letters of Collaboration*).

Quantifying the impact 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. It is important for Alaska that we answer this question, given how rapidly its waters are warming; luckily, the state also offers a straightforward solution. Sub-regions of the Gulf of Alaska have warmed at different rates, 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. Here, we propose a project that will accomplish three objectives.

Objective 1. Assess whether marine fishes of Alaska are experiencing increasing or decreasing parasite burdens through time.

Objective 2. Identify the parasite species that are increasing through time, the regions that are the most heavily burdened with parasites, and the regions where parasite burdens are changing most rapidly.

Objective 3. Test the contribution of climate to any changes in parasite species abundance.

Preliminary findings

With the support of a pilot research grant from the Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), we have already completed parasitological dissections for 3 of 10 proposed species (*Gadus chalcogrammus, Sebastes aleutianus, Mallotus villosus*). These preliminary data confirm the observations of our industry partners: most of the parasite species we detected increased in abundance between the 1940s and the present day (Figure 1f). However, we do not currently have sufficient replication to determine whether this increase is correlated with climate change or to describe the spatial patterns in parasite burden; support from NPRB would allow us to expand our dataset and rigorously test the contribution of warming to these dramatic increases in parasite abundance (Objective 3), and to identify the regions that are the most heavily burdened with parasites and the regions where parasite burdens are changing most rapidly (Objective 2).

Objectives

1. Assess whether marine fishes of Alaska are experiencing increasing or decreasing parasite burdens through time.
2. Identify the parasite species that are increasing through time, the regions that are the most heavily burdened with parasites, and the regions where parasite burdens are changing most rapidly.
3. Test the contribution of climate to any changes in parasite species abundance.

Design & Approach

The problem

Lafferty et al. (*1*) documented 67 instances in which parasites reduced the growth, survivorship, or marketability of commercially important marine fish species. Among these examples are crustacean parasites, which can reduce growth and induce mortality (*2-4*) (Figure 2a); nematodes, which can erode the intestinal lining of their hosts, reducing digestive efficiency (*5*; Figure 2b); monogeneans, which reduce fish survival (*6*; Figure 2c); trematodes, which can induce mortality (*7*) and reduce marketability (*8*) of fish (Figure 2d); and tapeworms, which reduce fish growth (*9*; Figure 2e). All of these groups of parasites exist in Alaskan waters.

These parasitic threats may be on the rise as oceans warm (*10-13*). Climate change could influence parasite transmission by increasing rates of parasite reproduction or the length of the reproductive season for parasite species (*11*), shifting the ranges of hosts and parasites such that hosts are exposed to new parasite species, or eroding host immune defenses that would otherwise keep parasites at bay (*14-15*). For example, warm waters resulting from industrially produced thermal pollution can increase the transmission to fish hosts of eye-infecting trematodes (*16*), intestinal tapeworms (*17*), and gill-infecting monogeneans (*18*) by prolonging the parasites' reproductive season (*16*). In the mid-1980s, the deadly oyster parasite dermo (*Perkinsus marinus*) expanded the northern boundary of its range from Long Island to Maine, killing oysters along the way – a range extension attributed to climate change (*19-20*). Elevated temperatures can reduce white blood cell and lymphocyte counts in fish, resulting in greater susceptibility to new infections (*14*) and lower ability to tolerate existing infections (*15*). A "rising tide" of disease may therefore be in store for warming oceans, as our group's previous work on sushi worms (Figure 1a-d) has already suggested.

However, not all parasites will respond positively to climate change; in fact, some are probably even more sensitive to climate change than are their hosts. In a recent project that spanned 85 parasite species in Puget Sound, WA, our group found that most parasites tended to decline in response to rising sea surface temperatures (*21*; Figure 1e-f). This effect was concentrated among parasites with complex life cycles (i.e., those that obligately require >1 host species to complete their life cycles), and we think that it occurs because, as climate change reshuffles marine communities, parasites with more obligately required hosts species are more likely to lose a host (*21*). Their sensitivity to environmental change could make parasites the most imperiled species of all (*24*).

So: which is it? Will a warming ocean bring more parasites, or fewer? At the moment, there is insufficient knowledge to predict which parasites will increase and which will decline in a changing world. Data on the historical abundance of marine parasites are so rare as to be practically non-existent (*25*). The few time series that have been constructed (*26-28*) represent only a tiny fraction of all marine parasites affecting fished species. Given the threat that marine parasites represent to coastal ecosystems, fisheries, and aquaculture, it is imperative that we understand how and why the abundance of parasites is changing through time.

The problem for Alaska

This question is particularly germane in Alaska, where marine fisheries generate $5.7B annually (*29*) and account for 60% of national fisheries production (*30*), and where marine resources are the lifeblood of coastal communities (*31-32*). In April of 2020, our partners at the Seafood Products Association conducted a survey of members, which revealed a common need: members wanted to know whether the recent increases in parasite abundance that they had observed were related to climate:

- "Parasite prevalence during warmer/cooler years?"
- "The rise in nematodes in pink salmon this year in Alaska may be due to temperature but we don't know."
- "Customers ask us why there are so many [parasites], and we don't really have a response."

The primary group of parasites that concern SPA members are the "sushi worms", or nematodes in the family Anisakidae, but other parasites also affect the marketability of their products, including *Ichthyophonus* (*33*), "milky flesh disease" caused by *Henneguya* (*34*), "soft flesh syndrome" caused by *Kudoa* (*35*), "black spot disease" caused by the trematode *Cryptocotyle lingua* (*36*), "white and yellow grubs" caused by a variety of trematode species (*37*), and a tapeworm that, if eaten raw, can grow to 25 feet long in the human intestine (*Diphyllobothrium; 38*). Only some of these parasites represent a threat to food safety, but all affect food quality, as they are visible to the naked eye and are extremely unappetizing, affecting seafood marketability and the cultural and social value of seafood resources for subsistence consumers.

To keep fisheries profitable and sustainable, Alaskan policy makers and stakeholders need to know what parasites are a threat, where these parasites currently are, where they will be soon, and why their abundance is changing.

The solution

The fact remains that almost no historical datasets exist to document parasite abundance in the past (*25*); without a baseline to compare against the abundance of parasites in contemporary ecosystems, ecologists are left with no research avenues for understanding how parasitism has changed through time. Our team recently circumvented this problem by validating an approach for extracting historical information on parasite burden from museum specimens. Our team demonstrated that parasites are detectable in liquid-preserved fishes held in natural history collections – so detectable, in fact, that there is no difference in parasite detectability between fresh host specimens and host specimens that have been fixed using museum preservation protocols (*28*). This validation study makes it possible to use parasitological dissection of museum specimens to reconstruct long time series of parasite abundance.

Our team proposes to use natural history collections to develop time profiles of parasite abundance in the Gulf of

Alaska, encompassing more than 70 years (1950 to present day) and bracketing major turning points in the history of ocean ecosystem degradation. Given that climate warming is happening much more rapidly in Alaska than in the rest of the US (*41*), and given that fishing is one of Alaska's most vital industries (*29*), there is high potential for climate-driven impacts of parasitism on important Alaskan fisheries, yet little research to suggest how parasitic threats might change with a changing Alaskan climate. Luckily, sub-regions of the Gulf of Alaska have experienced divergent trajectories of warming (*42*) (Figure 3). This variability across space will allow us to parse the influence of climate on parasite burden, because it gives us the ability to investigate whether rates of parasitism increase more rapidly in the presence of fast warming than in the presence of slow warming.

Objective 1. Assess whether marine fishes of Alaska are experiencing increasing or decreasing parasite burdens through time

We will use parasitological dissection of preserved specimens to develop time profiles of parasite abundance encompassing more than 70 years and bracketing major turning points in the natural history of the Gulf of Alaska. We have chosen 10 host species (Figure 4), and we will source museum lots of these species from the University of Alaska Museum of the North (UAMN; with permission from Andrés López, who is Co-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, see *Letter of Collaboration*). We will dissect individuals of each fish species from at least five points in time, spanning at least a 70-year range (Figure 4). We will target 30 individuals from each of five time bins for all species (30 individual fish * 5 time bins = 150 individuals). The selected species span nearly the entire range of trophic levels for fishes in the Gulf of Alaska (Figure 4). This diversity of fish host species will allow us to draw conclusions about parasitic infection across the Gulf of Alaska food web.

Specimen acquisition – The UW Fish Collection has served the archival center for NOAA's Alaska Fishery Science Center for more than two decades and is home to the largest collection of Alaskan fishes in the world. The UAMN Fish Collection is the only repository of research specimens in Alaska and hosts an important historical collection developed by and formerly housed at the NOAA's Auke Bay Laboratories in Juneau. We have already received approval for the proposed use of specimens outlined here (see *Letter of Collaboration*). The vast majority of specimens we propose to semi-destructively sample will originate from UAMN and UWFC, but we will also request lots from a few other collections to fill gaps in the time series (red points in Figure 4). We have made similar arrangements with partner institutions in the past, including the California Academy of Sciences, Smithsonian Institution's National Museum of Natural History, and others (*21*). We will use the collections of museums other than UW and UAF primarily to obtain specimens from earlier time points (Figure 4).

Specimen meta-data acquisition – The fish to be targeted for this study are extensively documented in the databases of their respective museums and on iDigBio, a collaborative georeferencing project that aggregates meta-data for specimens in natural history collections across North America (*43*). Currently, 93% of all specimens from the UW Fish Collection and 86% of specimens from the UAMN Fish Collection have been georeferenced on iDigBio. We will collect meta-data for each fish from two sources: (a) data recorded on paper tags included with the specimen and (b) data associated with the specimen in iDigBio. Metadata fields will include institutional catalog number, host Latin name, preparation type, latitude and longitude of collection, collection locality (i.e., the name of the collection site), collection date, depth, and collector/collection expedition ID.

Specimen dissection protocol – We will use established best practices for parasitological dissections that maximize information gained and minimize damage to irreplaceable specimens (*44*). All specimens will be photographed, measured (total length, fork length, and standard length), and weighed prior to dissection. We will then make a longitudinal incision along the ventral surface of the fish, from the vent through the pectoral girdle to the isthmus. We will remove the organs of the body cavity (stomach, cecae, intestine, gallbladder, spleen, liver, gonads) into individual dishes. The gill arches and heart will also be removed through this incision. Each organ will be examined separately under a dissecting microscope for parasites. Any parasites found in this material will be identified, counted, and vouchered, and the location of infection within the host noted. Finally, the incision will be spread open widely and placed over a strong light source, to indicate the presence of any nematode or cestode larvae in the muscle tissue. Organs will be individually labeled and returned to the lot of origin.

Parasite identification and cataloging – We will use established best practices for identifying and cataloging parasites from museum material (*44*). Once parasites are removed from fish, they will be studied under magnification and identified to the lowest possible taxonomic level using parasitological references (*45-50*), hostspecific literature resources, and, for difficult identifications, with assistance from parasitologists with appropriate taxonomic expertise.

Ideally, we would perform both morphological and molecular identification of parasite species. However, almost all museum specimens collected between ~1930s and the present day have been fixed with a formalin soak, which fragments host and parasite DNA. There are some labs working on molecular techniques for re-assembling the fragmented DNA of formalin-fixed parasites, but these techniques are still in the very early stages of development (*51*). We will accession all parasites as vouchers so that, at some point in the future when the technology is sufficiently advanced, our group (or another group) can sequence the DNA of these parasites.

Preliminary data – With the support of a pilot research grant from the Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), we have already completed parasitological dissections for 3 of the 10 proposed species (Figure 1f; grey rows in Figure 4; *Gadus chalcogrammus, Sebastes aleutianus, Mallotus villosus*). Therefore, only 1,050 of 1,500 dissections remain to be completed. Support from NPRB would allow us to complete this dataset and perform the analyses described herein.

Statistical analysis – Our team has extensive experience in analyzing long-term trends in parasite abundance (*21, 26-28, 44, 52*); Tim Essington (University of Washington) conducted the analysis of our preliminary data (Figure 1f) and has agreed to collaborate on the statistical analyses for the larger project, should it be funded. We will assess whether parasite abundance has changed over time by modeling parasite abundance (# parasite individuals of a given species / host individual) in a generalized linear mixed model with year as a fixed factor, life cycle complexity (i.e., number of obligately required host species) as a fixed factor, an interaction between year and life cycle complexity (to account for the possibility that the temporal trajectory of parasite burden might differ between parasites with different levels of life cycle complexity), a year term with a random slope and a random intercept varying across sites (to account for the fact that samples from the same site are likely to be more similar than samples from different sites), and negative binomial error, using the *glmer.nb()* function in the lme4 package in R (*53*). We will also include a year 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 year (i.e., change over time) for each parasite species (as in Figure 1f), and to account for the fact that samples from the same host species are likely to be more similar than samples from different host 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 host body size on parasite burden. To test for spatial autocorrelation, we will use Moran's I, implemented using the *Moran.I()* function of the fields library in R. We will also produce a spatial variogram, implemented in the gstat library in R, to test for a relationship between distance and semivariance, which would indicate spatial autocorrelation in the dataset. In the absence of spatial autocorrelation, we will proceed with analysis. If spatial autocorrelation is indicated, we will eliminate spatial autocorrelation before proceeding with analysis (e.g., by combining nearby sites into a single site with a centroid that is the average of the latitude and longitude of the two sites). The fixed effect of year will indicate whether parasite abundance in the ten focal host species has generally increased, decreased, or remained the same over the study period.

Accounting for differences in fish body size over time – Body size tends to be positively correlated with parasite burden in marine fishes (*54*), so if mean body size drifts over time and body size is not accounted for, we might conclude that parasite burden is changing when in fact the pattern is driven entirely by change in host body size. We will do two things to make sure that host body size does not unduly influence our conclusions:

(1) We will ensure that we keep average body size consistent across time. We will accomplish this by setting maximum and minimum body sizes for sampling and selecting only specimens that fall within this range.

(2) We will also include body size as a covariate in statistical models to account for the influence of fish body size on parasite burden (see *Statistical analysis*, above).

Statistical power – One consistent challenge for historical ecology is that of statistical power (*59*). There are hard limits on the amount of material available for examination set by what has been accessioned into natural history collections; we can't just go out and do more sampling to increase replication (*51*). In this project, the level of replication represents a balance between what is available in the collection, what a curator is willing to part with (given that our dissection technique is partially destructive), and what level of replication is needed to detect the hypothesized patterns. By limiting our replication and thereby sparing specimens from semi-destructive data collection methods, we are ensuring that it will be possible for future researchers to extract information that they might need.

With this constraint in place, does our design have sufficient statistical power to detect the hypothesized patterns? We've put substantial care into assuring that it does. We have conducted a power analysis designed to tell us how much replication is needed (*39*). In this simulation, we generated data based on a negative binomial distribution – a distribution that accurately represents most parasite populations (*60*). We varied the sample size and the amount of change in parasite burden over time (and therefore variance, because variance is based on the mean in a negative binomial distribution) to determine the level of power needed to detect change over time. We assumed that a small effect size would be equal to 0.2, a moderate effect would be equal to 0.5, and a large effect would be equal to 0.8 (*61*). Using the simulated data, we then created and ran generalized linear models using negative binomial error distributions. The first model included the effect of group (i.e., fish are split into two groups, e.g., past and present), while the second was a null model. After running the two models, we compared them using Akaike's information criterion (AIC) and recorded whether the full model was the better model (i.e., greater than 2 AIC units lower than the null model). We repeated the simulation 1,000 times for each sample size and degree of change over time and used the proportion of times the full model was supported by AIC to calculate power for each combination of sample size, mean, and difference between means. **This power analysis reveals that the proposed sample size of 1,500 fish gives us the ability to detect a small (= 0.2) temporal change in parasite burden 99% of the time.** Therefore, the analysis is sufficiently powered to detect the hypothesized effects.

Further evidence for the sufficiency of our proposed level of replication comes from other analyses with similar or lower levels of replication (*21, 26, 28, 52*). For example, **we recently detected temporal change in parasite abundance of Puget Sound, WA, with 699 fish hosts (*21*) (Figure 1e) – less than half of the level of replication that we propose here**. We are therefore confident that the proposed experimental design can detect even small amounts of temporal change in parasite burden, if such change exists in this system.

Objective 2. Identify the parasite species that are increasing through time, the regions that are the most heavily burdened with parasites, and the regions where parasite burdens are changing most rapidly

We will address Objective 2 by isolating the random effects from the model above (see *Objective 1 / Statistical analysis*, above).

Statistical analysis – We will extract random effects from the model described above to answer the questions posed in Objective 2. The model described above contains a year term with a random slope and a random intercept varying across parasite species nested within host species. These random slopes will provide a unique estimate of year for each parasite species, allowing us to explore which parasite species are "winners" and which are "losers" – that is, which are increasing in abundance over time and which are declining. The model also contains a year term with a random slope and a random intercept varying across sites, which both corrects for the fact that samples from the same site are likely to be more similar than samples from different sites, and allows us to calculate which sites are most heavily burdened with parasites (intercept) and which are changing in burden most rapidly (slope).

Objective 3. Test the contribution of climate to any changes in parasite species abundance

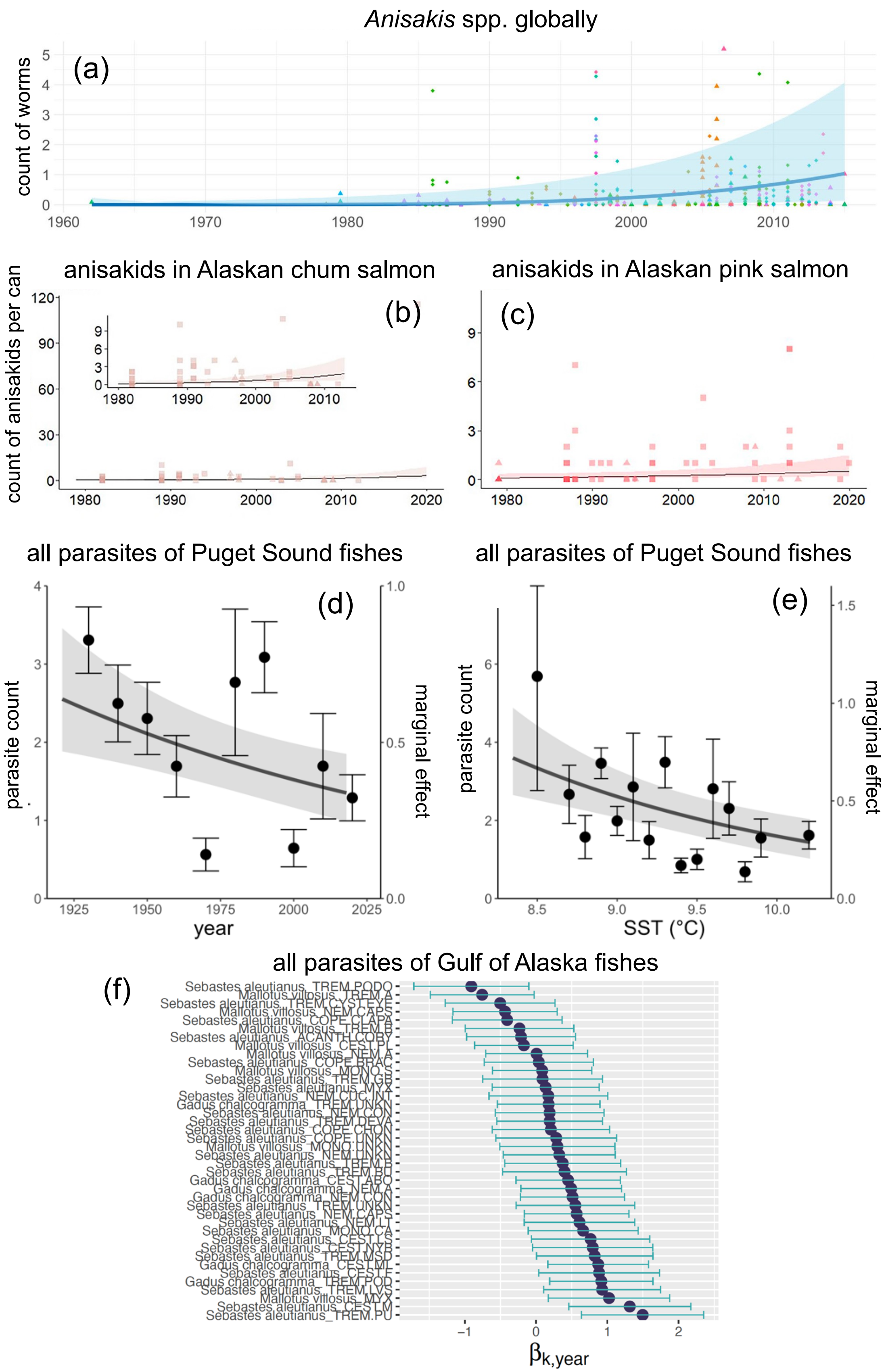
Sub-regions of the Gulf of Alaska have experienced divergent trajectories of warming (*42*; Figure 3) and this variability in sea surface temperature (SST) across space will allow us to parse the influence of climate on parasite burden.

Acquiring climate data – We will obtain reconstructed climate data for the Gulf of Alaska matched to the temporal scope of our parasitological data. The primary climate dataset we have selected (*62*) provides reconstructed SST at monthly and 1° resolution for 1870–present day across the Gulf of Alaska. To match parasitological and climate datasets, we will 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.

Statistical analysis – We will 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 (*53*). We will build a model with a fixed effect of temperature (*62*), 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.

What about potential environmental drivers other than climate change? – Factors other than climate change (i.e., pollution, host density) may also drive long-term changes in parasite abundance. But we have designed *Objective 3* so that it will specifically isolate the influence of climate from these other drivers. The natural experiment we propose should make it possible for us to parse climate from other potential drivers because we have selected a study area where the trajectory of climate warming varies across space in a manner that is disjunct from other long-term changes (e.g., in pollution or host density). The analysis proposed in *Objective 3* is a kind of before–after–control–impact study, where we have data from control (i.e., slowly warming) and impact (i.e., rapidly warming) sites, before change started intensifying (i.e., early part of the time series) and after climate change started intensifying (i.e., later part of the time series). In short: this study is designed to isolate the influence of climate and the inclusion of other potential drivers is not needed to accomplish this parsing.



Anisakis spp. globally
(a)
count of worms
0
1
2
3
4
5
1960
1970
1980
1990
2000
2010
anisakids in Alaskan chum salmon
(b)
count of anisakids per can
0
30
60
90
120
1980
1990
2000
2010
2020
anisakids in Alaskan pink salmon
(c)
0
3
6
9
1980
1990
2000
2010
2020
all parasites of Puget Sound fishes
(d)
parasite count
marginal effect
year
1925
1950
1975
2000
2025
all parasites of Puget Sound fishes
(e)
parasite count
marginal effect
SST (°C)
8.5
9.0
9.5
10.0
all parasites of Gulf of Alaska fishes
(f)
Sebastes aleutianus_TREM.PODO
Mallotus villosus_TREM.A
Sebastes aleutianus_TREM.CYSTEYE
Mallotus villosus_NEM.CAPS
Sebastes aleutianus_COPE.CLAPA
Mallotus villosus_TREM.B
Sebastes aleutianus_ACANTH.COBY
Mallotus villosus_CEST.PL
Mallotus villosus_NEM.A
Sebastes aleutianus_COPE.BRAC
Mallotus villosus_MONO.S
Sebastes aleutianus_TREM.GB
Sebastes aleutianus_MYX
Sebastes aleutianus_NEM.CUC.INT
Gadus chalcogramma_TREM.UNKN
Sebastes aleutianus_NEM.CON
Sebastes aleutianus_TREM.DEVA
Sebastes aleutianus_COPE.CHON
Sebastes aleutianus_COPE.UNKN
Mallotus villosus_MONO.UNKN
Sebastes aleutianus_NEM.UNKN
Sebastes aleutianus_TREM.B
Sebastes aleutianus_TREM.BU
Gadus chalcogramma_CEST.ABO
Gadus chalcogramma_NEM.A
Gadus chalcogramma_NEM.CON
Sebastes aleutianus_TREM.UNKN
Sebastes aleutianus_NEM.CAPS
Sebastes aleutianus_NEM.LT
Sebastes aleutianus_MONO.CA
Sebastes aleutianus_CEST.LS
Sebastes aleutianus_CEST.NYB
Sebastes aleutianus_TREM.MSD
Gadus chalcogramma_CEST.ML
Sebastes aleutianus_CEST.F
Gadus chalcogramma_TREM.POD
Sebastes aleutianus_TREM.LVS
Mallotus villosus_MYX
Sebastes aleutianus_CEST.M
Sebastes aleutianus_TREM.PU
–1
0
1
2
βk,year

Figure 1. *(a) Change over time (1962–2015) in* Anisakis *spp. abundance with 95% confidence interval. Reproduced from Fiorenza et al. 2020. Point shape indicates organ from which estimate was derived, with squares = alimentary tract, circles = filet, triangles = viscera, and diamonds = whole fish. (b) Change over time (1979–2019) in abundance of nematodes in the family Anisakidae in chum salmon* (Oncorhynchus keta) *with 95% confidence interval. Reproduced from Mastick et al. 2024. Point shape indicates size of the can from which estimate was derived, with circles = 106 g, diamonds = 213 g, and squares = 418. (b) Change over time (1979–2019) in abundance of nematodes in the family Anisakidae in pink salmon* (Oncorhynchus gorbuscha) *with 95% confidence interval. Reproduced from Mastick et al. 2024. Point shape indicates size of the can from which estimate was derived, with circles = 106 g, diamonds = 213 g, and squares = 418. (d) Change over time (1921–2019) in abundance of all parasites of eight Puget Sound fish species (left axis, points) and fitted relative density of predictions (right axis, line). Reproduced from Wood et al. 2023. (e) For all parasites of eight Puget Sound fish species, parasite count as a function of sea surface temperature (SST) in degrees Celsius in the year of the host's collection (left axis, points) and fitted relative density of predictions (right axis, line). Reproduced from Wood et al. 2023. (f) For all parasites of three Gulf of Alaska fish species (host name and parasite code listed along the y-axis), estimated year effect coefficients, where negative coefficients represent parasite species that are declining through time and positive coefficients represent parasite species that are increasing through time. The majority of parasite species are increasing through time. Data are preliminary and were produced with support from a CICOES pilot research grant. Analysis conducted by Tim Essington (University of Washington).*

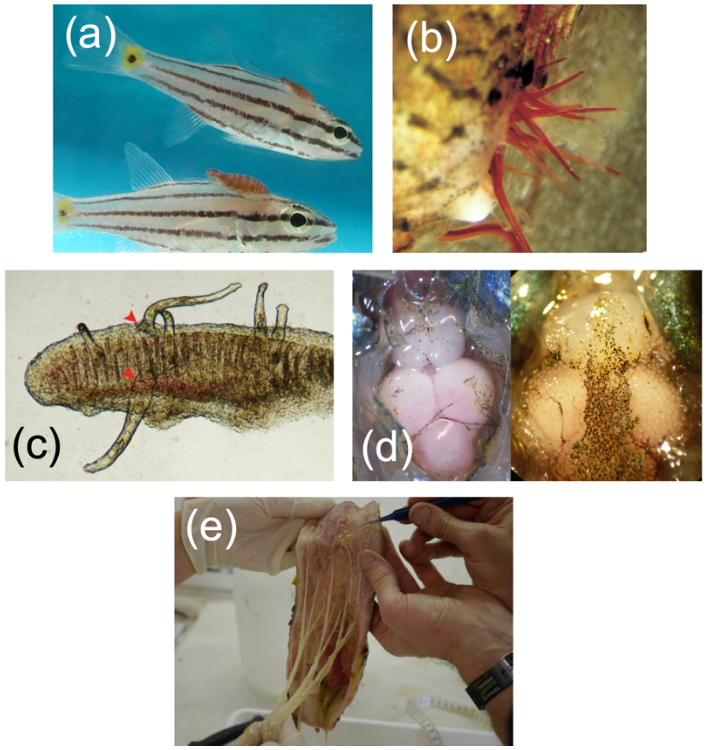


Figure 2. *Parasites can impose significant fitness costs on fishes: (a) five-lined cardinalfish* (Cheilodipterus quinquelineatus) *infected with cymothoid isopods* (Anilocra apogonae)*; (b) intestinal nematodes protruding from the anus of a fish; (c) monogenean worms attached to a fish gill filament (red arrows indicate attachment points); (d) dorsal view of the brain of an uninfected fish (left) and a fish infected with larvae of the trematode* Euhaplorchis californiensis *(right), courtesy of K Weinersmith; (e) tapeworms clinging to the intestinal lining of an ocean sunfish, courtesy of Richard Saunders, South Australia Museum.*

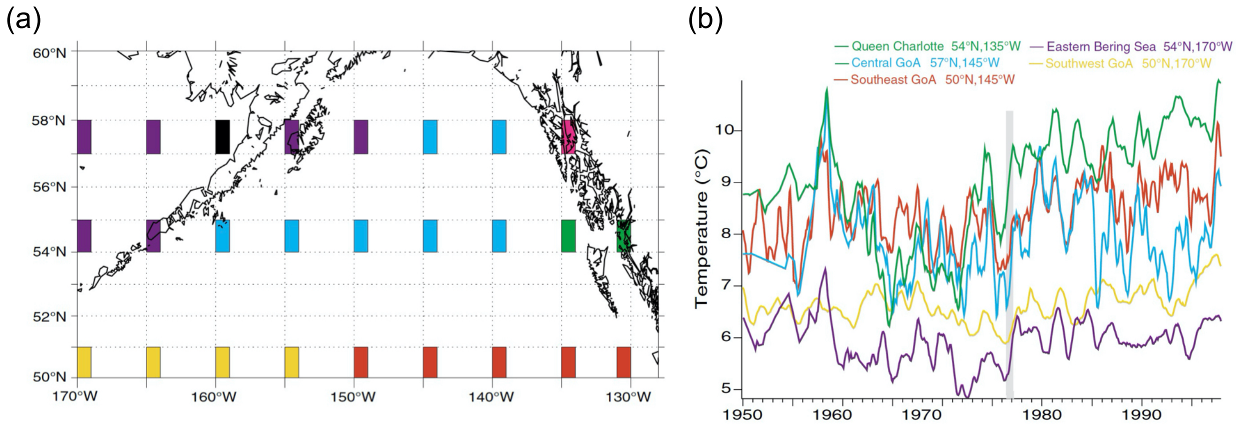


Figure 3. *(a) Map showing regional differences in sea surface temperature (SST) variability across the Gulf of Alaska, where regions were grouped by cluster analysis of SST data. Colors correspond to (b), which shows reconstructed sea surface temperature values for five geographic regions in and around the Gulf of Alaska. Reproduced from [43].*

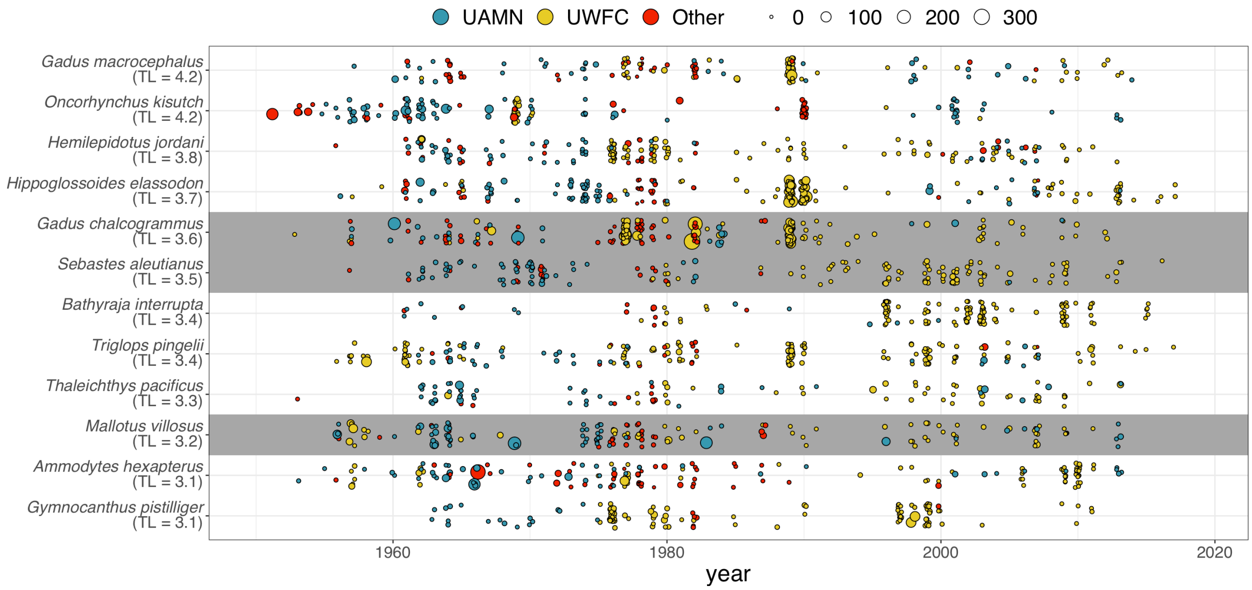


Figure 4. *Availability of specimens for the proposed project. Each point is a lot (i.e., a jar of fish). Colors indicate the natural history collection in which lots are held (UAMN = University of Alaska Museum of the North, UWFC = UW Fish Collection). Point sizes indicate the number of individual fish held in each lot. Each fish species' Latin name and trophic level (according to FishBase) are shown on the y-axis. Twelve fish species are displayed even though only 10 will be dissected, to show that back-up species exist in case actual holdings for one or two species are fewer than what is reflected in publicly accessible databases. Grey horizontal bars indicate fish species where parasitological dissections have already been completed with support of a CICOES pilot research grant. Museums hold a handful of specimens that were collected before 1950 (not shown) and these will be dissected opportunistically; however, we will focus our efforts on the period of 1950–2020, where the availability of specimens is high.*

Management or Ecosystem Implication

Our partners at the Seafood Products Association suspect that there is a new problem brewing for Alaskan fisheries: rising rates of parasitism, driven by climate change. Today, no data exist to test whether their suspicions are warranted. This proposal would provide the data needed to assess whether Alaskan marine fisheries are likely to face new challenges associated with parasitism into the future:

(Objective 1) Objective 1 will provide valuable ecosystem information by assessing whether parasitism represents an **emerging threat to ecosystem health** in the Gulf of Alaska.

(Objective 2) The data produced in Objective 2 will **promote sustainable fisheries** by isolating parasite species of importance to the value and safety of fisheries harvests and determining whether they represent a rising threat in a warming world; it will also identify the fishing regions most at risk of increasing parasite burdens, allowing commercial fishing operations to make **informed decisions about how to distribute fishing effort** and arming subsistence fishers and local communities with the information they need to navigate the years ahead.

(Objective 3) If we do find that parasites are on the rise, this project will identify **whether climate is a probable driver of this threat**, giving communities, managers, and decision-makers the information they need to adapt management strategies to changing environmental conditions.

Finally, our *Engagement Plan* will provide new learning tools in the form of a physical museum exhibit at the University of Alaska Museum of the North, a publicly available virtual museum exhibit, and online videos providing peer-reviewed information about parasites in a fun and engaging way. The Engagement Plan will also promote **sustainable fisheries** through the establishment of the Healthy Seafood Working Group, an industry advisory group.

Engagement Strategy

***Engaging Alaskan coastal communities* –** We propose to develop a **new 225-ft^2 physical exhibit at the University of Alaska Museum of the North (UAMN),** in collaboration with Co-I Roger Topp, Director of Exhibits, Design, and Digital Media at UAMN. The exhibit will introduce the concept of parasitism, feature several charismatic parasites, explain the links among parasitism, ecosystem health, and fisheries sustainability, and showcase the results of our NPRB-supported research. We will also develop a **virtual version of the exhibit (as a downloadable app)**, which will be freely available through the UAMN website, to ensure that users across the greater geographic region have access to the exhibit materials and project results during and after the run of the physical museum exhibit. These resources will allow K–12 learners, their families, and other members of the public to learn about the biology of parasites, their role in local Alaskan ecosystems, and their trajectory in a changing Gulf of Alaska.

Industry partnerships – This proposal was inspired by a list of research priorities generated by seafood industry participants, solicited and compiled by the Seafood Products Association (SPA). Our proposed research is therefore directly responsive to industry concerns. We will continue to ensure a two-way exchange of information between our research team and industry partners by forming an **industry advisory group, the Healthy Seafood Working Group**. The group will meet virtually twice per year, will be facilitated by our collaborators, Claudia Coles and Bruce Odegaard at SPA, and will include representatives from at least five Alaskan seafood operations. The goal of the meetings will be to facilitate information exchange: for industry to communicate their information needs, concerns, and observations to scientists, for scientists to report their findings back to industry, and for the entire group to collaboratively brainstorm creative solutions.

We will also create **publicly available online videos** designed to provide rigorous, peer-reviewed scientific information on parasite biology and its intersection with seafood to interested members of the seafood industry and general public. Videos will include consumer-facing material (e.g., what's this worm in my filet?) as well as industry-facing material (e.g., what processing/handling techniques minimize worm burdens in seafood products?), and will be co-produced with and disseminated by SPA, the Healthy Seafood Working Group, and the Alaska Seafood Marketing Institute (see *Letters of Collaboration*).

Links to Prior NPRB Projects

Project Management

Available resources

This team is well-equipped to accomplish the scientific goals of the project. Co-PI López is Curator of Fishes and Marine Invertebrates at UAMN, a central resource for this project, and has deep expertise in fish diversity. PI Wood is a parasite ecologist and has been working on the historical ecology of parasitism for eight years (*44, 51*). She has designed and executed similar projects in the past (*21, 26, 28, 52*); one was recently published in the *Proceedings of the National Academy of Sciences* (*21*) and received international news coverage, including in the *New York Times*. Co-PI Wood has mentored six graduate students (3 MS and 1 PhD awarded, 2 PhDs in progress), including four students who focus on historical ecology questions and use natural history collections in their thesis work. Research Technologist Katie Leslie, who has been with the Wood Lab for eight years and who would be supported by the proposed grant, is an experienced dissector of fixed fish specimens, with thousands of completed dissections under her belt; along with Co-PI Wood, she will help to train the funded graduate student in parasitological dissection protocols. Co-PI Bograd is the leader of the Climate and Ecosystem Program at NOAA's Southwest Fisheries Science Center; with hundreds of highly cited papers on climate science, Co-PI Bograd is the ideal partner for interpreting the influence of climate in our parasitological dataset. Finally, Co-PI Wood and PI López already have a proven track record of productive collaboration, having already accomplished 30% of the dissections proposed here with support from a CICOES Pilot Research Grant.

Project partners

Our project partners will make it possible to accomplish the ambitious engagement goals we have set. Co-I Roger Topp is the Director of Exhibits at UAMN. With an MS in physical oceanography and an MFA in creative writing, Co-I Topp is well-positioned to guide the development of a new museum exhibit on parasites, to be displayed at the Museum of the North and exported as a virtual exhibit (see *Engagement Plan*). Finally, we have a longstanding partnership with the Seafood Products Association (SPA). SPA President Claudia Coles and Vice President of Product Services Bruce Odegard have already supported the proposal by surveying SPA members regarding their priorities and concerns, and plan to remain involved in the project by helping to coordinate the Healthy Seafood Working Group and guiding the development of publicly available online videos targeted to both consumers and industry (see *Engagement Plan*).

Anticipated outcomes and results

Parasites are already a problem for fisheries sustainability in Alaska, both in terms of their ability to redirect energy that might otherwise flow to fisheries, "stealing" fish biomass from commercial and subsistence stakeholders, and their direct impacts on seafood safety and marketability. At the moment, links between climate and parasite burden are poorly understood. This project will test whether climate change exacerbates parasite transmission, arming the seafood industry and subsistence users with the information they need to navigate the years ahead. This project will enhance the ability of Alaskans to understand how parasitism is changing in Alaskan waters, conserve marine wildlife at risk of increased parasite burden, and sustainably use marine fisheries resources.

What will the project deliver? – We expect to produce several scientific deliverables that will advance our understanding of climate impacts on parasite burden generally and rising (or falling) threats for the Gulf of Alaska in particular:

- **Paper # 1 – Target journal = *Nature or Science*** – One scientific paper addressing whether the burden of parasitism is increasing for marine fishes (Objective 1) and 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?
- **Paper # 2 – Target journal = *Fish and Fisheries*** – One scientific paper 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)*.
- **PhD dissertation** – The funded graduate student will produce a dissertation focused on climate as a potential driver of change in parasite populations (encompassing both the Gulf of Alaska and other regions). This Fellow will be enrolled at the School of Aquatic and Fishery Sciences at the University of Washington and co-supervised by PI Wood and Co-PI López.

These scientific products will be translated into engagement materials that package scientific insight for stakeholders, policy-makers, and coastal Alaskan communities, including children. These engagement deliverables (described in the attached *Engagement Plan*) include:

- A **physical museum exhibit** at UAMN
- A **virtual version of the exhibit** (downloadable app), freely available on the UAMN website
- Formation of an industry advisory group, the **Healthy Seafood Working Group**
- Publicly available **online videos** that include both consumer- and industry-facing information, to be produced and disseminated in collaboration with the Seafood Products Association, the Healthy Seafood Working Group, and the Alaska Seafood Marketing Institute (see *Letters of Collaboration*)

How will deliverables benefit user groups? – We expect that this project will benefit three user groups: scientists, communities, and industry. ***Scientists*** – This proposal contains an ambitious natural experiment with wide-ranging implications. It will constitute the world's first multi-species empirical test of whether climate change induces increases or decreases in parasite burden. Given the excitement around the smaller and less rigorously controlled study we recently published (*21*), we expect that results from the study proposed here will be broadly interesting, which is why we plan to submit it to a top journal. In addition to pushing the frontier of knowledge in global change biology, the paper will also deepen our understanding of Alaskan coastal ecosystems, revealing hotspots of infection across both space and time. The proposal will also allow the funded graduate student to receive cutting-edge training in a brand new and rapidly growing field: the historical ecology of parasitism (*51*). ***Communities*** – Our engagement plan proposes a new exhibit at the University of Alaska Museum of the North, which will allow K–12 learners, their families, and other members of the public to learn about the biology of parasites, their role in local Alaskan ecosystems, and their trajectory in a changing Gulf of Alaska. The virtual museum exhibit will be free to download and extend our impact beyond Fairbanks. ***Industry*** – The Healthy Seafood Working Group will provide a forum for members to get their questions about parasites answered, communicate their research needs to scientists, and be the first to learn of project results. From our research, Working Group participants will learn where hotspots of parasite abundance exist in the Gulf of Alaska and how parasite burdens are likely to change in the future, so that they can plan their business activities accordingly. From our publicly available videos, all interested seafood businesses (including producers, processors, retailers, and restaurants) will learn how to handle consumer concerns about parasites and how to handle/process seafood products so as to minimize parasite burden; videos will also contain our research findings and general information on marine parasites.