Long-term changes in Puget Sound shrimp abundance

Karl Veggerby1, Chelsea L. Wood1, Tom Quinn1, Mark D. Scheuerell2

1: School of Aquatic and Fisheries Sciences, University of Washington, 1122 NE Boat St, Seattle, WA 98105

2: U.S. Geological Survey Washington Cooperative Fish and Wildlife Research Unit, School of Aquatic and Fisheries Sciences, University of Washington, 1122 NE Boat St, Seattle, WA 98105

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**Data availability**

All data used in this study, and all the R code is available online at zenodo.org, DOI: insert DOI here when paper is accepted.

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**Abstract**

In 2013 through 2016, a severe marine heatwave in the North Pacific coupled with a strong El Niño event caused widespread changes to the Pacific coast of North America. Dubbed ‘the blob’, the event has allowed researchers to explore how marine communities change in response to a rapidly warming ocean surface. We used yearly trawl data from 1999–2019 in central Puget Sound to study long-term trends in the abundance of pink shrimp (*Pandalus Jordani*), spot shrimp (*Pandalus Platyceros*), and Northern Crangon shrimp (*Crangon Alaskensis*). In contrast to past El Niño and warm-phase PDO (Pacific Decadal Oscillation) events when pink shrimp abundance declined, shrimp abundance increased dramatically in 2013–2015 concurrent with a strong El Niño. Time series analysis demonstrated that yearly abundance of these shrimps was better explained by PDO phase than El Niño phase or random chance. This indicates that the cool-phase Pacific Decadal Oscillation within the latest El Niño event may have mitigated the expected negative response of several species of shrimp to warmer surface waters from the El Niño and warm blob.

**Introduction**

In Washington State, shrimp are an important commercial and recreational fishery, and an abundant resource (ref). Recreational shrimping takes place throughout Puget Sound and across the outer coast of Washington, while a large, stable, and long-term commercial fishery for *Pandalus jordani* (pink shrimp) has existed on the coast of Washington since the 1950’s (Groth and Hannah 2018, Lorna et al. 2016). The pink shrimp fishery is viewed locally as extremely productive and sustainable, with a population driven largely by environmental conditions (Groth and Hannah 2018). There have been record pink shrimp landings in recent years, with the largest landings in the history of the fishery occurring in 2014 and 2015 (Washington Department of Fish and Wildlife annual pink shrimp reports).

A marine heatwave in 2014 and 2015 coupled with a strong El Niño caused an increase in North Pacific surface water temperatures. Sea surface temperatures were up to 3.9 degrees Celsius warmer than the historical average (NOAA climate prediction center), causing large-scale shifts in the marine community (Brodeur et ala 2019). Historically, periods of strong El Niño conditions were followed by large declines in pink shrimp abundance, because warm surface water conditions are not favorable for larval shrimp development (Rothlisberg and Miller 1983). The reasons why shrimp appear to have responded differently to the latest strong El Niño are not well understood (Morgan et al. 2019), but are important to identify, so that fisheries managers can anticipate and prepare for rapidly changing ocean conditions.

On the Washington Coast, pink shrimp population trends are well studied (ref). However, within Puget Sound, population trends of all species are virtually unknown, with incomplete survey data supplemented with recreational harvest catch data (WDFW, personal communications). To address this data gap, we set out to study how several key shrimp populations in Puget Sound have changed over time, and if those changes were related to El Niño or PDO cycles. We used catch data from a 20-year trawl dataset collected by the University of Washington in central Puget Sound paired with local environmental data to examine the following questions:

1. Have the abundances of pink, spot and Crangon shrimp changed over time in central Puget Sound?
2. Is shrimp abundance in central Puget Sound related to El Niño or PDO conditions?

**Methods**

Study Area

Port Madison is a small bay located on the west/central shore of Puget Sound along the Northern shore of Bainbridge Island (Figure 1). Puget Sound itself is a complex and highly productive ecosystem within the Salish Sea, consisting of several large, environmentally distinct sub-basins (Ruckelshaus et al. 2007). Within Port Madison, depth varies greatly, with average depth decreasing rapidly across a relatively short distance. The large variation in depth within a single bay allows trawl surveys to be conducted at varying depths within a single geographic area (Figure 1).

Sample Collection

Benthic trawl surveys were conducted in Port Madison between 1999 and 2019 by students and faculty from the University of Washington School of Aquatic and Fishery Sciences. The intent of the trawls was to collect a snapshot of the community composition of nearshore fishes and invertebrates. Surveys were conducted over the course of two days in mid-May of each year, with depths of 10, 25, 50, and 70 meters sampled. Within the two-day annual sampling effort, a survey boat conducted trawls in five shifts a few hours apart to quantify any diel vertical migration of target species: “afternoon”, “evening”, “night”, “early morning”, and “mid-morning”. Afternoon trawls began shortly after 14:00, evening trawls began shortly after 19:00, night trawls began shortly after 0:00, early morning trawls began shortly after 05:00, and morning trawls began shortly after 10:00. Each shift conducted four trawls in the same approximate locations: one at each depth of 10 m, 25 m, 50 m, and 70 m.

Each trawl survey used a Southern California Coastal Water Research Program otter trawl. The net measured 3.5-m wide, 1-m high, with a 35-mm mesh size. For each tow, the otter trawl was deployed and towed on the seabed for approximately 370 m before being retracted. All captured fish and invertebrates were placed in live wells and were identified to the lowest taxonomic level possible, measured, and released. Metadata consisting of the current tide, time of capture, capture depth, and date were recorded with every tow.

Data Analysis

Of the 25 taxa of shrimp sampled in Puget Sound, we selected three taxa that were sufficiently abundant (n ≥ 1,500) and for which observations spanned the entire time series. A total of 5,393 shrimp from the genus *Crangon* (*Crangon alaskensis*), and 13,028 shrimp of the genus *Pandalus* (pink shrimp: *Pandalus eous/jordani*, spot shrimp: *Pandalus platyceros*) were caught in Puget Sound between 1999 and 2019. The species *Pandalus eous* and *Pandalus jordani* were not differentiated in the trawl data, and so they were lumped together as “pink shrimp” for the purpose of this study.

We extracted the Oceanic Niño Index and Pacific Decadal Oscillation values from NOAA’s Climate Prediction Center (ref) and NOAA’s National Centers for Environmental Information (ref) respectively. Oceanic Niño Index and Pacific Decadal Oscillation values were averaged over the previous 12 months from each year’s sampling effort.

We fit different forms of a random walk model to the time series of shrimp catches to examine 1) whether trends in shrimp CPUE were common among all species or unique to each genus; 2) whether trends in CPUE had any systematic bias upwards or downwards; and 3) whether any bias in over time was related to the ONI and PDO. We then evaluated the data support for each form of model using Akaike’s Information Criterion corrected for small sample size (AICc). All CPUE data were log-transformed prior to analysis to meet assumptions of normally distributed errors.

For a single time series *i*, we modeled the log-CPUE at time *t* (*xi*,*t*) as a biased random walk, whereby

*xi*,*t* = *xi*,*t*-1 + *ui* + *wi*,*t* (1)

and *ui* is the upward or downward bias. We assumed that the errors were normally distributed, such that *wi*,*t* ~ N(0, *qi*). For models that included the ONI or PDO as drivers of abundance, the single bias term in equation (1) was replaced by the estimated effect (*bi*) of the specific covariate *j* at time *t* (*cj*,*t*), such that

*xi*,*t* = *xi*,*t*-1 + *bi* *cj*,*t* + *wi*,*t* (2)

The biased random walks given by (1) and (2) were then compared to a simple random walk where either *ui* = 0 or *bi* = 0.

Because our trawl data were an incomplete census of the true population size, we included an additional data model within a state-space framework to account for sampling (observation) errors. Specifically, we assumed that the estimated log-CPUE for genus *i* at time *t* (*yi*,*t*) was equal to the true log-CPUE plus an offset (*ai*) and some sampling error (*vi*,*t*), such that

*yi*,*t* = *xi*,*t* + *ai* + *vi*,*t* (3)

and the observation errors were independent and identically distributed with *vi*,*t* ~ N(0, *r*).

To evaluate whether any of the genera shared common trends in catches over time, or whether any bias in the trends was common to all genera, we fit multivariate forms of the models specified in equations 1-3. Specifically, the biased random walk is given by

(4)

where *C* denotes *Crangon* and *P* is for *Pandalus*. The model changes slightly when the two genera are assumed to have the same bias, such that

(5)

The multivariate model with covariates is then

(6)

when the effects of the covariate are different for the two genera, or

(7)

when the effects of the covariate are the same for the two genera.

The observation model is given by

(8)

When the underlying state processes are assumed to be unique, or

(9)

When there is only one state process for both genera.

We fit all models with version 3.11.3 of the MARSS package (Holmes et al. 2020 Holmes EE, Ward EJ, Scheuerell MD, Wills K (2020). MARSS: Multivariate Autoregressive State-Space Modeling. R package version 3.11.3.) for the R software (version 4.0; R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/). All data and code necessary to reproduce our analyses and results are available on GitHub at https://github.com/veggerk/Puget-Sound-shrimp-paper.

**Results**

*Crangon* shrimp abundance began to increase around 2010 and remained high through the end of the dataset in 2019 (Figure 2). Both pink shrimp and spot shrimp abundances increased dramatically in 2013 and also remained high through the end of the dataset in 2019. Pink shrimp in particular have had consistently high abundances since 2013 (Figure 2). Spot shrimp have had more varied abundance since 2013, with 2015 abundance similar to pre-2013 levels. Abundance subsequently increased again, with 2019 spot shrimp abundance being the highest on record.

Model selection results showed the most data support for a model with a common state shared by both genera, and an upward bias driven by the Pacific Decadal Oscillation (Table 1; Figure #). In contrast, we found much less evidence that El Niño intensity had a measurable impact on *Crangon* and *Pandalus* shrimp CPUE within the study time frame. Something about the other top models with delta-AIC values < 2…

**Discussion**

Recently changing environmental conditions have resulted in shifts in shrimp and other marine invertebrate populations (Brodeur et al. 2019; Peterson et al. 2017; Sakuma et al. 2016). For example, the abundance of shrimp, krill, and other crustaceans declined in the surface and midwaters off the Washington coastline during the 2014–2015 blob event, in conjunction with a dramatic increase in the abundance of warm-water gelatinous organisms (Brodeur et al. 2019; Sakuma et al. 2016), and a decline in marine biomass of salmon (Cheung and Frölicher 2020) associated with a lack of quality marine prey (Daly and Brodeur 2017). The invertebrate community still has not returned to historical levels of abundance and composition, and the shift may be permanent (Brodeur et al 2019). These changes may be due to a decline in absolute abundance, or a shift in habitat usage (Brodeur et al 2019). For example, pink shrimp move up in the water column at night to feed, but may have begun to avoid surface waters that were unfavorably warm (Brodeur et al 2019). XXX.

The abundances of shrimp observed in Puget Sound had not returned to their pre-blob levels as of 2019, even though the El Niño phase ended in 2016. Indicating that this may be an example of a semi-permanent community shift in response to the blob event. In fact, the spot shrimp CPUE from 2019 was higher than the initial 2013 spike.

The positive response of these species to warmer-than-average temperatures during 2014–2015 agree with the observations of Groth and Hannah (2018), who noted that shrimp responded differently to this latest phase of warmer water compared to prior events where growth and abundance were depressed during warm periods. Previous analysis has indicated that warmer water from El Niño and/or warm phase PDO events can depress pink shrimp growth and abundance (Rothlisberg and Miller 1983). The specific mechanisms that caused shrimp to respond differently in 2014–2015 were previously unknown, but our data suggest that it may be related to different dynamics during the 2014–2016 El Niño compared to the previous significant El Niño events in 1982–1983 and 1997–1998 (Groth and Hannah 2018, Jacox et al. 2016). Lower pink shrimp mortality rates relative to historical rates may have offset negative effects of the El Niño. In particular: predation risk from Pacific hake has declined over time (Livingston and Bailey 1985, Hannah 1995, Berger et al. 2017), and fishing pressure on younger individuals is low relative to historical levels pre 1999 (Groth and Hannah 2018).

Another likely explanation for why shrimp responded differently to the 2015 El Niño is a buffering effect due to the Pacific Decadal Oscillation being in a cool phase. In the random walk models we performed, Pacific Decadal Oscillation was a better predictor of shrimp abundance than either El Niño or random chance. During the previous strong El Niño events of the 1980s and 1990s, the Pacific Decadal Oscillation was in a warm phase, possibly exacerbating the effects from El Niño. In contrast, the Pacific Decadal Oscillation has generally been in a cool phase for the past 20 years. This cool phase potentially mitigated the effects of the strong El Niño and warm blob event during 2014–2016.

The years 2010–2011 were also strong La Niña years, which roughly coincided with the Pacific Decadal Oscillation reaching its lowest coolest phase value since the 1950’s (NOAA’s National Centers for Environmental Information). Given that pink shrimp mature in 1–2 years, the overlapping strong La Niña and strong cool phase Pacific Decadal Oscillation in 2010 and 2011 likely created ideal conditions and was responsible for the massive increase in adult shrimp observed 2 years later in 2013.

In contrast to the increases in abundance seen in this study, Brodeur et al. (2019) observed a decrease in the abundance of krill and shrimp in the unusually warm surface and mid-waters in the California Current during the blob event. However, Brodeur et al. (2019) noted that their trawl surveys were conducted in the warmer upper layers of water above the thermocline, and thus could not ascertain the community composition in deeper layers, which may have not been as affected by the blob since the largest temperature differences as a result of the blob occurred in the top 50–80m of water, with deeper temperatures remaining close to their long term mean along the Washington Coast (Auth et al. 2018; Peterson et al. 2017). Paired acoustic data from the same study showed anecdotal evidence of possible aggregations of euphausiids and other micronekton below the warmer surface layer of water (Brodeur et al. 2019), indicating possible changes in shrimp and krill diel vertical behavior in response to unfavorable temperatures near the surface.

As environmental conditions shift over the coming decades, there will be winners and losers among species. Those that can tolerate or even thrive in warmer, more acidic waters may expand their ranges and increase in abundance. Although the species studied here showed a positive response in abundance during periods with warmer than average temperature, previous responses of Pink Shrimp to El Niño and Pacific Decadal Oscillation have been negative, possibly due to concurrent warm phase Pacific Decadal Oscillation and El Niño. It is also important to note that temperature is not the only aspect of the marine environment predicted to change in the coming decades. Predicted changes in ocean acidity under future climate change scenarios (Caldeira and Wickett 2005; Cao and Caldeira 2008; Orr et al. 2005; Steinacher et al. 2009) could offset or reverse the trends seen in this study.

Pink and spot shrimp are an important resource for recreational and commercial fisheries. Interest in both the commercial and the recreational fishery is increasing as the value of shrimp has gone up, with catch quotas usually reached in recent years (Don Velasquez WDFW, personal communication). Although the ultimate effect of climate change on these species is unclear, judging by the negative responses to increased average water temperatures during concurrent warm phase Pacific Decadal Oscillation periods and El Niño, a shift in abundance will likely occur in the coming decades as average sea surface temperatures begin to mirror what currently would be considered above average or extreme. In particular, periods of both strong El Niño and strong warm phase Pacific Decadal Oscillation patterns will likely be correlated with a reduction in shrimp abundance. This study provides a brief analysis of possible environmental driver of shrimp abundance, as well as 21 years of time series data on abundance of three common shrimp species in Puget Sound in an area where previous survey data is limited or non-existent.

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Map

Description automatically generated

Figure 1. Map of Puget Sound with study area highlighted.



Figure 2. Catch per unit effort (CPUE) over time of the primary three species of shrimp found in Puget Sound trawls from 1999 to 2019.



Figure 4. Time series of standardized log-CPUE (colored points) and the best-fit model that included the Pacific Decadal Oscillation as a driver of change over time (black line). Grey lines indicate the approximate 95% confidence interval around the fitted trend line.

Table 1. Ranking of candidate models based upon AICc. The bias column indicates whether or not there was a bias term in the model, and if so, whether it was unique to each genera or shared between them. The state column indicates whether there were two states unique to each genera or one common state.

|  |  |  |  |
| --- | --- | --- | --- |
| **Bias** | **State** | **Covariate(s)** | **ΔAIC** |
| none | common | PDO | 0 |
| none | common | PDO & ONI | 0.4 |
| shared | common | none | 0.8 |
| shared | unique | PDO | 1.6 |
| none | common | none | 2.2 |
| shared | unique | none | 2.3 |
| none | common | ONI | 4.2 |
| shared | unique | ONI | 4.2 |
| unique | unique | PDO | 4.4 |
| unique | unique | none | 5 |
| none | unique | none | 11.7 |