Long-term changes in Puget Sound coast pink shrimp, spot shrimp, and Crangon shrimp abundance

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**Abstract**

In 2013 through 2016, a severe marine heatwave in the North Pacific coupled with a particularly strong El Niño event caused widespread and lasting changes to the marine ecosystem across the Pacific coast of North America. Dubbed ‘the blob’, the event has led to a range of research exploring how marine communities changed in the face of a rapidly warming ocean surface. Yearly trawl data from 1999-2019 in central Puget Sound was used to study long term trends in the abundance of pink shrimp, spot shrimp, and Northern Crangon shrimp. Contrary 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. Random-walk time series analysis predicted that yearly abundance of these species of shrimp was best explained by PDO phase compared to El Niño phase or random chance. Indicating that the cool phase Pacific Decadal Oscillation within this latest El Niño event mitigated the expected negative response of several species of shrimp to warmer surface waters from the El Niño and warm blob which co-occurred with the cool phase PDO.

**Introduction**

Across the North Pacific there are numerous genera of shrimp distributed in coastal waters from Baja California to the Chukchi Sea in Northern Alaska (Campos et al. 2012; Komai 1999; Zhang and Fong 2021). In Washington State, shrimp are an important commercial and recreational fishery, and an abundant resource. Recreational shrimping exists throughout Puget Sound and the coast, 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 in large part by environmental conditions (Groth and Hannah 2018) with evidence for changes to the age structure of the population due to previous fishing pressure (Hannah and Jones 1991). 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). Historically, periods of strong El Niño conditions were followed by large declines in pink shrimp abundance due to unfavorably warm conditions for larval shrimp (Rothlisberg and Miller 1983). The reasons why shrimp appear to have responded differently to the latest strong El Niño are not well understood. Parsing out and understanding the reasons for the observed shifts in marine community composition and abundance is critically important. Understanding why these shifts have occurred and predicting the direction and magnitude of future shifts will help fisheries managers better understand and prepare in the face of rapidly changing ocean conditions. One way to do this is to examine how shrimp and other marine species have reacted to previous shifts in climate over year or multi-year time scales. A well-known and popular study topic is the infamous ‘warm blob’ event that occurred off the west coast of the US from Alaska to Oregon in 2014 and 2015 in conjunction with an extremely strong El Niño cycle. Sea surface temperatures in the North Pacific were an average of 3.9 degrees Celsius warmer than the historical average (NOAA climate prediction center).

These 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). In recent years, these changes have been extreme, highly variable, seemingly contradictory; and in some cases not well understood (Morgan et al. 2019). For instance: there was a large observed decrease in the abundance of shrimp, krill, and other crustaceans in the surface and midwaters off the Washington coastline during the 2014-2015 blob event, in conjunction with an explosion 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 semi-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). Pink shrimp for example move up in the water column at night to feed, but may have begun to avoid surface waters that were unfavorably warm.

This event, and the many observed ecosystem responses, gives a preview of potential future baseline conditions under predicted climate change scenarios. Average air temperatures in the Pacific Northwest are expected to increase by 1.8°C - 5.4°C by the 2080s (compared to the 1980s), and summer precipitation is expected to decrease by about 10% (IPCC 2007; National Climate Assessment 2014). To study how 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.

This study attempted to examine the following questions:

1. Has pink, spot and Crangon shrimp abundance in central Puget Sound changed over time?
2. Do these three shrimp species exhibit diel vertical migration behavior?
3. 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). The 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 with students and faculty from the University of Washington School of Aquatic and Fisheries Sciences. The intent of the trawls was to collect a snapshot of the community composition of nearshore fish 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 yearly sampling effort, a survey boat conducted trawls in 5 different shifts a few hours apart from each other in order 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 10m, 25m, 50m, and 70m.

Each trawl survey used a Southern California Coastal Water Research Program otter trawl. The net measured 3.5m wide, 1m high, with a 35mm mesh size. For each trawl, the otter trawl was deployed and towed on the seabed for approximately 370m before being retracted. All captured fish and invertebrates were placed in live wells before being 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 individual.

Data Analysis

El Niño/ La Niña Intensity Index and Pacific Decadal Oscillation values were taken from NOAA’s Climate Prediction Center and NOAA’s National Centers for Environmental Information respectively. Oceanic Niño Index and Pacific Decadal Oscillation values were averaged over the previous 12 months from each year’s sampling effort and added to the shrimp data by year.

A random-walk time series model in the ‘MARSS’ package in R was used to model Puget Sound shrimp CPUE and ONI values over time (MARSS ref). Coastal pink shrimp were excluded as the sample size was too small. AIC values were calculated to determine model fit (ref). The model containing ONI values was considered to be a better fit if it predicted shrimp CPUE values better than a model using only random chance.

Of the 25 taxa of shrimp sampled in Puget Sound, a total of three taxa were selected for further examination based upon the following criteria: (1) taxon containing many individuals (n ≥ 1,500) and (2) taxon contained enough individuals caught over a large number of years. A total of 5,393 shrimp from the Crangon genus (*Crangon Alaskensis*), and 13,028 shrimp of the Pandalus genus (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 were lumped together as pink shrimp for the purpose of this study. Yearly abundance over time and capture depth and capture timing were plotted in order to quantify abundance changes over time, and possible vertical diel migration between different depths. All analysis was conducted in R version 4.1.2 and Rstudio version 2022.02.0.

**Results**

Crangon shrimp abundance began to increase around 2010, and has remained at a high level since then (Figure 2). Both pink shrimp and spot shrimp abundances increased dramatically in 2013, and have remained at elevated levels since. 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.

Consistently across the Puget Sound trawl, the vast majority of shrimp were caught in the 50m and 70m depth trawls (Figure 3). Crangon shrimp and spot shrimp both showed signs of diel vertical migration (Figure 3). Pink shrimp showed no signs of diel vertical migration within the range of depths sampled. However, it’s possible that pink shrimp diel vertical migration took place at deeper depths that our sampling design simply missed. The only times that Crangon shrimp were found in the shallower 10- and 25-meter trawls was at night (Figure 3). Spot shrimp were almost always found at the 70 meter depth. They were present at the 50-meter trawls only at night or morning, indicating some amount of vertical migration into shallower water during the night.

The time series model showed no evidence that El Niño intensity had a measurable impact on *Crangon* and *Pandalus* shrimp CPUE within the study time frame. The model performed no better than random chance based upon AIC values (ref), indicating that El Niño along failed to explain the increase in shrimp abundance across the state. The Pacific Decadal Oscillation model with a shared state was however successful in predicting shrimp CPUE better than random chance, El Niño, or a combination of El Niño and Pacific Decadal Oscillation (Figure 4, Table 1). Pacific Decadal Oscillation thus appears to have a greater impact shrimp CPUE than El Niño.

**Discussion**

The abundance of shrimp observed in Puget Sound through 2019 have not returned to their pre-blob levels, 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 are in line with 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 depress pink shrimp growth and abundance (Rothlisberg and Miller 1983). The specific mechanisms that caused shrimp to respond differently this time around have previously been unknown but may be related to different dynamics during the 2014-2016 El Niño compared to the previous significant El Niño events in 1982/83 and 1997/98 (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. Based on the random walk model we performed, Pacific Decadal Oscillation is a better predictor of shrimp abundance than either El Niño or simple random chance. During the previous strong El Niño events during 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 abundance increases seen in this study, in a study of a different Northeast Pacific marine system, the California Current, there was an observed decrease in the abundance of krill and shrimp in the unusually warm surface and mid waters during the blob event (Brodeur et al. 2019). 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. While 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 condition 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) may very well offset or reverse the trends seen in this study.

**Management Implications**

Pink and spot shrimp are important for recreational and/or commercial harvest. Interest in both the commercial and the recreational fishery is increasing as the value of shrimp has gone up, with catch quotas usually always reached in recent years (Don Velasquez WDFW, personal communication). While the ultimate effect that climate change will have 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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**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.

**Citations**

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Map

Description automatically generated

Figure 1. Map of the 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 3. Catch per unit effort (CPUE) of the primary three species of shrimp found in Puget Sound trawls from 1999 to 2019 over the course of a consistent 24 hour sampling effort each year.



Figure 4. The most parsimonious Random walk model (based on AIC values) with Pacific Decadal Oscillation as a predictor of Crangon and Pandalus genus log standardized CPUE. Black line shows predicted model state (CPUE), grey lines show standard errors.

Table 1. random walk model results predicting Crandon and Pandalus CPUE using Pacific Decadal Oscillation and El Niño/ La Niña intensity.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **model** | **bias** | **states** | **predictors** | **delta AIC** |
| 8 | none | shared | PDO | 0 |
| 9 | none | shared | PDO & ONI | 0.4 |
| 7 | shared | shared | none | 0.8 |
| 4 | shared | unique | PDO | 1.6 |
| 6 | none | shared | none | 2.2 |
| 2 | shared | unique | none | 2.3 |
| 10 | none | shared | ONI | 4.2 |
| 11 | shared | unique | ONI | 4.2 |
| 5 | unique | unique | PDO | 4.4 |
| 3 | unique | unique | none | 5 |
| 1 | none | unique | none | 11.7 |