Comparison of long-term changes in Puget Sound and coastal Washington 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 paired with yearly catch data from 2011-2019 on the Washington Coast to compare long term trends in the abundance of pink shrimp across the state. Contrary to past El Niño and warm-phase PDO (Pacific Decadal Oscillation) events when pink shrimp abundance declined, shrimp abundance increased dramatically in 2013-2014 across both regions, but was not significantly correlated across the longer study period. The largest commercial haul of Washington coast pink shrimp ever recorded occurred in 2014. Yet, shrimp abundance was not correlated with El Niño intensity within the study period. Increases in Puget Sound abundance were only observed at deeper trawl depths, indicating that in addition to increasing in abundance, shrimp may be altering their diel vertical migrations in response to unfavorable temperatures in surface waters. Pink shrimp responded very differently during the 2014-2016 El Niño compared to previous extreme El Niño events, indicating that the currently poorly understood dynamics within this latest event mitigated the expected negative response of shrimp to warmer surface waters.

**Keywords: climate change, shrimp, Pandalus jordani, pink shrimp, Puget Sound, abundance**

**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 (Komai 1999; Campos et al. 2012; 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 (Wargo et al. 2016; Groth and Hannah 2018). 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 (Wargo and Ayres 2016; Ayres et al. 2017, 2018, 2019, 2020, 2021). 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 (National Oceanic and Atmospheric Administration 2019).

These recently changing environmental conditions have resulted in shifts in shrimp and other marine invertebrate populations (Sakuma et al. 2016; Peterson et al. 2017; Brodeur et al. 2019). 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 (Sakuma et al. 2016; Brodeur et al. 2019), and a decline in marine biomass of salmon (Cheung and Frolicher 2020) associated with a lack of quality marine prey (Daly et al. 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; US Global Change Research Program 2014). To study how shrimp populations in Washington have changed over time, we used two datasets to examine shrimp abundance over time: A 20 year of trawl dataset collected by the University of Washington in central Puget Sound, and shrimp catch per unit effort data from the commercial pink shrimp fishery on the Washington Coast.

This study attempted to examine the following questions:

1. Has shrimp abundance in central Puget Sound changed over time?
2. Are changes in shrimp abundance in central Puget Sound and the Washington Coast correlated?
3. Has shrimp abundance in central Puget Sound changed over time in tandem with El Niño 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. The coastal shrimp fishery operates all along the Washington Coast in federal waters between 3-200 miles offshore (Figure 1), with most of the catch occurring from Gray’s Harbor in the South to La Push in the North (Wargo et al. 2016).

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: “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.

Commercial shrimp catch per unit effort data for the coast was obtained from WDFW pink shrimp annual newsletters (Wargo and Ayres 2016; Ayres et al. 2017, 2018, 2019, 2020, 2021) and (Wargo et al. 2016). Catch per unit effort data was not available prior to 2011, when more extensive shrimp fishery monitoring began.

Data Analysis

El Niño/ La Niña Intensity Index values were taken from NOAA’s Climate Prediction Center (National Oceanic and Atmospheric Administration 2019). Oceanic Niño Index values were averaged over the previous 12 months from each year’s sampling effort and added to the shrimp data by year. Based on ONI conditions, catch data of each shrimp species was separated by year into three groups: “El Niño conditions”, “La Niña conditions”, and “no signal” based on the average ONI values of the previous 12 months prior to each yearly sampling effort. ONI values at or above 0.5 are defined as El Niño conditions by NOAA, indicating temperatures are warmer than average. ONI values at or below -0.5 are defined as La Niña conditions, indicating temperatures are cooler than average. Values that fall between -0.5 and 0.5 are defined as having neither condition present. This categorical classification was the primary variable examined, and was used in leu of the average ONI values in order to lump years into groups based on similar climate conditions.

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. 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.

**Results**

Of the 25 taxa of shrimp sampled in Puget Sound, a total of two taxa were selected for further examination based upon the following criteria: (1) taxon containing a large number of 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, and 13,028 shrimp of the Pandalus genus (pink shrimp) were caught in Puget Sound between 1999 and 2019.

Consistently across the Puget Sound trawl, the vast majority of shrimp were caught in the 50m and 70m depth trawls. There was no significant correlation between yearly Pandalus CPUE in Puget Sound and the Coast (R2=0.06). However, the massive increase in CPUE in 2013 and 2014 reported by the coastal commercial fishery was clear in the Puget Sound CPUE (Figure 2, Figure 3). Both Crangon and Pandalus genus surveyed in Puget Sound exhibited a similar increase in 2013 and remained at elevated CPUE levels thru 2019 relative to past CPUE (Figure 2). Pandalus CPUE along the Washington Coast dropped after the 2013-2014 boom, and annual landings have returned to historical levels (Ayres et al. 2020, 2021).

The time series model showed no evidence that El Niño intensity had a measurable impact on shrimp CPUE within the study time frame. The model performed no better than random chance, indicating that El Niño along failed to explain the increase in shrimp abundance across the state.

**Discussion**

When comparing Puget Sound catch per unit effort across depths, the majority of shrimp were consistently caught in 50m and 70m trawls. The large shifts in abundance observed were almost entirely driven by changes at these depths. Catch per unit effort at 10m and 25m trawls remained virtually unchanged across the entire study. The trend of increasing shrimp abundance starting in 2013/2014 onward was driven entirely by catch at deeper depths. Puget Sound catch per unit efforts at these depths have never returned to pre-2013 levels. Indicating that this may be an example of a semi-permanent community shift in response to the blob event. In fact, the CPUE from 2019 Puget Sound trawls 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 are 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 (Jacox et al. 2016; Groth and Hannah 2018). 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; Johnson et al. 2021), and fishing pressure on younger individuals is low relative to historical levels pre 1999 (Groth and Hannah 2018).

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 (Peterson et al. 2017; Auth et al. 2018). 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.

This study’s findings suggest the large increase in shrimp abundance during and after the blob years occurred entirely at depths of 50m and greater. lending more support to the theory that shrimp altered their diel vertical migrations to avoid potentially harmful water temperatures near the surface. In the case of the Port Madison trawls, this would mean avoiding the shallower areas of the bay entirely. This would help explain the increased abundance of shrimp shown in this paper and others (Wargo and Ayres 2016; Ayres et al. 2017, 2018, 2019, 2020, 2021; Groth and Hannah 2018), which appears contradictory to previous studies showing large shrimp declines over the same period along the coast.

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 PDO have been negative. 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 (Caldeira and Wickett 2005; Orr et al. 2005; Cao and Caldeira 2008; Steinacher et al. 2009) may very well offset or reverse the trends seen in this study.

**Management Implications**

Several of the species studied here are important for recreational and/or commercial harvest. While the ultimate effect that climate change will have on these species is unclear, judging by the strong negative and positive responses to increased average water temperatures, 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. The specific mechanistic effects causing the increased shrimp abundance during this latest strong El Niño phase is not clear. Further work to quantify why shrimp responded so differently to these recent warmer conditions compared to previous El Niño cycles is warranted.

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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**

Map

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



Figure 2. Catch per unit effort (CPUE) of the primary two genus of shrimp found in Puget Sound trawls from 1999 to 2019.



Figure 3. Comparison of catch per unit effort (CPUE) of pink shrimp (Pandalus) caught in Puget Sound trawls (top) and by the commercial fishery off the coast of Washington (bottom).