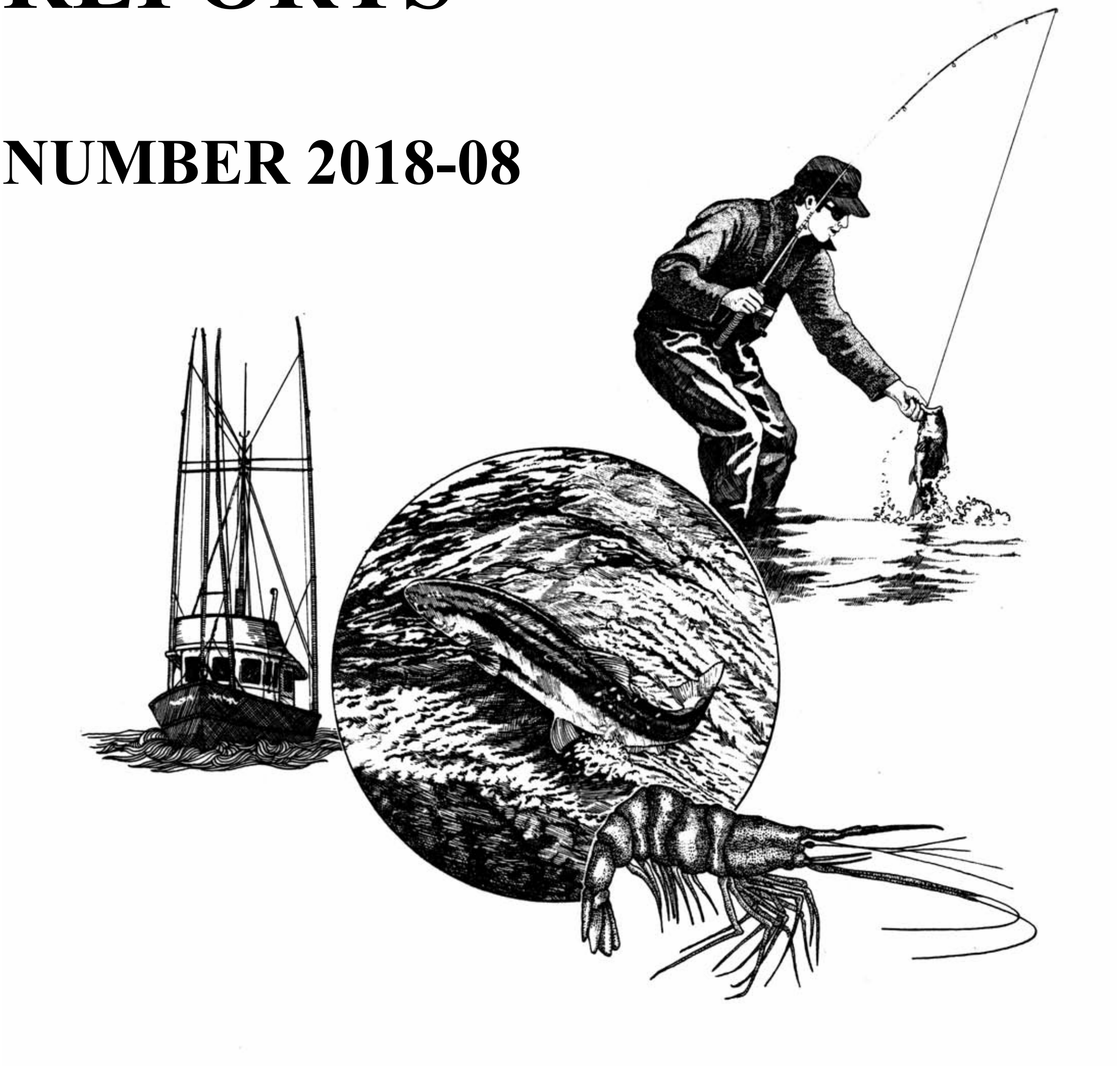
INFORMATION REPORTS

NUMBER 2018-08



FISH DIVISION

Oregon Department of Fish and Wildlife

An evaluation of fishery and environmental effects on the population structure and recruitment levels of ocean shrimp (*Pandalus jordani*) through 2017

An evaluation of fishery and environmental effects on the population structure and recruitment levels of ocean shrimp (*Pandalus jordani*) through 2017

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December 2018

Preface

Periodically evaluating the effects of fishing and the environment on population structure and recruitment is critical to assuring sustainability in a fishery. Oregon’s ocean shrimp (*Pandalus jordani*) trawl fishery is managed as a sustainable fishery and was the first shrimp fishery certified as “sustainable” by the Marine Stewardship Council (MSC). In accordance with MSC recommendations, the Oregon Department of Fish and Wildlife (ODFW) published reports in 2014 and 2016 evaluating population structure and recruitment effects for ocean shrimp, for the purpose of documenting ongoing monitoring and analysis (Hannah and Jones 2014, Hannah and Jones 2016). In this report, we build on previous work by adding the most recent two years of data and discuss new issues that affect the ocean shrimp stock and fishery. These long term datasets and analyses provide us metrics that allow us to have confidence in the sustainability of Oregon’s ocean shrimp fishery.

This report series (population structure and recruitment of ocean shrimp), was developed by Hannah and Jones (2014; 2016) as a template to add future data to and maintain continuity in the reevaluation of fishery parameters (Hannah, pers comm 2018). Hannah and Jones effectively monitored, researched and managed Oregon’s ocean shrimp fishery from 1985-2016, helping Oregon’s ocean shrimp fishery attain MSC certification. This report purposefully borrows heavily from previous reports in this series to provide continuity in the analytical methods and update datasets in an organized, uniform way.

I. Fishery-induced changes in the population structure of ocean shrimp (*Pandalus jordani*), an update for the 52 years from 1966 to 2017

Introduction

Understanding how fishing and environmental variation interact to alter the size, age and sex composition (population structure) of an exploited stock is a key goal of fisheries science. The population structure of a stock can be important for a variety of reasons. Larger fish or invertebrates are frequently more commercially valuable than smaller individuals. Harvesting, especially size-selective harvesting, can greatly reduce the average size or age of individuals in a population (Fenberg and Roy 2008). Age truncation within a population can have the effect of making it more sensitive to environmental variation (Rouyer et al. 2011). It has also been argued that the loss of older breeders, and the higher quality larvae they produce, can adversely affect stock productivity in some species (Sogard, Berkeley and Fisher 2008).

Over time, ocean shrimp stocks have been evaluated to determine the effects of fishing. In a 1991 study, the population structure of ocean shrimp was found to have been altered by harvest pressure from the developing trawl fishery (Hannah and Jones 1991). Ocean shrimp support an extensive and intensive fishery on the west coast of North America between northern California in the United States (US) and northern British Columbia, Canada (Hannah 1993). The fishery began in the mid-1950s then developed slowly throughout the 1960s, but was constrained by the technical challenges of processing these small shrimp. Ocean shrimp live only about 4 years and reach sizes of only about 10-12 grams. The fishery for ocean shrimp grew with the advent of mechanized cooking and peeling in the mid-1960s and again with the adoption of double-rigged, high-rise box trawls in the 1970s. By the 1980s, landings exceeding 18,000 metric tons per year had become common (Hannah and Jones 1991). In a 1991 study of the dockside fishery sampling data for the years 1966-88 and statistical sampling areas 19-28 (Figure 1), Hannah and Jones showed that as the fishery reached higher effort levels around 1979, the shrimp population structure began to be altered. As the stock was “fished down” to lower average levels of catch-per-unit-effort (CPUE), size-at-age increased and the population also became “juvenated”. The age composition of the catch shifted from a mix of ages 1-3 to mostly age 1 shrimp however, the sex composition of the population was not greatly altered (Hannah and Jones 1991). Ocean shrimp breed in the fall each year and function first as males, typically at age 1, and then as females at older ages, typically ages 2 and 3 (Butler 1980). Ocean shrimp have flexible rates of sex change that respond to changes in their demographic environment (Charnov, Gotshall and Robinson 1979, Charnov and Hannah 2002). They transition into females more readily at younger ages whenever age 1 shrimp are relatively more abundant (Charnov and Hannah 2002). They also can remain male for an extra year when older age (often female) shrimp dominate. Age 1 females are referred to as “primary females” and were shown to have increased in frequency to average rates of 30-50% of the age 1 population in response to exploitation, maintaining an approximately balanced sex composition in the stock. Due to the limited time-series of data available at the time of the earlier study, the relative importance of fishing and environmental variation were not conclusively linked to the factors behind the observed changes in shrimp growth (Hannah and Jones 1991).

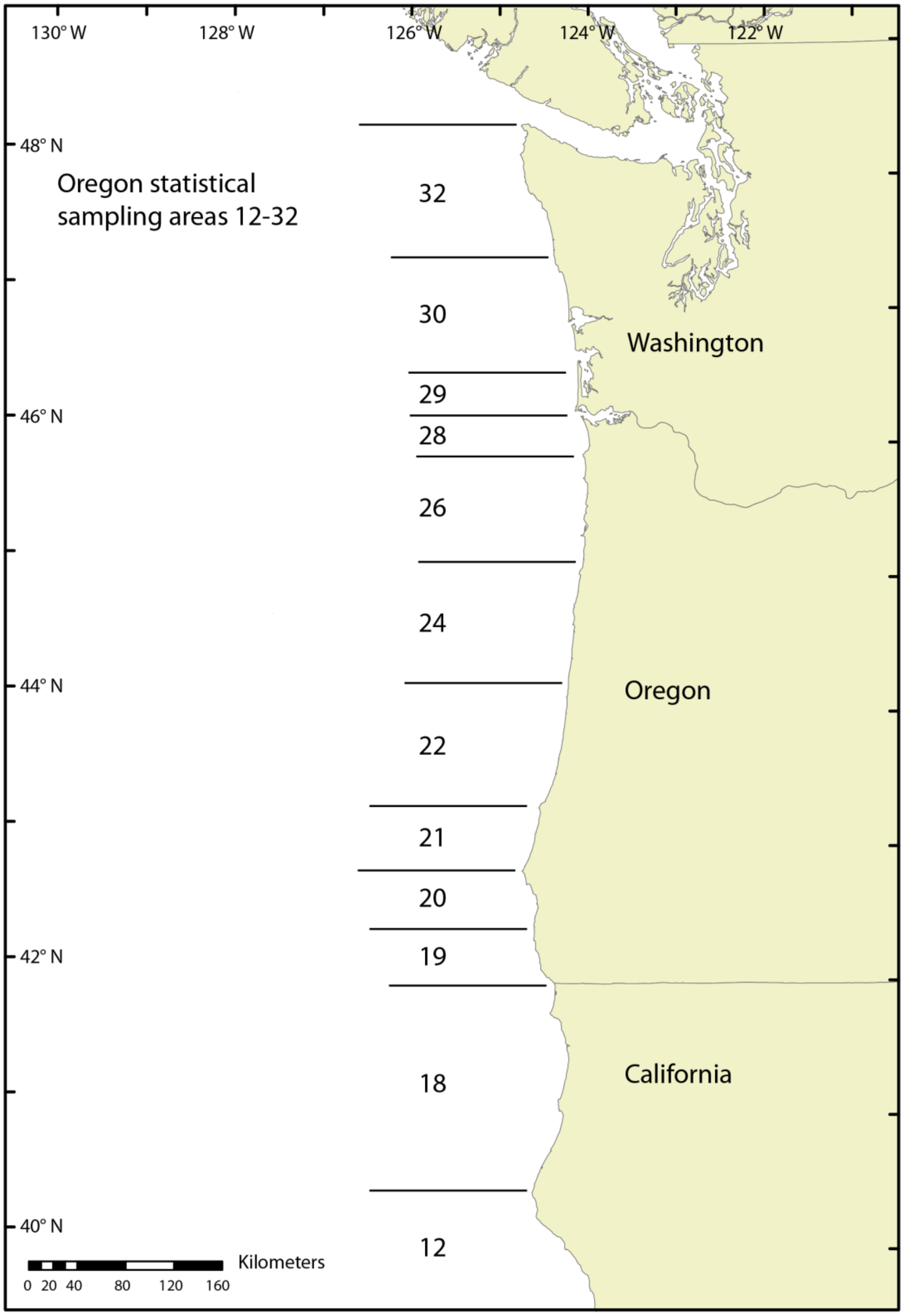

Figure 1. Map showing Oregon's statistical sampling areas 12-32 for the ocean shrimp fishery.

In the many years since the 1991 study, total ocean shrimp catch from marine waters off of Oregon has remained high but variable (Figure 2). However, total fishing effort (standardized to single rig equivalent hours, SREH, (Hannah 1993) in the same areas has been reduced relative to the late 1980s (Figure 3). Due to inconsistencies in the availability of fishery logbook data for California, Washington and British Columbia, standardized effort data from Oregon are shown here as a proxy for the regional fishery. A variety of factors have contributed to the decline in effort, including limited entry programs enacted by the states of California, Oregon and Washington, as well as a federal groundfish vessel buyback program implemented in 2003 that eliminated some vessels that fished both groundfish and shrimp. This large decline in fishing effort has been accompanied by a large increase in CPUE (Figure 4) as a result of several large recruitment events (see Section II for recruitment data). This large increase in shrimp density suggest conducting a new analysis of the relative influence of changes in fishery exploitation and environmental variation on ocean shrimp growth.

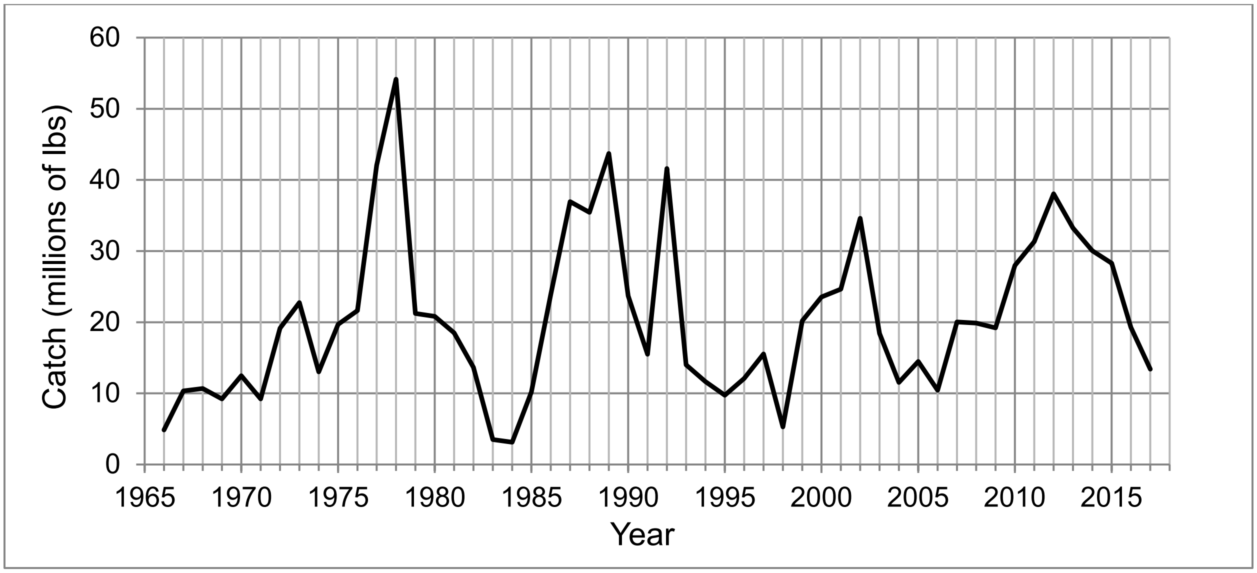

Figure 2. Time series of ocean shrimp (*Pandalus jordani*) catch landed into Oregon ports from waters off of Oregon (areas 19-28, Figure 1), 1966-2017.

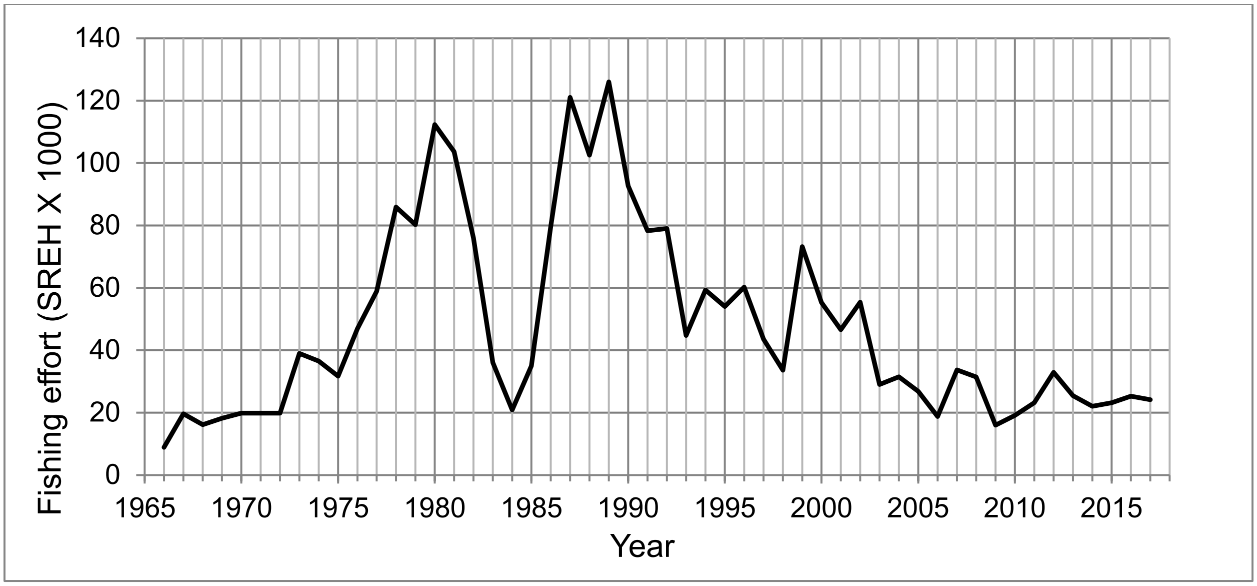

Figure 3. Time series of trawl fishing effort (single-rig-equivalent h) for ocean shrimp (*Pandalus jordani*, areas 19-28, Figure 1), 1966-2017.

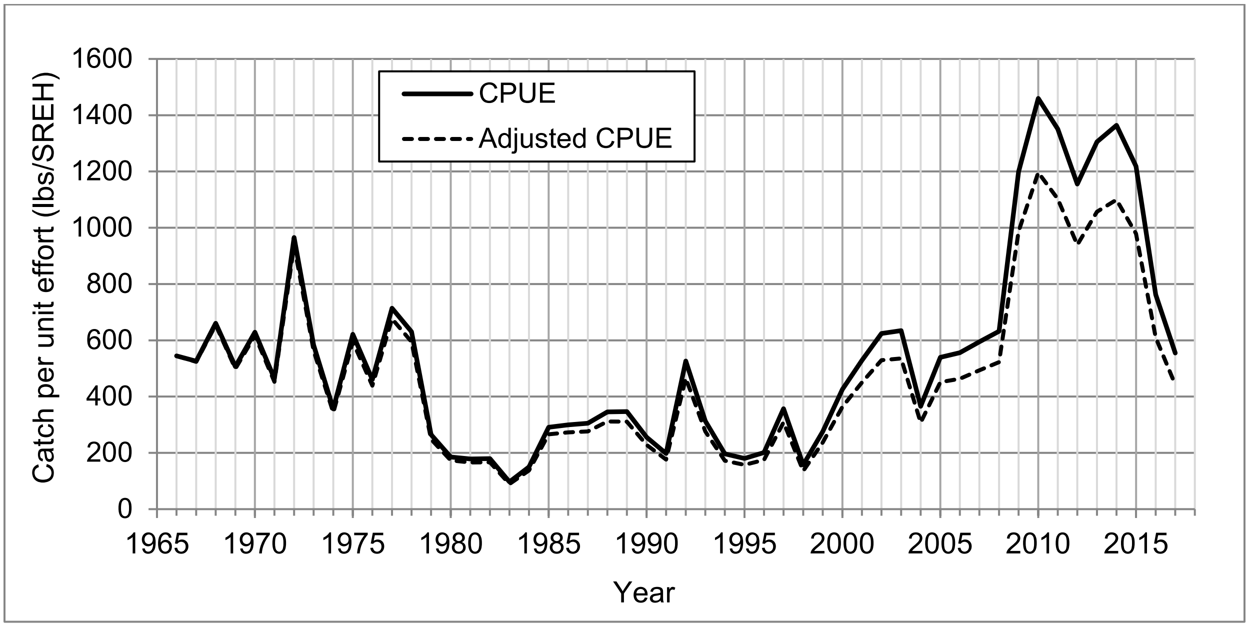

Figure 4. Oregon ocean shrimp (*Pandalus jordani*) trawl fishery catch-per-unit-effort (CPUE, lbs/single-rig-equivalent h (and adjusted CPUE, see text), areas 19-28, 1966-2017.

Here, we review the complete 52-year time series (1966-2017) of dockside fishery sampling of ocean shrimp catch from the marine waters off Oregon. The main objective was to determine how the population structure of ocean shrimp has been affected by changes in fishing effort and CPUE and how it has changed since 1988, the last year included in the 1991 study. An additional objective was to re-examine the relative effects of fishing and environmental variation on shrimp growth rates now that a full 52 years of fishery sample data are available.

Methods

The methods used to understand changes to population structure in ocean shrimp were similar to those of the 1991 study (Hannah and Jones 1991), with a few minor changes. To examine time trends in shrimp growth, we examined carapace length-at-age data for the same 8 index area-months and ages (Table 1, Figure 1), as in the earlier study. Samples of the landed catch of ocean shrimp have been collected monthly during the April to October fishing season for the full 52-year time series, with the sampling goal of collecting a number of different samples of at least 100 shrimp from each of areas 19-28 (Figure 1, (Hannah and Jones 1991)). Fishery sampling goals have varied slightly over time and sampling occurs outside these index strata as well. Year-to-year variation in where the fishery operates also makes it impossible to obtain samples from every area-month each year, leaving some gaps in the time series for individual area-months. The area-months selected for the 1991 study were those with the best sample density over the time series that was then available. Fortunately, these area-months have continued to be fished and sampled regularly over the ensuing years. The sampling methods and techniques used to assign age and sex to individual shrimp were the same as in the 1991 study (Hannah and Jones 1991). Briefly, ages are assigned based on modal analysis of carapace length frequency, and sex (male, female or transitional) is designated based on close inspection of the inner ramus of the first pleopod, following conventional methods (Tegelberg and Smith 1957) .

To generate a single index of shrimp growth for the full time series, we first subtracted the long-term average carapace length for each index area-month from the annual data to create an annual "carapace-length anomaly". The annual anomalies were then averaged across all 8 indices (Table 1) to generate a single annual growth index. As an index of interannual variation in the ocean environment, we used the annual average of January-June monthly values for the Pacific Decadal Oscillation (PDO) index (Mantua and Hare 2018, Mantua et al. 1997). Multiple regression analysis conducted in NCSS 11® was used to evaluate the influence of changes in density and the PDO on shrimp growth. The appropriateness of a simple linear model was confirmed by testing the model residuals for normality (Shapiro-Wilk test). We again used fishery CPUE as an index of shrimp density. The CPUE index was based on total landed catches (lbs) and fishing effort expended in Oregon fishery sampling areas 19-28 (Figure 4). For the years 1966 to 1992, catches and effort by vessels landing shrimp from these areas into the states of California, Washington and Oregon were used. For the years after 1992, only catches and effort by vessels landing into the state of Oregon were included, due to the lack of available logbook data for the other two states. Although fishing effort was standardized between single-rigged and double-rigged vessels for all years (Hannah 1993), other changes in fishing practices and trawl gear have probably increased vessel efficiency over this long time series. For comparative purposes, we also calculated an adjusted CPUE index that was discounted at a rate of 0.5 percent per year, a rate that was admittedly arbitrary, but was an effort to correct for increasing vessel efficiency over time.

Table 1. Months and statistical areas (Figure 1) from which fishery samples were used to construct an annual growth index for ocean shrimp, 1966-2017.

Month	Oregon statistical sampling area	Age	Number of years with samples
July	21	1	39
August	19	1	29
August	22	1	44
August	26	1	41
April	22	2	45
May	26	2	47
June	21	2	35
August	19	2	29

As in the earlier study, we also examined trends in the percentage of age 1 shrimp in the catch and the percentage of primary females and males observed in September and October catch samples, a time period just prior to mating. We calculated an annual index for the percent primary females and males for the entire 52-year series as a simple average of the percentages in all of the September and October samples from the areas off of Oregon each year, statistical sampling areas 19-28 (Figure 1). To better evaluate the low-frequency variation in these indices, we also calculated a 5-year moving average.

Results

The ocean shrimp growth index shows that shrimp growth was variable by era, depending on shrimp density and ocean conditions. Early years (1966 to 1978), were characterized by slow growth of ocean shrimp, in a subsequent era (1979 to 2003) size-at-age was increased, then recently (2004 to 2017) size-at-age was again decreased (Figure 5). Although recent ocean shrimp growth has been reduced, it has not decreased to the levels seen prior to the fishery becoming fully developed, which started in about 1979. Over the same 2004 to 2017 period, fishery CPUE increased greatly and the PDO index has frequently been negative, indicating colder sea surface temperatures (SST, Figure 6), relative to the prior period (1979 to 2003). Multiple regression analysis for the full 52-year time series showed that fishery CPUE was still negatively correlated with shrimp growth ($P=0.0031$) and that SSTs, as reflected in the PDO index, were positively correlated with shrimp growth ($P= 0.0083$, Table 2). The full model incorporating both variables explained about 31% of the variation observed in average ocean shrimp size-at-age over 52 years ($P=0.0001$, Table 2). Substituting the adjusted CPUE index improved the model fit, increasing the total explained variation in shrimp growth to about 34% and improving the statistical significance of CPUE ($P=0.0009$, Table 2). Both models produced residuals that were normally distributed ($P>0.05$).

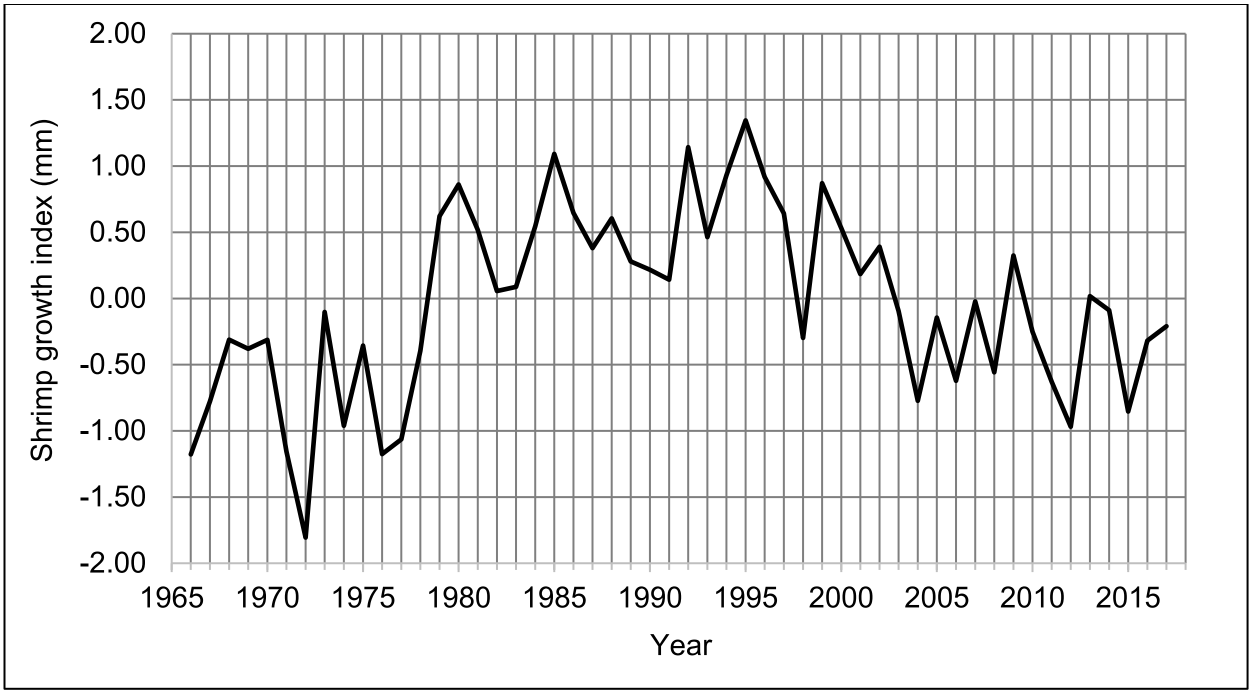

Figure 5. Ocean shrimp (*Pandalus jordani*) growth index, 1966-2017.

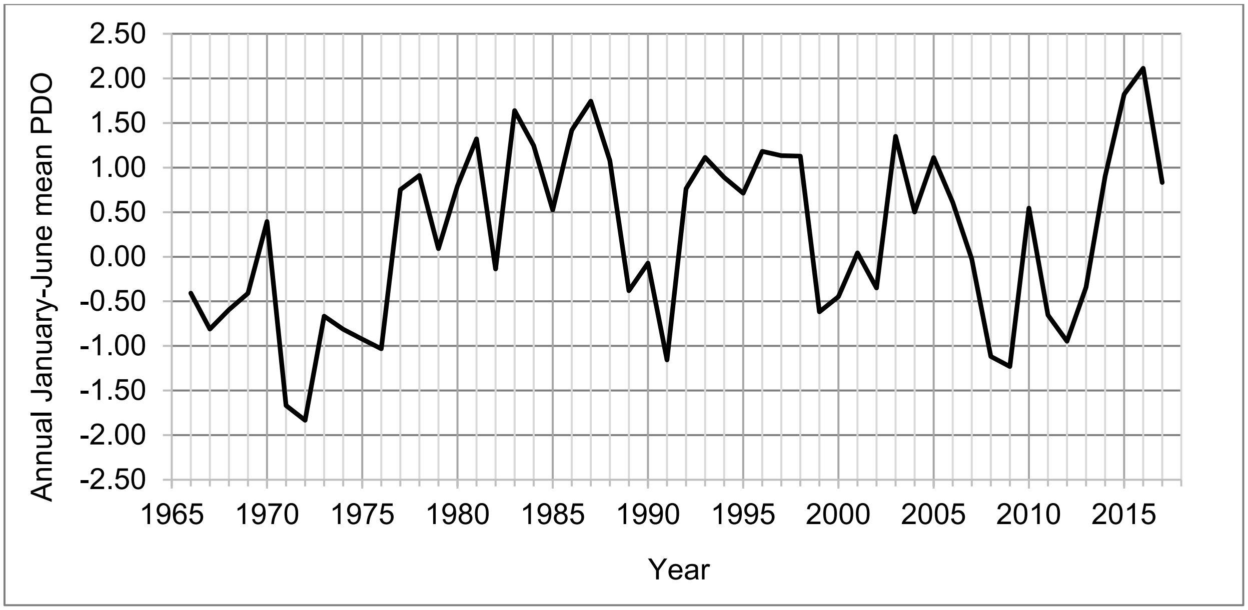

Figure 6. Annual average January-June Pacific Decadal Oscillation (PDO) index, 1966-2017.

Table 2. Results of multiple regression analysis of the ocean shrimp growth index on the annual mean January-June Pacific Decadal Oscillation index (6 month PDO) and simple and adjusted (see text) fishery catch-per-unit-effort (CPUE, lbs/single-rig-equivalent h) in the trawl fishery in waters off Oregon, 1966-2017.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
Ocean shrimp growth index	Intercept	0.3139	0.1594		
	Trawl fishery CPUE	-0.0008	0.0002		0.0031
	6-month PDO	0.2386	0.0867		0.0083
	Full model			0.3108	0.0001
Ocean shrimp growth index	Intercept	0.4037	0.1663		
	Adjusted trawl fishery CPUE	-0.0023	0.0006		0.0009
	6-month PDO	0.2138	0.0860		0.0164
	Full model			0.3423	0.0000

The percentage of age 1 shrimp in the catch continued to vary greatly from year to year after 1988 due to variation in ocean shrimp recruitment (Figure 7). In recent years, the average percentage of age 1 shrimp has declined to the levels seen between 1979 and 2003, although the most recent two years of data added (2016 and 2017) were dominated by age 1 shrimp. Similarly to shrimp size-at-age, the percentage of age 1 shrimp in the catch remained above the levels observed prior to 1979 (Figure 7). A similar trend can be seen in the average percentage of primary females in September and October samples through 2014 (Figure 8). However, the most recent two years have had very high percentages of primary females, with 2016 being the highest percentage on record, likely driven by catch being highly comprised of mostly age 1 shrimp. As shown in the earlier study (Hannah and Jones 1991), the sex composition of the September-October catch has remained roughly balanced (Figure 9).

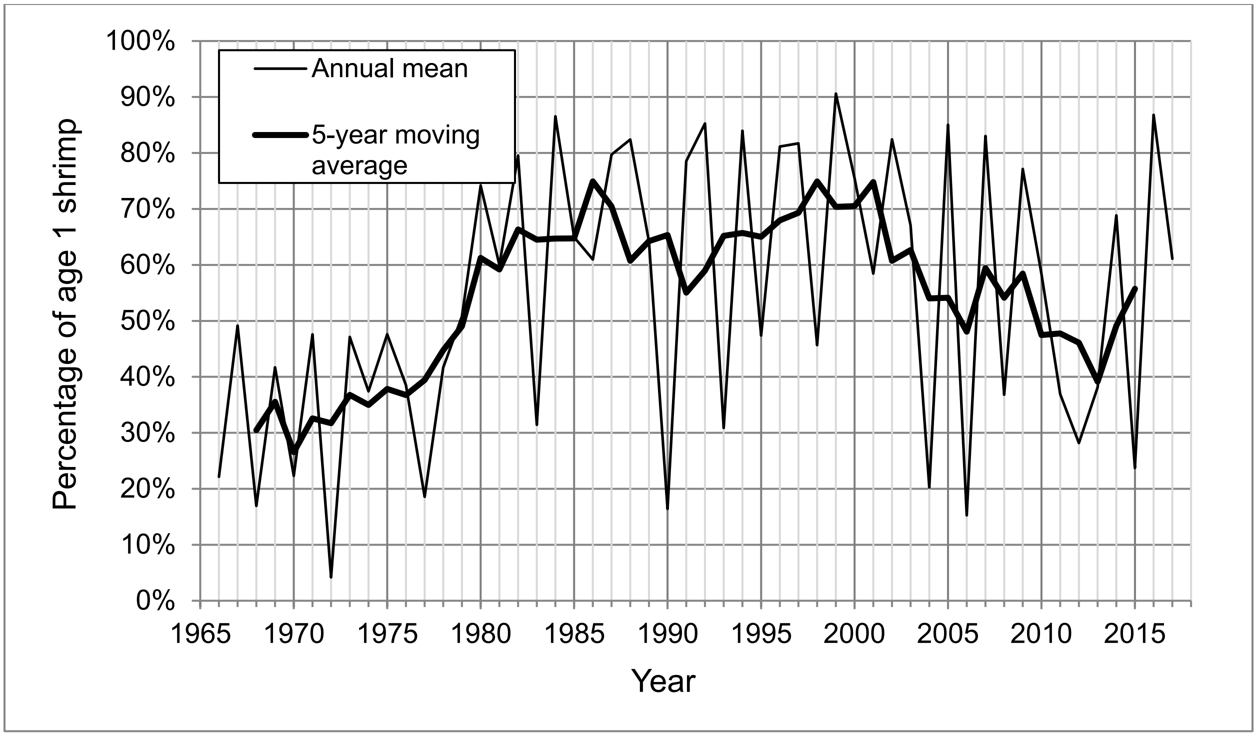

Figure 7. The percentage of age 1 shrimp in the trawl fishery catch of ocean shrimp (*Pandalus jordani*), 1966-2017.

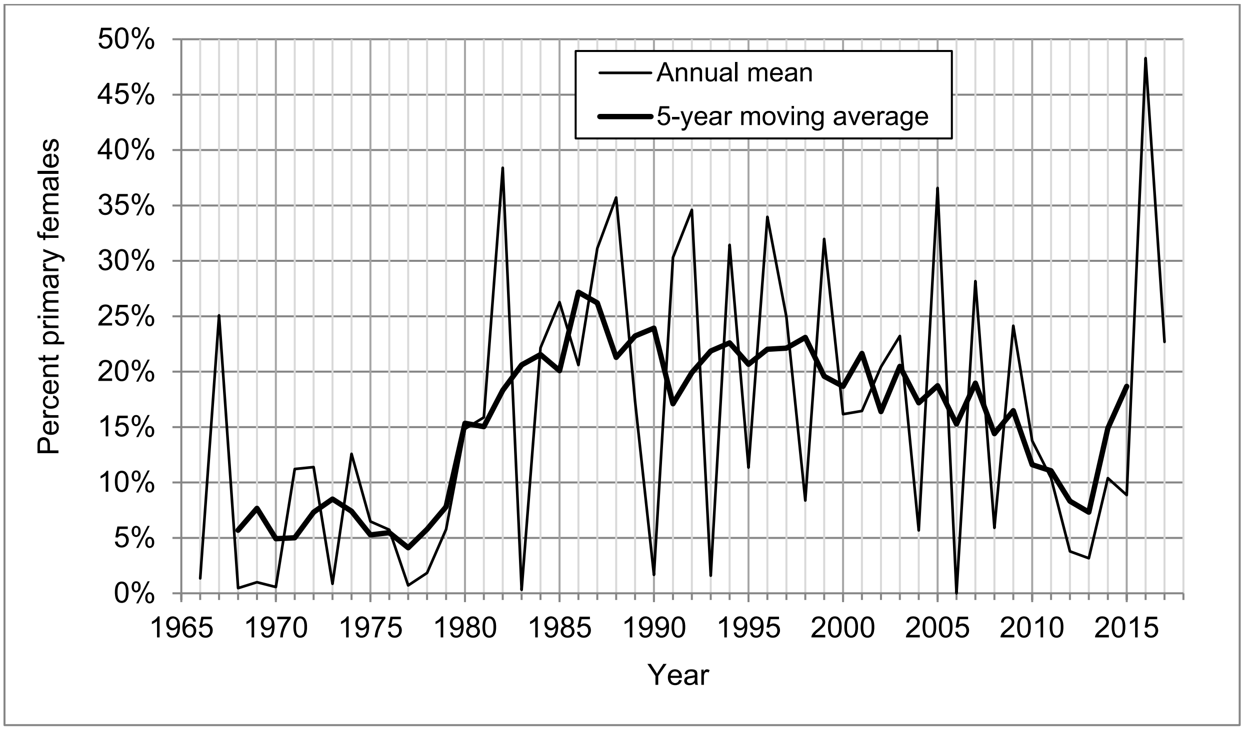

Figure 8. Annual mean and 5-year moving average of the percentage of primary (age 1) female ocean shrimp (*Pandalus jordani*) in September and October trawl fishery samples, 1966-2017.

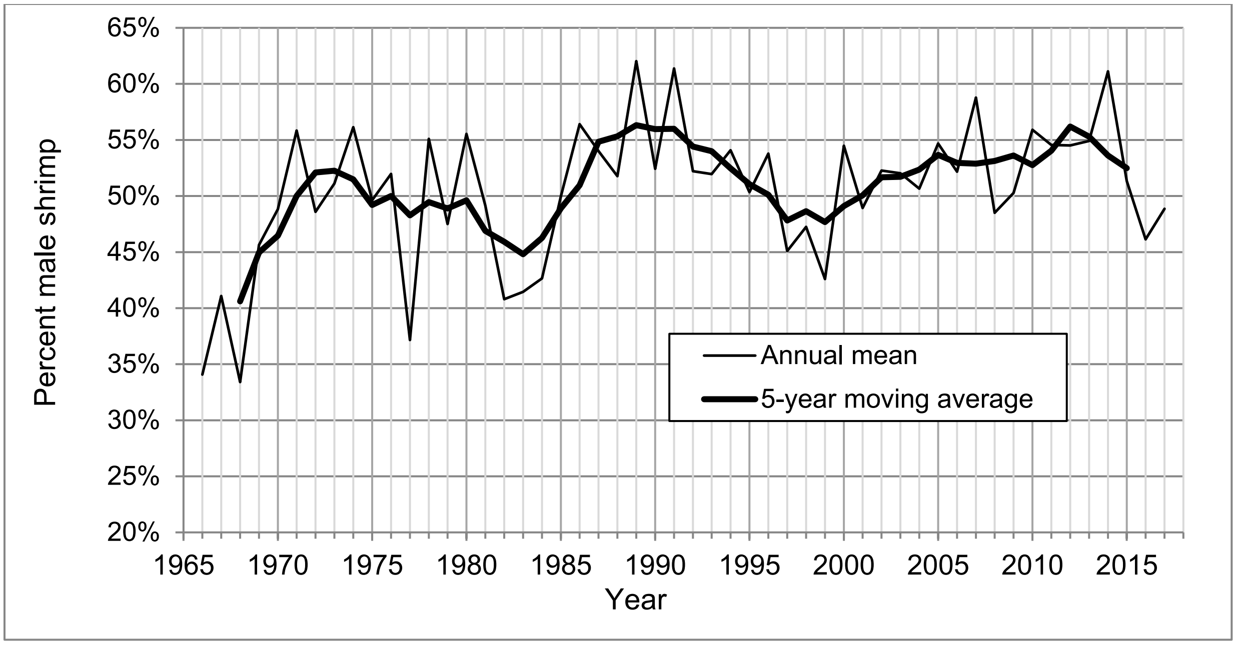

Figure 9. Annual mean and 5-year moving average of the percentage of male ocean shrimp (*Pandalus jordani*) in September and October trawl fishery samples, 1966-2017.

Discussion

Very few exploited fish stocks have the combination of a short life span and a very long time series of biological data to allow examination of low frequency changes in population structure in response to variation in density and the environment. Examination of this long term sample data show that the ocean shrimp population structure has responded to the recent increase in average density resulting from large recruitments and lower fishing effort; shrimp growth has declined as average density has increased. The age composition of the catch has shifted back to lower levels of age 1 shrimp. The average percentage of primary females has declined to lower levels than seen during the earlier period of higher fishing effort between 1979 and 2003. Notably however, although fishing effort has declined to nominal levels last seen in the early 1970s when the fishery was still developing, the population structure has not returned to the state observed in those early years, characterized by slower growth, an older age structure and primary females being a rare occurrence (Hannah and Jones 1991). The most likely explanation is that nominal fishing effort, even after correction for the difference between double and single rigged vessels, is not comparable across this long of a time period (gear efficiency has increased). This is supported by the much higher levels of total catch that are occurring at these lower effort levels (Figure 2).

Over the last several decades, a variety of improvements in fishing technology have developed that have not been corrected for in our measure of fishing effort. These include vessels using higher doors to increase the vertical net opening, larger vessels and nets, modern netting materials and better navigation technology. Fishing technology moves quickly; since the most recent report in this series, video and sonar technology have been adopted by many vessels which allow real time monitoring of catch, further improving efficiency (ODFW unpublished data). The development of highly efficient bycatch reduction devices (BRDs), which have been mandatory for all ocean shrimp trawling since 2003 (Hannah et al. 2011), may also have increased catch efficiency by improving shrimp retention in the trawl nets. Another effect of high-efficiency BRDs is that they allow vessel operators to set the trawl anywhere they believe a high catch of shrimp may be obtained, without concerns of excessive bycatch, likely increasing vessel efficiency by reducing the number of dumped hauls. This trend of increased vessel efficiency is likely to continue. In 2014, research determined that attaching a series of green Lindgren-Pitman® LED fishing lights to the footrope of ocean shrimp trawls greatly reduced the residual bycatch of small demersal fish and this new technology was very rapidly adopted by the Oregon shrimp fleet (Hannah, Lomeli and Jones 2015). In 2017, researchers tested 5, 10 and 20 lights per net and determined that using more lights was not significantly more effective than using fewer lights, however, using any amount of light was significantly more effective than using no lights (Lomeli et al. 2018). In 2018, Oregon Fish and Wildlife Commission (OFWC) adopted the requirement of using 5 lighting devices on each net (Groth 2018). While both BRD and light requirements substantially reduced bycatch in the fishery, they also have likely contributed to the increased efficiency of the fleet, via reducing the sorting time and need to transit away from areas of high bycatch. These bycatch reduction requirements combined with the changes in the size of vessels and technologies used has sequentially improved the catch efficiency of the ocean shrimp fleet.

The time series of sample data available for the ocean shrimp fishery is now long enough to detect both density-dependent and environmental effects on shrimp growth. The multiple regression model (models 1 and 2, Table 2) showed that ocean shrimp size-at-age was decreased (increased) by high (low) densities and also decreased (increased) by the environmental conditions associated with low (high) Pacific SSTs as reflected in the 6-month PDO. It should be stressed that the density increase in recent years is due to a combination of factors. Reduced fishing effort on larger average population sizes has left higher densities of shrimp on the fishing grounds most years. Ocean shrimp recruitment success has consistently been linked to variation in coastal sea level height during the larval period, which is in turn linked to the strength and timing of the spring transition in coastal currents (Huyer, Sobey and Smith 1979, Hannah 1993, Hannah and Jones 1991, Hannah 2011). From 1999 to 2014, cold-phase PDO conditions, which are favorable for ocean shrimp larval survival (Rothlisberg and Miller 1983) were more frequent in the northeast Pacific ocean (Figure 6), contributing to the rise in density and the modest reduction in size-at-age (Figure 5). From 2015 to 2017, warm water conditions prevailed in the Pacific. Typically, warm water (El Niño) conditions are extremely poor for ocean shrimp survival. Ocean shrimp catch and recruitment immediately following 1982-1983 and 1997-1998 large El Niño events were very low (Figure 2 and Figure 11). However, the 2014-2016 El Niño appears to have not affected recruitment or growth as strongly as past events, possibly because the dynamics of this recent event were different than the other two significant El Niño events (1982-1983 and 1997-1998) within the ocean shrimp dataset (Jacox et al. 2016).

The reduced percentage of age 1 ocean shrimp in fishery catches (Figure 7) in recent years suggests that the reduction in fishing effort and increased recruitments have also reduced total mortality rates of ocean shrimp from levels reported for the years between 1980 and 1990 (Hannah 1995). This is supported by the reduction in the average percentage of primary females, a result that suggests a change in the average demographic environment of age 1 shrimp (Charnov and Hannah 2002). It should be noted that the inferred reduction in mortality rates is likely a result of a variety of factors, not just reduced fishing effort. It may also result from a reduction in natural mortality rates due to declines in predator populations, or changes in their distribution (Agostini et al. 2008), particularly Pacific hake, *Merluccius productus*, (Livingston and Bailey 1985, Hannah 1995, Berger et al. 2017). The change in age composition of the ocean shrimp catch has probably also been influenced by changes in fishery selectivity. Prior to 1999, the ex-vessel price paid for ocean shrimp was typically a single price regardless of the mix of sizes or ages of shrimp that were landed. Beginning in the fall of 1999 and continuing to date, shrimp processing companies have mostly utilized a split-pricing structure for ocean shrimp, with a lower (higher) price for smaller (larger) ocean shrimp. The implementation of split-pricing may have increased the economic incentives for vessel operators to target larger, older ocean shrimp, and avoid, to some extent, age 1 shrimp.

II. Effects of climate and fishing on recruitment of ocean shrimp: an update of recruitment models through 2017

Introduction

A key component of Oregon's approach to managing the ocean shrimp fishery is an active program for monitoring the status of the stock. The goal of this program is to identify any adverse population-level effects from fishery harvest so that improved management strategies can be developed and implemented as needed. Oregon's monitoring program has been in place since the early years of the ocean shrimp trawl fishery (Zirges and Robinson 1980) and is ongoing. The basic elements of the monitoring program include fishery landing receipts (fish tickets) and vessel logbooks, from which catch and fishing effort by statistical area (Figure 1) can be derived, along with a program to systematically collect biological samples of landed shrimp to determine age and sex composition of the catch and carapace length-at-age (Hannah and Jones 1991).

Ocean shrimp have a life history that makes them resilient to large changes in mortality rates, whether natural or fishery-caused (Zirges and Robinson 1980, Collier and Hannah 2001, Hannah 1995, Charnov and Hannah 2002). Studies of the effects of trawl fishing on the ocean shrimp stock have consistently indicated that recruitment is strongly environmentally driven (Hannah 1993, Hannah 1999, Hannah 2011, Hannah and Jones 2016). Exactly how variation in the ocean environment during the pelagic larval period modulates recruitment remains poorly understood. However, variation in the timing and intensity of the spring transition in coastal currents is believed to strongly influence larval transport and also influences sea surface temperatures through upwelling of deep, cold, nutrient-rich water (Huyer et al. 1979, Hannah 1993). However, extremely strong spring upwelling has also been linked to locally depressed recruitment, probably through excessive offshore near-surface transport of larvae (Hannah 2011). The various studies evaluating the effects of fishing on ocean shrimp have consistently shown very weak evidence for reductions in recruitment due to reduced spawning biomass as a result of fishery harvest (Hannah 1993, Hannah 1999). Here, we re-examine that finding by updating the indices of recruitment and spawning stock to include available data through 2015.

Methods

Indices

This update to ocean shrimp recruitment models follows the methods detailed in Hannah and Jones 2014 and the methods will not be presented in detail here. Briefly, we indexed recruitment using a simple virtual population estimate (VPE) for northern and southern Oregon waters, following Hannah 2011, as well as a combined index for both areas. We also calculated a VPE-based spawning stock index (Hannah and Jones 2014, Hannah and Jones 2016). The spawning stock index was also updated through 2015 for northern and southern Oregon waters, as well as a combined index for both areas. As in the prior analysis, both indices were calculated exclusively for the shrimp population inhabiting statistical areas 19-28 (Figure 1).

Regression analysis

As in the 2014 and 2016 updates, we conducted multiple regression analysis to determine how the relationships between recruitment, spawning stock and selected marine environmental variables from the larval period have been influenced by the addition of two years of additional data. We again fit a variety of models similar to the ones previously evaluated by Hannah (1999, 2011), both with and without the spawning stock indices. This analysis utilized log-transformed values of the recruitment and spawning stock indices and assumed a log-normal error structure. To evaluate this assumption, the residuals from the best fitting model were tested for normality with a goodness of fit test. We included the marine environmental variables which were concurrent to the pelagic larval period of ocean shrimp, and which have previously been shown to be related to their recruitment, specifically April sea level height (SLH) and April-January mean SLH, both measured at Crescent City, California, and for southern Oregon ocean shrimp, the April-July upwelling index at 42° N. latitude (Hannah 2011, Hannah and Jones 2014, Hannah 2016, Hannah and Jones 2016). It should be noted that many different marine environmental variables are strongly cross-correlated and most are also autocorrelated, making the selection of a single "best" variable or time period for understanding environmental forcing of ocean shrimp recruitment problematic.

Sensitivity of recruitment to variation in the spawning stock

We evaluated the relative effects of variation in the ocean shrimp spawning stock and the ocean environment on age 1 recruitment. We first selected a multivariate regression model that included both the spawner index and environmental variables and then profiled predicted recruitment across varied levels of these variables. We modeled the effect of spawning stock on recruitment using the mean, and 10th and 90th percentiles of the spawning stock index to represent average, low and high spawner abundance, respectively. Using the same values for the environmental variables, we evaluated the effect of variation in spawner abundance on predicted recruitment under average, favorable and unfavorable conditions for larval survival.

Results

Indices

The updated recruitment index for northern and southern Oregon (Table 3, Figure 10) showed continued variability and recent trends of higher recruitment in southern areas. Since 2008, Age 1 recruitment in southern Oregon waters has been much stronger than that of northern waters. While in previous years (1980-2007) the average age 1 recruitment was higher in northern areas than southern areas, in recent years (2008-2015) recruitment in southern areas was nearly three times higher (Table 3, Figure 10). Age 1 recruitment for the combined areas (state areas19-28) was near a record high in 2014, then near a record low in 2015. Recent year's age 1 recruitment has been high overall, as the combined index for Oregon waters shows that 5 of the last 7 year classes have been above average (Table 3, Figure 11).

Table 3. VPE-based recruitment index (numbers of shrimp) for northern and southern Oregon ocean shrimp (see text) for age 1 recruitment years 1980-2015.

Year	Northern Oregon recruit index	Southern Oregon recruit index	Combined index
1980	728,616,363	2,019,024,896	2,747,641,259
1981	405,882,000	1,159,289,000	1,565,171,000
1982	360,356,000	1,401,452,000	1,761,808,000
1983	85,954,000	107,994,000	193,948,000
1984	422,350,000	411,394,000	833,744,000
1985	1,207,136,000	544,513,000	1,751,649,000
1986	1,210,598,000	1,164,884,000	2,375,482,000
1987	3,459,191,000	1,352,859,000	4,812,050,000
1988	2,969,139,000	2,568,127,000	5,537,266,000
1989	1,997,855,000	2,986,657,000	4,984,512,000
1990	322,311,000	263,278,000	585,589,000
1991	814,968,000	1,449,799,000	2,264,767,000
1992	1,103,498,000	4,088,133,000	5,191,631,000
1993	123,130,000	403,052,000	526,182,000
1994	438,091,496	1,261,901,052	1,699,992,548
1995	296,599,432	338,872,938	635,472,370
1996	485,416,725	1,106,990,917	1,592,407,642
1997	376,535,724	1,475,139,756	1,851,675,480
1998	294,338,065	198,348,198	492,686,263
1999	2,006,092,327	1,115,996,493	3,122,088,820
2000	2,412,733,990	644,085,999	3,056,819,989
2001	1,502,743,294	672,373,104	2,175,116,398
2002	4,056,114,228	492,166,634	4,548,280,862
2003	2,547,679,356	99,802,655	2,647,482,011
2004	401,818,540	79,094,079	480,912,619
2005	2,249,139,156	701,863,226	2,951,002,382
2006	196,403,843	209,927,836	406,331,679
2007	2,096,425,166	1,687,833,415	3,784,258,581
2008	309,505,532	980,923,212	1,290,428,744
2009	832,893,452	2,569,655,714	3,402,549,166
2010	932,201,506	3,547,139,865	4,479,341,370
2011	859,111,929	3,595,117,951	4,454,229,880
2012	1,179,126,508	2,101,784,582	3,280,911,090
2013	843,791,134	1,540,075,350	2,383,866,484
2014	1,826,997,512	3,234,868,623	5,061,866,135
2015	232,172,701	764,292,901	996,465,602
Average	1,155,192,111	1,342,741,955	2,497,934,066

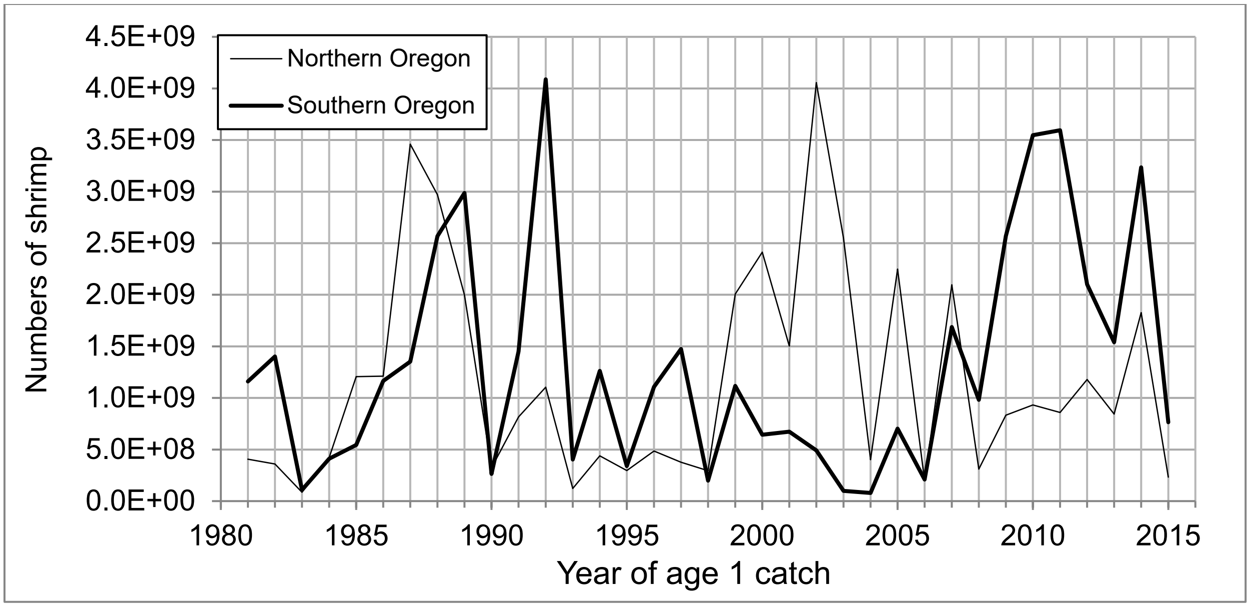

Figure 10. Ocean shrimp VPE-based recruitment index for northern (areas 24-28, Figure 1) and southern (areas 19-22, Figure 1) Oregon waters, for age 1 recruitment years 1980-2015.

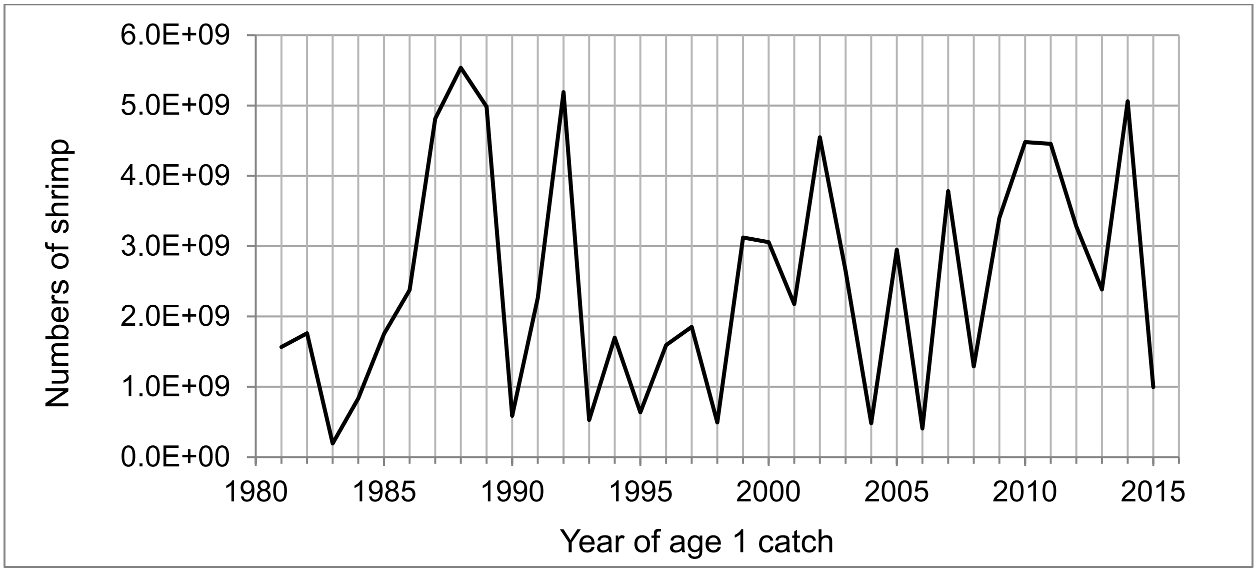

Figure 11. Ocean shrimp VPE-based recruitment index (see text) for both areas combined (areas 19-28, Figure 1), for age 1 recruitment years 1980-2015.

Similar to the updated index of age 1 recruitment, a VPE-based spawner index shows high variability and an overall reduction from record levels of 2009-2012 (Table 4, Figure 12). In northern Oregon waters, spawner levels were double the long-term average in 2014, then, in the next year fell to nearly the lowest recorded level. Similarly, in southern Oregon waters 2014 spawner levels were nearly the highest in the dataset, while 2015 spawner levels were near record lows. Given the synchronous high levels of both northern and southern Oregon spawners in 2014, then ensuing lowering in 2015, the combined index follows a like pattern (Table 4, Figure 13).

Table 4. VPE-based spawner index (numbers of shrimp) for northern and southern Oregon ocean shrimp (see text) for fall spawning years 1981-2015.

Year	Northern Oregon spawner index	Southern Oregon spawner index	Combined spawner index
1981	188,170,000	226,602,000	414,772,000
1982	50,392,000	215,823,000	266,215,000
1983	22,953,000	51,855,000	74,808,000
1984	356,766,000	144,190,000	500,956,000
1985	922,524,000	297,198,000	1,219,722,000
1986	722,498,000	344,031,000	1,066,529,000
1987	505,496,000	376,698,000	882,194,000
1988	938,984,000	1,021,971,000	1,960,955,000
1989	827,756,000	1,077,499,000	1,905,255,000
1990	221,313,000	238,875,000	460,188,000
1991	312,064,000	473,292,000	785,356,000
1992	445,053,000	512,118,000	957,171,000
1993	96,678,000	156,991,000	253,669,000
1994	164,232,496	394,888,052	559,120,548
1995	116,133,928	184,533,990	300,667,918
1996	231,805,096	179,616,795	411,421,891
1997	267,939,673	94,185,783	362,125,456
1998	147,667,705	123,827,880	271,495,585
1999	586,190,800	158,222,804	744,413,604
2000	1,104,875,975	152,063,065	1,256,939,040
2001	677,281,471	137,715,692	814,997,163
2002	917,327,895	27,523,752	944,851,647
2003	1,076,233,654	56,868,459	1,133,102,113
2004	260,371,914	68,488,966	328,860,880
2005	761,457,715	436,528,597	1,197,986,312
2006	303,244,166	207,657,531	510,901,697
2007	978,246,483	642,792,536	1,621,039,019
2008	240,005,163	402,224,048	642,229,211
2009	475,128,479	1,210,638,823	1,685,767,302
2010	472,807,710	2,310,419,672	2,783,227,382
2011	749,927,385	2,856,106,997	3,606,034,382
2012	871,569,709	1,420,576,436	2,292,146,145
2013	472,203,173	854,624,486	1,326,827,658
2014	1,005,978,871	1,605,715,782	2,611,694,653
2015	28,474,204	372,175,904	400,650,109
Average	500,564,305	543,843,973	1,044,408,278

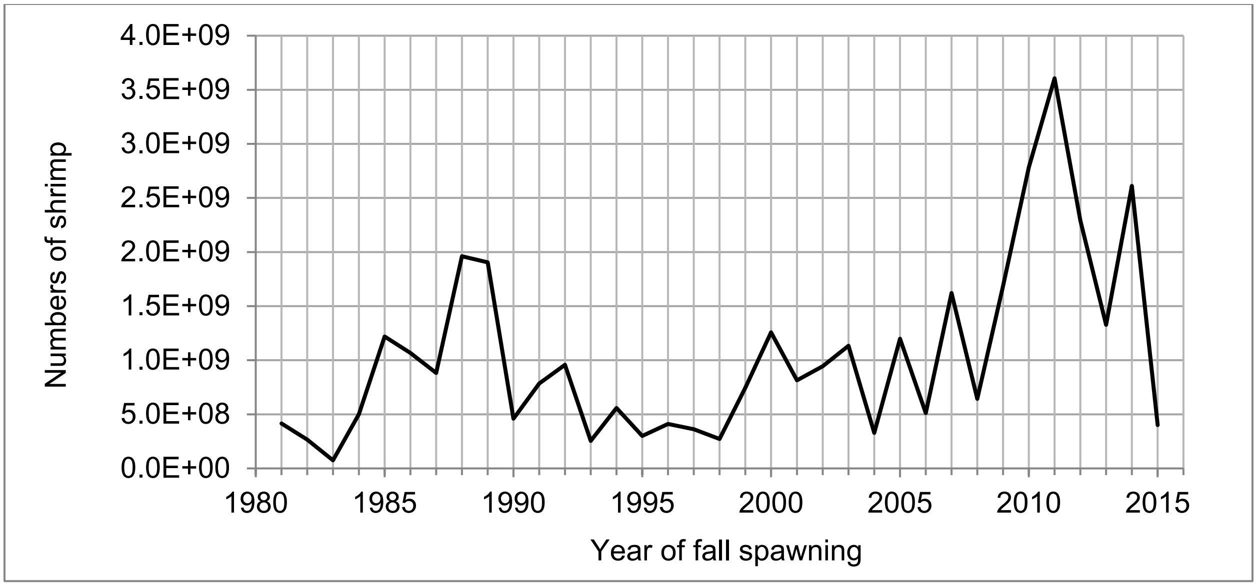

Figure 13. Ocean shrimp VPE-based spawner index for both areas combined (areas 19-28, Figure 1), for spawning years 1981-2015.

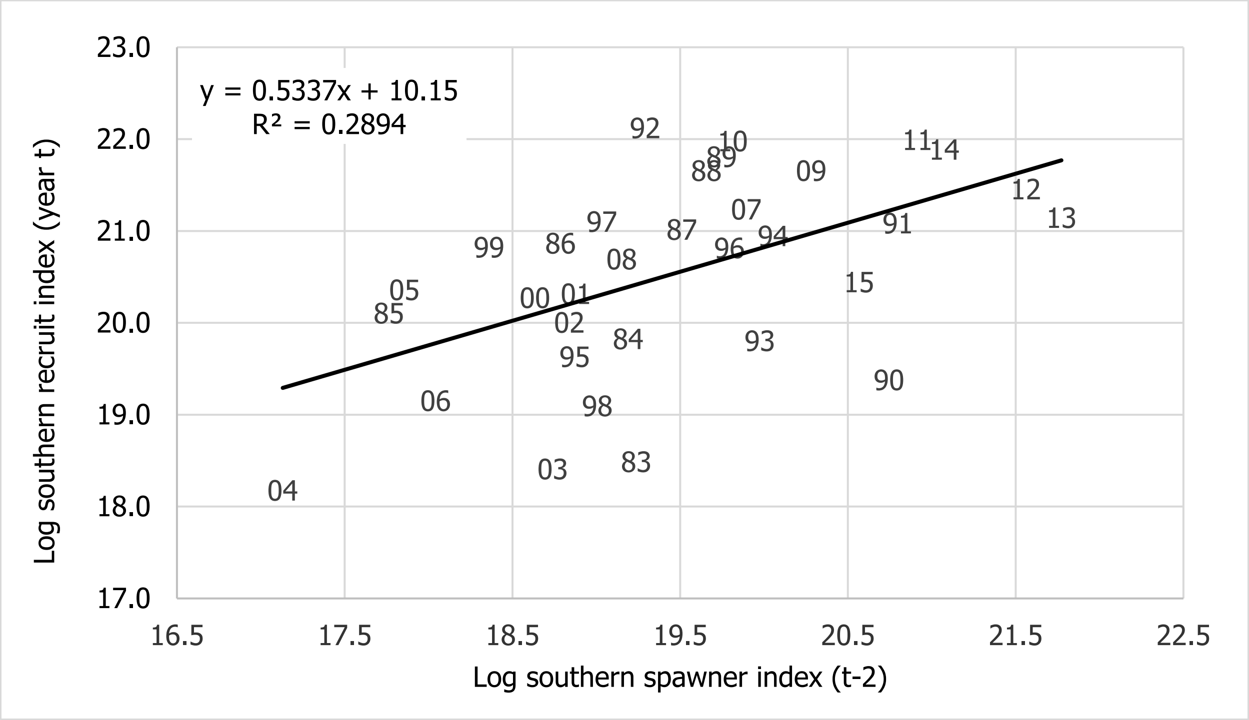

Figure 14. Log of the southern ocean shrimp recruit index (year t) versus the log of the southern VPE-based spawner index (year t-2) for the southern area (statistical areas 19-22, Figure 1) for age 1 recruitment years 1983-2015.

Results of regression analysis for the northern portion of the shrimp stock show very little evidence for meaningful positive effects (12% of variation) on recruitment from higher levels of the spawning stock index (model 1 in Table 5, P=0.0488). The best regression model includes a single predictor variable, April-January SLH at Crescent City, CA during the larval period, explaining 40% of the variation in $\log_e$ recruitment (model 3 in Table 5, $P<0.0001$). Log_e spawning stock index was not statistically significant in a multiple regression that also included April-January SLH (model 4 in Table 5, $P=0.5948$).

In the southern area, there is some evidence for a statistically significant positive effect of $\log_e$ spawning stock on $\log_e$ recruitment (model 1 in Table 6, $P=0.0012$) however this may be an artifact of serial autocorrelation in the environment and a strong dependence of spawning stock on same-year recruitment. Examination of a graph of the $\log_e$ recruitment index and $\log_e$ spawning stock index for the southern area shows that the relationship is strongly influenced by a cluster of recent, sequential, large recruitment years from 2009-2014 (Figure 14). The regression model incorporating April-January SLH and April-July upwelling index at 42° N. latitude explained 39.5% of the variation in $\log_e$ recruitment (model 3 in Table 6, $P<0.0002$). Adding the $\log_e$ spawning stock index to this regression model did modestly improve overall model fit (model 4 in Table 6, $R^2 = 0.5238$). However, the effect of autocorrelation in the environmental variables on sequential recruitments makes it difficult to confidently assert a meaningful role for the spawning stock index in determining future recruitment. If we assume this model is correct for the southern portion of the shrimp stock, we can model the relative effects of spawning stock and variation in the environment on subsequent recruitment (Table 7 and Figure 15). The results show that the ocean environment during the larval period has a much greater influence on shrimp recruitment than the size of the shrimp spawning stock. Across the range of spawning indices modeled (Table 7), variation in the spawning stock index caused 3 fold variation in recruitment, for a fixed larval environment (Figure 15). In contrast, the modeled variation in the larval environment caused 11 fold variation in shrimp recruitment for any fixed level of the spawning stock index (Figure 15). These results show that even if the spawner index is contributing to subsequent recruitment levels in southern Oregon waters (model 4 in Table 6), trying to maintain high shrimp recruitment by maintaining higher levels of spawning stock is unlikely to be a successful management strategy.

Regression modeling using the recruitment index for both areas combined as the dependent variable showed that the best model was a simple linear regression of $\log_e$ recruitment index on April-January SLH in the larval period (model 3 in Table 8, $P<0.0001$). For the combined areas, neither $\log_e$ of the spawner index or April-July upwelling at 42° N. Latitude contributed significantly in a multiple regression with April-January SLH (models 4 and 5 in Table 8, $P>0.05$).

Table 5. Results of multiple regression analysis of the log-transformed northern Oregon ocean shrimp recruitment index (year t) on the log-transformed spawner index (year t-2) and selected environmental variables during the pre-recruit period (year t-1), for age 1 recruitment years 1980-2015.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log northern recruit index (t)	Intercept	13.1000	3.6122		
	Log spawner index (t-2)	0.3753	0.18230		
	Full model			0.1195	0.0488
2-Log northern recruit index (t)	Intercept	33.9012	4.5358		
	April SLH (t-1)	-1.8909	0.6376		
	Full model			0.2055	0.0055
3-Log northern recruit index (t)	Intercept	55.0130	7.2487		
	April-Jan SLH (t-1)	-4.7085	0.9875		
	Full model			0.4007	0.0000
4-Log northern recruit index (t)	Intercept	51.5543	10.1288		
	Log spawner index (t-2)	0.08971	0.1669		0.5948
	April-Jan SLH (t-1)	-4.4723	1.1261		0.0004
	Full model			0.4229	0.0000

Table 6. Results of multiple regression analysis of the log-transformed southern Oregon ocean shrimp recruitment index (year t) on the log-transformed spawner index (year t-2) and selected environmental variables during the pre-recruit period (year t-1), for age 1 recruitment years 1980-2015.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log southern recruit index (t)	Intercept	10.1502	2.9306		
	Log spawner index (t-2)	0.5336	0.1502		
	Full model			0.2894	0.0012
2-Log southern recruit index (t)	Intercept	31.9878	5.2387		
	April SLH (t-1)	-1.5026	0.7262		0.0464
	April-July upwelling index	-0.0072	0.0044		0.1107
	Full model			0.1582	0.0583
3-Log southern recruit index (t)	Intercept	57.7872	8.4299		
	April-Jan SLH (t-1)	-4.9245	1.1331		0.0001
	April-July upwelling index at 42° N. Lat.	-0.0106	0.0038		0.0090
	Full model			0.3952	0.0002
4-Log southern recruit index (t)	Intercept	43.5799	9.3423		
	Log southern spawner index (t-2)	0.3734	0.1343		0.0095
	April-Jan SLH (t-1)	-4.0224	1.1048		0.0011
	April-July upwelling index at 42° N. Lat.	-0.0079	0.0037		0.0411
	Full model			0.5238	0.0001

Table 7. Input values used with model 4 in Table 6 for predicting southern Oregon age 1 shrimp recruitment across a range of spawning stock levels and environmental conditions during the larval period.

Dependent variable	Selection criteria	Larval conditions	Input value
Spawning stock index	Mean		543,843,973
	10th percentile		63,840,763
	90th percentile		1,494,632,174
April-January SLH (larval period)	Average	Average	7.341
	10th percentile	Unfavorable	7.553
	90th percentile	Favorable	7.169
April- July Upwelling (larval period)	Mean	Average	102.74
	10th percentile	Unfavorable	166.0
	90th percentile	Favorable	55.0

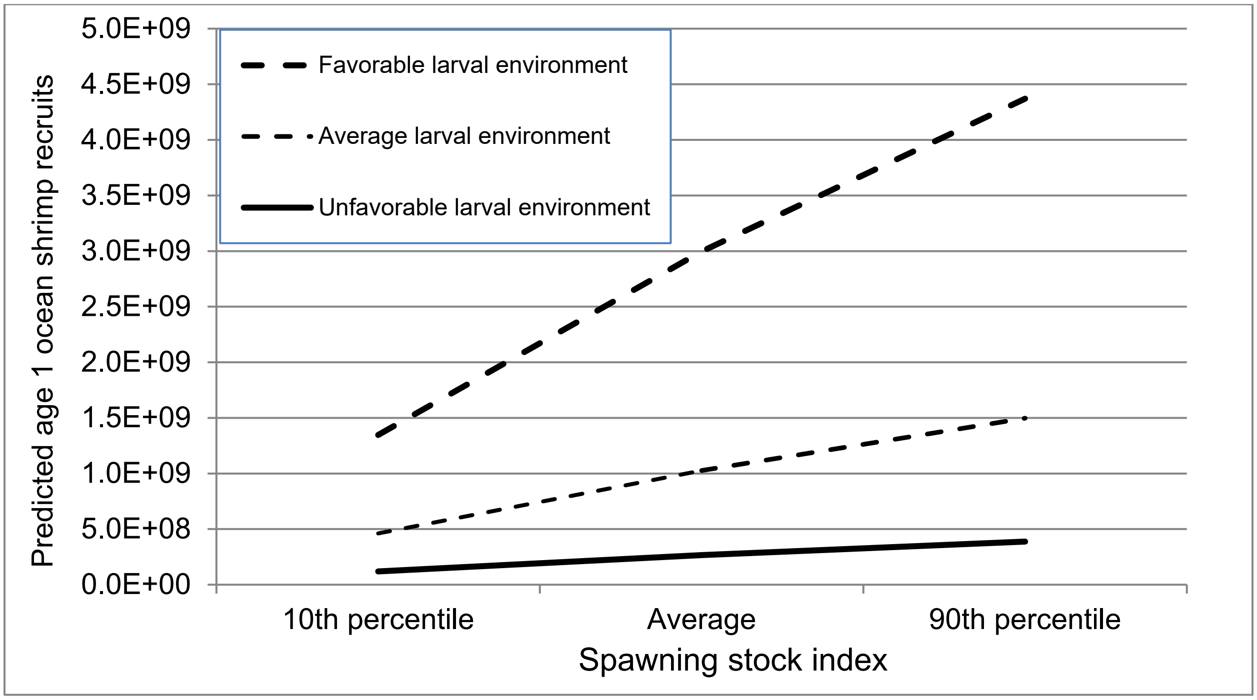

Figure 15. Predicted southern Oregon age 1 ocean shrimp recruitment using model 4 in Table 6, profiled across a range of spawning stock indices and larval environmental conditions (Table 7).

Table 8. Results of multiple regression analysis of the log-transformed combined Oregon ocean shrimp recruitment index (year t) on the log-transformed combined spawner index (year t-2) and selected environmental variables during the pre-recruit period (year t-1), for age-1 recruitment years 1980-2015.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log combined recruit index (t)	Intercept	14.0346	3.7733		
	Log combined spawner index (t-2)	0.3579	0.1844		
	Full model			0.1083	0.0615
2-Log combined recruit index (t)	Intercept	33.9319	3.9659		
	April SLH (t-1)	-1.7691	0.5575		
	Full model			0.2285	0.0032
3-Log combined recruit index (t)	Intercept	54.7616	6.0156		
	April-Jan SLH (t-1)	-4.5521	0.8196		
	Full model			0.4757	<0.0001
4-Log combined recruit index (t)	Intercept	52.2566	8.6865		
	Log combined spawner index (t-2)	0.0676	0.1556		0.6672
	April-Jan SLH (t-1)	-4.3995	0.9417		0.0001
	Full model			0.4838	<0.0001
5-Log combined recruit index (t)	Intercept	56.2669	6.3885		
	April-Jan SLH (t-1)	-4.7283	0.8587		<0.0001
	April-July upwelling index at 42° N. Lat.	-0.0022	0.0029		0.4646
	Full model			0.4843	<0.0001

Discussion

This analysis was an update of the shrimp recruitment modeling reported in Hannah and Jones (2014 and 2016) with two additional recent years of shrimp data added. The additional data consisted of index values for the 2014 and 2015 year classes. Having recruitment indices for 2014 and 2015 facilitated the inclusion of spawning stock indices for fall 2012 and 2013 into the models of spawning stock effects on recruitment. The regression modeling results were not greatly influenced by the additional 2 years of data, and were very similar to the findings of Hannah and Jones (2014 and 2016). Thus, the results remain consistent with the characterization of recruitment in ocean shrimp as being primarily driven by environmental conditions during the pelagic larval phase and not strongly influenced by fishery harvest.

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