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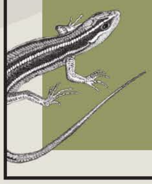
An Evaluation of Fishery and Environmental Effects on the Recruitment Levels of Ocean Shrimp (*Pandalus jordani*) through 2019).



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An evaluation of fishery and environmental effects on the recruitment levels of ocean shrimp (*Pandalus jordani*) through 2019

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CONTENTS

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, 2016, 2018, and 2021 evaluating recruitment effects for ocean shrimp, for the purpose of documenting ongoing monitoring and analysis (Hannah and Jones 2014, Hannah and Jones 2016, Groth and Hannah 2018, Groth et al. 2021). In this report, we build on previous work by adding two additional 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) as a template to add future data to and maintain continuity in the reevaluation of fishery parameters (Hannah, pers. comm. 2018). Suitable periodicity of testing recruitment model performance was determined to be each two years, while testing fishery effects to the population structure (e.g., average size at age) is expected to be more appropriate at a 10-year interval (future analysis scheduled for 2028). ODFW has effectively monitored, researched, and managed Oregon's ocean shrimp fishery, helping Oregon's ocean shrimp fishery maintain MSC sustainability 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 and uniform way.

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 Oregon state statistical area (Figure 1) can be derived. Oregon state statistical areas are roughly delineated at rocky headland areas, often affecting oceanographic currents, then consequently growth and spatial dispersion of fishes and invertebrates. Both elements are used along with a program to systematically collect biological samples of landed shrimp to determine age and sex composition and carapace length-at-age of the catch (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, Hannah 1995, Collier and Hannah 2001, Charnov and Hannah 2002, Charnov and Groth 2019). 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, Groth and Hannah 2018, Groth, Smith et al. 2021). 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, Sobey 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 2019.

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, Groth and Hannah 2018). The spawning stock index was also updated through 2019 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).

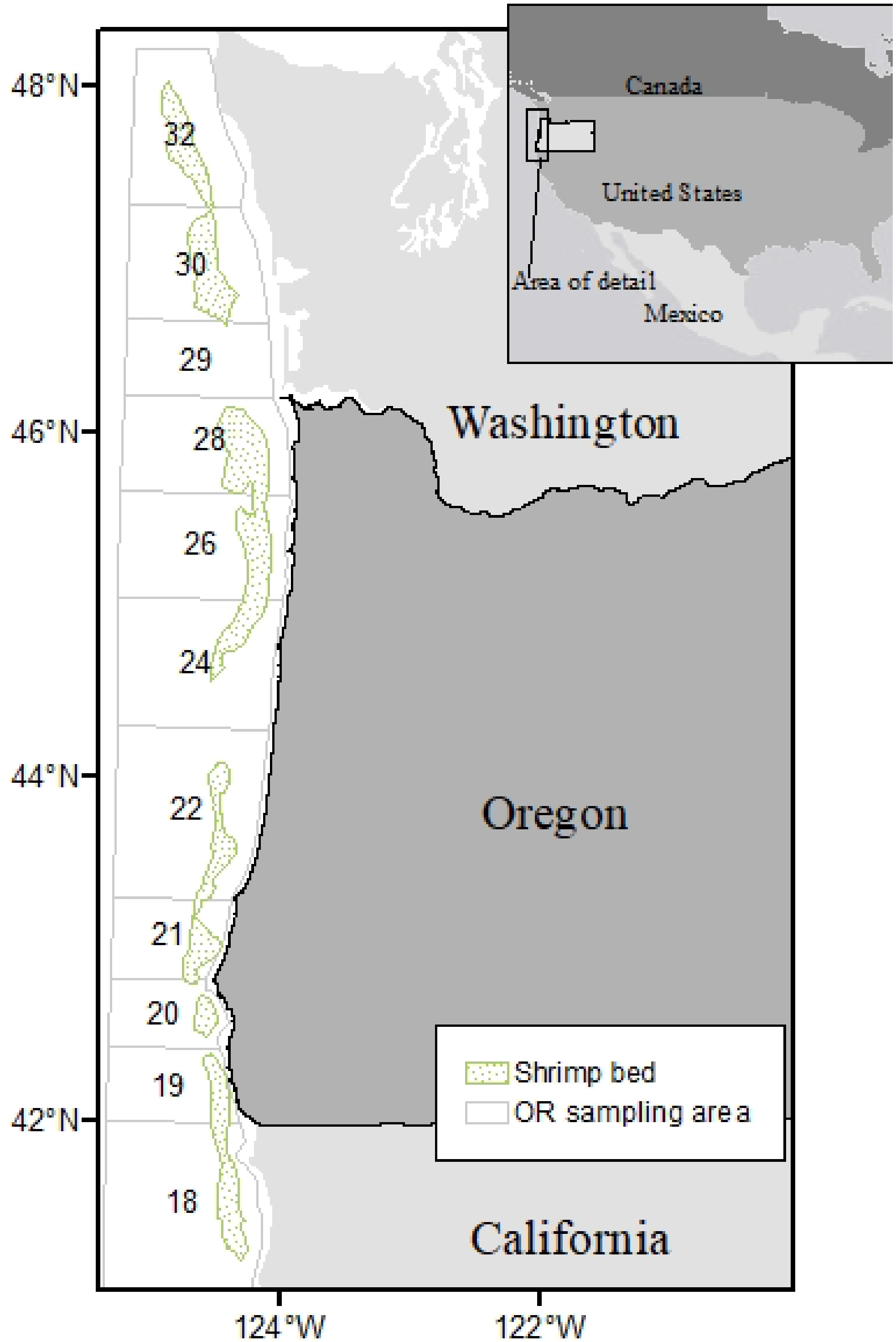

Figure 1. Chart of P. jordani shrimp beds and Oregon state statistical areas.

Regression analysis

As in the previous updates, we conducted multiple regression analysis to determine how the relationships between recruitment, spawning stock, and selected marine environmental variables from the larval period are influenced by the addition of two years of 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 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, we included April sea level height (SLH) and April-January mean SLH, both measured at Crescent City, California. For southern Oregon ocean shrimp, we also included the April-July upwelling index at 42° N. latitude (Hannah 2011, Hannah and Jones 2014, Hannah 2016, Hannah and Jones 2016, Groth and Hannah 2018, Groth et al. 2021). 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 multiple regression model that included both the spawner index and environmental variables to predict 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 ocean shrimp (Table 1, Figure 2) showed continued variability and recent trends of higher recruitment in southern areas. Since 2008, age 1 recruitment in southern Oregon waters has been 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 (2008-2019) recruitment in southern areas was nearly three times higher (Table 1, Figure 2). Age 1 recruitment for the combined areas (state areas 19-28) was near a record high in 2014, then near a record low in 2015. Recent year's age 1 recruitment has been consistent with long term averages, with the combined index for Oregon waters for the most recent 10 years (2.9 billion shrimp) being above the historical average (~2.2 billion shrimp, for 1980-2009) (Table 1, Figure 3).

Table 1. VPE-based recruitment index (numbers of shrimp) for northern and southern Oregon ocean shrimp (*P. jordani*) (see text) for age 1 recruitment years 1980-2019.

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
2016	75,771,732	2,815,288,147	2,891,059,879
2017	92,945,209	1,211,838,590	1,304,783,800
2018	661,045,585	2,298,274,717	2,959,320,302
2019	667,436,997	708,910,941	1,376,347,938
Average	1,077,102,888	1,384,325,570	2,461,428,457

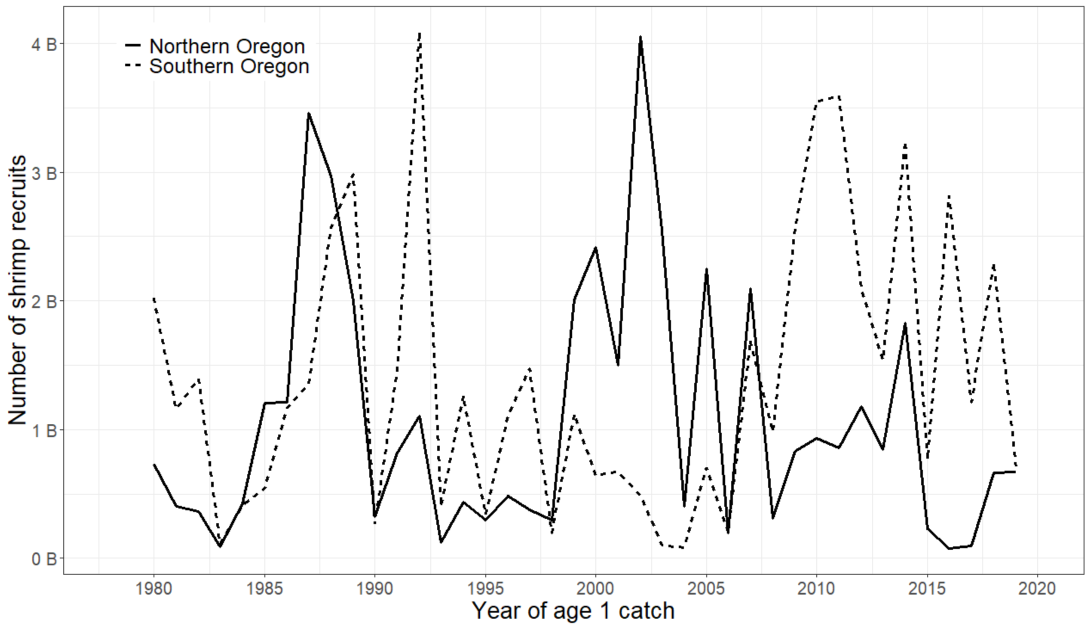

Figure 2. Ocean shrimp (P. jordani) VPE-based recruitment index for northern (areas 24-28, Figure 1) and southern (areas 19-22, Figure 1) Oregon waters, for age 1 recruitment years 1980-2019.

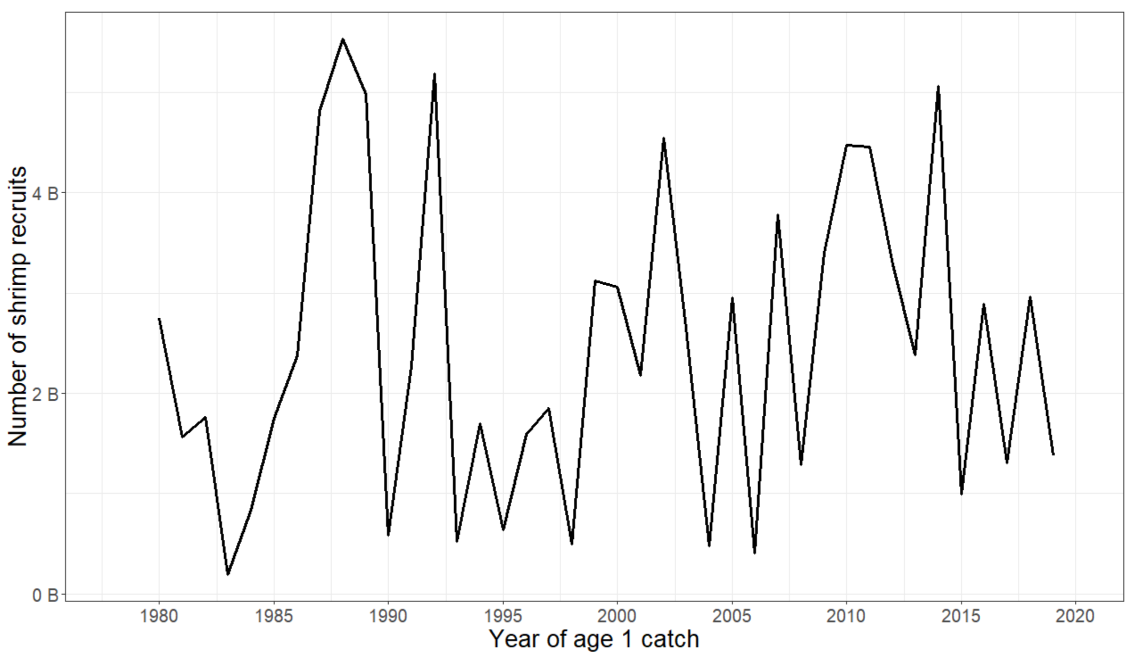

Figure 3. Ocean shrimp (P. jordani) VPE-based recruitment index (see text) for both areas combined (areas 19-28, Figure 1), for age 1 recruitment years 1980-2019.

Like 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 2, Figure 4). In northern Oregon waters, spawner levels were double the long-term average in 2014, then, in the next year fell precipitously and remained low. Similarly, in southern Oregon waters 2014 spawner levels were nearly the highest in the dataset, but ensuing years have been very low. The combined index follows a similar pattern as both northern and southern Oregon spawners due to the synchronously high levels of spawners in 2014 and lowering levels in 2015 (Table 2, Figure 4).

Table 2. VPE-based spawner index (numbers of shrimp) for northern and southern Oregon ocean shrimp (*P. jordani*) (see text) for fall spawning years 1981-2019.

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
2016	17,357,766	695,123,220	712,480,986
2017	87,693,632	231,931,495	319,625,127
2018	443,670,233	251,828,413	695,498,646
2019	181,731,268	184,733,258	366,464,526
Average	467,953,938	523,029,627	990,983,564

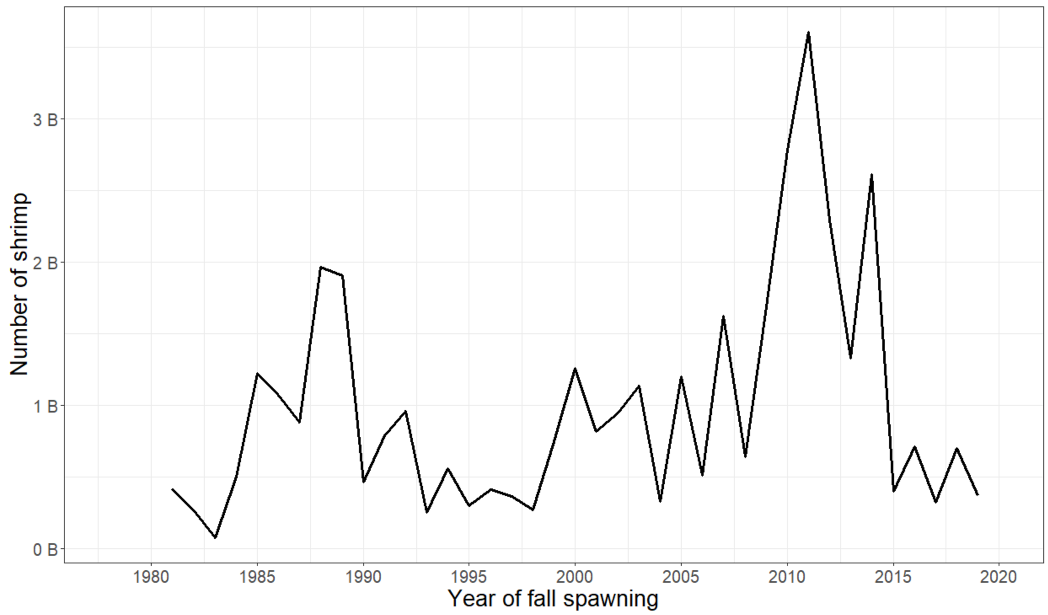

Figure 4. Ocean shrimp (P. jordani) VPE-based spawner index for both areas combined (areas 19-28, Figure 1), for spawning years 1981-2019.

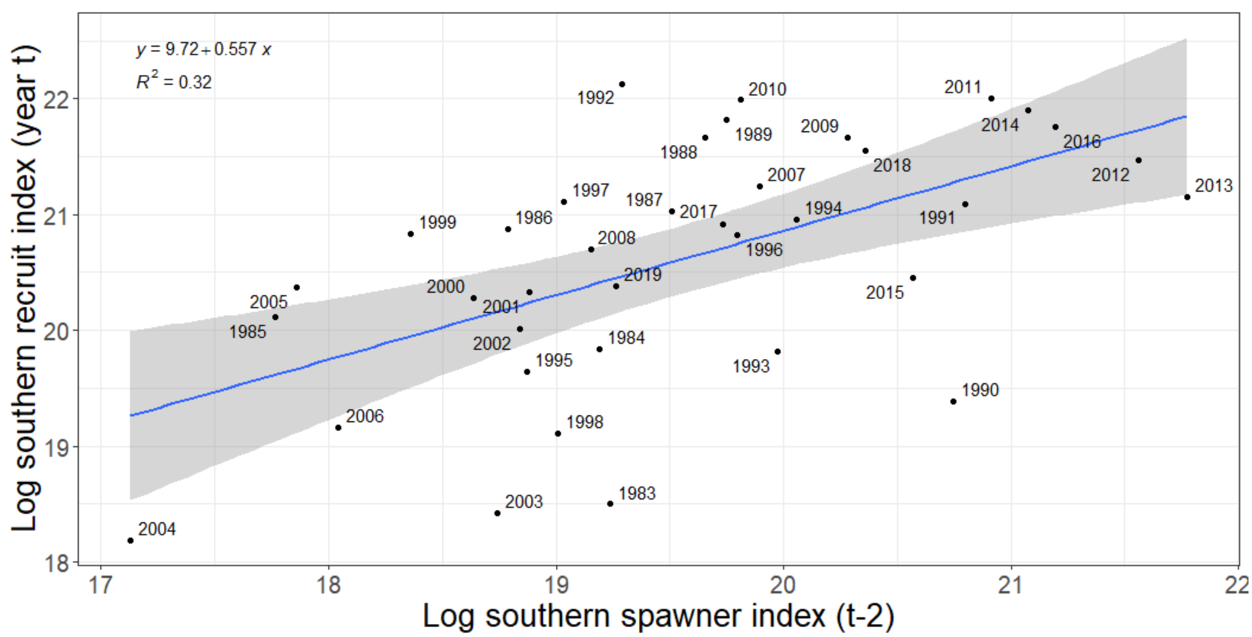

Figure 5. Log of the southern Oregon ocean shrimp (P. jordani) recruit index (year t) versus the log of the southern VPE-based spawner index (year t-2) for the southern area (statistical areas 19-22, Figure 1) for age 1 recruitment years 1983-2019.

Results of regression analysis for the northern portion of the shrimp stock show insignificant evidence for meaningful positive effects (10% of variation) on recruitment from higher levels of the spawning stock index (model 1 in Table 3, P=0.0629). The best regression model includes a single predictor variable, April-January SLH at Crescent City, CA during the larval period, explaining 38% of the variation in $\log_e$ recruitment (model 3 in Table 3, 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 3, P=0.2509).

In southern Oregon, there is some evidence for a statistically significant positive effect of $\log_e$ spawning stock on $\log_e$ recruitment (model 1 in Table 4, P=0.0009) 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 2009-2016 (Figure 5). The regression model incorporating April-January SLH and April-July upwelling index at 42° N. latitude explained 27% of the variation in $\log_e$ recruitment (model 3 in Table 4, P<0.0002); however, for the first time in this series analysis, upwelling is not a significant contributor to this model (P = 0.11). Adding the $\log_e$ spawning stock index to this regression model substantially improved overall model fit (model 4 in Table 4, $R^2 = 0.4938$). 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 5 and Figure 6). The results show that the ocean environment during the larval period has a greater influence on shrimp recruitment than the size of the shrimp spawning stock. Across the range of spawning indices modeled (Table 5), variation in the spawning stock index caused 4-fold variation in recruitment, for a fixed larval environment (Figure 6). In contrast, the modeled variation in the larval environment caused 6-fold variation in shrimp recruitment for any fixed level of the spawning stock index (Figure 6). These results show that even if the spawner index is contributing to subsequent recruitment levels in southern Oregon waters (model 4 in Table 4), trying to maintain high shrimp recruitment by maintaining higher levels of spawning stock is unlikely to be a successful management strategy.

Regression models using the recruitment index for both areas combined as the dependent variable showed that a simple linear regression of $\log_e$ recruitment index on April-January SLH in the larval period remains a very strong model (model 2 in Table 6, P<0.0001). For the combined areas, $\log_e$ of the spawner index is significant (model 1 in Table 6, P<0.05), but does not contribute substantially when mixed with April-January SLH (model 3 in Table 6). April-July upwelling at 42° N. Latitude no longer contributes significantly in a multiple regression with April-January SLH (models 4 in Table 6, P=0.7813).

Table 3. Results of multiple regression analysis of the log-transformed northern Oregon ocean shrimp (*P. jordani*) 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 1980-2019.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log northern recruit index (t)	Intercept	14.5626	3.0275		
	Log spawner index (t-2)	0.2969	0.1545		
	Full model			0.0954	0.0629
2-Log northern recruit index (t)	Intercept	31.9433	5.0341		
	April SLH (t-1)	-1.6320	0.7077		
	Full model			0.1228	0.0267
3-Log northern recruit index (t)	Intercept	57.4932	7.7531		
	April-Jan SLH (t-1)	-5.0613	1.0560		
	Full model			0.3767	0.0000
4-Log northern recruit index (t)	Intercept	52.2635	9.1926		
	Log spawner index (t-2)	0.15308	0.1311		0.2509
	April-Jan SLH (t-1)	-4.7526	1.1158		0.0002
	Full model			0.4101	0.0000

Table 4. Results of multiple regression analysis of the log-transformed southern Oregon ocean shrimp (*P. jordani*) 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 1980-2019.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log southern recruit index (t)	Intercept	9.7224	2.6647		
	Log spawner index (t-2)	0.5569	0.1361		
	Full model			0.3237	0.0009
2-Log southern recruit index (t)	Intercept	31.0397	5.1740		
	April SLH (t-1)	-1.3979	0.7174		0.0590
	April-July upwelling index	-0.0043	0.0040		0.2899
	Full model			0.1081	0.000
3-Log southern recruit index (t)	Intercept	51.7168	8.6646		
	April-Jan SLH (t-1)	-4.1461	1.1681		0.0011
	April-July upwelling index at 42° N. Lat.	-0.0061	0.0037		0.1101
	Full model			0.2663	0.0002
4-Log southern recruit index (t)	Intercept	36.5458	8.4867		
	Log southern spawner index (t-2)	0.4770	0.1236		0.0005
	April-Jan SLH (t-1)	-3.3760	1.0361		0.0026
	April-July upwelling index at 42° N. Lat.	-0.0046	0.0033		0.1728
	Full model			0.4938	0.0001

Table 5. Input values used with model 4 in Table 4 for predicting southern Oregon age 1 Ocean shrimp (*P. jordani*) recruitment across a range of spawning stock levels and environmental conditions during the larval period.

Dependent variable	Selection criteria	Larval conditions	Input value
Log spawning stock index	Mean		20.075
	10^{th} percentile		18.042
	90^{th} percentile		21.074
April-January SLH (larval period)	Average	Average	7.341
	10^{th} percentile	Unfavorable	7.553
	90^{th} percentile	Favorable	7.169
April- July Upwelling (larval period)	Mean	Average	104.65
	10^{th} percentile	Unfavorable	164.95
	90^{th} percentile	Favorable	55.15

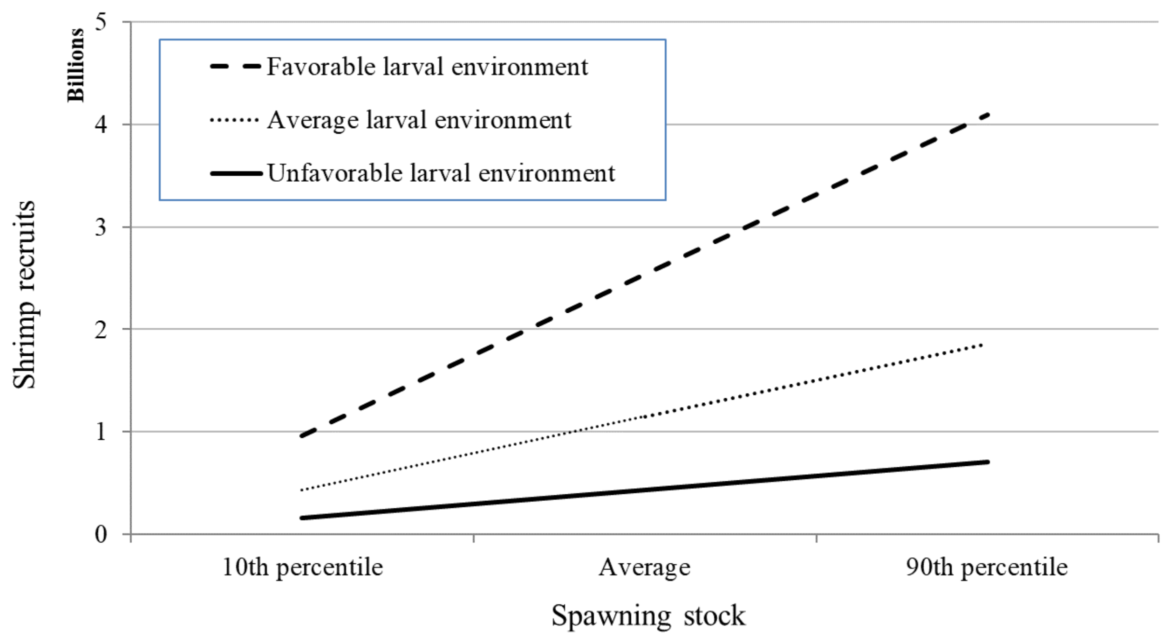

Figure 6. Predicted southern Oregon age 1 ocean shrimp (P. jordani) recruitment using model 4 in Table 4, profiled across a range of spawning stock indices and larval environmental conditions (Table 5).

Table 6. Results of multiple regression analysis of the log-transformed combined Oregon ocean shrimp (*P. jordani*) 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 1980-2019.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
1-Log combined recruit index (t)	Intercept	14.0056	3.3691		
	Log combined spawner index (t-2)	0.3597	0.1647		
	Full model			0.1199	0.0358
2-Log combined recruit index (t)	Intercept	52.7338	5.8628		
	April-Jan SLH (t-1)	-4.2737	0.7985		
	Full model			0.4298	<0.0001
3-Log combined recruit index (t)	Intercept	47.2262	7.7428		
	Log combined spawner index (t-2)	0.1596	0.1386		0.2575
	April-Jan SLH (t-1)	-3.9680	0.8673		0.0001
	Full model			0.4553	<0.0001
4-Log combined recruit index (t)	Intercept	53.1650	6.1323		
	April-Jan SLH (t-1)	-4.3220	0.8266		<0.0001
	April-July upwelling index at 42° N. Lat.	-0.0007	0.0026		0.7813
	Full model			0.4310	<0.0001

DISCUSSION

This analysis was an update of the shrimp recruitment modeling reported in Hannah and Jones (2014 and 2016), Groth and Hannah (2018) and Groth et al. (2021), with two additional recent years of shrimp data added. The additional data consisted of index values for the 2018- and 2019-year classes.

Oregon ocean shrimp recruitment models have remained strong throughout the addition of these data since 2014. Total model strength has remained high (R^2~ 0.4 [north] and R^2~0.5 [south]- Tables 3 and 4). However, relative contribution of each regressor has changed, particularly in recent interactions of the details of these ANOVA models (Figure 7). The primary change to the contribution of regressors is from spawners to the southern model (Figure 7b). Regressor contribution shifted, due to larval conditions of 2015 and subsequent age one recruitment in 2016. When 2016 is removed from this dataset, contributions via environmental conditions increased substantially (Figure 8). Past data include El Nino events of 1982-83 and 1997, which resulted in poor recruitment and is key to shaping the model. Marine heatwave events in 2015 produced similar SLH; however, unlike previous high SLH events, consequent recruitment (2016 age 1) was high.

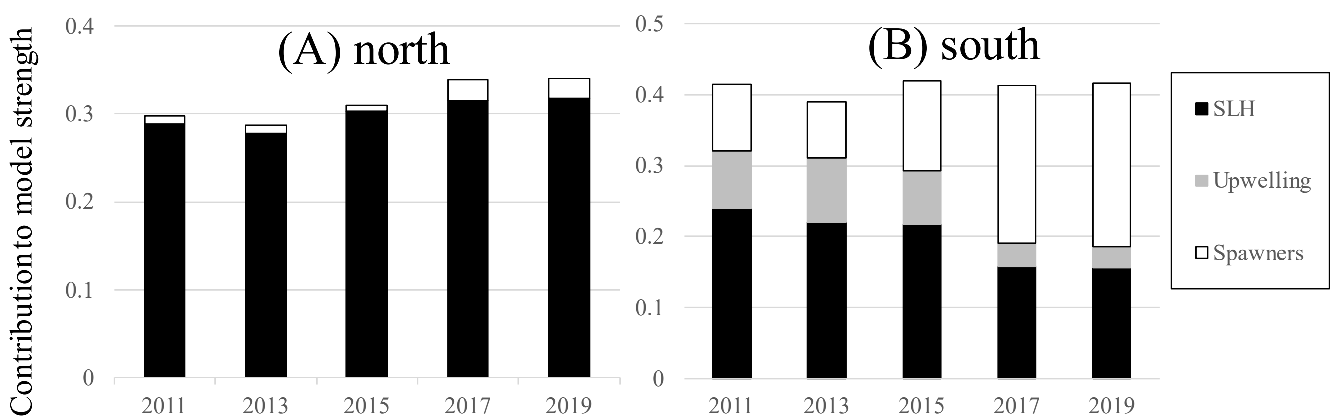

Figure 7. Trends in relative contribution of regressors across analysis inclusion into model strength of ocean shrimp (P. jordani) recruitment for North (table 3, model 4) and South (table 4, model 4) Oregon waters from each iteration of these analysis.

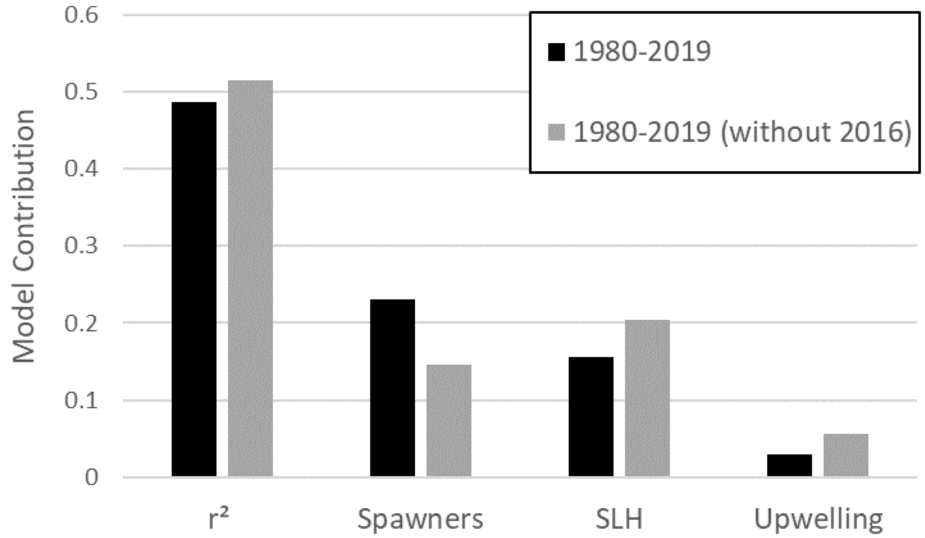

Figure 8. Model results (Table 4, model 4) from southern Oregon waters (1980-2019) and relative contribution by each regressor, with (black) and without (grey) the age one recruitment year 2016.

Having recruitment indices for 2016 to 2019 facilitated the inclusion of spawning stock indices for fall 2014 to 2017 into the models of spawning stock effects on recruitment. For northern and combined indices, the regression modeling results were not greatly influenced by the additional years of data and were very similar to the past findings (Hannah and Jones 2014, Hannah and Jones 2016, Groth and Hannah 2018). For southern indices, the addition of the 2016 age 1 cohort (exposed to 2015 larval environment) into this model increased dependence on spawners; however, further understanding of this effect is warranted. 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 catch.

Next steps in this analysis series:

Reviewing Oregon's ocean shrimp recruitment models each two years has shown that the assumptions used in management remain tenable; however, it is important consider the changes shown in this reports results. Recent years data have shown increased importance of spawners in the southern model (Table 4, models 1 and 4), while northern and combined models showed little change. While models are highly dependent on environmental data, changes to this environment (i.e., climate change) may affect the data series and need to be accounted for (van Oldenborgh, Hendon et al. 2021). Next, consideration for new environmental variables has been made periodically and appears appropriate with the next iteration of this report. Last, the use of log-based indices has come under some scrutiny (O'Hara and Kotze 2010) and consideration for a generalize linear methodology (GLM) may be applicable.

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