APPENDIX MS2013-05. ASSESSING THE RISK OF OCEAN ACIDIFICATION IN THE CALIFORNIA CURRENT TO TWO KEY FISHERY SPECIES, DUNGENESS CRAB (*CANCER MAGISTER)* AND PINK SHRIMP (*PANDALUS JORDANI)*

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INTRODUCTION

Marine ecosystems face stressors from multiple anthropogenic sources (Halpern et al. 2008, Halpern et al. 2009) resulting in unknown consequences on species and their interactions (Hughes et al. 2003, Turley and Gattuso 2012). While effects of anthropogenic CO_2 emissions on climate and ocean pH levels are widely acknowledged, predicting which species are most susceptible to these effects remains a challenge. Ocean acidification in particular has been demonstrated to negatively impact a number of marine organisms (Kroeker et al. 2013) but responses to date have been highly variable (Branch et al. 2012, Greene et al. 2012). Given the uncertainty, it is important to gain a better understanding of the risk faced by marine species, especially those that play an important ecological and/or economic role.

Ecological risk assessment is defined as the *assessment of environmental effects of certain stressors and their immediate and long-term damage or harm to an ecosystem* (Chen et al. 2013). Risk assessment is aimed at better identifying which species might be most adversely affected by a stressor by assessing the probability, or risk, of effects (Burgman 1993, Harwood 2000). Within the context of marine systems, risk assessment has been applied to compare the importance of individual stressors and to identify which species face the greatest threat from individual or multiple stressors (Hobday et al. 2011, Samhouri and Levin 2012). Identifying ecological risks is a crucial first step in determining where to focus future research, when considering monitoring programs and when deciding whether to implement precautionary or responsive management policies (Astles et al. 2009).

For the California Current Integrated Ecosystem Assessment (IEA; Levin et al. 2009), risk assessments are a key step to explore the susceptibility of ecosystem attributes to natural and human pressures. This work is aimed at addressing risk of future ocean acidification impacts faced by two key fishery species in the California Current: Dungeness crab, *Cancer magister*, and pink shrimp, *Pandalus jordani*. Dungeness crab and pink shrimp

fisheries provided a cumulative $206.2 million USD in 2012, 32.5% of West Coast commercial fishery revenues for the year (PacFIN 2012). The California Current System is highly impacted by multiple anthropogenic stressors (Halpern et al. 2009) and is particularly susceptible to ocean acidification as low levels of carbonate saturation already exist within the near-shore environment (Gruber et al. 2012).

Here we apply an ecological risk analysis to gauge the risk of ocean acidification for each life history stage of these two species. A life-stage specific approach is important, because the sensitivity, exposure, and consequence of ocean acidification likely varies among life history stages (Kurihara 2008). Adult forms are what we harvest for most species, however the earlier life stages, such as eggs and larvae, may be more susceptible and thus a limiting factor when it comes to surviving ocean acidification (Baumann et al. 2011, Frommel et al. 2011, Hurst et al. 2013). It is important to understand the risk faced by early life stages to better understand the potential impacts on fisheries depending on these marine resources.

METHODS

The risk metric used in this analysis is similar to that used by Samhouri and Levin (2012) and for the California Current IEA (Levin & Wells 2013) including components of exposure and sensitivity, each rated on a scale of 1 (low exposure or sensitivity) to 3 (high exposure or sensitivity). The risk metric for each species, R_i, is dependent on exposure, E, and sensitivity, S such that:

$$R_i = \sqrt{(E-1)^2 + (S-1)^2}$$

Exposure to ocean acidification was determined from the overlap of species' distributions with pH predicted for the year 2050 (see methods and references below). Sensitivity was determined from a literature review of papers that have examined the responses of Dungeness crab and pink shrimp, or related species, to acidification.

DATA SOURCES

PH PREDICTIONS

Predicted pH levels for the California Current were obtained from modeling by Gruber et al. (2012) for the year 2050. Gruber et al. (2012) implemented a Regional Ocean Modeling System (Schepetkin and McWilliams 2005) for the California Current, including an ecosystem model that tracks nitrogen and marine inorganic carbon. The model is forced by the A2 high-CO_2 emissions scenario from the IPCC (Nakicenovic et al. 2000). The model assumes present day boundary conditions for all variables except CO_2 and dissolved inorganic carbon; thus it simulates ocean acidification but not potential changes in temperature, currents, or other aspects of climate change.

The Gruber et al. (2012) model predicted anomalies of high pH values off the coast of Washington, where we would expect low-pH water due to upwelling. Consequently, the

present analysis may underestimate the extent of exposure to low-pH environments, particularly in waters off Washington.

SPECIES DISTRIBUTIONS

Distributions of the multiple life history stages of both Dungeness crab and pink shrimp were determined from a literature review and discussions with experts on each species. Life history stages mapped for Dungeness crab include: egg, zoeal larvae, megalopal larvae, and adults. For pink shrimp the stages were: egg, larvae, and adults. Maps were produced in ArcGIS (ESRI 2013) of the distribution of each life history stage during every month of the year. Details for species distributions came from Reilly (1983), Pauley et al. (1986), Hobbs and Botsford (1992), Hobbs et al. (1992 and Rasmuson et al. (2013) for Dungeness crab, and Dahlstrom (1970), Dahlstrom (1973), Rothlisberg and Pearcy (1976), Rothlisberg and Miller (1983) and Hannah (2011) for pink shrimp.

Details on the distributions of Dungeness crab life history stages are outlined below. Dungeness crab adults are predominantly found between 30-90 m depth; they are only occasionally found in the surfzone (Rasmuson 2013). Dungeness crabs are found from Alaska to Santa Barbara, California and for this work were mapped from the outer coast of Washington to Santa Barbara California. The eggs of Dungeness crab are retained on female crabs and are found off the coasts of Washington and Oregon between October-March and off California between September-February (Reilly 1983, Pauley et al. 1986, Rasmuson 2013). Dungeness crab larvae have exhibited movement far offshore, starting as zoeae over the continental shelf and progressively moving out past the continental shelf before metamorphosing into megalopae (Reilly 1983, Hobbs and Botsford 1992, Hobbs et al. 1992, Rasmuson 2013). Pelagic crab larvae are found down to 70 m depth. Megalopae move into the nearshore environment to settle (Reilly 1983, Rasmuson 2013). Megalopae were broken into two groups, 'megalops' and 'settled megalops' to account for their presence both in the open ocean and in benthic environments where adult crabs are found.

Pink shrimp adults are similarly found within a limited depth range, with the highest concentrations between 80-230 m depth (Hannah 2011). Like Dungeness crabs, female pink shrimp retain their eggs, and ovigerous females are found off Oregon and Washington in October-March, off Northern California in October-April and Southern California in November-June (Dahlstrom 1970, 1973). The distribution of pink shrimp larvae has been minimally investigated, with most of the research conducted in the 1970s (Rothlisberg and Pearcy 1976, Rothlisberg and Miller 1983). The estimated distribution of pink shrimp larvae therefore depends on a number of assumptions. Larvae are found within 55 km of shore for the first month present in the water column, and then out to 110 km as they disperse via advection and diffusion. Therefore larval shrimp distribution covers a large area from 2 km offshore out to 110 km from shore during most months of the year when they are present. Pink shrimp larvae have been found between the neuston and 150 m depth, with the majority above 100 m, thus the depth of 100 m was used in this analysis.

SENSITIVITY DATA

A literature review was conducted for both species to find papers examining their sensitivity to low pH waters. We also identified relevant studies of species in the same genus. Using Web of Knowledge and Scopus, the following search criteria were used for Dungeness crab: 1. "*Cancer magister*" "ocean acidification", 2. "*Cancer*" "ocean acidification" 3. "Crab" "ocean acidification". For shrimp it was similar: 1. "*Pandalus jordani*" "ocean acidification", 2. "*Pandalus*" "ocean acidification", 3. "Shrimp" "ocean acidification". Papers testing the impacts of pH were retained.

EXPOSURE METRIC

The life history stage of each species was assigned an exposure value from 1-3 based on the fraction of its distribution that will be exposed to 'low-pH' waters in 2050. The following criteria were used: 1 = 0-10% of their distribution will be exposed to low-pH waters, 2 = 10-50% will be exposed to low-pH waters and 3 = 50-100% will be exposed to low-pH waters. The 'low pH' value used was a pH of 7.7, which is at the lower end of what species experience currently (using model-predicted pH for 2013 and comparing it to species distributions). pH is a continuous metric and thus using a single value as a cutoff creates a coarse measure of exposure dependent on binary information. This cutoff value was used to provide a means to determine what is and is not low pH, however future applications of this work will aim to include a value that is not binary.

ArcGIS (ESRI 2013) was used to determine pH exposure for each species and life history stage during every month of the year. Therefore the exposure maps address both spatial and temporal exposure to low-pH waters. The pH maps obtained from Gruber et al. (2012) were in a 5 x 5 km grid, and using GIS the grid was clipped based on the area where the species' life history stage is found (e.g. Figure MS5-1). Assuming the low-pH value of 7.7, we determined the fraction of the distribution that experiences low pH, using R Statistical Software (R Development Core Team 2005).

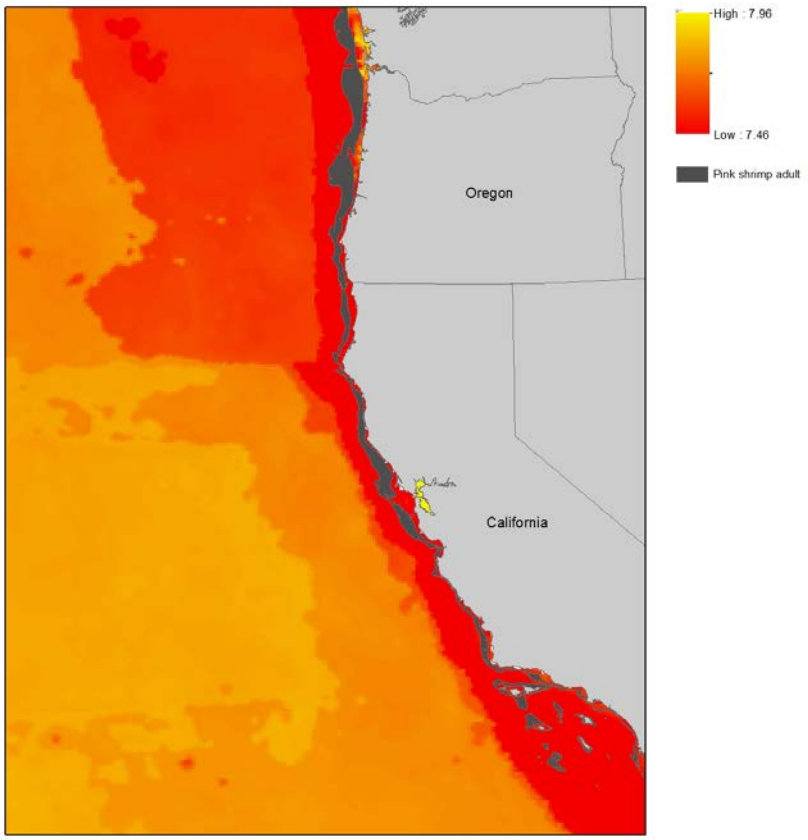

Figure MS5-1. Example exposure map for pink shrimp adults, found between 80-230 m depth (gray shaded areas), during the month of January. pH predictions from Gruber et al. (2012) for the year 2050 along the sea floor.

SENSITIVITY METRIC

Sensitivity values for each species' life history stages were assigned based on relevant literature and pre-existing knowledge about species distributions and tolerance levels. Table MS5-1 provides written categorizations. Using literature published on both species, other species in the same genus or other shrimp or crab species for general information, sensitivity metrics were determined. For those species where the only publications were on a related species, the sensitivity metric was assigned an additional 0.5 value to account for uncertainty.

Table MS5-1. Methods for categorizing species sensitivity levels.

Sensitivity	Category Description
1	High confidence in capacity of life stage to tolerate exposure. Confidence is based on direct experimentation on this or very closely related species, or based on known exposure patterns in sustained populations.
2	Some confidence in capacity of life stage to tolerate exposure, based on evidence suggesting limited, but not full, tolerance to exposure. Empirical evidence shows some effect, but effect size is moderate. Evidence may come from this or from a related species or similar life stage.
3	Little confidence in capacity of life stage to tolerate exposure. This may be based on direct demonstration of demographic effects on this or closely related species. Demographic effects are deemed to be probable based on physiology response or other lines of evidence.

PORT EXPOSURE

In addition to determining the exposure and sensitivity of the different life stages of Dungeness crab and pink shrimp to low pH waters, we also conducted a preliminary exposure assessment for four key fishery port groups on the Pacific Coast. According to PacFIN (2013) four of the port groups landing over $10 million in Dungeness crab in 2012 were: Washington coastal area ports (including Westport Washington), Crescent City area ports, Eureka area ports and San Francisco area ports. Using ArcGIS (ESRI 2013), exposure to low pH waters along the sea floor was determined for the 100-km region around the major city for each port group, for every month of the year.

RESULTS AND DISCUSSION

The life history stage most at risk for the two species examined is larvae for pink shrimp and settled megalops for Dungeness crab (Figure MS5-2, Table MS5-2). Shrimp larvae have the highest risk because they are both highly sensitive and experience high levels of exposure. Within their distribution, 81.3% of the waters they inhabit at 100 m depth are predicted to be at a pH of <7.7 by year 2050. Their sensitivity estimate is derived from experiments on a related species, *Pandalus borealis*, for which it has been found that there is no impact on survival but that development is affected (Bechmann et al. 2011, Arnberg et al. 2012) and therefore this closely related species exhibits some tolerance but not complete tolerance (sensitivity categorization based on Table MS5-1). Although Dungeness crab settled megalops are rated as having some level of tolerance to low pH waters, their categorization of 3 for exposure results in a relatively high final risk score. Settled megalops are found in low-pH waters along the bottom and thus are highly exposed: by year 2050, 59% of waters they inhabit are predicted to be more acidic than a pH of 7.7.

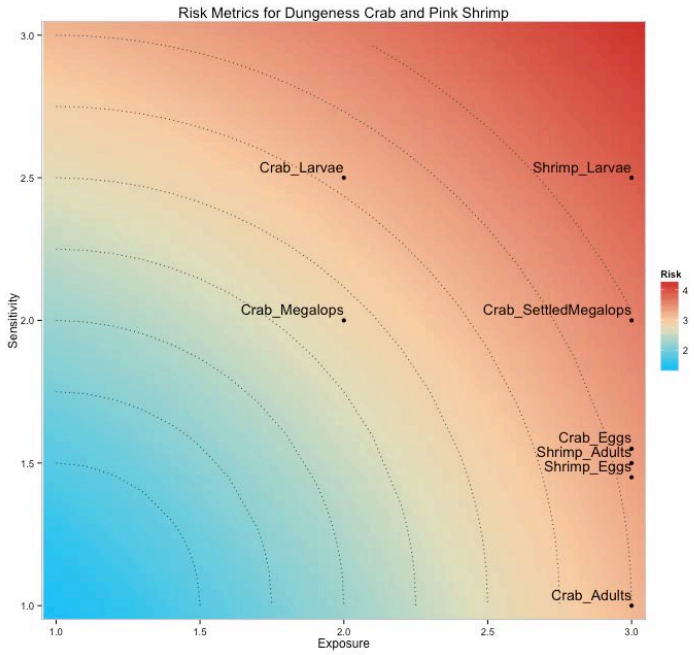

Figure MS5-2. Risk plot demonstrating risk scores for each species and life history stage. Sensitivity values come from the literature and exposure values are specifically related to exposure to pH < 7.7.

Table MS5-2. Summary of Sensitivity and Exposure ratings for each species and life history stage combination, and their final Risk Score. Sensitivity values come from the literature and exposure values are specifically related to exposure to below 7.7 pH.

Species by Life History Stage	Sensitivity Value	Percent Exposure	Exposure Value	Risk Score
Crab Eggs	1.5	87.6	3	3.4
Crab Larvae	2[1]	35.5	2	2.8
Crab Megalops	2	29.1	2	2.8
Crab Settled Megalops	2	58.6	3	3.6
Crab Adults	1[2,3]	76.2	3	3.2
Shrimp Eggs	1.5[4]	95.9	3	3.4
Shrimp Larvae	2.5[4,5]	81.3	3	3.9
Shrimp Adults	1.5[6]	89.1	3	3.4

[1] (Jason Miller, unpublished results) [2] (Pane and Barry 2007) [3](Metzger et al. 2007) [4] (Arnberg et al. 2012) [5] (Bechmann et al. 2011) [6] (Hammer 2012). Conclusions reach for sensitivities of life history stages for which there was no publication relied on information known about similar life history stages or known information about the pH in the environment where the species is currently found.

Although pink shrimp larvae and settled Dungeness crab megalops are the most at risk, all life history stages of both species are likely to experience a high degree of exposure to acidic waters (pH <7.7 in year 2050) in >10% of their distributions, falling into exposure levels 2 and 3 (Figure MS5-2, Table MS5-2). Of the eight life history stages of the two species examined, six are predicted to be exposed to pH less than 7.7 in 59-89% of their distribution (exposure level 3). This is largely due to the temporal and spatial distributions of these species. Both Dungeness crab and pink shrimp adults are found along the bottom where pH is the lowest. Since their eggs are attached to the adults, eggs also experience these low-pH conditions. Thus, although some of these life history stages are not categorized as highly sensitive, due to their exposure their final risk metric falls close to 2.

The species and life history stage combinations experiencing the lowest risk are Dungeness crab larvae and pre-settlement megalops. Their low risk score is due to a lower exposure level. Both of these life history stages are found at shallow depths, away from the low-pH waters at depth. They are also found offshore for a large proportion time, allowing them to escape nearshore, low-pH upwelling waters.

From this work we have hypothesized the most at-risk life history stage for each species. Two questions remain. One, which life history stage is the most important for the long term sustainability of each species? Two, is that life history stage able to avoid risk based on its spatial and temporal distribution? Next steps will aim to address these questions using stage-structured population models. Once models have been developed for each species, sensitivity analysis of the populations to their vital rates (e.g. survival, reproduction) will be performed to determine the relative importance of each vital rate for species survival and the relative importance of each life history stage (Morris and Doak 2002).

From the port level comparisons, the ROMS model predicts high exposure to low-pH waters for the three ports in California (Table MS5-3). Although it appears that the

Washington coastal area port has lower risk of exposure, this is likely a result of the high-pH anomalies that were observed in the Gruber et al. (2012) model but are not supported by field observations. Since exposures between 92-100% are observed for California, this analysis demonstrates that low-pH waters may be found nearby at least some major ports with high Dungeness crab landings and revenue.

Table MS5-3. Summary of exposure results for port level comparisons, values represent percent exposure to waters with pH below 7.7 for the 100-km radius around the major city in the port group.

Port Group	Percent Exposure
Washington area ports, WA	65.7%
Crescent City area ports , CA	100%
Eureka area ports, CA	100%
San Francisco area ports, CA	92.6%

Results from this analysis are subject to assumptions regarding the oceanographic model used and thus are a preliminary draft that should be interpreted with caution. There are a number of components that need to be refined, including further investigation of the anomalously high pH predicted by Gruber et al. (2012) near the Washington coast, and possible comparison of conclusions when using an alternative oceanographic model. Additionally, the exposure value is dependent on which pH is chosen as the 'low pH' value and thus will vary depending on the value used. Finally, data used to determine shrimp and crab distributions varied for each life history stage included. For both species, adult distributions are known because they are of fishery value and eggs are attached to adults. However, for both species data on larval distributions are limited and therefore assumptions had to be made in order to make definitive maps.

We aim to expand this work to additional species that are likely to be impacted by ocean acidification (Branch et al. 2013, Kroeker et al. 203), to allow better understanding of the relative risk for particular species and fisheries. Direct impacts of low pH can be assessed using the risk score methodology above, as well as the proposed stage-structured population models. Indirect effects propagated through the food web, for instance to predators that rely on shelled organisms, can be forecast by ecosystem models that include trophic relationships and geography. Such models (e.g. (Fulton et al. 2011)) can be used to evaluate impacts on fishery harvests and management (Kaplan et al. 2010), and potential synergisms between ocean acidification and the changing climate (Griffith et al. 2011).

ACKNOWLEDGEMENTS

We would like to thank Nicolas Gruber, Albert Hermann, Bob Hannah, Kelly Andrews, Leif Rasmuson, Paul Reilly, Peter Rothlisberg and Jason Miller for their contributions in providing both data and recommendations for the analysis. Funding for this work was provided by the NOAA Ocean Acidification Program and the School of Aquatic and Fishery Sciences, UW.

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