Completion Report

Essington, Tim

Period: 2/1/2012 - 1/31/2013
Project: R/OCEH-3 - *How does hypoxia impact marine food webs and fisheries? Evaluating distributional shifts in Hood Canal, WA.*

:: STUDENTS SUPPORTED

Hennessey, Shannon, unknown, University of Washington, School of Aquatic and Fishery Sciences, status:cont, field of study:Marine Biology, advisor:Essington, degree type:BS, degree date:2013-06-01, degree completed this period:No
Student Project Title:
Nearshore community responses to hypoxia

Involvement with Sea Grant This Period:
Capstone

Post-Graduation Plans:
Graduate School
Nelson, Halley, henelson@u.washington.edu, University of Washington, School of Aquatic and Fishery Sciences, status:cont, *no field of study*, advisor:Essington, degree type:PhD, degree date:2015-06-01, degree completed this period:No
Student Project Title:
Ecological effects of Hypoxia in marine Estuarine Ecosystmes

Involvement with Sea Grant This Period:
Graduate Research Assistant

Post-Graduation Plans:
unknown

:: CONFERENCES / PRESENTATIONS

Nelson, H., Essington, T.E., Beaudreau, A.H, (2011). Movement patterns and distributional shifts of Dungeness crab (Cancer magister) in response to hypoxia. Oral Presentation at the American Fisheries Society Annual Meeting. Seattle, WA Sept. 4-8., public/profession presentation,, public/profession presentation, 70 attendees, 2011-09-08
Essington, T.E. 2011. Effects of hypoxia on an urban estuary. UC Santa Cruz Department of Ecology and Evolutionary Biology., public/profession presentation, 30 attendees, 2011-03-01

:: ADDITIONAL METRICS

K-12 Students Reached:	**Acres of degraded ecosystems restored as a result of Sea Grant activities:**
Curricula Developed:	**Resource Managers who use Ecosystem-Based Approaches to Management:**

Volunteer Hours:	**HACCP - Number of people with new certifications:**
Cumulative Clean Marina Program - certifications:	

:: PATENTS AND ECONOMIC BENEFITS

No Benefits Reported This Period

:: TOOLS, TECH, AND INFORMATION SERVICES

Description		Developed	Used	Names of Managers	Number of Managers
Acoustic, video tracking of Dungeness crab, English sole movement in response to hypoxia events in Hood Canal, WA for use in fisheries management. R/OCEH-3	**Actual** (2/1/2012 - 1/31/2013) :	0	1	NOAA Fisheries	1
	Anticipated (2/1/2013 - 1/31/2014) :	0	1		

:: HAZARD RESILIENCE IN COASTAL COMMUNITIES

No Communities Reported This Period

:: ADDITIONAL MEASURES

Safe and sustainable seafood

Number of stakeholders modifying practices
Actual (2/1/2012 - 1/31/2013) :
Anticipated (2/1/2013 - 1/31/2014) :

Number of fishers using new techniques
Actual (2/1/2012 - 1/31/2013) :
Anticipated (2/1/2013 - 1/31/2014) :

Sustainable Coastal Development
Actual (2/1/2012 - 1/31/2013) :
Anticipated (2/1/2013 - 1/31/2014) :

Coastal Ecosystems
Actual (2/1/2012 - 1/31/2013) :
Anticipated (2/1/2013 - 1/31/2014) :

:: PARTNERS

Partner Name: NOAA Fisheries
Partner Name: Skokomish Tribal Nation

:: IMPACTS AND ACCOMPLISHMENTS

Title: **Washington Sea Grant research links hypoxia to crab fisheries with potential to prevent overfishing**

Type: impact
Relevance, Response, Results:
Relevance: Hypoxia or low dissolved oxygen has become a pervasive problem in Washington’s inshore waters

during the summer months, particularly in Hood Canal. Hypoxia's causes have been intensively researched, but its ecological effects have received relatively little study. Fish kills are its most visible impact, but sublethal ecological consequences may be far more widespread, potentially affecting food-web structure and species' movements, productivity, and vulnerability to fishing.
Response: Washington Sea Grant-funded researchers assessed the movements of Dungeness crab and English sole in two regions of Hood Canal during late summer periods of low dissolved oxygen. Using acoustic tags, stationary and mobile receivers, weekly tracking, and video surveys, they tracked the movement of animals locally (from deep to shallow water) and regionally (south to north) to avoid hypoxia.
Results: The research revealed greater species diversity in the less-hypoxic northern region but more faunal density, with less week-to-week variation, in the south. This suggests that relatively hypoxia-tolerant species in the southern area are finding unexpected refuges. There is surprisingly little evidence of regional movement. Sole travel extensively throughout Hood Canal, but these large-scale movements did not reflect changes in oxygen level. Crabs move to shallower water, where fishing is more intense, as oxygen levels decline. The results are being used to evaluate use of water quality as part of the harvest management strategy and will provide direct guidance for adapting the fishery to hypoxia-related changes in access to crab stocks. This will benefit coastal recreational and tribal crab fishermen by establishing safeguards to prevent overfishing.

Recap:
Washington Sea Grant-funded research found that Dungeness crab and English sole in Hood Canal do not move far to escape hypoxia. Crabs shift to shallower water where they are more easily caught, suggesting the need to reevaluate how the fishery is managed.

Comments:
Primary Focus Area – OCEH (SSSS)
Secondary Focus Area – LME (HCE), COCC (HRCC)

Associated Goals: Improve understanding and management of emerging and cumulative threats to ocean and coastal health (SSSS Supply).
Strengthen ecosystem approaches to management of living marine resources through improved understanding of marine biodiversity, marine and coastal ecosystem function, climate change and other sources of variability (HCE Science).
Improve understanding of coastal hazards and environmental change and develop tools and approaches for observation, prediction, planning and adaptation (HRCC Risks).

Related Partners:

Hood Canal Salmon Enhancement Group
National Marine Fisheries Service (US DOC, NOAA, NMFS)
Northwest Fisheries Science Center (US DOC, NOAA, NMFS, NWFSC)
Skokomish Tribal Nation
University of Washington, School of Aquatic and Fishery Sciences, College of the Environment (UW)

:: PUBLICATIONS

No Publications Reported This Period

:: OTHER DOCUMENTS

No Documents Reported This Period

:: LEVERAGED FUNDS

Type: influenced Period: 2012-02-01::2013-01-01Amount: $30000

Purpose:
Student fellowship for graduate Ph.D. Training

Source: National Science Foundation

Washington Sea Grant Final Report R/OCEH-3

How does hypoxia impact marine food webs and fisheries? Evaluating distributional shifts in Hood Canal, WA.

2/2010 – 2/2013

Section I:

This was the final year of our three-year WA Sea Grant project. We budgeted for 5 months of effort (graduate student, 0.25 months of PI) to finalize analysis and to prepare publications. Thus, our total level of activities is less than one would expect compared to our previous full years of activity and funding.

Our activities have focused on two main areas. First was completing manuscript for peer-reviewed publication summarizing the findings from our telemetry work. The second was to complete video analysis and data analysis of the nearshore drop camera survey and prepare a draft manuscript to be submitted for publication in a peer reviewed journal. The first has involved partnership with our project PIs at NOAA fisheries but has primarily been conducted by the project graduate student, Halley Froehlich (née Nelson), and the lead PI, Tim Essington. This manuscript was submitted to Marine Biology in June, 2012. Unfortunately we received one strongly negative review that unfairly challenged our study design. Regrettably the handling editor did not indicate the degree of weight to assign to this review, so we opted not to attempt a revision (taking up valuable time) because we felt we could not change the mind of the reviewer who was obviously not used to considering large-scale field studies. We instead re-submitted to Estuaries and Coasts, where we believe we are likely to get reviewers who are accustomed to evaluating controlled field comparative studies. The paper was submitted in December 2013 and we anticipate response back shortly.

Our analysis of the nearshore data has progressed according to schedule and we currently have a draft manuscript that is in the final stages of editing before submission. This work was conducted primarily by Halley Froehlich but also with considerable efforts by Shannon Hennessey, a SAFS graduate student who developed her capstone project around this work. She presented the results of her work at the SAFS Capstone symposium in Dec. 2012. We describe details of this work in Section II.

A final piece of the project has been to engage stakeholders. Here we have faced more challenges. Our contact at WDFW who had arranged to establish a briefing session ceased responding to our messages to him. We have not been successful at finding an alternative contact. We anticipate having greater success once our paper is submitted – we wish to impress upon WDFW the fact that (1) crab catchability in pots may depend on offshore DO levels; (2) flatfish movements are extensive throughout Hood Canal; and (3) behavioral responses to low DO seem to involve local refuges that are not necessarily related to nearshore habitats. Our plan is to distribute the manuscript as a PDF to WDFW staff and then arrange a briefing meeting to summarize the findings. We will also engage the Skokomish Tribal Nation who partnered with us in this research. We were in regular contact with the replacement for Mr. Rasmussen (project

PI and former shellfish management biologist), but unfortunately that individual has since left her position and it is now vacant.

Section II

Rationale

In Washington State, USA, Puget Sound is a large, marine ecosystem that supports a diverse array of marine species, including commercially important Pacific salmon (*Oncorhynchus* spp.) and Dungeness crab (*Metacarcinus magister*). Hood Canal is an 80 km, fjord-like estuary comprising the western arm of Puget Sound that regularly experiences seasonal hypoxia (Newton et al. 2007). Although hypoxia has been reported in Hood Canal since the 1950s, oxygen conditions appear to be deteriorating even further due to a combination of natural (*e.g.*, climate) and anthropogenic (*e.g.*, nitrogen and carbon loading) influences (Newton 1995, Fagergren et al. 2004). A sill at the narrow northern opening and the steep bathymetry of Hood Canal reduces tidal currents and hydrological exchange rates from north to south (Newton 1995). As a result, DO levels throughout the southern regions decline throughout summer while the vertical extent of hypoxia expands through the water column, reaching depths of 20–30 m (Newton 1995). Due to the natural environmental (DO) gradient and relatively small spatial scale, Hood Canal is an ideal system to study the effects of hypoxia on marine biota.

Two main types of biological impacts are typically associated with hypoxia. First, low oxygen conditions can directly cause mortality. Second, hypoxia can alter the behavior of mobile organisms, commonly in the form of an avoidance response. Avoidance behavior reduces hypoxia exposure through distributional shifts, documented as short-term reductions in densities of mobile fauna in hypoxia-impacted areas (Pihl et al. 1991, Diaz and Rosenberg 1995, Petersen and Pihl 1995, Eby et al. 2005). Although these behaviors reduce direct mortality, substantial shifts in species distributions and habitat use can impact the fitness of organisms, including impeding individual growth (Eby et al. 2005). In addition, these mass shifts of organisms can cause significant changes in species composition (Diaz and Rosenberg 1995, Conley et al. 2007, Vaquer-Sunyer and Duarte 2008), resulting in alterations to the local food web (Pihl et al. 1992, Baird et al. 2004, Eby 2004, Seitz et al. 2009) and potentially the productivity of the system (Diaz 2001). As a result, detecting and measuring these complex responses to hypoxia can greatly improve upon the understanding of the state and stability, and thus the management, of seasonally hypoxic estuaries.

Hypotheses & Objectives

We hypothesized two, non-mutually exclusive types of distributional shifts that might result in localized reductions in density of mobile taxa in hypoxia-impacted regions of Hood Canal. First, individuals may shift into nearby shallow oxygenated areas (Pihl et al. 1991, Petersen and Pihl 1995), which in Hood Canal usually consists of a small band of habitat that is less than 25 m in depth (Essington and Paulsen 2010). However, due to the limited amount of area unaffected by hypoxia this response alone may be insufficient to account for the sharp decline in densities. Alternatively, hypoxia can have a cascading effect (Lenihan et al. 2001), where individuals could follow the regional oxygenated gradient that spans Hood Canal from south to north, thereby reducing hypoxia exposure by moving into more oxygen rich northern habitat.

The research sought to evaluate these hypotheses through a combination of direct tracking of individuals via acoustic telemetry and through monitoring nearshore habitats at index stations positioned throughout Hood Canal. We focused on two common species for direct monitoring of movement: Dungeness crab and English sole. Dungeness crab's commercial and recreational value and English sole's wide distribution and abundance in the system made them ideal candidates to improve our general understanding of distributional shifts while simultaneously contributing to the scientific information needed for more informed harvest policy decision making in Hood Canal.

Methodology

We had two primary methods to assesses distributional shifts: (1) acoustic telemetry that provide continuous observations of distributional and habitat shifts of individual Dungeness crab and English sole and (2) under water (drop-camera) video to measures changes in nearshore local density over time. We used acoustic telemetry (VEMCO) to monitor the horizontal and vertical movements of two common species in Puget Sound: Dungeness crab (*Metacarcinus magister*) and English sole (*Parophrys vetulus*). We tagged (VEMCO V9-2 and V9P-2) and tracked individual movements in two years, 2009 (N=16: 6 crab, 10 sole) and 2010 (N=44: 30 crab, 14 sole) by using a combination of stationary (VEMCO VR2W) and mobile (VEMCO VR100) acoustic receivers (Fig. 1). The 2009 sampling was a pilot study that tracked individuals from July – November in the hypoxia-impacted region (Fig. 1). The 2010 sampling spanned June – September, and featured a paired study design consisting of two study regions, one in the southern portion of Hood Canal and a second site located approximately 10 km northward (Fig. 1). By treating the northern site as a reference location we could potentially distinguish changes in behavior due to hypoxia from seasonal patterns and shifts that were unrelated to low oxygen conditions. All sampling was accompanied by weekly water quality monitoring (temperature [°C], salinity [PSU], and dissolved oxygen [$mg \cdot L^{-1}$]).

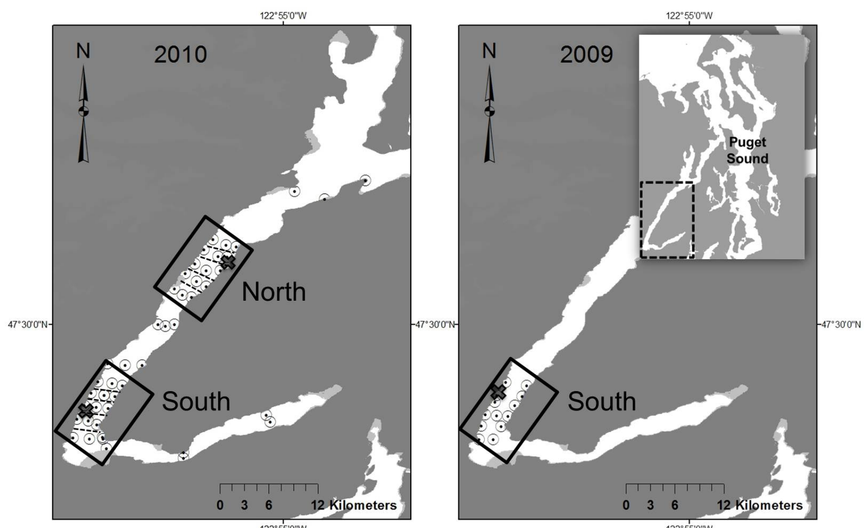

Figure 1. Paired Study Design. Specimen capture/release locations (*black Xs*) and passive acoustic receivers (*solid points*) in Hood Canal, Washington, USA in 2010 and 2009. *Outer circles* represent the 90% detection range (350m). *Rectangles* enclose the central north and south study sites. *Dotted lines* indicate mobile tracking transects.

We developed a drop-camera methodology to count fish and macro-invertebrates at depths ranging from 10 – 30 m. A downward facing drop-camera ("splash cam"), fitted with parallel lasers at a known distance (5.5 cm). The splash cam provided a live feed to a monitor onboard a vessel and transmitted a video feed to a recorder for future detailed analysis. We ran transects along isobaths at fixed depth intervals. The depth range over which this method is effective spanned the expected threshold depth beyond which hypoxia is common. Thus, we could test the hypothesis that the relative abundance of each species in shallow (< 20 m) compared to deeper (> 20m) areas should increase in hypoxia impacted areas, but otherwise remain constant in unimpacted areas. A total of four drop camera stations in each study site consisting of three sampling depths (10, 20, 30 ± 3m) were sampled for 10 weeks during the summer. Post-processing of the 25 hrs of video was conducted at the laboratory. All conspicuous mobile organisms were identified down to species level, or later grouped into order.

Major Findings & Conclusions

Water quality

Weekly dissolved oxygen profiles indicated substantial differences in the vertical extent and intensity of hypoxia between the southern and northern sites. In early June 2010, the deep waters had uniformly low DO throughout the southern channel of Hood Canal; the shallowest hypoxic depth was initially near 90 m (Fig. 2a). As the summer progressed, the extent of hypoxia rapidly expanded vertically into the shallows, reaching approximately 20 m by week 12 (Fig. 2a). In contrast, the northern DO conditions stayed relatively constant. The 2009 hypoxia was less severe throughout Hood Canal, and did not expand into the southern shallows until late September (Fig 2a).

Acoustic Data

We found no evidence of either crab or sole exhibiting large-scale directional movement out of the hypoxia-impacted southern region. These findings appear consistent with results from other studies that have documented movements of fish and macro-invertebrates over relatively short distances from hypoxia (Pihl et al. 1991, Eby and Crowder 2002, Craig and Crowder 2005, Tyler and Targett 2007, Craig 2012). Comparisons of attrition (*i.e.*, emigration) and transfer rates of tagged individuals from and between regions, respectively, were also counter to what we expected – emigration rates were lowest in the hypoxia-impacted site. *Unlike other estuarine systems (Lenihan et al. 2001), these results provided little evidence of a large scale cascading effect caused by hypoxia*.

However, Dungeness crab did exhibit significant shifts towards shallower waters during both years, particularly in the more hypoxic southern region (Fig. 2). In addition, the range of crab vertical activity appeared to increase with declining dissolved oxygen concentrations. Increased activity and density of crabs into the narrow band of shallow normoxic refugia may increase their vulnerability to stationary fishing gear (Selberg et al. 2001) *Our findings suggest hypoxia has a more localized impact on the mobile fauna in Hood Canal.* However, more detailed

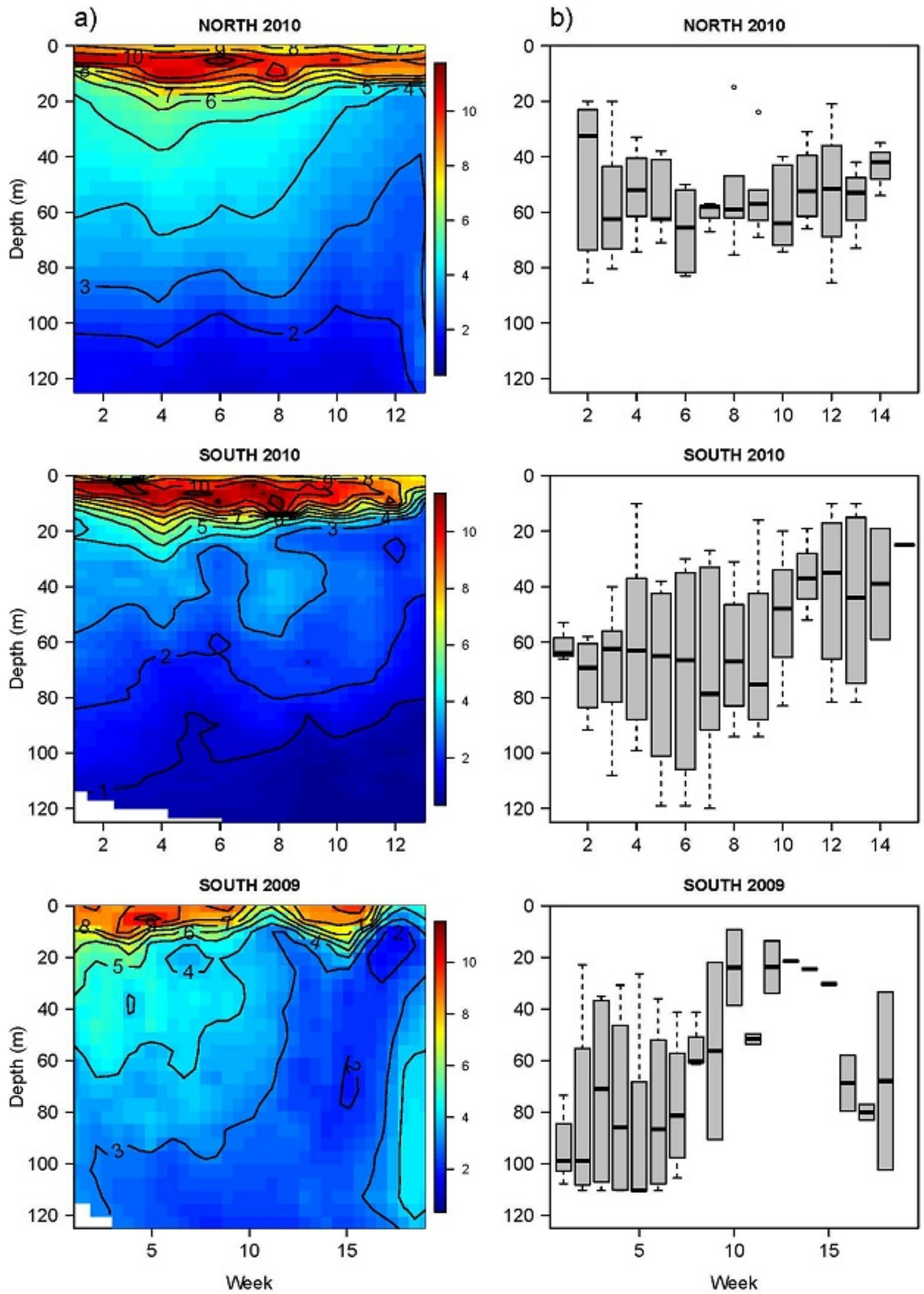

Figure 2. **a)** Interpolated average dissolved oxygen (DO) conditions of the 2010 north and south focal study sites and 2009 pilot study. Each graph depicts the contour (*black lines*) and gradient (*color*) of DO as depth and time increase. In 2010, the hypoxic (DO < 2 mg L^{-1}) layer in the northern region remained deep, while low DO in the southern region rapidly decreased in depth over time. In 2009, the low oxygen levels appeared later in the summer (September), but quickly established within a shallow range of the water column. **b)** Range of maximum weekly depth (m) of each crab in 2010 and 2009. Each graph shows the median (*black line*) and the upper and lower bounds of the crabs detected each week. The 2010 northern crabs remained above the hypoxia layer, while the southern crabs where in sync with the extending hypoxia layer and moved into shallower depths. The 2009 southern crabs exhibited a similar shoaling pattern.

information concerning the local oxygen dynamics and responses of these species, such as English sole vertical movement, is essential to fully comprehend the population and community level effects of hypoxia. Currently, this manuscript is in review at the journal of *Estuaries and Coasts*.

Drop-Camera
Overall density of marine conspicuous marine fauna was greater in the southern region, accounting for 61% of the total species abundance; the largest proportion of organisms belonged to Decapoda (53%). Although average densities and depths of species and groups of species (orders) fluctuated through time, the variability did not appear to correspond with the onset of hypoxia (Fig. 3). However, evaluation of species richness and evenness revealed lower average number of species in the southern region compared to the north. Further assessment of community assemblages showed distinct groupings between the two regions and less difference in southern community structure from week to week than the north. Although the weak density and diversity signal is inconsistent with other evidence of distributional shifts occurring in Hood Canal (Essington and Paulsen 2010), our results provide a potential indication of the heterogeneous nature of the available oxygenated refugia and relatively constant, but less diverse, hypoxia-tolerant community in the south during severe hypoxic episodes. If the oxygenated locations are indeed more patchily distributed, knowledge of such aggregate 'hot spots' of condensed organisms may prove valuable to understanding the level of secondary ecological impacts, as well as implementation of more focused management tactics. *Thus more detailed information concerning the nearshore oxygen spatio-temporal patterns and species responses is needed to fully understand the population and community level effects of hypoxia.*

Significance of Results

We identify at least 3 main results that are relevant for understanding ecological consequences of hypoxia in Hood Canal and that lead to considerations for specific management / policy actions.

1. Dungeness crab catchability in nearshore crab pots may be enhanced by deep water hypoxia. Current harvest management for Dungeness crab is based on effort restrictions (no fishing at night, constraints on the number of days / week when fishing is permitted, limitations on the duration of crabbing season). Currently, the summer crab recreational fishery ends after Labor Day weekend. Our findings indicate that hypoxia should be monitored in August and crabbing effort be regulated more strictly when hypoxia at depth >30m is present because the crabs may become more vulnerable to crab pots under these conditions. We are continuing this line of work by planning (1) to review results with WDFW biologists and policy makers (2) outlining components of a management strategy evaluation to (3) test different feedback control rules with respect to minimizing the probability of overfishing.

2. Flatfish movements can be extensive. Although movements do not appear to be associated with the onset of hypoxia, it is clear that English sole can and do regularly move great distances throughout Hood Canal. This implies that current harvest restrictions for flatfish recreational fisheries have biological merit, as fishing activities occurring in the northern portion of Hood Canal are likely to capture fish that reside throughout Hood Canal, including the hypoxia-

impacted area. Thus, harvest restrictions are one way to reduce cumulative impacts on these populations.

3. Hypoxia avoidance behavior relies on unknown refuges. Previous trawling surveys indicated sharp reductions in mobile fauna density during the onset of hypoxia. There was little evidence of large regional scale movements (i.e., from the South to the North), nor was there evidence of shoaling in nearshore habitats. We conclude that many mobile fauna move as little as possible to avoid harmful DO levels, which makes them vulnerable to further deterioration in water quality. Moreover, we currently do not understand the nature or location of these refuges. For instance, in Summer 2010 we were only able to capture flatfish on single trawl tow located on a slightly elevated rise in the Southern sampling region (in 2010, hypoxia was established in deep water very early in the season). There is therefore a need to protect all benthic habitats because some are likely playing a critical role as hypoxia refuge

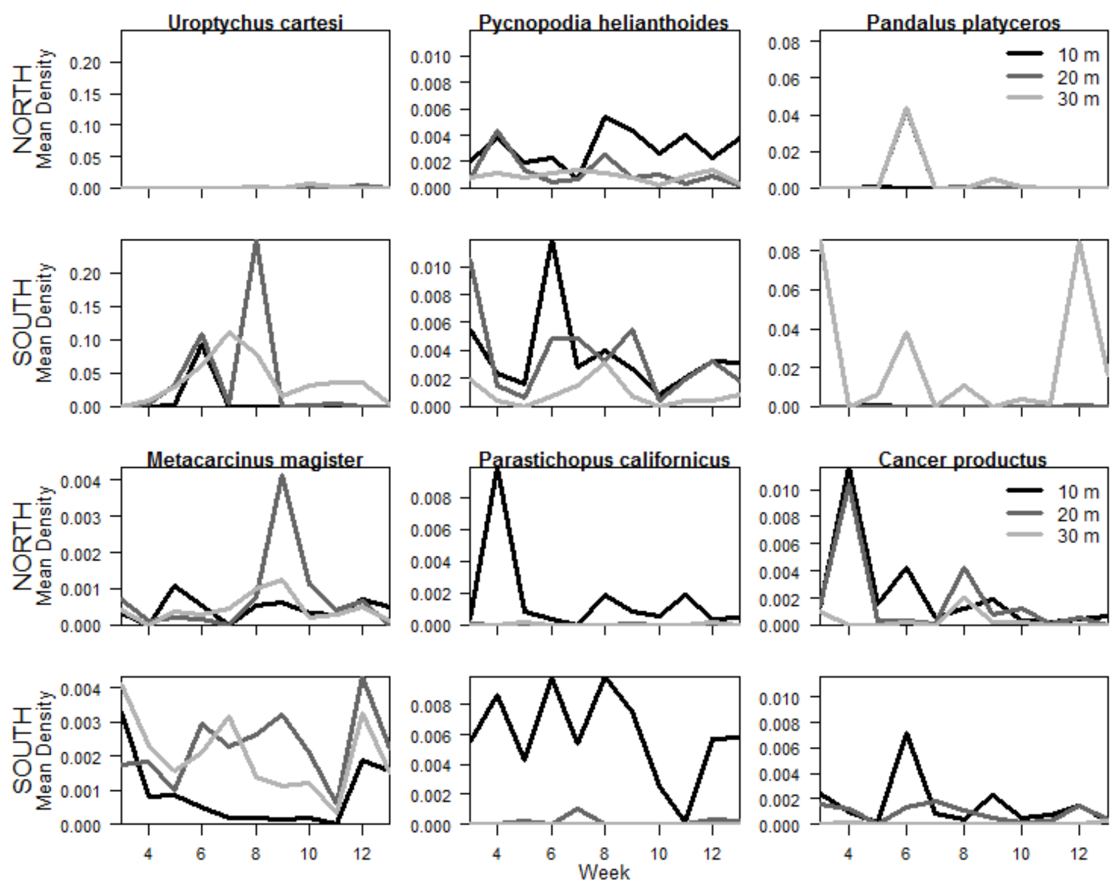

Fig 3. Mean species density (no. species m^{-2}) at three distinct strata within the north and south study regions. The six most abundant species included squat lobster (*Uroptychus cartesi*), sunflower star (*Pycnopodia helianthoides*), spot prawn (*Pandalus platyceros*), Dungeness crab (*Metacarcinus magister*), giant California sea cucumber (*Parastichopus californicus*), and red rock crab (*Cancer productus*). The *black, dark gray, and light gray lines* indicate the densities of the specific species at 10, 20 and 30 m, respectively. Although densities varied over time, changes in abundance were not indicative of a hypoxia avoidance response.

Students Supported

Halley Froehlich (née Nelson) Ph.D. student, 2010 – present

Shannon Hennessey, B.S. student, 2011 - 2012

Partnerships and Outreach

This work would not have been possible without two key partners – NOAA fisheries and the Skokomish Tribal Nation. Our NOAA partners (co-PI Levin) were involved in all components of the project, including study design, logistics, and sharing equipment that permitted us to enjoy the benefits of an unusually extensive receiver array. Our NOAA partners are deeply engaged in integrated ecosystem assessments (IEA), applied to Puget Sound as well as the U.S. west coast where hypoxia is also common. The specific findings of our research will therefore be relevant for future development of IEA applied regionally. Our Skokomish Tribal partners were also critical – from fine-tuning study design, collecting crabs for tagging and assisting with receiver retrieval and deployment. The project could not have been conducted without their participation. A final report will be submitted to the appropriate Skokomish Tribal Nation staff (currently, the marine shellfish manager position is vacant).

Our outreach activities thus far have focused on scientific and academic audiences. Both the graduate student (Froehlich) and the PI (Essington) have given public presentations about our hypoxia-related work in Hood Canal. Further, I regularly use results from this study in my classroom teaching at SAFS – particularly in "FSH 323 Conservation and Management of Aquatic Resources". I also give guest lectures for the Marine Biology senior seminar specifically about our tagging work in Hood Canal. We intend broader sharing of results to stakeholders – particularly policy makers but also residents of Hood Canal – once papers are accepted for publication. Notably, we are attempting to engage WDFW staff on a briefing meeting that will lead to novel model results to test current and alternative harvest strategies for Dungeness crab in Hood Canal.

Information / technology transfer activities

Because there were multiple tagging projects being conducted during Summer 2010, we were able to share data from our acoustic receiver array to other researchers. All acoustic receiver data from our array was shared and uploaded to the regional "POST" project (http://www.postcoml.org/). This is a multi-institutional effort that seeks to develop a sharable tool for tracking marine animal movements in NE Pacific. This information transfer will allow other researchers to access our data (e.g. crabs and English sole) while also using detected transmissions of tagged salmon, steelhead and other species. Notably, this receiver array was a key piece of an associated project being conducted by NOAA scientists on movements of large medusa jellyfish (Lion's Mane and Fried Egg). In this study, jellyfish were tagged and tracked using our receiver array to determine movements relative to tidal currents and diel cycle. This work was recently published in MEPS (Moriarty et al. 2012) *as the featured article of the volume*

(Volume 455), and was specifically highlighted by Dr. Jane Lubchenco in her Facebook feed highlighting cutting edge science being conducted by NOAA.

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