Sensitive Barnacles:
A Case Study for Collaborative Sustainable Fishery Development

by

Julia Bingham

A THESIS

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Honors Baccalaureate of Science in Biology
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Current human – ocean relationships are dominated by unsustainable extraction of marine resources having both ecological and socio-economic consequences. Sustainable fishery management utilizing stakeholder collaboration must become a proactive strategy to prevent or reduce further long-lasting impacts. In Oregon, USA, a newly developing fishery for gooseneck barnacle (*Pollicipes polymerus*) presents a real-world opportunity to reframe fisheries management. Commercial gooseneck fishing in Oregon requires the development of harvest management to prevent patterns of gooseneck overharvest seen historically in Europe, but relevant scientific information on the natural population dynamics and life-history of Oregon goosenecks is lacking. To begin filling this need, I studied the spatial and temporal variability of life history patterns and population structure of *Pollicipes polymerus* at several sites along the central Oregon coast. I documented (i) significant correlation between regional differences in oceanography and gooseneck population density (ii) site-specific variation in the size-frequency distribution of individuals, particularly in the fraction of individuals of harvestable size, (iii) seasonality in population brooding patterns, and (iv) slow rates of population recovery spanning multiple years in a manipulative harvest simulation experiment on natural substrates. These findings suggest future necessary scientific investigations of *P. polymerus* populations and support preliminary sustainable harvest management design in Oregon.

Key Words: Gooseneck Barnacles, *Pollicipes, Pollicipes polymerus*, sustainable fishery management, overfishing, collaborative resource management, fishery reform

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Julia Bingham, Author

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I. SUSTAINABLE HARVEST MANAGEMENT IN A GLOBAL CONTEXT

Oceans and Humans: A Call for Change

Overfishing in general has become widely recognized as an immediate threat to the world's marine systems (Guichard et al. 2004, Hilborn et al.2003, Hilborn et al.2012). Since WWII, a rapidly expanding human population and technological advancements of fishing practices has placed increasing pressure on marine species targeted for harvest (Thompson et al. 2002). In most cases, target marine species and their ecosystems simply cannot support this increased pressure indefinitely. The majority of today's fisheries are overfished (Costello et al. 2016). Populations decline as fishing removes more individuals than are produced per generation. Maximum size of individuals and overall reproductive output of a population decreases as the largest, most fecund adults are preferentially selected by fishers (Hilborn et al. 2003). This has been seen, for example, in Atlantic bluefin tuna, which has suffered not just massive population decrease but an entire shift in population structure surrounding average adult size and reproductive output (Shoemaker & Kcakaya 2015). Additionally, trophic interactions and ecosystem functions falter or collapse as species are fished to the point of population decimation. Overall biodiversity falls, and non-target species experience population shifts as the species they interact with either competitively, through facilitation, or through predation become overfished (Hilborn et al. 2003). For example, the overfishing of tuna, groupers, and other predators has resulted in population bursts of prey species like anchovies and sardines (Hilborn et al. 2003, Halpern et al. 2010).

Human systems must change as a result of overfishing as well. General seafood diets shift as overharvested species become nearly unavailable while others experience temporary booms due to overfishing-triggered trophic cascades (Shoemaker & Akcakaya 2015). Economies that rely on specific fisheries for significant monetary support decline when fisheries collapse due to overfishing and other anthropogenic effects (Hilborn et al. 2012). Social systems constructed around those economies are subsequently impacted by fishery collapse. Members of fishery-based coastal communities may have to migrate to find still-productive fishing opportunities. This has been seen in Peru, for example, when overfishing in the 1950s caused the collapse of several localized intertidal fisheries and fishers subsequently moved to coastal communities in Ecuador and Chile that still had access to substantial nearshore shellfish and echinoderm populations (Charles 2013). Other fishers may switch professions: in tourism-heavy areas like the Caribbean, more locals are involved in tourist services than in fisheries. Still others may turn to the black market: illegal shark finning persists globally, and especially in areas like the Galápagos where local fisheries have been heavily impacted and triggered strict management policy but resources for enforcement are limited (Paladines et al. 2015).

Each effect is exacerbated by synergistic interactions with other human-driven oceanic degradation such as pollution, tourism, and anthropogenic climate change and ocean acidification. The specific effects of the last two cannot be easily predicted on local scales, as environmental changes manifest in varying ways and at varying intensities across multiple spatial and temporal gradients (Thompson et al. 2002, Helmuth et al. 2006). Adding over-extraction to unpredictable effects of climate change and ocean acidification further destabilizes fisheries. Human behavior is more easily controlled than climate change, so solutions to overfishing generally come in the form of modifying fishery management (Hilborn 2007). However, to pursue actualized sustainability of productive fisheries with benefit to both healthy ecosystems and productive fishery markets, existing management of fisheries must be reformed (Costello et al. 2016).

One way to combat the effects of overfishing is to simply close a fishery once overharvest impacts are observed. The logic behind this strategy is simply the expectation that removal of the initial problem (overly intensive fishing) will allow populations to recover. In some cases, this can work to re-establish populations. However, once a target species' populations have recovered to a certain extent, it is common to re-open the fishery without much revision of policy, and the effects of overfishing may return with repeated or even increased speed and intensity. This was seen in the Galápagos, where the sea cucumber fishery was closed multiple times when populations dropped to levels near local extinction, then recovered only partially before fishing was reopened and the cycle repeated (Hearn et al. 2005). Sea cucumber populations in the Galápagos have dropped below the possibility of population recovery, and limpet and lobster populations there are following the same track (Hearn et al.2005, Castrejón & Charles 2013). Additionally, full closure of a fishery completely cuts off a market, which may be a vital socio-economic pillar for human communities dependent on that fishery (Hilborn 2007, Hilborn et al. 2006, 2012, Costello et al. 2016). Especially in developing nations and isolated coastal communities, closure of a fishery that serves as a primary source of income for local people can trigger increased localized unemployment and poverty, social instability, and political unrest in response to policies perceived as unfair, oppressive and autocratic. It can also cause nations to redirect extraction-based industry at other types of ecosystem resources which may not be better suited to sustaining such pressure such as eco-tourism or fossil fuel extraction, patterns seen throughout coastal countries in South America (Castrejón & Charles 2013). Full fishery closure isn't guaranteed to allow populations of target species to recover. In many cases, overfishing effects extend beyond a single species' populations to an ecosystem-wide problem (Castrejón & Charles 2013, Halpern et al. 2010). Successful and sustainable harvest management requires a more systems-based approach to solutions.

An increasingly common approach to solutions for overfishing, therefore, is ecosystem-based management or EBM. Rather than the quick-and-dirty "solution" to overfishing by prohibiting access to a specific species in a specific location as an immediate response to overfishing, EBM is a strategy used to design harvest management policy that utilizes Marine Protected Areas (MPAs) and Marine Reserves (MRs) to incorporate ecosystem-level considerations for recovering or protecting a fishery species, its associated habitat, and other species with which it interacts directly or indirectly (Hilborn et al. 2004, Halpern et al. 2010). The Pacific coast of the United States is one of the earliest and most successful examples of the positive environmental effectiveness of EBM strategies, including the California Marine Life Protection Act Initiative and the Oregon Marine

Reserve Program (Young & Carr 2015, ODFW 2015). Unfortunately, management policy based on EBM science can potentially be just as exclusive for fishers as full fishery closure strategies. Ecosystem-based management design without consideration of dependent human communities connected to the fishery of concern may still have negative socio-economic effects (Hilborn 2006, 2012). However, more recent EBM policy has been incorporating socio-economic concerns into solutions for overfishing effects. MPAs allow for limited access compared to the no-take nature of MRs (Halpern et al. 2010). Both can be spatially oriented and strategically sized to enhance ecosystem restoration without eliminating fishery access to a specific population. Halpern et al. (2010) show that these ecosystem-based approaches can actually improve the monetary stability of a fishery-based economy in the long run. The spillover effect is one such example: by protecting species in an ecological context both spatially and temporally, populations of target species can improve dramatically enough that the enhanced population numbers expand beyond the boundaries of a Marine Reserve, benefiting the local fisheries (Goñi et al. 2010). MPAs and MRs can also help generate other markets around ocean resources. Improved ecosystem function in reefs, for example, can provide restored habitat for improved quality of non-extractive eco-tourism activities like recreational snorkeling and diving (Castrejón & Charles 2013). These activities can bring additional economic benefit to local coastal communities.

Unfortunately, even though EBM based design of MPAs and MRs is expanding in integrative approaches and has recognizable socio-economic benefits, compliance by fisher and fisher communities can be difficult to attain (Hilborn 2012). Effectiveness of policies also relies on effective enforcement and maintenance. When designed and implemented exclusively by government based agencies, resource management policy risks non-compliance by the communities they affect (Hilborn 2007, Shindler & Gordon 2005). A lack of communication and collaboration between agencies, scientists, fishers, and the general public fosters distrust, misinformation, unintended socio-economic consequences, public acceptance of policy, reduced efficiency and effectiveness, and resistance to enforcement of policy (Shindler & Gordon 2005, Feldman & Khademian 2007). Intentionally cooperative networks of stakeholders in the management design process can help overcome these potential issues. According to Borja et al. (2006), community-based fisheries rely on several key factors including consensus on management goals, compatibility with public interest, respect, organized and active participation, full representation of stakeholders, clear boundaries and constraints, resource dependency of the community, shared enforcement responsibility, and recognized shared interests. Territorial user rights for fishing (TURFs) are one structural design meant to incorporate these elements into a multi-stakeholder, community-based approach to fisheries management, with varying levels of success (Molares & Freire 2003). With so many aspects to successful cooperation, collaborative and community-based fisheries potentially face multiple barriers to successful cooperation and implementation. Shindler and Gordon (2005) and Feldman and Khademian (2007) outlined several strategies for successfully overcoming these barriers, namely through intentional outreach and inclusion of the public in decision making processes and careful and open communication and shared participation to improve trust and transparency. For small scale fisheries, these goals can be obtained by pursuing shared costs and benefits of management and conservation efforts by all stakeholders, improved education of local communities in ecosystem and conservation science concepts, conflict resolution strategies, equity in negotiations and decision making between fishers, agencies, scientists, and other marine resource users, and personal commitment by all individuals within these groups (Molares & Freire 2003, Hilborn et al. 2007). Collaborative resource management with improved ecosystem function and fully sustainable and efficient, high-quality resource production utilizing these techniques and strategies has been successful in initial examples, both in terrestrial and marine systems (Feldnman & Khademian 2007, Costello et al. 2016). Most of the time, this simply comes down to organization and skilled communication between and within stakeholder groups.

Sustainable fisheries are not impossible to develop and maintain. Indeed, marine resources for food are potentially the only solution to feeding a global population growing this quickly. For example, the edible protein energy return of investment in North Atlantic fisheries is estimated at 29% compared to the 1.9% of beef (Hilborn 2012). The freshwater use, nutrient input, and carbon footprint of land-based animal protein production are orders of magnitude higher than those of sustainable fisheries (Costello et al. 2016). However, we cannot add pressure to current fishing efforts for the sake of global sustainability while overfishing and ineffective fishery management dominates the fishery industry. Pressure to expand harvest from coastal ecosystems is increasing and threatens to perpetuate overfishing patterns of the past (Thompson et al. 2002). A reframing of fishery management strategies worldwide must first shift towards collaborative frameworks, integration of environmental science and socio-economics, and sustainability – oriented goals following developing bioeconomic theory (Costello et al. 2016). We can start by making sure all new, expanding, or shifting fisheries move towards these goals, using lessons of overfishing and collaborative management strategies of the past.

Case study: Gooseneck Barnacles

Percebes: Pollicipes as an Iberian lesson for the Americas

In the Iberian Peninsula, gooseneck barnacles are considered a culinary delicacy. Their muscular peduncle is of particular interest, traditionally consumed after flash-boiling freshly collected goosenecks in seawater (Borja et al. 2006). They are known locally as "percebes" and have been a popular seafood throughout Spanish and Portuguese history, and the barnacles are deeply ingrained into Iberian food culture. Indeed, they have been a part of coastal life for thousands of years - evidence exists of collection of *Pollicipes* by the Mesolithic and Neolithic peoples of southwest Europe, dating back to 8000 BC in some cases (Alvarez Fernandez 2009, Dean 2010). Harvest of percebes is an economically important component of Spanish and Portuguese coastal communities (Bald et al. 2006, Alvarez Fernandez, 2009). Gooseneck barnacles fetch a high price as seafood, especially in the Spanish market. Dean (2010) reports the seafood as sold for €60 - €80 per kg depending on the season, and I personally observed percebes sold in a Barcelona market in December 2015 for €88 per kg.

Due to their economic return to fishing communities, the profession of "percebeiro" (the Spanish name for a gooseneck barnacle fisher) is not uncommon, despite its risks (Alvarez Fernandez, 2009). Fishing for goosenecks is particularly dangerous, especially on the coast of northern Spain, where remaining populations of percebes only exist on isolated and extremely wave-beaten offshore rocks (Bald et al. 2006About 400 tons of goosenecks are reported as harvested annually, though the real amount is likely far higher due to poaching, compromising the effectiveness of existing management (Sestelo and Roca-Pardiñas, 2011).The high market value of *percebes* and the community tradition of *percebes* fishing means that, in small coastal communities where recent economic stress in Europe and particularly the Iberian peninsula had an especially negative effect, some have turned to fishing *percebes* illegally as a means of personal income (Templar & Hugh-Junes 2011). Percebeiros are equipped with wetsuits, ropes, harnesses and clamps resembling rock climbing gear, and mesh nets and metal tools like flat spades to scrape off and collect patches of barnacles in the midst of the waves (Dean 2010, Templar & Hugh-Junes 2011). Those with a permit within the existing management system are so well equipped. Poachers, however tend to be limited in equipment and experience, and as a result, about five deaths are reported annually due to the high risk nature of this fishing practice (Templar & Hugh-Junes 2011). Economic strain competing with strict management and harvest policies combined with these deaths feeds socio-economic tensions in coastal communities.

A long history of food culture, a high modern day market value, increasing human populations, and long term intensive fishing practices drove overharvest and had detrimental effects on *Pollicipes* populations in Spain and Portugal (Bernard 1988, Cardoso & Yule 1995, Cruz 2000, Molares & Freire 2003, Bald et al. 2006).Strict management policies to try to recover populations followed. Extant demand in the Spanish market led to the importation of *Pollicipes* spp. from France, Morocco, Portugal, and, more recently, British Columbia, Canada where it was already harvested on a much smaller, localized scale, mostly by indigenous coastal communities (Sestelo and Roca-Pardiñas 2011).

In 1970, *Pollicipes* populations had dipped low enough that import from France began to supplement localized Spanish harvests (Molares&Freire 2003, Bald et al. 2006). By 1984, their harvest in Galicia, Spain, was officially restricted by the Spanish government using a full-fishery closure for five months (Goldberg, 1984). In the Gaztelugatxe coastal area, a moratorium-styled fishing management design followed the 1998 establishment of a marine reserve in the Basque Country of Northern Spain (Bald et al. 2006). The temporal and spatial design of following management strategies in the region were successful at helping slow recovery of the barnacle population, but were focused entirely on specific life history patterns of goosenecks and caused complex socio-economic consequences in nearby percibeiro communities (Bald et al. 2006). Other strategies attempting gooseneck population recovery without complete closure of the fishery were more successful in the socio-economic realm. In 1992, co-management using TURFS began in NW Spain, where shared responsibility between fishery authorities and regionally supervised fisher guilds called "cofradías de Pescadores" (Molares & Freire 2003). TURFS opened opportunities for innovative development of collaborative management between fishers and their local communities, localized and regional organizations, and regional and national government authorities (Molares & Freire 2003). Only licensed fishers within the cofradías have legal access to percebes, however, the cofradías are granted localized authority for enforcement of management policy and exploitation strategies are revised annually within government policy. Cofradías are granted ability to commercialize their harvest, but are expected to collaborate with the government to partake in strict enforcement of local and national policies to prevent illegal fishing (Molares & Freire 2003). Molares and Freire (2003) report that the improved success of cofradías has been demonstrated when more extensive community involvement, combined with increased government collaboration to offer resources for socio-economic assessment of exploitation plans and scientific stock assessments, as well as technical support and innovation for improved enforcement, harvest reports, and communication between cofradías and government agencies. Success is measured by the maintenance of a productive localized fishery, with improved and recovering populations after past overexploitation.

Some of the cofradía – government collaborative efforts of NW Spain have developed the most successful management strategies in the Iberian peninsula thus far. Challenges have included limited quality data for stock assessments on a regional level, which has been filled in utilizing localized recording of catch, effort, and size frequency distributions of catch by cofradías. Where cofradías lack the expertise necessary for analyzing this data in order to effectively inform harvest management design, Galician government-based professionals and the development a multiple-cofradía network using data-sharing and GIS software have helped turn that data into more integrative and sustainable exploitation strategies supported through consensus and compliance both locally and regionally (Molares & Freire 2003). Other successful management strategies of gooseneck fisheries which have allowed for economic market stability and recovery of *P. pollicipes* populations in Asturias, Spain, have also focused on cooperative action and highlighted using adaptive resource management strategies (Rivera et al. 2016). Commitment to collaboration, sharing of costs and benefits, cooperative data assessment and management planning, intentional conflict resolution strategies and efforts for equitable and transparent communication, organization, and negotiation not only add trust and efficiency to the cooperative framework but improve social, economic, and ecological success of gooseneck fishery management in Galicia and Asturias, Spain.

Oregon Pollicipes: an opportunity to break the cycle

To meet extant market demands in Spain, gooseneck harvest in British Columbia, Canada, and more recently some parts of coastal Washington, USA, has expanded for exportation (Sestelo & Roca-Pardiñas 2011).*Pollicipes polymerus* (Sowerby 1833) has historically been harvested in small, localized amounts in BC and parts of Washington by indigenous communities (Pacific Rocky Intertidal Monitoring 2014). Harvest for export has expanded there since the overexploitation of Spanish and Portuguese populations created extant market demands for importing goosenecks (Sestelo & Roca-Pardiñas 2011). Now, harvest is expanding in the United States for local consumption as well. Goosenecks have started to appear in the menu of American Pacific Northwest coast cuisine, which has experienced a growth in the popularity of locally sourced and culturally unusual food items. The combined international and local demands open cultural and economic niches for intertidal fishing of *P. polymerus*. In British Colombia, the pattern of gooseneck overharvesting has already caused drops in the *P. polymerus* population (Pacific Rocky Intertidal Monitoring 2014). As northern *Pollicipes* populations drop, Iberian percebes demands perpetuate, and the US Pacific Northwest culinary culture of "weird food" expands, harvesting will likely intensify on the Oregon coastline. Without any existing management plan, gooseneck barnacle harvesting and potential overfishing threatens the ecological intertidal community in Oregon.

Interest in developing an Oregon-based gooseneck barnacle fishery is rapidly expanding. Locally based, small scale fishers in southern Oregon are actively open to communication and collaboration with agencies like Oregon Fish and wildlife, scientists at Oregon State University and the University of Oregon, and members of the public to pursue well-informed and sustainable harvest management policy design as they pursue *Pollicipes polymerus* fishery expansion. To avoid overharvest in Oregon, sustainable harvest management policy must be implemented as the fishery develops rather than as an after-the-fact treatment to a suffering ecosystem following overharvest. The successful collaborative strategies seen in Spain and Portugal can potentially help frame such harvest management strategies, especially in a socio-economic context.

Cooperative sustainable fishery design in Oregon should utilize scientific, economic, and social resources on a local and regionally networked scale, potentially mirroring the successful cofradías in Spain. Collaborative management design for Oregon *Pollicipes* requires scientific knowledge to help inform decisions for successful biological goals surrounding conservation and ecosystem function. The extent of the ecological function of *P. polymerus* has not been fully explored, but *Pollicipes* do play a role as filter feeders in intertidal systems and are a favored food source for seagulls and other shorebirds (Broja et al. 2006). Further information about Oregon goosenecks is extremely data-limited. We currently lack knowledge about the specific dynamics of their population structure or about variability of their life history patterns. Due to their fragmented distributions and seasonally constrained life history processes, *Pollicipes* spp. are potentially highly susceptible to overfishing should harvest in Oregon expand. However, data and literature describing Oregon *Pollicipes polymerus* populations specifically are lacking, creating a knowledge gap in the steps towards ecosystem based collaborative management of sustainable gooseneck fishing. To fill this gap, it is vital that scientific investigation be a key part in pursuit of collaborative harvest management.

Collaboration should also come from some level of government funding and support and agency involvement to help financially support, design, implement, and enforce management decision in coordination with members of the public. Social support for this process must exist for any level of effectiveness. The joint efforts and involvement of stakeholder and local communities is vital. Agencies must pursue inclusivity in their actions and foster compliance, support, and even shared management and enforcement responsibilities from local fisher communities. Fortunately, the Oregon coastline has a well-established and relatively novel system of MPAs and MRs established over the last ten years through an EBM approach which actively engaged members of the public, fisher communities, scientists, government agencies and NGOs (ODFW 2013, 2016, Oregon Ocean Information). A culture of collaboration in the design, implementation, and maintenance of sustainable marine resource management already exists in Oregon. This makes an interdisciplinary and integrative approach to sustainable design of a new fishery more feasible by having pre-established levels of trust and relatively open communication between stakeholder groups (Oregon Ocean Information). Consensus and inclusivity of the general public can be utilized as well, given that the intertidal communities in which goosenecks live are of interest beyond commercial harvest. Tidepoolers, beachgoers, and private fishers are just a few public member groups tied to the marine resources of the rocky intertidal apart from commercial fishers (ODFW 2013, 2015). Agencies and state government recognize this and have supported funding for past management efforts. Furthermore, marine management agencies and research groups have had at least some experience collaborating with stakeholders and the general public in past and ongoing marine resource management spatial planning, implementation, and monitoring (Oregon Ocean Information). Consensus and compliance in Oregon marine resource management is somewhat less novel and faces fewer barriers than some other natural resources. The supportive socio-economic and interested scientific structure already exists in Oregon to include goosenecks into a cooperative, multi-stakeholder plan for sustainable harvest management. Facilitated communication between stakeholders, scientists, policymakers, agencies, and the public can be used in Oregon to establish a sustainable management design for the fishing of goosenecks *before* uncontrolled fishery expansion potentially damages the *P. polymerus* populations.

In Oregon, goosenecks are currently minimally harvested. The only official regulations restrict harvest to collection on manmade structures under the consideration of goosenecks as “other” shellfish (ODFW 2015). There is high risk for Oregon *Pollicipes* fishery expansion to cause overfishing and a subsequent struggle to recover populations through trial-and-error approaches to harvest management solutions. However, the particular location, stakeholder interest, and underdeveloped fishery context of Oregon *P. polymerus* populations provides a unique opportunity to pursue a trial in reformed fishery development. Reflection on lessons learned by the story of *Pollicipes* in the Iberian Peninsula and the extensive knowledge available on global overfishing effects can help prevent the gooseneck overharvest cycle from repeating in a new location.

I. SENSITIVE BARNACLES

Quantifying life history processes of Oregon *Pollicipes polymerus* to inform sustainable harvest management design

Figure 1: A small patch of *P. pollicipes* at Yachats Beach, settled onto the carapace of *Semibalanus cariosus*. At least two age classes are present: small adults and juveniles.

INTRODUCTION

Pollicipes spp., commonly referred to as gooseneck barnacles, are among many marine species impacted by the effects of overharvesting under insufficient or belated management. Goosenecks are pedunculate cirripedes with populations all over the world. Three specific species are intertidal and harvested by coastal communities (Molares & Freire 2003). The harvest of gooseneck barnacles occurs in the Iberian Peninsula (*Pollicipes pollicipes*), Costa Rica and Peru (*Pollicipes elegans*), as well as the Pacific coast of North America (*Pollicipes polymerus*; Bernard 1988, Pinilla 1996, Lauzier1999, Ramirez et al. 2008). Rural fisher communities in coastal Spain and Portugal are historically dependent on harvesting and selling *Pollicipes pollicipes* (Gmelin, 1789), locally known as percebes, to meet Iberian market demands for the cultural culinary delicacy (Borja et al. 2006, Templar & Hugh-Junes 2011, Rivera et al. 2016). Strong cultural and economic ties between coastal human social and economic systems and the local intertidal ecological community resulted in the overexploitation and subsequent ecological collapse of *P. pollicipes* populations. Socio-economic ramifications were also severely negative (Templar & Hugh-Junes 2011, Rivera et al. 2016). Collaborative, multi-stakeholder, and ecosystem-based management of Spanish and Portuguese percebes fisheries have proven successful at recovering decimated populations to some extent. Strict management has perpetuated socio-economic strains in coastal communities that traditionally harvested the barnacles in high numbers. The Iberian percebes market demand is still high and requires higher harvest efforts than careful and strict management of a limited and recovering *Pollicipes* population can allow. To meet extant market demands in Spain, gooseneck harvest in British Columbia, Canada and more recently some parts of coastal Washington, United States has expanded (Sestelo & Roca-Pardiñas 2011). *Pollicipes polymerus* (Sowerby 1833; Fig. 1) is harvested for export and has started to increase for local consumption, attracting the interest of fishers in other parts of the northwestern United States. In central and southern Oregon, there is currently stakeholder interest in developing a gooseneck fishery. Presently, little to no intertidal harvesting management exists in the Northeastern Pacific for species other than bivalve shellfish. Data and published research on *P. polymerus* is extremely limited

Despite an extensive history of scientific investigations and literature on the Oregon rocky intertidal ecosystems, little literature exists describing Oregon *Pollicipes polymerus* populations specifically. This knowledge gap is a barrier in the steps towards ecosystem based collaborative management of sustainable gooseneck fishing. Due to their limited abundances and seasonally constrained life history processes, *Pollicipes spp.* are potentially highly susceptible to overfishing should harvest in Oregon expand. To avoid overharvest in Oregon, sustainable harvest management policy must be implemented as the fishery develops rather than as an after-the-fact treatment to a suffering ecosystem following overharvest. The successful collaborative strategies seen in Spain and Portugal can potentially help frame such harvest management strategies, especially in a socio-economic context. To scientifically inform such efforts, the life history and the structure and dynamics of Oregon *P. polymerus* populations must be well understood.

P. pollicipes, *P. elegans*, and *P. polymerus* are morphologically similar, with calcified plates on a capitulum protecting the head, body, cirri, and male gonads, atop a strong and fleshy stalk called a peduncle, which contains the ovary and is covered by a leathery casing with calcified scales (Barnes, 1996). *Pollicipes* spp. are known to prefer rocky benches of steep declination and extreme exposure to high wave impact (Barnes & Reese 1960, Molares & Freire 2003). They typically form patchy aggregations, called hummocks, below the lower edge of mussel beds. They extend into the mussel beds in smaller, patchier distributions. Their localized distribution seems to be determined by a combination of factors including nutritional availability, wave impact, space competition, and available recruitment habitat (Lewis 1975, Lewis & Chia 1981).

Pollicipes ssp. are hermaphroditic, but exclusively reproduce sexually and so rely on proximity of other goosenecks for successful reproduction. They can be reproductively active year-round. Egg development and brooding within the peduncle follows fertilization and can take several months before larvae are released (Bald et al. 2006). Larvae are pelagic for several weeks before returning to shore, where successful recruitment and settlement appears to be highly dependent on available habitat. Goosenecks are gregarious, and recruit most successfully to the peduncles of other goosenecks (Bald et al. 2000, 2006; Molares & Freire 2003, Borja et al. 2006). Subpopulations of *Pollicipes spp.* are connected through a shared offshore larval pool, creating a metapopulation structure lacking clear stock-recruitment relationships and necessitating assessment of multiple local populations when pursuing spatially-explicit resource management of goosenecks (Freire & García-Allut 2000, Molares & Freire 2003).

All three species of *Pollicipes* have consistent general life histories, though the specific population dynamics may vary significantly between species and their geographic location. Latitudinal location of ecosystems and associated oceanic regimes on regional and local scales determine both species composition of ecosystems and species-specific population dynamics (Schoch et al. 2006). In multiple studies, larval advection and recruitment patterns of *Pollicipes spp.* and other cirriped species have been linked to geographically determined oceanographic patterns, especially to high intensity and high frequency upwelling regimes and to high levels of primary productivity (Lewis & Chia 1981, Lagoset al. 2008, Menge et al. 2015). Reproductive output, growth rate, and the maximum size of adults in subpopulations is likely influenced by food availability, at least partially determined by regional oceanographic regimes and productivity levels (Lewis & Chia 1981). Interestingly, investigations have also shown site-specific conditions such as the physical and morphological dynamics of the surf zone and shore shape are strong drivers of settlement and recruitment patterns of intertidal species, and that perhaps oceanographic regimes play a minimally important role in these processes (Shanks & Shearman 2009, Shanks et al.2010). Both regional and site specific conditions therefore potentially influence spatial variations of multiple life history dynamics characterizing *Pollicipes* populations in Oregon.

On the Iberian Peninsula, *P. pollicipes* exhibits temporal and spatial variation in life history processes, correlated primarily with regional conditions (Boukaici et al. 2012). Iberian *P. pollicipes* recruitment is generally most intense in late autumn, following peaks in growth rate and reproductive activity in late spring (Cruz 1992, Cruz et al. 2010, Sestelo & Roca-Pardiñas 2011). Spanish and Portuguese populations of goosenecks utilize a habitat niche too extreme in wave action for large algas in the low zone. In the mid zone of areas with substantial wave action, they are limited by space competition with mussel beds of *Mytilus* spp. (Barnes & Reese 1960). Pacific gooseneck barnacles, *Pollicipes polymerus*, are an abundant species in the low and middle zones of the rocky intertidal of the Eastern Pacific coastline (Barnes & Reese 1960, Lewis 1975, Cimberg 1981, Lewis & Chia 1981). Goosenecks are broadly distributed from northern British Columbia to Baja, California, and exhibit patchy aggregate distribution on rocky cliffs and slopes (Barnes & Reese 1960, Hoffman, 1988). On the Oregon coast, *P. polymerus* grows in a limited and highly specific habitat of the rocky intertidal. The habitat range and general distribution of *P. polymerus* populations in Oregon appears to mirror those of the Atlantic species. In Oregon, they have also been observed settling on to *Semibalanus* spp., *Mytilus* ssp. and some coralline and turfy algae, though they rarely survive into adulthood to establish patches when settled onto other species (Barnes & Reese 1960, Lewis & Chia 1981). Like other intertidal barnacles in Oregon, Pacific goosenecks appear to peak in successful recruitment in the fall and early winter (Menge 2000 & unpublished data), suggesting that settlement is seasonal. Other reports claim settlement of ciprids to be a relatively continuous year-round process, where apparent recruitment peaks are effects of post-settlement mortality rather than seasonal distributions and larval delivery to shore (Lewis 1975, Shanks 2009). Localized distributions of *P. polymerus* appear to vary both temporally and spatially, as do seasonal patterns of reproduction (Cimberg 1981). However, far more is known about the variability of population dynamics and life history processes of the Atlantic *P. pollicipes*. I expect dynamic spatial and temporal variability of life history patterns exist in the Pacific species, correlated to offshore patterns of nutrient availability.

An assessment of the life history processes, population structure, and community dynamics of *P. polymerus* on the Oregon coast is a necessary first step to informing a successful preemptive management plan. I have therefore studied *P. polymerus* life history patterns and population dynamics including abundances, the distribution of sizes of individuals, and population-wide frequencies of reproduction on the Oregon coast from May 2015 until April 2016. I have aimed to address temporal and spatial variations among populations due to fluctuations of seasonal environmental factors and regional variation in oceanographic productivity-regimes through regular intervals of seasonal surveys at multiple locations. I hope to gather knowledge vital informing future cooperative management schemes for sustainable harvest in the United States. Specifically, I aim to answer the following questions:

1. How do *Pollicipes* life history processes vary over time and space?
    - A. Are spatial variations regional or site-specific?
    - B. Do regional and seasonal variations match known near shore oceanographic patterns of primary productivity?
    - C. Are variations consistent across low and middle tidal zones?
2. What is the recovery time of *P. polymerus* abundances after harvesting?

Bald et al (2006) developed a system dynamic model (Fig. 2) for *P. pollicipes* which considers the effect of reproductive output, recruitment, and growth rate on the population dynamics of this species. I have used that model to identify the stages of *P. polymerus* life history potentially influenced by environmental conditions. These factors include level of larval output of reproduction, larval retention, recruitment levels, and post-recruitment survival and growth (Lewis & Chia 1981, Bald et al. 2006). Figure 2 describes these measures as the stages of spawning, settlement, and maturation, and shows how these processes create a positive loop building the overall adult population of *P. polymerus*. Figure 3 (Bald et al. 2006) demonstrates how these processes are affected by exploitation in the form of gooseneck harvest. Previous laboratory studies show that the formation and persistence of *P. polymerus* aggregations depend on larval recruitment rates to the pedunculate stalks of adult, and that water temperature and availability of food are driving factors in reproductive activity, brooding, and larval survival (Cimberg 1981, Lewis & Chia 1981, Hoffman 1988).Other barnacle species on the Pacific coast have also been shown to have regional, cape - specific life history patterns directly correlated to upwelling and phytoplankton abundances in nearshore waters (Broitman et al. 2008, Menge 2000). For my investigation, I specifically focused on populations in Cape Foulweather and Cape Perpetua, two highly productive but oceanographically distinct regions of the central Oregon coastline known to have substantial populations of gooseneck barnacles.

Cape Perpetua (44.28° N, 124.11° W) is characterized by a wider continental shelf and more frequent high-intensity upwelling events than Cape Foulweather (44.7723° N, 124.0760° W), and has been shown to have higher primary productivity correlated to these patterns (Menge et al. 2015). Leslie et al. (2005) correlated these types of oceanographic conditions to high abundance, increased growth, and high levels of reproductive activity in populations of *Balanus glandula* and other cirripeds. Frequent and intense upwelling at Cape Perpetua relative to Cape Foulweather brings a frequent cycling of nutrients and cold water to nearshore waters (Menge et al. 2015). Nutrient cycling promotes primary productivity and increases food availability in nearshore waters of Cape Perpetua. Nearshore productivity, food availability, and cool waters have all been shown to improve larval survival, survival of recruits and juveniles, maturation and growth rates, and reproductive activity in *P. polymerus* and other Eastern Pacific Cirripeds (Lewis 1975, Cimberg 1981, Lewis & Chia 1981, Hoffman 1988, Leslie et al. 2005). The wide shelf of Cape Perpetua potentially improves larval retention (Menge et al. 2015). Figure 1 demonstrates that positive improvement on larval survival adds to the positive inputs determining potential abundances (Bald et al. 2001).

I hypothesized that the results would show slow, relatively constant overall growth rates of *P. polymerus* and strong seasonal fluctuation in recruitment patterns across all sites, with a decreased ability to recruit and colonize in previously cleared patches. I expect these quantitative responses to vary across oceanographic regimes, with the highest growth and recruitment rates in the most productive sites. The null hypothesis states densities of *P. polymerus* will not vary between Cape Perpetua and Cape Foulweather. Additionally, the null assumes that key life history characteristics including size frequency distributions and proportion of reproductively active individuals do not vary between sites or over time. However, I expect that variations in population dynamics of *P. pollicipes* will correlate to the oceanographic regimes typical of the two capes. More robust, high density populations containing individual *P. polymerus* of larger sizes and higher rates of reproduction should exist along Cape Perpetua, where sites experience regional oceanographic regimes of higher productivity than those at Cape Foulweather. The high nutrient regime present at Cape Perpetua will provide more subsidies for growth and reproduction in the *P. polymerus* population (Leslie et al. 2005), and will result in a higher proportion of fecund individuals, populations with higher densities, and larger individuals.

This study provides insight into how oceanographic conditions such as shelf width and upwelling regimes determining temperature and food availability affect the population densities, size distribution, and reproductive output of *P. polymerus* in the Oregon rocky intertidal. This information is useful for developing an effective management scheme for collection and harvest of gooseneck barnacles along the Oregon coast. By measuring the proportion of fecund adults, comparing the size distributions of individuals, and measuring population densities I will attain three ways to quantify the effect of oceanographic conditions and seasonal variability on the *P. polymerus* populations, important life history traits to consider for management purposes. Results of this survey will help suggest areas for further research in understanding the population structure of *P. polymerus* in Oregon. Additionally, I intend to provide evidence for the need of preemptive fishery management plans for harvesting gooseneck barnacles in the Oregon intertidal by identifying highly sensitive aspects of their life history processes and population structure. Identifying and understanding environmentally sensitive patterns of gooseneck barnacle populations will be useful in understanding highly dynamic intertidal community structure and in developing a sustainable, collaborative management scheme for future harvest. Such management would promote sustainable harvesting in Oregon and ultimately protect *P. polymerus* populations from the overharvest patterns seen elsewhere.

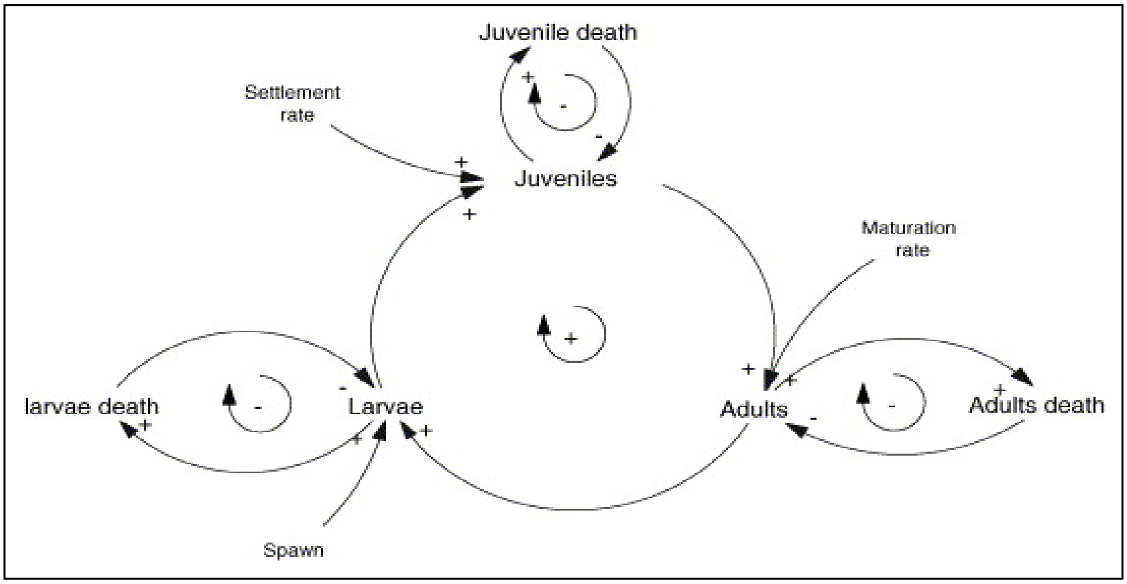

Figure 2: Causal loop diagram model of the life history processes describing population dynamics of *Pollicipes pollicipes* (Bald et al. 2006). My study highlights population dynamics determined by reproductive and maturation processes (positive loops within model) potentially influenced by regional oceanographic patterns. The positive feedback loop results in increased population densities under ideal environmental conditions.

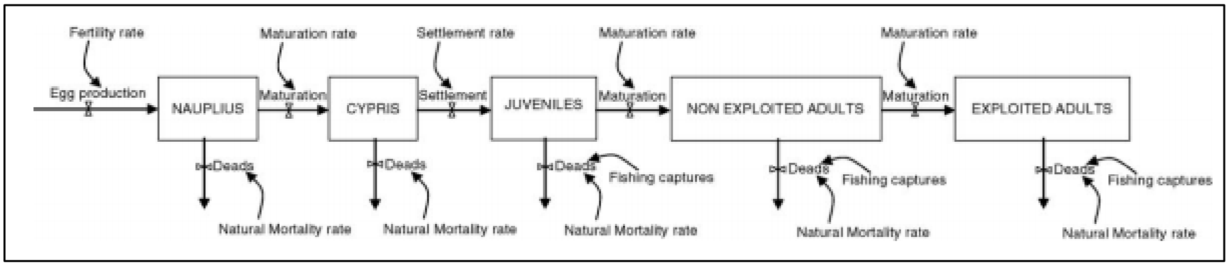

Figure 3: A stock and flow diagram of an aging chain for gooseneck barnacles, from Bald et al. (2006). Each population of a specific age class within the gooseneck population necessarily depends on the rates of input by reproduction, settlement, and maturation proceeding it, as well as mortality rates due to natural causes and fishing pressure. Harvest adds to the mortality of multiple age classes, beyond the adults targeted for exploitation. Of these processes, my survey addresses the existing densities of adults and juveniles, the rate of egg production estimated by frequency of brooding, and the effect of intensive fishing capture on adult abundances.

METHODS

I surveyed *Pollicipes polymerus* populations on the central Oregon coastline, repeating sampling surveys at least monthly from May 2015 to April 2016. Oregon coastal waters are characterized by generally high productivity, a wide continental shelf, and seasonal patterns of strong upwelling (Menge et al. 2015). The oceanographic regimes are fed in part by the characteristics of the extensive California Current System and so reflect regional dynamics of climate and primary productivity (Checkley & Barth 2009). All sites I surveyed were on Cape Perpetua or Cape Foulweather. Cape Perpetua generally has more extreme examples of each oceanographic regime characteristic than Cape Foulweather (Figure 4). I surveyed in the low and lower-mid tidal zones of rocky intertidal habitats, to which distributions of *P. polymerus* are generally limited.

Cape Perpetua sites included Yachats Smelt Sands, Yachats Beach, and Tokatee Klootchman. Yachats Smelt Sands and Yachats Beach are two sites located north of Yachats, Oregon and are less than a kilometer apart. I used Yachats Beach for regional surveys and Yachats Smelt Sands for seasonal surveys, in order to investigate populations at Yachats on a spatial and temporal scale without overlapping transect surveys. Yachats is characterized by extremely high wave energy and waves which break near shore. The intertidal zone at Yachats consists of large rocks that form tall benches parallel to coastline, the faces of which receive direct wave impact. The low zone is a spatially limited narrow strip between the mussel bed and a sandy subtidal, dominated by patches of *P. polymerus* and coralline algae and subject to seasonal sand deposits (Fig 5). The mid tidal zone is characterized by dense and extensive *Mytilus trossulus* mussel beds (Fig. 6). Yachats is known for its dense and diverse invertebrate community with especially large individuals relative to other comparably productive sites in Oregon (Menge et al. 2015). The site is protected from harvest of any species as one of five Oregon Marine Reserves, overseen by Oregon Department of Fish and Wildlife (ODFW 2013). Tokatee Klootchman is dominated by long strips of gravel beach interspersed with rocky benches and tide pools, most of which are relatively flat compared to Yachats. Waves break farther offshore, and the intertidal zone's shallow slope experiences lower wave energy than Yachats. The low zone is dominated by large algae and kelp. Scattered, taller benches lie perpendicularly to shore and incoming waves and host *Pollicipes* hummocks in the low and lower middle intertidal. Tokatee Klootchman is frequently visited by beachgoers interested in tidepooling and is not closed to harvest of shellfish. Cape Foulweather sites included Boiler Bay and Fogarty Creek. Boiler Bay is a relatively protected cove with low wave energy but a wide intertidal zone. *Pollicipes* distribution is limited to three large rocky benches which extend out from the cove into areas of higher wave energy (Fig. 7) and have a steeper slope than the low zones of the rest of the cove, otherwise characterized by surge channels, surfgrass, and other algas and large kelp in low zones. Boiler Bay is a popular location for tidepooling and is open to harvest of shellfish. Fogarty Creek is more comparable to Yachats in physical characteristics, topographically consisting of wide rocky benches. It is dominated by extensive tide pools and surge channels hosting a diverse intertidal community. *Pollicipes* hummocks are large but limited to low zones of seaward facing benches extending out near where waves break with high energy onto the bench. Fogarty creek can only be entered via access to the private land on the landward side of the site, so has limited human impact.

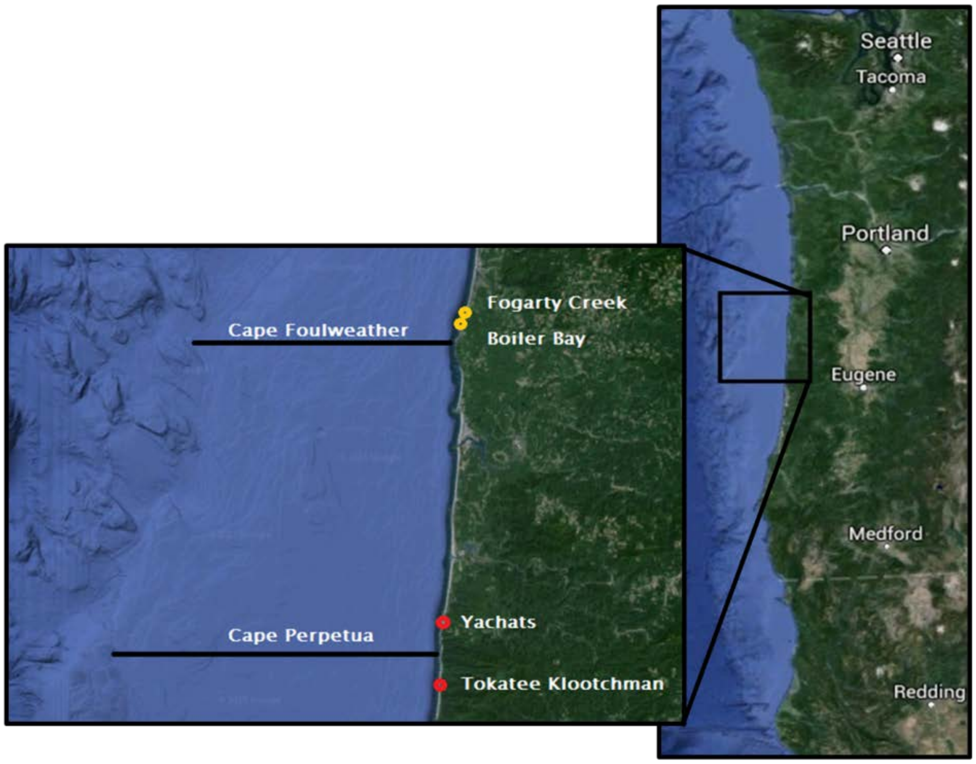

Figure 4: Location of survey sites along the central Oregon coast. In addition to high levels of productivity and frequent upwelling relative to Cape Foulweather, Cape Perpetua sites are also coastal to a wider continental shelf than Cape Foulweater sites (represented by black bars).

Figure 5: A low tidal zone transect and quadrat at Yachats Beach, dominated by patchy hummocks of *P. polymerus* below the mussel zone.

Figure 6: A mid tidal zone transect at Yachats Smelt Sands, dominated with near continuous coverage by mussels, *Mytilus trossulus*, with sparsely distributed barnacles including *Pollicipes*.

Figure 7: A typical low tidal zone rock extending into incoming waves at Boiler Bay, hosting a narrow band of small hummocks of *Pollicipes* between the mussel bed and extensive coverage by coralline algae.

Assessment of Spatial Variation

I surveyed all sites in mid May of 2015, representing the start of the warm season and about one month after seasonal upwelling began. I repeated the survey in mid July of 2015 representing the middle of the warm season and nearing the end of seasonal upwelling patterns. For all surveys, I conducted transect-quadrat sampling (Fig. 5, Fig. 6). I placed three transects of 30m each within the *P. polymerus* habitat low zones of each site, and randomly selected 10 locations along that transect to place $0.25m^2$ quadrats. I took photos of each quadrat which I later analyzed digitally using ImageJ to tally the number of individual *Pollicipes* per patch (Rasband 1997-215). I haphazardly collected about 10 individuals from each quadrat, sampling from patches nearest the corner of the quadrat located at the assigned meter marker on the transect line. This gave 300 samples per site per survey which I later processed in the laboratory. There, I analyzed individuals for evidence of reproductive activity through peduncle dissection and collected individual dry masses. I first scraped the peduncle and carapace of each individual clear of sand, barnacle recruits, algae, and other encrusting species. I then cut open the peduncle to check if individuals were brooding, evident by the presence of an orange egg mass (Fig. 8). I used the presence of egg masses to confirm sexual maturity, and the percentage of sexually mature individuals presenting peduncular egg masses as an estimation of population brooding activity (Lewis & Chia 1981, Cruz & Hawkins 1998, Cruz &Araujo 1999, Cruz 2000, Pavón 2003, Sestelo & Roca-Pardiñas 2011). I then dried each individual in a drying oven at 70°C for at least 48 hours before collecting individual mass. Allometric assessments of *Pollicipes pollicipes* suggest that *Pollicipes* spp. peduncular growth is not necessarily proportional to rostral-scootum length, rostral-scootum length per age varies per site, and neither are consistent predictors of dry mass (Lewis & Chia 1981, Sestelo & Roca-Pardiñas 2011). I used individual dry mass to standardize weight measurements and have a single consistent metric to estimate individual size.

Figure 8: An egg mass (circled in red) within the peduncle of a brooding gooseneck barnacle.

Assessment of Temporal Variation

I sampled populations at Yachats Smelt Sands between May 2015 and April 2016 to assess seasonal variability of *P. polymerus* life history patterns. Surveys were initially bi-weekly. After October 2015, winter weather conditions limited site accessibility, and surveys were monthly until April 2016, excluding December 2015 and March 2016 due to storm conditions which made the site inaccessible during potential low tide survey dates. Again, I used a transect-quadrat survey strategy to collect data. I surveyed *P. polymerus* populations in both the low and middle zones using three ten-meter transects in each zone. I placed five 0.25m^2 quadrats along each transect, located on the seaward side at the 0m, 2.5m, 5m, 7.5m, and 10m markers. I repeated the location of each transect and quadrat rather than randomizing locations in order to ensure that data followed the same subpopulations through potential seasonal variations. I took photos of each quadrat and about 10 samples from each quadrat (if *P. polymerus* were found within the quadrat) for a total of 150 samples per zone per site per survey (up to 300 samples per site per survey). The low zone transects were inaccessible during all surveys from November 2015 to March 2016 due to high wave and surge conditions.

Determining Harvestable Size

Generally, based on conversations with stakeholders, an individual gooseneck barnacle with a peduncle about 4cm in length and 0.5cm in width is sufficiently large enough to be of harvest for food, though larger individuals are preferred. At each site, I collected a small selection of "harvestable" individual gooseneck barnacles from the low zone. I dried these samples using the same methods as all other biomass investigation lab procedures to determine the expected dry biomass of an individual gooseneck of potential interest for fishers. Peduncle length is a more key determinant of harvest interest than carapace dimensions, so I preferentially selected these samples based on peduncle length.

Recovery from Intensive Harvest

I used experimental patches at Yachats Smelt Sands to assess the recovery rate of *Pollicipes* after destructive harvest. As part of a different experiment performed by the OSU Novak laboratory, 18 1.5x1.5m patches in the middle intertidal zone were completely cleared of all encrusting organisms in June of 2013. These clearings simulated localized destructive harvesting. Nine haphazardly-located permanent 0.25x0.35cm quadrats within each patch were photographed at least monthly through April of 2016. A subset of three photos per patch were selected from each survey from June 2013 to November 2015 to analyze digitally to record the abundances of *Pollicipes* and analyze the time it took for populations to recover after harvesting.

Analysis

I used R to analyze all data. I assessed the density of patches as a measurement of abundances using tallies from photocount data from spatial variation surveys. Due to time constraints, photos from temporal surveys could not be analyzed. I assessed individual size distribution, percent brooding individuals, minimum size of reproductive maturity, and average size of reproductive adults from each survey. I used ANOVA and Tukey-Post Hoc assessments of the results to compare data between zones and over time at Yachats Smelt Sands for temporal surveys and to make comparisons between all sites and between Capes for regional surveys.

RESULTS

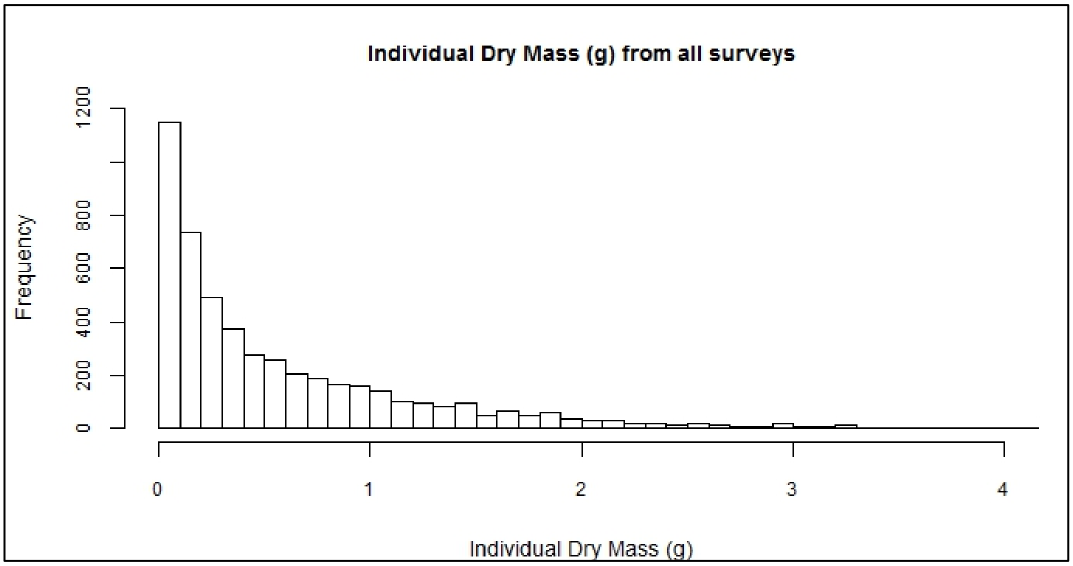

Figure 9: Distribution of individual dry mass (g) of *P. polymerus*; data pooled from all sites and dates of all surveys.

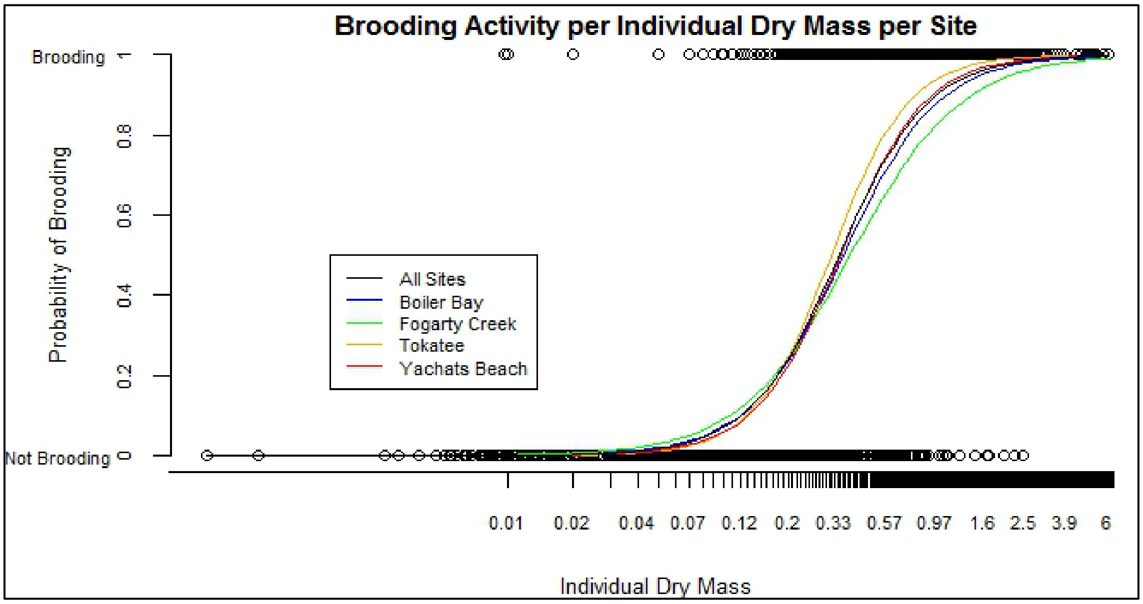

Figure 10: % of brooding *P. polymerus* in May and July per individual dry mass; data is log transformed. Significant site-specific trends of biomass-brooding relationship ($p \leq 0.0002$) are displayed by trendlines.

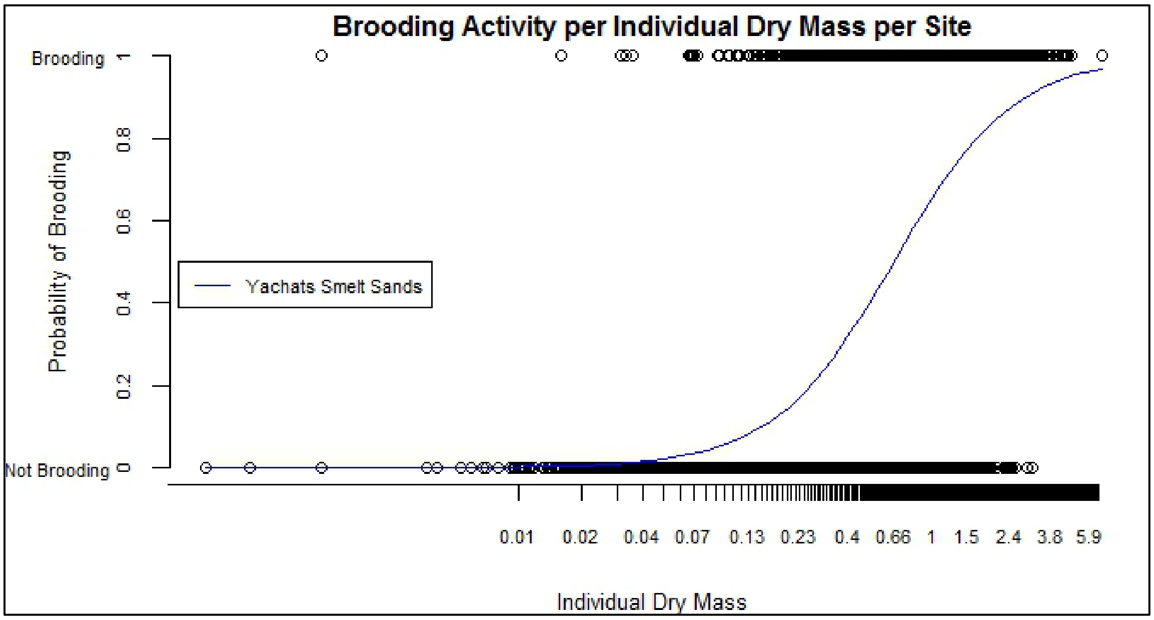

Figure 11: % of brooding *P. polymerus* between May 2015 and April 2016 at Yachats Smelt Sands, per individual dry mass ; data is log transformed. Significant site-specific trends of biomass-brooding relationship (p≤0.0002) are displayed by trendlines.

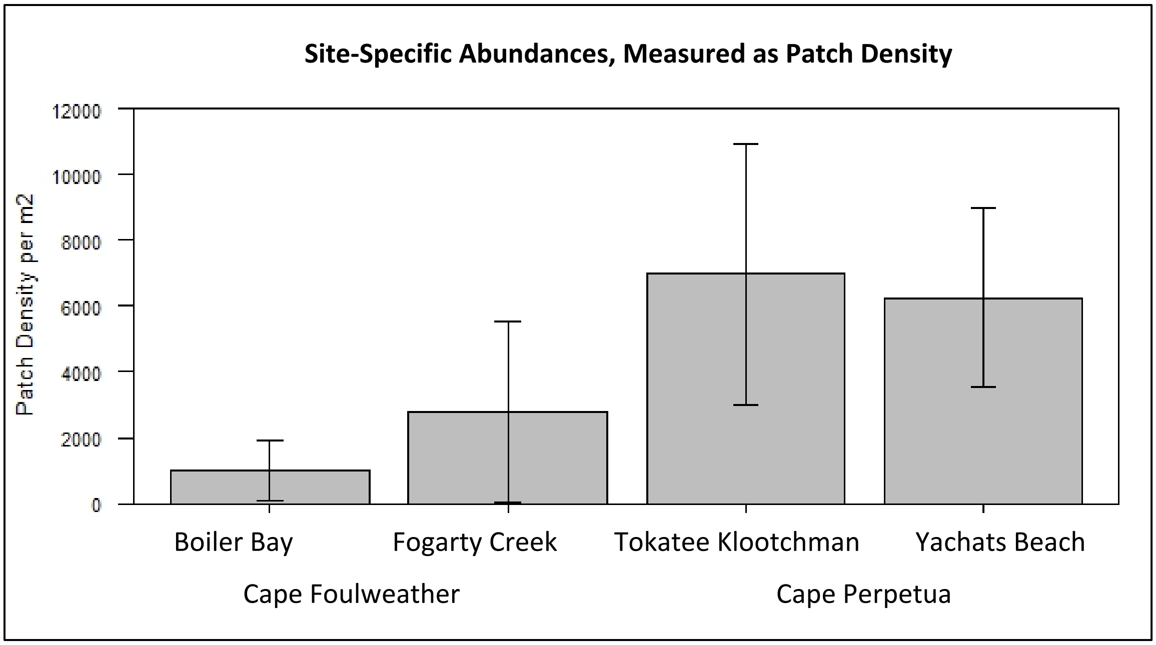

Figure 12:*P. polymerus* abundances of adults and juveniles (excludes recruits) at various sites in May and July 2015. Error bars indicate +/- 1 standard deviation.

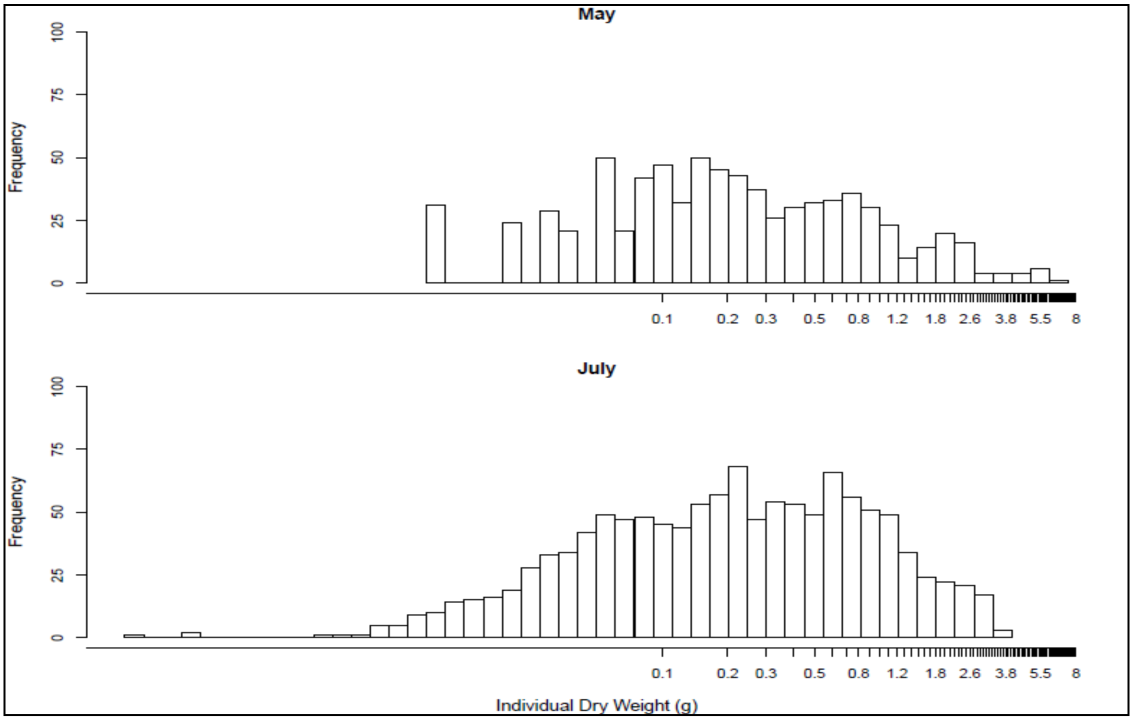

Figure 13: Distribution of individual dry mass (g) of adult *P. polymerus* in May 2015 and July 2015; data pooled from all sites used in regional surveys. Data is log transformed.

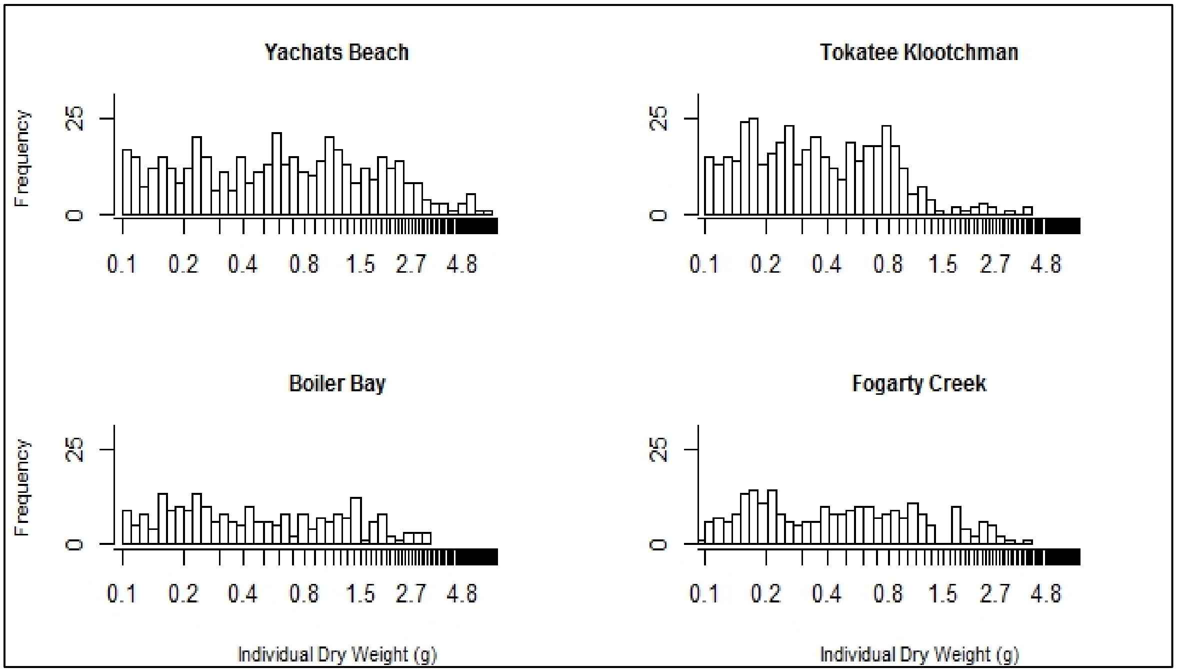

Figure 14: Distribution of individual dry mass (g) of adult *P. polymerus* at each site in May and July 2015. Data is log transformed.

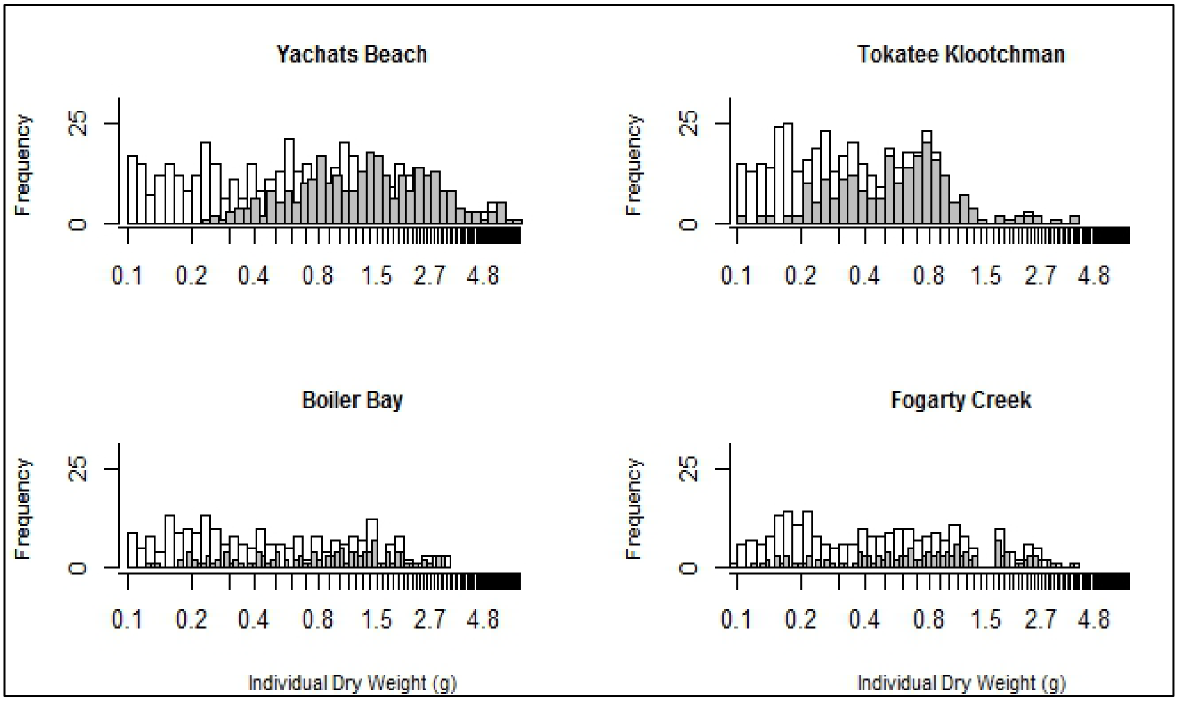

Figure 15: Distributions of individual dry biomass (g) of adult *P. polymerus* at each site, with frequency of brooding individuals per individual dry biomass denoted by grey bars. Data is log transformed.

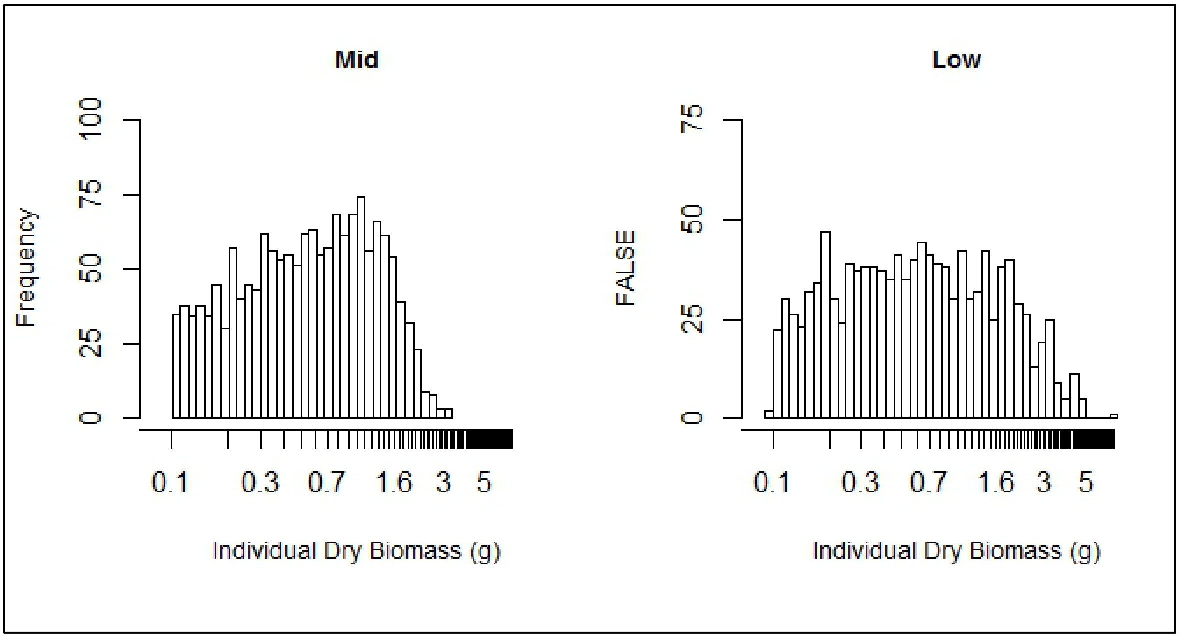

Figure 16: Distributions of individual dry biomass (g) of adult *P. polymerus* in the low zone versus mid zone surveys at Yachats Smelt Sands. Data is log transformed and pooled from all dates of temporal surveys.

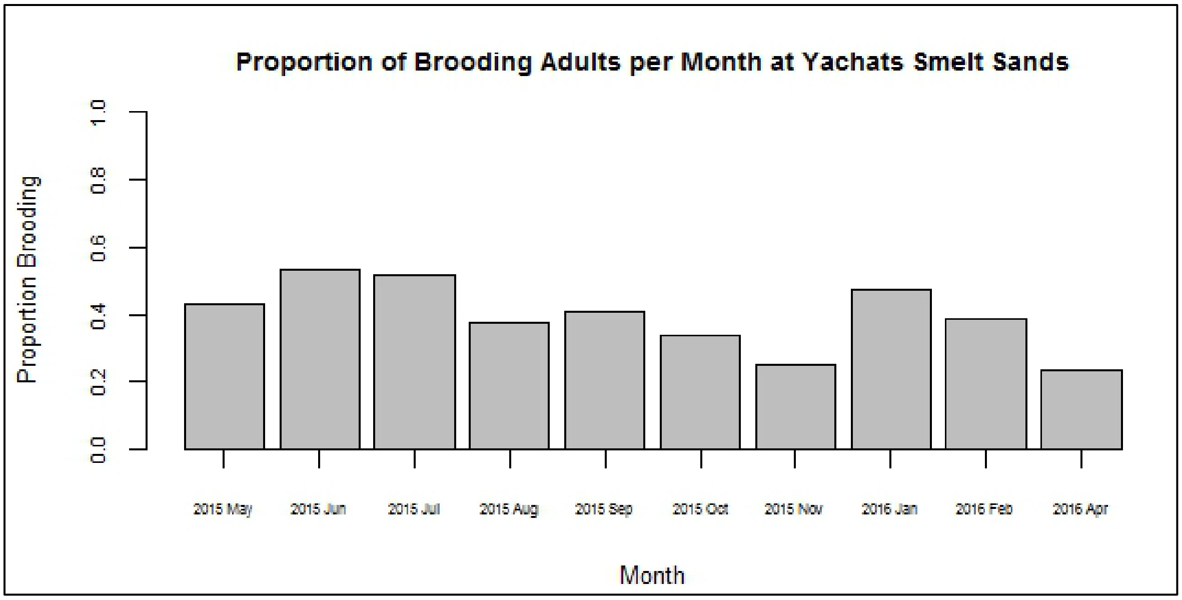

Figure 17: Proportions of adult *P. polymerus* found to be fecund at Yachats Smelt Sands per month. Fecundity was determined by brooding activity: the presence of egg masses within the peduncle of the barnacle. Data is pooled from both zones of temporal surveys.

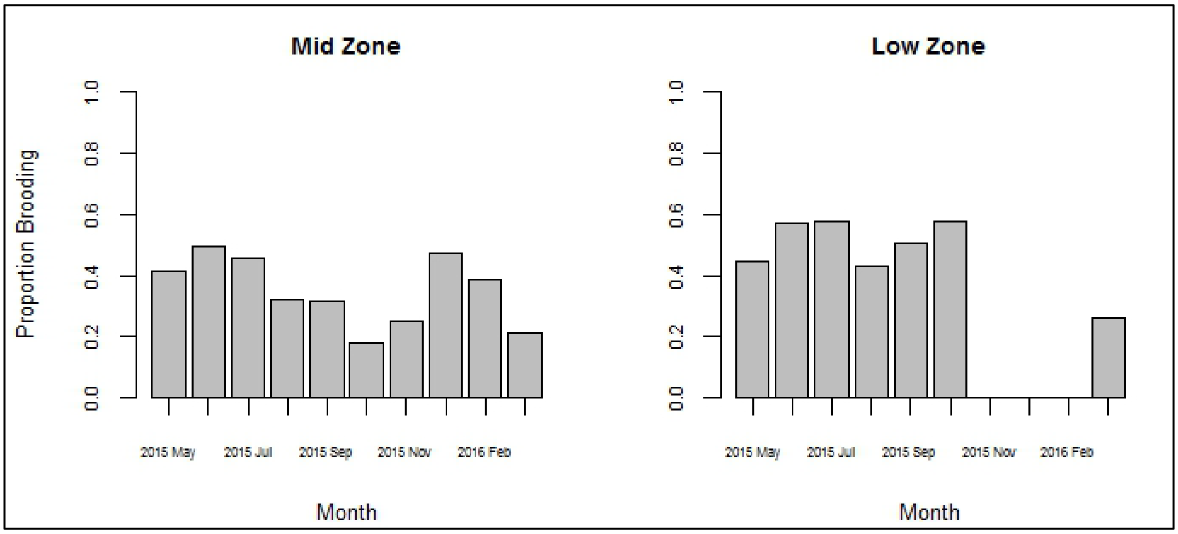

Figure 18: Proportions of adult *P. polymerus* found to be fecund at Yachats Smelt Sands per month in the mid intertidal zone vs. in the low intertidal zone. Fecundity was determined by brooding activity: the presence of egg masses within the peduncle of the barnacle. The low zone transects were inaccessible from November 2015 through February 2016, and the lack of bars on these months reflects a lack of data rather than no existence of brooding individuals. Both zones were inaccessible in December 2015 and March 2016.

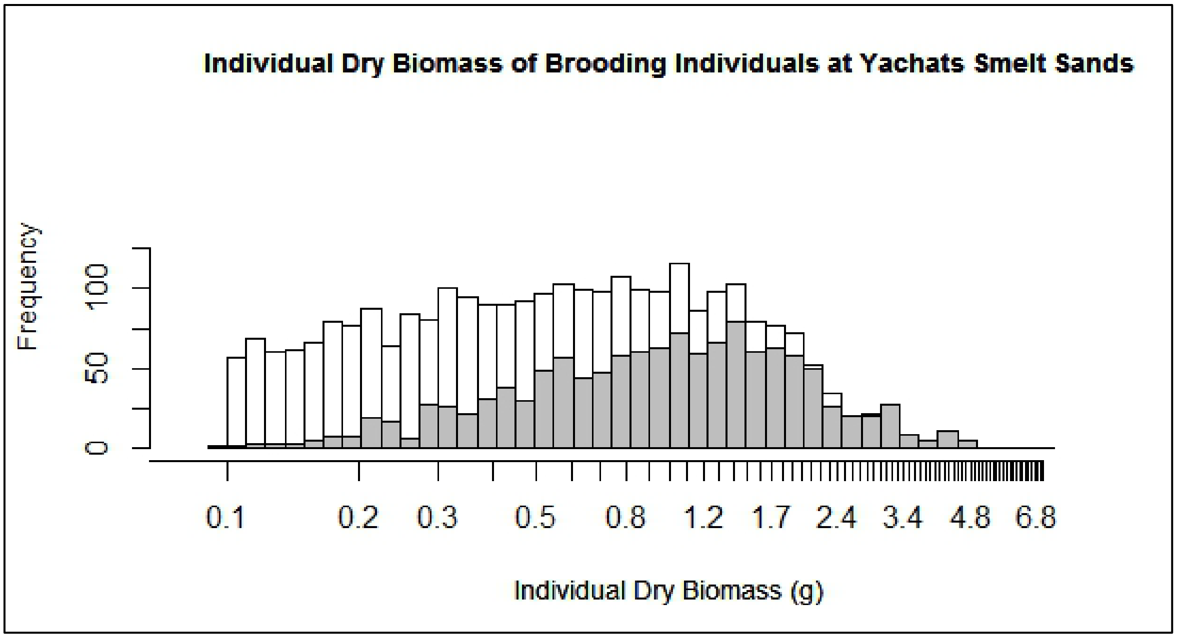

Figure 19: Distributions of individual dry biomass (g) of adult *P. polymerus* at each Yachats Smelt Sands, with frequency of brooding individuals per individual dry biomass denoted by grey bars. Data is log transformed and pooled from both zones and all months surveyed

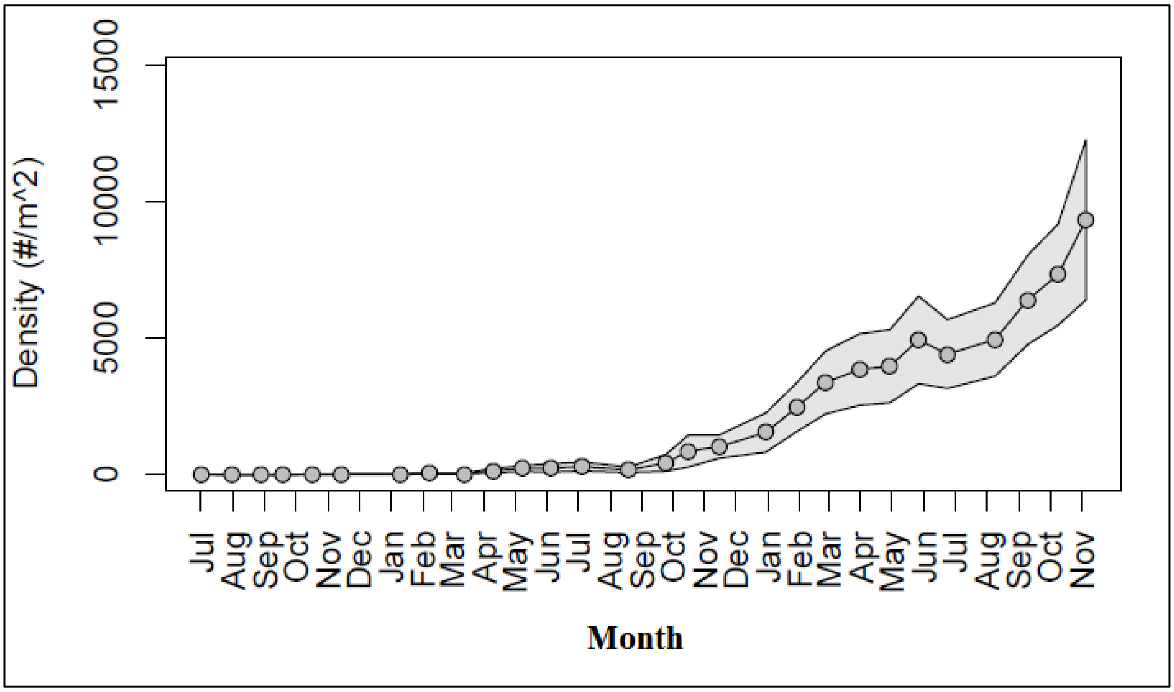

Figure 20: Abundances of *P. polymerus* in experimental patches after simulated complete harvest in June 2013, expressed as density per m^2. Grey area indicates standard deviation.

Table 1: Mean individual adult dry mass (g), patch density (per m^2), and the % of fecund adult individuals at each site in May and July 2015.

Cape	Site	Average Adult Individual Dry Mass (g)	Standard error	Average Patch Density per m^2	Standard error	% Reproductive
CP	YB	0.811	0.744	6243	2726	46.86
	TK	0.489	0.479	6967	3965	38.74
CF	BB	0.700	0.691	999.2	912.1	32.18
	FC	0.680	0.679	2792	2761	33.74

Table 2: ANOVA of individual adult dry mass (g) and patch density (per m^2), at each survey and comparing all spatial and temporal variables. Pr(>F) ≤ 0.05 is considered statistically significant.

	Variables Compared	Df	Response					
			Adult Individual Dry Mass (g)		**Full Population Individual Dry Mass (g)**		**Density (individuals per m^2)**	
			F	**Pr (>F)**	**F**	**Pr (>F)**	**F**	**Pr (>F)**
Regional Surveys	Cape	1	58.79	$1.504e^{-11}$	9.5653	$2.000e^{-3}$	58.79	$1.504e^{-11}$
	Site	3	23.646	$< 2.2e^{-16}$	26.375	$< 2.2e^{-16}$	21.59	$1.064e^{-10}$
	Month	1	0.32442	0.4688	1.623	0.2027	4.02	0.0478
Temporal Surveys at Yachats Smelt Sands	Zone	1	53.957	$2.682e^{-13}$	42.08	$6.558e^{-13}$	NA	NA
	Month	9	5.0361	$9.173e^{-7}$	7.4342	$7.972e\text{-}^{11}$	NA	NA
	Month, Mid Zone	9	3.9814	$4.846e^{-5}$	4.667	$3.842e^{-6}$	NA	NA
	Month, Low Zone	6	6.3133	$1.505e^{-6}$	6.442	$1.029e^{-6}$	NA	NA

Table 3: Tukey assessment of the difference between individual adult dry mass (g) and patch density (per m^2), at each site in May and July 2015. p ≤ 0.05 is considered statistically significant.

Capes Compared	Sites Compared	Adult Dry mass (g)		Density (individuals per m^2)	
		Difference	**p-value**	**Difference**	**p-value**
CF-CF	FC-BB	-0.020	0.9984	1793	0.2366
CP-CF	TK-BB	-0.212	$5.619e^{-3}$	5969	$< 1e^{-9}$
CP-CF	YB-BB	0.233	$1.597e^{-3}$	5244	$2.000\ e^{-7}$
CP-CF	TK-FC	-0.191	0.01265	4176	$3.18e^{-4}$
CP-CF	YB-FC	0.252	$3.391e^{-4}$	3451	$9.104e^{-3}$
CP-CP	YB-TK	0.444	$< 1e^{-9}$	-725.2	0.7860

General Oregon Population

In general, gooseneck barnacle populations were dominated by relatively small individuals. At all sites and during all seasons, distributions of individual dry biomass were heavily skewed. This pattern was mirrored both by the pooled data (Fig. 9), as well as all individual survey dates, sites, and tidal zones. Adults reached up to 7g in dry mass, but the majority of individuals measured less than 0.5 g. Given that few individuals below this size were found to be brooding during any study, it can be assumed that most of these small individuals were juveniles or even relatively recent recruits. I used the five smallest brooding individuals found at each site to determine an exact minimum size at which Oregon goosenecks can be considered adult in size. I found the average minimum dry mass correlated to sexual maturity across all samples to be 0.1g (standard deviation of 0.04g). For analysis of the adult population, all samples recorded to be below 0.1g were therefore removed, as they represent juveniles and recruits in the population.

Even with juveniles removed, biomass distributions were skewed and dominated by smaller individuals, though less extremely so. I therefore completed assessing the data using the $\log_{10}$ of individual dry biomass measurements to better assess any variations between populations that may be otherwise masked by the effect of a dominant small size class.

The dry mass of a "harvestable" individual that meets minimum requirements for fisher interest with a peduncle of at least 5cm in length is, on average, about 1.3g. Limiting most population assessments to the adult size class therefore still incorporates all individuals of targeted harvest interest.

A further exploration of the relationship between biomass and sexual maturity, denoted by brooding, suggests that larger individuals were more likely to be sexually mature, and the frequency of brooding per size increases with size class. Figures 3 and 4 explore the probability of an individual to be fecund based on biomass. In general, individuals above 0.35g were more than 50% likely to be fecund and actively brooding (Fig. 10). Nearly all individuals above 1g in dry mass were fecund. At Yachats Smelt Sands specifically, the general mass-fecundity relationship also holds true, but a substantial proportion of large individuals, even up to 3g, were found to not be brooding and the 50% probability mark fell at about 0.5g (Fig. 11).

Spatial Variations: regional and site comparisons of low (harvest target) zones

Abundances

The two Cape Perpetua sites had significantly higher densities of goosenecks than the two Cape Foulweather sites ($p < 0.0009$, Fig. 12, Table 2). Both TokateeKlootchman and Yachats Beach had patch densities averaging over 6000 per m^2 compared to Fogarty Creek and Boiler Bay's averages of about 2800 per m^2 and 1000 per m^2, respectively. Transect-level standard deviations were large at all sites, ranging from 1000-4000. Variability was highest relative to respective site averages at both Boiler Bay and Forgarty Creek relative to the Cape Perpetua sites (Table 1).

Biomass

Across all sites, populations are dominated by small individuals. July had a much higher frequency of juvenile and recruits (Figure 13). The skewed population distributions generated means of individual dry biomass which did not appear to vary significantly per site (Table 1). However, an ANOVA test showed significant variation between individual adult dry biomass at both the site and cape level of spatial variation (Pr(>F) <0.002, Table 2). Yachats Beach has by far the largest individuals (up to 7g) than any other site ($p < 9e^{-9}$, Table 3) and Tokatee Klootchman generally has smaller individuals than other sites ($p<0.013$, Table 3). Boiler Bay and Tokatee Klootchman had very few individuals above 2g (Fig. 14). May and July surveys did not differ significantly in individual dry biomass. There is no clear difference in distribution patterns between sites. At each site, distributions of adult individual biomass measurements are not fully continuous but rather suggest the existence of at least two size classes (Figure 14).

Brooding

An investigation of the distribution of individual dry biomass measurements of brooding individuals echoed the brooding-biomass relationship found earlier for the general population: larger adult individuals were more likely to be brooding. At all sites, smaller adults were less frequently evidently fecund, and most individuals found to be brooding were larger adults (Fig. 15). It was also shown that the smallest brooding individuals at Yachats Beach were far larger than the smallest brooding individuals at any other site – about 0.2g compared to 0.1g (Fig. 15). All other sites are comparable in percent brooding adult goosenecks (Table 1).

Seasonal Surveys – variation over time in mid and low intertidal zones

Temporal Variation

Abundance

For the purpose of this report, I have summarized seasonal variations of abundances based on observations rather than photo data. Time constraints prevented the complete analysis of the Yachats Smelt Sands photo data, though quadrat photos from each survey are available for future analysis.

In general field observations, I noted a clear difference in population structure between the two zones. Abundances of *P. polymerus* are generally far higher in the low zone than in the mid zone. Patches are larger, denser, and with larger adults in the low zone, and the distribution of gooseneck hummocks is generally less patchy compared to the mid zone barnacle populations. Abundances in the low zone dropped to nearly 0 in some areas after a sand incursion in Fall 2015, which was swept away in early 2016, smothered and then scoured most benthic organisms in the low zone. The mid zone transects did not display any obvious temporal variability.

Biomass

There is no obvious seasonal pattern of mean individual adult biomass at Yachats Smelt Sands. An ANOVA and Tukey analysis shows that biomass does significantly differ per month across the entire Yachats Smelt Sands *P. polymerus* population ($\Pr(>F) = 9.173e^{-7}$, Table 2). Specifically, individuals of September and October 2015 populations in the low zone were generally larger than those of April 2016 ($p<0.007$). In mid zone transects, individuals in May 2015 and February 2016 were larger than in July 2015 and January 2016 individuals ($p<0.013$). When combining the two zones, October and September 2015 were found to be significantly larger than June 2015 individuals as well as January and April 2016 individuals ($p<0.034$), but that all other month comparisons in each zone were functionally identical.

Low zone populations are more evenly distributed along a wider range of adult individual dry biomass. Adults in the low zone reach a larger maximum size than in the mid zone; about 7g versus 4g (Fig. 16). An ANOVA test confirms that biomass of individual barnacles differ significantly between zones ($\Pr(>F)=2.682e^{-13}$, Table 2), and Tukey test confirms that low zone barnacles are larger ($p<0.0001$). Both zones are still dominated by smaller individuals. These patterns persisted throughout the year without evident seasonality.

Brooding

At any given month, the proportion of individuals brooding at Yachats ranged between 0.23 and 0.56 (Fig. 17). Figure 17 shows an apparent temporal pattern of periodic brooding activity. Peaks in brooding occurred in June and July of 2015 and again in January and February 2016. The lowest proportions of brooding individuals were observed in October 2015 and again in April 2015. In the low zone, a peak in brooding was seen in October 2015.

In all months where I was able to complete low zone surveys, the proportions of apparently fecund individuals were higher in the low zone populations than in the mid zone populations. Both zones showed variation over time in proportions of brooding individuals. However, the exact temporal patterns of the low zone for the year I studied can't be completely assessed since the low zone transects were inaccessible from November 2015 through March 2016. Interestingly, the low zone shows a second peak in population brooding activity in October 2015, the lowest month observed in the mid zones (Fig. 18).

The individual size – brooding probability relationship observed at other sites in the summer months was reflected at Yachats Smelt Sands as well. Proportions of brooding individuals increased in larger size classes. A vast majority of individuals above 1.5g in dry mass were found to be brooding regardless of season (Fig. 19).

Post - harvest response and recovery

In all of the experimental patches, it took a minimum of 15 months for recruits to settle successfully and establish significant abundances (Fig. 20). In the late fall of 2014, successful settlement began to increase abundances of recruits and juveniles in the experimental patches. It took another year for recovering *Pollicipes* abundances to reach densities comparable to non-harvested areas (Fig. 20). Densities generally continued to increase through November 2015, however variability between patches also increased as distributions began to be less continuous within patches. The individuals from the first successful round of settlement in 2014 had, by late 2015, grown in carapace size and I noted through general observation that they appeared to be near or larger than the minimum size for sexual maturity I found in the transect-quadrat surveys of undisturbed populations, though this could not be confirmed without sampling for dry mass measurements. As of April 2016, no patch had individuals with peduncles large enough to be of interest for harvest.

DISCUSSION

General Oregon Population

Populations of *P. polymerus* are dominated by recruits, juveniles, and small adults. Most individuals are far below a size suitable for harvest, and most are likely not yet sexually mature. They grow slowly, especially after reaching sexual maturity, as demonstrated by the experimental patches, and described by Lewis & Chia (1981). Large adults are likely multiple years old. Most fecund individuals are large (and likely older) adults. Smaller adults are less likely to be brooding at any given point, suggesting that *P. polymerus* allocate more resources to individual growth and survival, even after reaching sexual maturity, until reaching a large enough size at which point they put more effort into reproductive output. Growth likely slows or even stalls at this point unless sufficient nutrients are available to sustain both individual processes, as described by Barnes & Reese 1960 and Lewis & Chia (1981) in their exploration of growth in *P. pollicipes* and *P. polymerus* populations, respectively.

There is a relatively low proportion of large, apparently fecund adults within populations across the coast relative to the dominance of juveniles and recruits. Settlement rates may be high, generating a dominance of small, young individuals in the population. However, the gregarious nature of patches containing multiple age classes suggests that recruitment is context specific and appears to only be successful after settlement onto other barnacles. Recruitment patterns may not necessarily reflect settlement patterns, as argued by Shanks in the investigation of other cirriped species (2009). Ciprid mortality due to a variety of potential factors likely results in the patchy nature of gooseneck distributions. Post-recruitment mortality and mortality rates at each of the following age or size classes is high enough to drastically reduce the numbers of individuals per age class. This suggests that differential mortality occurs across age classes. Only a small percentage of individuals successfully survive through each stage of settlement, recruitment, growth, and sexual maturation to eventually establish hummocks and grow to a large adult size. Others have found evidence of post-settlement processes of recruitment in other barnacle species along the Oregon coast, such as *Balanus glandula,* correlate to site-specific variables more than to regional oceanographic regimes (Shanks 2009). It is possible that this pattern exists in goosenecks as well.

Distribution of individual biomass of apparently fecund individuals in this study suggests that reproductive output of gooseneck populations potentially relies on a relatively small proportion of the overall population. The size of the larval pool and number of potential future recruits for future generations is limited by the number of large, fecund individuals in a population. These make up a minority of the overall population and are the target for gooseneck fishers due to their size, further adding to overfishing sensitivity and detrimental potential effects to the population if future harvest is not sustainably managed. The average individual dry mass of a gooseneck barnacle that meets minimum standards for harvest interest, 1.3g, falls far above the size found to be a predictor for reaching sexual maturity, 0.1g. At most sites, a majority of individuals of this size were found to be fecund. All individuals targeted for harvest can therefore be expected to be sexually mature and likely brooding. They are also a minority within all populations. They are potentially significant contributors to the larval pool, though quantification of their sexual productivity by spawning should be investigated to confirm.

Spatial Variations: regional and site comparisons of low (harvest target) zones

Regional Patterns: effect of oceanographic regimes

I observed high densities in dense and numerous patches in areas of high oceanographic productivity. I expected the more frequent, higher intensity oceanic upwelling patterns and wider shelf of Cape Perpetua sites to have a generally positive effect on abundances, average individual size of adults, percent of brooding adults, and proportion of recruits in *Pollicipes* populations relative to at Cape Foulweather sites. Oceanographic regimes including upwelling frequency and intensity and general productivity differ between the two capes, and are the likely drivers of regional patterns of invertebrate population dynamics (Menge 2000, Leslie et al. 2005, Menge et al. 2015). The clear difference between densities of gooseneck barnacles at each cape shows that abundances are correlated to regional patterns. The results suggest that the wide continental shelf and nutrient-rich oceanographic regime characteristic to Cape Perpetua has a strong positive influence on densities of individuals of *P. polymerus* in the low, wave-exposed intertidal zone. Variability of densities was high at all sites, reflecting the patchy aggregations typical of *Pollicipes* distributions without correlation to regional processes.

The other population dynamics I studied did not show a clear regional pattern. Statistical analysis suggested that individual dry biomass was not cape-specific. Fecundity, estimated as the proportion of brooding adults, also lacks a cape-specific pattern. This is particularly troubling given that abundances should be a metric which summarizes the net effect on population structure by all other life history processes. To have increased abundances either recruitment, growth, fecundity, survivorship, or some combination of these processes must also be high relative to areas of low abundance (Fig 2). Each component should be positively influenced by intense and frequent upwelling and generally high productivity, which combined provide increased oxygen and food resources to support these life history processes. So then, if there is a cape-specific pattern of abundances correlated to nearshore oceanic regimes, why is there not a cape-specific pattern in the other results?

It is possible that the direct effects of oceanographic patterns simply manifest more strongly on life history processes outside of the scope of this study. Regional productivity levels and upwelling patterns may have a stronger influence on rates of recruitment, settlement, and survivorship than on growth or fecundity (Lewis & Chia 1981). My investigation gives a better summary of general growth and fecundity of the population by studying patterns of individual biomass and brooding activity than it does of recruitment rates. It is also possible that effects of regional oceanographic regimes were masked by stronger effects of site-specific variables. Confounding variables on a local scale likely modify regional patterns of size and fecundity of established populations. Potential locally - scaled variables include species interactions, desiccation risk, wave exposure and impact, and substrate type and slope (Lewis & Chia 1981). I will explore this possibility further below.

Site - specific variation: localized variables

Both biomass and brooding patterns appeared to be site-specific patterns. Despite an ANOVA showing significant cape-level variation, the discrepancy between Yachats Smelt Sands and Tokatee Klootchman in the Tukey analysis showed that these patterns are ultimately determined by local rather than regional conditions. For example, the conditions at Yachats Beach allow adults to continue growing to a maximum size far beyond those at any other site. In fact, growth of individuals in Yachats appears positively influenced for all age groups: when comparing the smallest size of brooding individuals or the general maximum size of juveniles found at each site, Yachats goosenecks are larger as well. They appear to reach a larger size before becoming sexually active compared other sites. The 0.1g parameter set by this study then underestimated the minimum individual dry biomass marking sexual maturity at Yachats. It is doubtful that the individuals at Yachats have a longer duration of juvenile stage than at Tokatee Klootchman since individuals recruit from a regional pelagic pool of larvae. It is more likely that growth rates are enhanced at Yachats specifically.

Evidence of reproductive activity was assessed as a proportion of obviously fecund individuals out of the samples taken from the field, and the results were consistent across all sites except Yachats. No cape-specific pattern was observed, so this survey cannot confirm whether regional oceanographic regimes have affect population levels of fecundity. Yachats was again an anomaly, displaying higher levels of reproductive activity within the population than other sites. Because size was site specific, and larger individuals are more likely to be reproductively active, it makes sense that local patterns of reproductive activity correlated with the site specific pattern of individual biomass. Yachats populations not only had larger individuals, they had more reproductive individuals. Analysis showed a strong correlation between size and fecundity at each site. Yachats is actually recognized along the Oregon coastline as hosting invertebrates with the largest individuals out of coastal populations in general for several species. The cause of this phenomenon is unclear.

Individual weight and population brooding patterns are potentially influenced by oceanic regimes but ultimately determined more directly by site - specific variables. Those variables may include submersion time, desiccation risk, species interactions like predation and competition, available habitat space, nutrient limitations, water temperature, and localized patterns of wave energy (Lewis & Chia 1981). Size and brooding activity of *P. pollicipes* tend to be influenced most by food availability and environmental conditions of temperature, which are a part of regional oceanographic processes (Cimberg 1981, Borja et al. 2006, Leslie et al. 2010). However, while food availability may generally be determined by regional productivity, it is locally defined by wave impact. Intertidal zones of high wave impact have more food from the nearshore water column delivered to sessile filter feeders such as barnacles (Leslie et al. 2010). In fact, Borja et al. (2006) found that one could accurately estimate local biomass stricture of populations of *P. pollicipes* in Spain correlated more strictly to local wave regimes than to regional food regimes, as long as food was generally abundant offshore. Cimberg et al. (1981) similarly found that wave impact patterns can predict brooding activity, which is otherwise dependent on sufficient food resources. The Yachats Beach shoreline consists of steep or vertical sloped rocky faces and likely receives both higher wave impact (and therefore more food), and a reduced rate of desiccation, potentially allowing for larger individuals undergoing less reproduction-limiting environmental stress. Conversely, Tokatee Klootchman is characterized by fewer, smaller and less steeply sloped rocky benches, which do not directly face incoming waves. This may explain why Yachats appears to be a localized anomaly with large individuals and high reproductive activity while Tokatee Klootchman, within the same regional oceanographic regime, had the narrowest range of individual dry biomasses.

The Yachats Smelt Sands zonation of transects added insight to spatial variation within populations of gooseneck barnacles. Generally, individuals in the low zone populations reached a larger maximum adult size than in mid zone populations. The zone-specific habitat parameters appeared to add another level of spatial variation: within-site habitat variation. Additionally, strength of cape effects and regional oceanography may vary temporally. Nutrient regimes and upwelling patterns vary across seasons as well as regions (Schoch et al. 2006). While oceanographic regimes and upwelling patterns can be a strong regional predictor for some life history processes, interactions between environmental processes of different spatial and temporal scales such as regional upwelling, nearshore current circulation, and local geomorphology and wave patterns add a level of complexity that prevents any single environmental factor from consistently being the most reliable predictor of species-specific life history processes (Lagos, Castilla, & Broitman, 2008).My study does not describe temporal variations in oceanographic effects on recruitment and reproduction per site and so could miss regional patterns that manifest more strongly at another season. It also does not isolate any specific individual environmental parameter but rather categorizes regional versus local, preventing the ability to confirm the effects of individual environmental processes on gooseneck barnacle population dynamics.

Seasonal Surveys – variation over time in mid and low intertidal zones

In addressing the temporal investigation at Yachats Smelt Sands, it is important to initially note that climate patterns during the study were relatively abnormal. The Southern California Current System was characterized by warming temperatures, depressed thermoclines, and high stratification beginning in 2014 (Zhang, Hai, & Bin 2015, Zaba & Rudnik 2016). A large “Blob” of unusually warm water was observed off the coast of North America for most of 2015 (Zaba & Rudnik 2016). Additionally, a particularly strong El Niño occurred overlapping the 2015-2016 surveys (Becker 2016, Zaba & Rudnik 2016). Upwelling regimes on the Oregon coastline began unusually early in the spring of 2015, and unusually warm waters peaked in December (Becker 2015). Weather and ocean conditions were atypical during the following winter months especially, which may have influenced the intertidal ecosystem. El Niño conditions began to subside concurrently with the end of my study in March 2016 (Becker 2016). Potential effects of these climactic abnormalities can affect larval distribution and survival, frequency and intensity of upwelling, nutrient delivery to coastal systems, chlorophyll concentrations and levels of primary productivity, sea surface temperatures and heights, as well as intensity and frequency of disturbance due to storms (Zhang et al. 2015). Each of these dynamics can affect life history processes of intertidal invertebrates like gooseneck barnacles. The temporal patterns I observed during this study therefore may not exactly represent a "typical" year – though the frequency of "abnormal" conditions on the Eastern Pacific coastline have generally been increasing, with many shifts attributed to climate change effects (Zhang et al. 2015, Zaba & Rudnik 2016).

Abundances

Based on general observation, distribution and densities of hummocks of goosenecks is extremely sensitive to tidal zone. The exposed, mussel dominated mid zone hosts only sparsely distributed patches of a few small adults compared to the low zone's relatively extensive stretches of large, densely packed hummocks of large individuals. Future analysis of the photos from transect-quadrat surveys can help quantify this difference. The extreme drop in abundances in the low zone due to the fall sand incursion disturbance at Yachats was an abnormal event. Large areas of dense, extensive, and well-established hummocks were removed. These patches were likely several years old, as they were the locations where the largest (and therefore oldest) barnacles were found during any surveys. They also hosted high densities of juveniles and recruits attached to peduncles of adults. Multiple generations of barnacles were therefore lost with these patches in the sand disturbance. Low zone temporal variability was a result of natural disturbance. I did not observe any obvious seasonal variation of abundances in mid zone transects

Biomass

At Yachats Smelt Sands, gooseneck populations in both mid and low tidal zones are, as at all other sites surveyed, dominated by small individuals – namely, juveniles and recruits. The adult populations comprise mostly of smaller individuals as well. This trend persists throughout the year. There is no clear seasonal pattern. In the regional surveys, there were more juveniles and recruits in July survey samples than in May 2015. This may reflect a summer recruitment event. However, the Yachats Smelt Sands surveys did not show as clear a trend. The Tukey test comparing adult biomass distributions over time at Yachats Smelt Sands suggests that May, September, and October populations generally comprised of larger individuals than January, and April populations. However, it is unclear whether this decreasing trend was due to a large drop in the established adult population after sand and winter storm disturbances. Several areas containing hummocks of large and long-established adults were swept away by the sand incursion, as were entire stretches of recruit-dominated patches in the low zone. Discrepancies between months could also be due to growth of recruits and juveniles from the fall months, reaching "adult" size and adding to the pool of small adults in early 2016.

It would seem that distributions of individual biomass in the adult size classes are not subject to obvious seasonal variation. Growth and recruitment patterns could not be discerned from the data, and temporal changes across the population were likely highly influenced by the effect of natural disturbances. That is not to say that there is no seasonal pattern of individual growth rates or recruitment events for gooseneck barnacles. Rather, it is more likely that my methods were simply not targeted enough at these processes to distinguish them from a population which is otherwise stable in terms of a dominant small size class and relatively few larger, older adults.

Brooding

Brooding activity displayed a clear pattern of temporal variation. In general, fewer adults were found to be brooding in the fall months than in the summer 2015 and the winter of early 2016. Brooding activity never stopped completely, simply reduced. Populations of goosenecks included evidently sexually active adults throughout the year. At least half of the adult population was apparently fecund, and at least a quarter was brooding at any given point. Reproduction is potentially a regular cycle across the population, given that the proportions of individuals brooding form a nearly sinusoidal pattern over the year.

Peak brooding seasons were opposite in conditions. Warm summer months on the Oregon coast are characterized by frequent upwelling, night or early morning low tides, low rates of natural disturbance and contrast with cold, storm-ridden winter months characterized by less frequent upwelling and evening tides (Menge et al. 2015). This would suggest that temporal variation of *P. polymerus* brooding activity is not necessarily driven by seasonal conditions. Rather, it is likely that the timing of maximum percent of actively brooding individuals is determined by the frequency at which goosenecks undergo reproductive cycles, and how reproductively synchronized individuals are in a population. Similarly, Boukaici et al. (2012) found that *P. pollicipes* in Spain reproduce roughly1.5 times per year, synchronized with other individuals of the population rather than with seasonal environmental conditions. It is also possible that seasonality of sexual activity in the barnacles was altered during my survey due to the abnormal El Niño conditions, which altered typical environmental conditions in the winter especially.

Interestingly, the low zone populations show a different temporal pattern than the mid zone. As percent of brooding individuals dropped in September to a minimum proportion in October and November 2015, low zone individuals experienced a peak in population brooding activity. In the low zone, April 2016 results were once again comparable in both zones. The months in between unfortunately lack data and cannot be compared between zones. The different peak brooding months of each zone further suggests that seasonal conditions don't necessarily determine the timing or frequency of reproductive cycles in goosenecks. Instead, there may be hyper-localized conditions within each zone that influence sexual activity, causing mid and low zone barnacles to differ in timing, frequency, synchronicity, or some combination of population-wide brooding pattern characteristics (Lewis & Chia 1981).

It should be noted that the proportion of brooding individuals at one point does not encompass all sexually active individual barnacles, nor does it give insight to the gestation period of brooding *Pollicipes*. Furthermore, it can suggest when a population's peak spawning events may occur (in the months following peak brooding occurrences), but without knowing the gestation period and whether gestation itself is a variable process, it cannot give an exact description of seasonal variation of general sexual activity in barnacle populations. Rather, it provides a rough estimate of and method of comparison for general population fecundity at each site and suggests that there is enough seasonality in Oregon gooseneck reproductive cycles that further investigation should be pursued to understand the temporal variation of its components, including spawning and larval output.

Zonation

The seasonal surveys yielded unclear results for any definitive temporal pattern other than brooding. However, they were extremely useful in noting differences in population structure and life history processes between zones. The low zone consistently contained higher densities, larger individual adults, and a higher proportion of brooding adults than the mid zone, regardless of seasonal conditions. There are several potential drivers for this pattern. In the low zone, exposure to desiccation is significantly reduced (Broitman et al. 2008). Mussel beds are kept out of the low zone by predation by *Pisaster*. Large algaes and many encrusting species cannot survive the high wave intensity in the low zones at Yachats, so there are relatively few species competing for space (Broitman et al. 2008). Higher wave intensity and more subtidal exposure could help deliver more food resources to *Pollicipes* populations and offer more opportunities for larval *Pollicipes* to settle in the lower intertidal. All of these factors could enhance settlement success of recruits, survival of juveniles and adults, general growth rates, available resources for allocation towards sexual reproduction, and available habitat space (Lewis & Chia 1981). In Bard et al.'s 2006 model (Fig. 2), this would enhance each of the positive inputs into net population sizes. It may be that the factors which help enhance the intensity of life history processes in the low zone are limited enough in the mid zone that seasonal conditions have a greater effect in those populations. Competition by mussel beds and high exposure desiccation risk in the mid zone may influence and restrict abundances, brooding, and maximum individual biomass. Limitations of food availability in the mid zone could also be a driving factor of tidal zonation differences in population dynamics and seasonality of gooseneck barnacles.

Post - harvest response and recovery

Pollicipes polymerus prove to require an extensive amount of time to recover in population size after simulated harvest of a localized patch. In all of the experimental patches, it took a minimum of one year for recruits to settle successfully and establish significant abundances. Patches were cleared mid-summer of 2013, during the onset of what appears to be the peak in recruitment with successful settlement for barnacles: late summer through fall (Menge 2000).The first peak season of recruitment passed without successful settling. During and after the second peak recruitment season, in the late fall of 2014, settlement was more successful. This may have to do with the presence of other benthic intertidal organisms – namely *Balanus glandula*, some *Mytilus trossulus*, and a variety of turfy algas – which had more successful settlement during the first year and provided more complex surfaces onto which *Pollicipes* cyprids could recruit. Multiple studies have shown that settlement of *Pollicipes* recruits happens preferentially on other organisms – especially other *Pollicipes* - rather than directly onto the substrate (Lewis & Chia 1981, Hoffman 1988). It took another year for recovering *Pollicipes* abundances to reach a level comparable to undisturbed areas. The successful recruits from the first successful round of settlement in 2014 had, by late 2015, grown in carapace size and I noted through general observation that they appeared to be near or larger than the minimum size for sexual maturity I found in the transect-quadrat surveys of undisturbed populations. However, in no patch were they large enough to be of interest for re-harvest. The patches are currently nearing three years old and still do not contain any individuals with peduncles large enough to be harvestable. This suggests that in recovering populations, *P. polymerus* recruits and juveniles initially grow quickly to reach an adult state, and then slow in growth rate. The findings of (Cimberg 1981, Cruz 1993, Cruz et al. 2010, & Boukaici et al. 2012) show similar growth patterns for juveniles of the genus *Pollicipes* in general. Further direct studies quantifying the maturity and growth rates of harvest-recovering species should be performed to confirm this perceived trend.

Harvest is evidently a significantly detrimental disturbance for *Pollicipes* patches and recovery takes multiple years. This is on an extremely localized scale: the areas immediately surrounding the patches appear unaffected by the simulated harvest, so patch disturbance does not appear to immediately influence general population dynamics at a site. However, given the long delay in patch recovery in general, there is potential for a cumulative site-wide impact if harvesting were intense enough to clear a significant number of patches at a single location.

Implications for Management Decisions

Environmental conditions determine individual and population life history processes, which influence overall community structure across regional gradients (Schoch et al. 2006, Menge et al. 2015). It is therefore important to understand life history processes of a single species and environmental effects on that species in order to understand community dynamics of species populations and of whole ecosystems. Furthermore, understanding a species' life history traits is necessary to effectively manage sustainable harvesting from the population. Before increased or commercial harvesting of *P. polymerus* begins on the Oregon coast, a management scheme should be designed to avoid potential overharvesting. Successful gooseneck management efforts in Spain and Portugal are typically cooperative and are based on protecting variable and limited aspects of life history patterns, such as recruitment and reproduction (Molares and Freire 2003, Bald et al. 2006, Borja et al. 2006, Cruz et al. 2010, Bidegain et al. 2015). Understanding how environmental conditions affect these aspects of a population is the first step in creating a management scheme for those sensitive population dynamics. This study was far too limited in scope to be used exclusively to prescribe a full management strategy recommendation for fishing of Oregon *P. polymerus*. However, even with limited data my findings can help inform initial management considerations. The basic population patterns I found have several implications relevant to design of sustainable harvest policy.

Molares & Friere (2003) found that *P. pollicipes* management is most effective when accounting for traits under geographic patterns of oceanographic regimes. More abundant populations with higher levels of recruitment and growth are more resilient to harvesting (Molares & Friere 2003). Additionally, Bidegain et al. (2015) found that densities and abundance patterns are more reliable for a regionally prescribed sustainable management scheme than a minimum or maximum size-capture policy for *P. pollicipes,* since size varies too much across sites within a region to set an accurate single size limitation. My results show a similar lack of regional size pattern, which could suggest that Oregon management schemes should focus more on identifying abundant populations rather than limiting regional extraction by size. Regional patterns of *P. polymerus* in Oregon densities show that management decisions based on general population distributions can be informed on a regional scale. With general accuracy, management teams designing policy could predict where the highest density of gooseneck barnacles likely exist by recognizing where oceanographic regimes have high intensity and high frequency upwelling events, wide continental shelves, and generally high productivity. This is useful for determining regions where populations should be closed to harvest pressure or, alternatively, could sustain fishery yields based on abundance patterns. More site-specific management schemes could be further developed by identifying individual biomass and reproductive activity within a population.

The distribution and proportion of adults specifically is a key consideration for gooseneck fishery management design. All individuals of harvest are large enough that they are almost exclusively well-established adults which are likely to be brooding if not at least sexually active and contributing to the larval pool. While populations at all sites included individuals at least meeting the 1.3g dry weight estimate for minimum harvest size, they are generally a small proportion of the population. At Tokatee Klootchman especially, almost no individuals met this size requirement. Additionally, most goosenecks of this size or larger are fecund, and contribute significantly to the population of brooding individuals at each site. Investigations at Yachats suggest that, within site populations, these larger barnacles are restricted to the low tidal zone. Observations showed that harvestable individuals are often a part of established hummocks, which comprise of multiple age classes, and are the preferred settling site for recruits. Methods of harvest for goosenecks cannot separate large adults from established hummocks without also collecting or killing all attached juveniles and recruits and significantly disturbing that patch. Patch disturbance by harvest takes multiple years for full recovery of both densities and harvestable size of adults. Each of these trends make localized *P. polymerus* populations extremely sensitive to overfishing. Harvest removes current and future generations from an extremely specific portion of the population, with little chance for quick recovery. It is imperative, therefore, that if any harvest of natural populations were to occur and expand, it must be strategized and monitored to prevent overharvest.

Patterns of individual biomass and brooding cannot be so easily and generally predicted on a regional scale. Instead, they require more site-specific investigations. Individual biomass distribution varies per site rather than cape. Population levels of brooding and of more specific measurements of reproductive output in particular should be investigated at a localized level. Brooding is a temporal pattern among individuals of a large biomass and so definitively displays both seasonal and spatial variation. If relative frequencies and proportions of brooding individuals reflects significant variation in population fecundity, spawning events, and larval output, then sites with the highest proportion of brooding individuals likely contribute most significantly to the larval pool. Further investigation would help determine the size of future populations through reproductive output. High rates of fecundity in a localized population should be identified and intentionally protected from intense harvest pressure that could reduce population-wide reproductive output. Additionally, sustainable harvest management design could incorporate a temporal aspect to avoid harvest during peak seasons of reproduction in *P. polymerus* populations.

Gooseneck fishing targets a minority of the *P. polymerus* population by selecting for large individual barnacles. However, these individuals are a large proportion of the brooding population and are integrated into low-zone hummocks which consist of multiple age classes of goosenecks due to the barnacles' gregarious settlement patterns. Their habitat is limited to a portion of the rocky intertidal high in wave intensity and limited in exposure time, making harvest difficult, dangerous, and seasonally inaccessible. The coastal population of gooseneck barnacles exhibits regional, local, and temporal variation of abundances, size distribution, and brooding patterns, complicating the strategy of designing management for the expanding fishery.

Setting restrictions exclusively on a biological basis could restrict any fishery growth. Alternatively, fishery restrictions set exclusively by harvest interests could drastically reduce gooseneck populations. By intentionally protecting sites of high reproductive output, access to sites with a significant population of individuals large enough for harvest interest may be too restricted for sustaining a commercial market. Alternatively, by designing site access around populations of high densities and high proportions of large individuals, harvest could remove significant portions of the population that would otherwise heavily contribute to regional levels of reproduction and the abundance of future barnacle generations. Policies around take maximums also face trade-offs. If, for example, catch limits recognized that larger individual barnacles are more likely to be reproductively active and set a maximum individual target size and number of individuals collected, juveniles and recruits harmed or removed during harvest of patches could generate high levels of bycatch. Alternatively, a catch maximum on weight of all barnacles harvested or removed at one time would include any juvenile and recruits in that metric to reduce bycatch, but would not protect larger, more fecund individuals from harvest. Catch maximums could also be set at different spatial and temporal scales. In all cases, potential tradeoffs require both ecological and economic analysis. My results are useful from a species' population science approach, but require follow-up investigations and must be considered in coordination with socio-economic concerns of stakeholders beyond the scientific community for the use of designing fisheries policy.

Next Steps

This investigation is meant to serve as an initial study, necessarily followed by further investigations to round out the knowledge gaps in understanding *P. pollicipes* population dynamics in Oregon. On Cape Perpetua and Cape Foulweather, follow-up investigations should more directly measure recruitment and growth rates across sites and seasons. Additional interesting metrics to investigate include a quantified estimation of reproductive output of individuals and the population. This could be done by separating and measuring the egg mass from brooding individuals in terms of weight and number of eggs. Additionally, determining the actual frequency of reproduction would be useful, especially if investigations pursued determining the gestation period and the timing of spawning in addition to the general brooding activity of populations. Sestelo and Roca-Pardiñas (2011) found that *P. pollicipes* matching an estimated minimal size for sexual maturity size tend to reproduce about 1.7 times per year. Others have reported regional variability in *P. pollicipes* reproduction cycles, with spawning events occurring anywhere from one to four times annually depending on population (Lewis & Chia 1981, Hoffman 1988). It would be interesting to determine the specific spawning frequency of *P. polymerus* in Oregon, and it would be useful to know if and how the seasonal and regional patterns of this metric vary (Cruz & Araujo1999, Cardoso & Yule, 1995, Pavón 2003, Molares et al. 1994). Spawning likely varies at least seasonally, as we found general brooding activity to vary seasonally at Yachats, but we cannot confirm the gestation period, spawning frequency, and exact population fecundity from my study alone. This would also require a more direct methodology of investigating gooseneck reproductive cycles than my presence/absence of egg masses in adult barnacles. We could then more clearly identify where and when existing adult populations produce the greatest addition to the offshore larval pool.

The size distributions of many small individuals relative to the number of adults and especially to the number of large, harvestable barnacles begs for further investigation into the post settlement mortality patterns of gooseneck barnacles. Potential age-specific mortality rates and differential mortality per site are necessary to understand what proportion of each generation survive to sexual maturity and, subsequently, to reach harvestable size. Development of a life table analysis describing age structure and population growth (a Leslie matrix, for example) would be especially useful for inferring sustainable age and size stage – specific harvest rates, and could help assess the effects of harvest on population size and stability.

It should be noted no patches in the harvest simulation experiment were in the far low zone due to seasonal inaccessibility. Given that the far low zone is potentially the main target for harvesting due to the large individual biomass and high population tendency trends, additional investigation on harvest recovery patterns in these low tidal areas should be pursued.

The destructive nature of gooseneck harvest techniques, low recovery rates after disturbance, overlapping generations in gregarious patches, and limited numbers of large fecund adults in each population are general but important parameters to consider for pursuing specific next steps. Oregon gooseneck barnacles appear to be extremely sensitive to overharvest like that seen historically in the Iberian Peninsula due to the conditions listed above. Increased harvest pressure of any sort should be limited if not avoided until sustainable management design has been established. It would be useful to begin investigating the potential for mariculture with this species. If at all possible, facilitating recruitment and settlement and increasing growth rates of goosenecks cultured specifically for commercial harvest purposes would expand the local gooseneck barnacle market without placing all harvest pressure on naturally existing populations. This could allow for more stringent management and protection of natural populations without immediately limiting market expansion. Studies to establish trials for mariculture should therefore begin immediately.

Gooseneck life history processes and population distributions should also be explored in other regions of the Oregon coastline. The correlation between abundances and oceanographic regimes suggests that we could estimate based on shelf width, upwelling regimes, and productivity patterns where in Oregon we could expect the largest and most dense populations of gooseneck barnacles. However, the tendency for other population metrics to show site-specific variation more intensely than regional patterns means that future investigations should continue addressing specific sites of harvest interest rather than utilize regional generalizations. In particular, the south-central coastline of Oregon should be studied immediately, given that this region is of highest interest to existing fishers interested in harvesting goosenecks and expanding the Oregon *Pollicipes* fishery. The scientific investigations can and should be integrated into collaborative stakeholder efforts to generate both an ecologically and socio-economically sound structure of harvest management of goosenecks. This is an opportunity to proactively avoid overharvest and continue fostering a culture of cooperation and sustainability in Oregon fisheries and resource management.

II. MOVING TOWARD GLOBAL FISHING REFORM: Trial by Barnacles

Human – ocean relationships are currently dominated by unsustainable extraction of marine resources. Overfishing in particular presents ecological problems to marine species and socio-economic problems to human communities (Costello et al. 2016). Its detrimental effects to natural and human systems are widely recognized and well understood yet overfishing exists and persists in a majority of the world's fisheries. Various harvest management policy strategies exist as a response to overfishing, with the goal of refilling stocks when an overfished species' population size drops to dangerously low numbers (Costello et al. 2016). The most successful and sustainable examples of these policies incorporate a systems approach, using ecology and population science in conjunction with socio-economic and cultural understanding of the fished species, its environment and associated species, and the connected human community. Design, implementation, and enforcement of these policies are expected to be most effective and efficient when based on bioeconomic theory and performed collaboratively between all stakeholders including fishers, the public, fishery scientists and ecologists, agencies and policymakers, and local government officials (Costello et al. 2016). Despite developing sustainable fishery policies and strategies, fishery management is still in need of reform. Most sustainable management policy is designed and enforced only after overfishing has occurred and is viewed as a conservation solution. Fishery management must instead become a proactive strategy. Sustainability in the form of ecological and socio-economic stability needs to be a priority from the start in order to avoid repeating the same pattern of overfishing. We must alter our approach to fishery management to incorporate maintaining healthy ecosystems and preventing overfishing as proactive goals rather than post – over extraction solutions, recognizing that the most successful and sustainable policies utilize collaboration of stakeholders, scientists, policymakers, and the public to design, implement, and enforce resource management.

I have used the newly developing gooseneck barnacle fishery in Oregon as a case study to propose a real-world opportunity to exercise this reframing of fishery management. Gooseneck barnacles of the species of *Pollicipes* are harvested for food. In the Iberian Peninsula, they have a history of deeply connected socio-economic and culturally driven high market value driving overharvest. Populations of goosenecks were slowly recovered by cooperatively framed management of the fishery with sustainability oriented goals. In the mean time, harvest for export grew on the northern Pacific coast of North America. Commercial fishing in Oregon is expanding, necessitating the development of harvest management to prevent overfishing as seen in Europe. I examined the lessons available from the history of gooseneck fishing in the Iberian Peninsula to inform successful strategies for collaborative approaches to sustainable harvest management from a socio-economic and cultural perspective.

The exposed and violently wave-impacted habitat of goosenecks is difficult and dangerous to work in, whether for harvest or research purposes. Girard (1982) and Molares (1998) described varieties of direct population assessment using in-field surveying and sampling, which I have used to inform my methods. However, this strategy is limited to shores with calm enough conditions and shallow enough shores to reduce some of the extreme risk and ensure at least some seasonal access to the gooseneck populations. Gooseneck population information can also be informed using catch statistics and fisher behavior, reducing risk and cost but potentially limiting data accuracy (Freire & García-Allut, 2000). Monitoring of the species requires an additional level of intentional strategy when designing harvest management. In this fishery context especially, collaboration between stakeholders to generate multiple sources of scientific and socio-economic knowledge about goosenecks in the context of rocky intertidal ecosystems, coastal fisher communities, and shifting market demand is imperative for success.

Recognizing that designing resource management requires extensive scientific knowledge of that resource, but that data on the life history and population dynamics of Oregon gooseneck barnacles, I pursued to begin to fill that knowledge gap. I spent one year investigating the spatial and temporal variability of general life history and population dynamics of *Pollicipes polymerus* in Oregon. I specifically aimed to determine whether distributions and population densities, size-frequency distribution of individuals, and frequency of brooding varies in a way correlated to seasonal conditions and to regional oceanic regimes versus local site conditions. I used sites on the highly productive but oceanographically distinct Cape Perpetua and Cape Foulweather to study naturally occurring populations of *P. polymerus*. Additionally, I used experimentally cleared patches to follow recovery of goosenecks after simulated complete harvest over the course of nearly three years. The results show correlation between regional oceanographic conditions and population densities, but site-specific spatial variations of all other parameters. Individual size and fecundity are linked. Brooding frequency exhibits temporal variation and natural abundances are subject to seasonal disturbances. Recovery from disturbance and simulated harvest is an extremely long-term process. I then explored how each finding can be used to both direct future necessary scientific investigations of *P. polymerus* populations and to inform preliminary harvest management design in a collaborative framework.

My investigation of Oregon *P. polymerus* populations opens multiple follow-up paths of research to continue filling the knowledge gaps necessary for developing integrative gooseneck fishery management. Even as future studies are initiated and conducted, use of my investigation's findings can begin immediately. Harvest interest in goosenecks is growing in Oregon. The *Pollicipes* market demand still exists in Spain and Portugal and has expanded to BC and some parts of Asia, encouraging increased commercial export of *P. polymerus* from North America. The current lack of *Pollicipes* harvest management strategies in Oregon, the expanding local harvest interest, the past *Pollicipes* overfishing and delayed collaborative management patterns seen in the Iberian peninsula, and my findings that *Pollicipes* do not recover quickly after harvest on a localized scale show a great need for the immediate development of sustainable fishery policy and management design. Fishers in Port Orford are interested in developing a sustainable fishery through a collaborative approach, working with scientists, agencies such as Oregon Department of Fish and Wildlife, and other stakeholders to utilize data from this and future surveys. Opportunity exists to integrate ongoing investigations with reflection of the management successes and failures in *Pollicipes* fisheries in Spain, Portugal, and British Columbia. As harvest interest increases in Oregon, we must start using any and all existing data and immediately pursue further studies concurrently with initial efforts to ensure that any gooseneck barnacle fishery development and expansion in Oregon is sustainable both environmentally and economically and that it addresses the needs and priorities of all interested stakeholders.

Initial basic data on the life-history of *P. polymerus* can inform next steps for pursuing continued informative research and establishing initial collaboration between stakeholders. These can be combined with knowledge gained through the management successes and failures in Spain, Portugal, and British Colombia, capitalizing on public outreach. The existing interest of multiple stakeholders makes now the opportune time to use science-informed policy to ensure that any gooseneck barnacle fishery development and expansion in Oregon is sustainable both environmentally and economically through a collaborative process, addressing the needs and interests of all interested stakeholders while protecting and supporting the health of Oregon's intertidal ecosystems and gooseneck barnacle populations. A necessary immediate next step, therefore, is to open communication and efforts of collaboration between stakeholders to pursue the scientific and socio-economic knowledge necessary to generate a sustainable harvest management plan supported consensually by all involved groups. The Oregon coastline is potentially the ideal location to practice the relatively novel approach of integrative, collaborative, and co-management of fishery design for the purpose of sustainable harvest management *before* overfishing and its negative effects have had a chance to play out.

The specific socio-economic conditions of Oregon coastal communities and existing resource management structure can be combined with stakeholder participation and improved scientific knowledge to develop an integrative and relatively novel approach to resource management: one which embodies the type of global revision of fisheries management necessary for the stability of human and marine systems. Gooseneck barnacle harvest management design is one among a list of numerous fisheries across the world which must utilize a collaborative approach with goals of sustainability. On a local species level, it is of the utmost importance that a well-informed, collaborative approach to sustainable harvest management of Oregon gooseneck barnacles be taken as the fishery expands. On a global level, this fishery offers an opportunity to begin the necessary shift of the traditional approach to fisheries management strategies in a way that combats overfishing and its consequences proactively. My study is the first of several necessary steps towards that goal.

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