

The influence of ocean acidification on the economic vitality of shellfish hatcheries in the Pacific Northwest: A meta-analysis.

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## TABLE OF CONTENTS

ABSTRACT.....	iv
PREFACE.....	v
INTRODUCTION.....	8
BACKGROUND.....	9
METHODS.....	16
<i>ANALYZING MITIGATION STRATEGIES.....</i>	<i>17</i>
<i>SUSTAINABILITY IN THE PRESENCE OF OA.....</i>	<i>19</i>
<i>PROFITABILITY IN THE PRESENCE OF OA.....</i>	<i>19</i>
RESULTS.....	20
<i>OA IMPACT ON SUSTAINABILITY.....</i>	<i>20</i>
<i>CURRENT PROFITABILITY AND COSTS OF OA.....</i>	<i>22</i>
ANALYSIS OF RESULTS.....	28
<i>SUSTAINABILTY.....</i>	<i>28</i>
<i>COST OF OCEAN ACIDIFICATION.....</i>	<i>33</i>
DISCUSSION.....	37
CONCLUSION.....	47
BIBLIOGRAPHY.....	50

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## ABSTRACT

Ocean acidification is the chemical process that results in the decrease of ocean pH levels. This decrease is caused by the diffusion of atmospheric carbon dioxide into Earth's oceans. In other words, Earth's oceans act as a carbon sink for atmospheric carbon. Prior to the industrial revolution in 1760, the ocean regulated the amount of carbon in earth's atmosphere in a manner that did not threaten marine ecosystems. However, due to the increased combustion of fossil fuels due to rapid industrialization, urbanization, and population growth, oceans have begun to take up excessive amounts of carbon dioxide, resulting in an alteration of oceanic chemistry. The accumulation of hydrogen ions in ocean water due to the chemical reaction between carbonate carbon dioxide, and water have increased the acidity of the ocean. This has created a corrosive environment for shell-forming organisms that rely on carbonate for their exoskeletons. Many of these organisms, especially those in the Mollusca phylum, are commercially valuable. Ocean acidification has already begun its impact on the shellfish industry in the Pacific Northwest. However, if a business-as-usual scenario of carbon combustion prevails over use of alternative energy sources and mandatory terrestrial pollutant controls, the impact on shellfish aquaculture firms will only intensify and threaten the industry and its associated jobs and revenue. Local, state and federal authorities and agencies have begun to take steps to mitigate the effects of ocean acidification. Mitigation strategies are analyzed on their basis to effectively diminish the physiological and economic impact of ocean acidification on shellfish aquaculture operations. The question remains if these strategies will be able to successfully inhibit the ongoing process of ocean acidification, or simply just delay the impacts.

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## PREFACE

I would like to acknowledge the following names for their assistance and continued support throughout this process. Firstly, I would like to thank Dale Miller for his incredible diligence in ensuring the competent completion of this thesis. Secondly, I would like to thank Lisa Corwin for taking time out of her normal schedule to assist and further the progression of this document. Thirdly, I would like to extend my thanks to Steven Vanderheidan for taking time out his schedule to advise the development of my thesis. And lastly, I would like to thank Kathryn Tallman for providing me with valuable sources that provided fruitful data for the analysis of my research question. Without these contributors, it is difficult to imagine the successful completion of this thesis.





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## INTRODUCTION

This thesis examines the effects of ocean acidification on the shellfish industry in the Pacific Northwest of the United States and its associated relevant policy. This thesis examines the current state of the shellfish industry in Washington, Oregon, and Alaska to determine its profitability, sustainability, and future trajectory in the presence of ocean acidification, as well as identify and analyze the strategies that aim to address this threat. This document takes into account the ecological degradation ocean acidification imposes on both wild and aquaculture hatcheries and ties those environmental impacts to the future of the industry for the northwest region of the United States. In addition, this document analyzes how decreases in oceanic pH levels impact the physiological processes of mollusks. Data regarding the physiological impacts associated with decreasing oceanic pH gives insight to the acidification's effect on mollusk vitality, the pillar of mollusk production.

The ecological impacts of ocean acidification extend into higher marine trophic levels in. Increasing acidity and disabling the shell formation of calcifying organisms essentially causes a decrease in the abundance of shellfish organisms. This essentially lowers the food supply for organisms inhabiting higher trophic levels, increasing competition, thus creating an intensified struggle for survival for many marine species.

This document is a meta-analysis that entails the current state of the shellfish industry, the physiological impacts of ocean acidification on mollusks, the future of sustainability and profitability of the shellfish industry in the Pacific Northwest, and the analysis of mitigation strategies that aim to inhibit acidification. Shellfish harvest account for a significant portion of economic revenue in the region of the Pacific Northwest. The health and vitality of local and



regional shellfish populations is crucial to sustaining the region's seafood economy. I attempt to link together the current ecological state and trends of shellfish populations in Washington and correlate those trends with economic effects.

This document also utilizes and analyzes the data and results of studies, reports, and peer reviewed sources in order to gain insight on the current state of shellfish hatcheries and to what degree the industry is threatened by the current and continuous trend of acidification. I take into account rate of acidification and its impact on the shellfish industry based on future trajectories of production, profitability, and mitigation techniques.

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## BACKGROUND

Shellfish contribute a large portion to coastal marine economies, especially in the states of the Pacific Northwest. Harvesting, recreational licenses, recreational harvests, aquaculture, the seafood industry, and the restaurant industry all rely on substantial shellfish production. Decreasing levels of pH in coastal ecosystems has caused a decrease in returns on shellfish investments and harvest yields. This thesis aims to link the ecological degradation of climate change's associated ocean acidification on the shellfish industry in the Pacific Northwest of the United States. In addition, this thesis aims to evaluate mitigation strategies taken by federal and state government and agencies.

Shellfish make up an abundant proportion of Washington's marine fauna, many of which greatly contribute to the state's marine commercial activity. Washington is the top provider of farmed oysters, clams, and mussels in the U.S. (Ruckelshaus 2012). The annual sales of Washington's mollusks accounts for almost 85% of the entire U.S. west coast mollusk sales. Washington shellfish sales alone are directly responsible for \$270 million annual revenue. This

revenue supports the employment of about 3,200 people (Ruckelshaus 2012). Wild fisheries of oysters, mussels, and clams (geoducks, razors, and littleneck marina) generate over 2/3 of the total harvest value.

Anthropogenic use of fossil fuels beginning at the prior stages of industrial revolution have resulted in both a warmer climate and the acidification of Earth's oceans. Prior to the industrial revolution, atmospheric carbon fluctuated between 180-300 ppmv (parts per million by volume) (Fabry 2008). Since the introduction of large-scale fossil fuel use, the atmosphere consists of a carbon content of 380 ppmv, with a rate of a 0.5% increase per year (Fabry 2008). To put in perspective, that is a rate that is 100 times faster than pre-industrial intervals. This has had a profound effect on many of Earth's processes including but not limited to: storm formation, sea level rise, species migration, water availability, annual climate variation and ocean acidification.

Along with a changing climate due to increased levels of carbon dioxide in the Earth's atmosphere, the Earth's oceans are also undergoing their own carbon-caused phenomenon. The alteration of Earth's atmospheric and oceanic chemistry is a result of a steady increase in combustion of fossil fuels and deforestation since the industrial revolution of 1760. These two factors have caused a 40% increase in carbon dioxide content in the atmosphere since the end of the industrial revolution (Sea Technology) Like the atmosphere, Earth's oceans act as a carbon sink as it absorbs an immense amount of carbon from the atmosphere (Fabry 2008). One third of anthropogenic carbon emissions are ultimately absorbed by the oceans. This has resulted in an average decrease in pH of 0.1 pH (Miller et al.), with localized coastal areas experiencing even more acidification. In addition, there are natural forces that accelerate ocean acidification. Autotrophic cellular respiration, organic decomposition, and seasonal coastal upwelling increase carbon content in ocean water (Upton & Folger 2013).

While carbon uptake via ocean absorption mitigates further atmospheric warming, it greatly threatens marine biota, ecosystems, and their dependent industries via acidification. As previously mentioned, current ocean pH levels are generally 0.1 pH lower than preindustrial values. In a business-as-usual scenario, pH levels will decrease by another 0.3-0.4 units by the turn of the century. That is a 100-150% increase in H<sup>+</sup> ions (Orr et al. 2005). There has already been an observed profound effect on marine biota through these changes in ocean chemistry that have directly targeted calcifying organisms that rely on calcium carbonate for shell and skeleton formation (Fabry 2008). The deleterious impact on calcifying organisms has resulted in changes in biodiversity of shellfish that has ultimately affected higher trophic levels that depend on these calcifying organisms for prey (Fabry 2008). For example, carnivorous zooplankton and fish depend on eutecosomatous pteropods, a shellfish that is currently extremely at risk, for food supply. The associated alteration of oceanic chemistry via ocean acidification vastly threaten the abundance of pteropods. This essentially forces carnivorous zooplankton and large fish that depend on pteropods to alternate to new forms of prey, a biological mitigation strategy that will take time to initiate. This will impose pressure on juvenile fish and gymnosomes who prey exclusively on shelled pteropods. Gymnosomes will have to endure a shift in geographic distribution to latitudes where pteropod populations are still viable as prey. In order to accomplish this, gymnosomes will have to overcome thermal tolerance limitations, which will require necessary adaptations over many generations. Ultimately, all predators who specialize in calcifying organisms as prey are extremely at risk (Fabry 2008).

However, it is not simply the ocean's absorption of atmospheric carbon that is resulting in acidification. Localized events such as seasonal upwelling of carbon dioxide-rich waters, eutrophication, river discharge, and terrestrial runoff primarily from agricultural operations

intensifies acidification in localized, coastal regions (Ekstrom). Many of these regions are either in close proximity to shellfish farms or its waters flow into aquaculture operations via runoff or freshwater discharge (Ekstrom). This has created seasonal variation in acidic environments as well as has created a more hostile environment for shellfish harvesting in the critical areas where the industry is dependent.

Terrestrial runoff is another mechanism that increases the acidification of coastal regions. Rivers, estuaries, and nearby agricultural development are all prone to cause inflow of nutrients and discharge of freshwater into nearby coastal ecosystems where commercial shellfish harvests occur. Flash floods, intense precipitation, and unaccountability of the negative externalities of pollution produced by firms all increase the rates of runoff (Cordero 2013). Terrestrial freshwater is typically more acidic than ocean water. Therefore, nearby coastal ecosystems may experience hot spots of decreasing pH levels compared to open ocean (Cordero 2013). Coastal ecosystems are typically the most productive marine ecosystems in terms of mollusk production. They are also the most threatened by anthropogenic activity. Losing the productivity of these ecosystems will not only vastly degrade marine food-webs, but will also degrade the financial integrity of the various industries that depend on these food webs (Barbier 2011).

Due to its geographic location and ocean topography, the Pacific Northwest is particularly vulnerable to the effects of ocean acidification. The coastal upwelling that occurs on Washington's coast has enhanced and accelerated the dangerous ecological effects of ocean acidification for the region. Upwelling transports offshore water that is rich in carbon dioxide and very low in pH from deep parts of the ocean onto the shores of the continental shelf. This deep-water contains a combination of carbon from biological processes such as respiration and microbial consumption of organic detritus (Ruckelshaus 2012).

Coastal regions, such as Puget Sound, often experience an over-abundance of nutrient content due to an increase in runoff from nearby terrestrial agricultural practices, as well as organic carbon from plants and freshwater algae. Local emissions of carbon dioxide, nitrogen dioxide, and sulfur dioxide have also played a role in diminishing pH levels in Puget Sound (Ruckelshaus 2012).

Ocean pH levels are not the only corrosive response due to carbon absorption. Diminishing aragonite saturation state has also been identified as an additional threat to shellfish organisms. The aragonite saturation state is a measure of the thermodynamic stability of the mineral form of calcium carbonate that is used by bivalve larvae and other mollusks to develop shells (Ekstrom). A decline in the aragonite saturation state makes it more difficult and energetically costly for the shell formation of larval bivalves. Difficulty in shell formation in larval bivalves occurs well before the aragonite saturation state reaches its corrosive levels. A high aragonite saturation state is crucial for the development of shellfish larvae. Low aragonite saturation states can result in high mortality rates for shellfish larvae (Ekstrom), resulting in high implicit costs and a low rate of return for shellfish harvesters.

Ocean acidification consists of a wide range of physiological effects for a variety of different marine organisms. Photosynthesis, growth, respiration, recruitment, behavior, and reproduction are all sensitive to rises in acidification and carbon dioxide content in ocean water. However, organisms that utilize calcium carbonate to form shells, skeletons, and exoskeletons are particularly targeted due to the corrosive effect of acidification on calcifying organisms. The availability of carbonate ions, which is a key component to calcium carbonate, decrease drastically when pH levels drop. This creates a difficult environment for shell-formation, ultimately slowing growth rates, and resulting in higher mortality rates of shellfish species. Larvae and juveniles are

especially vulnerable when exposed to high rates of acidification (Fabry 2008).

The Pacific Northwest boasts some of the most productive and lucrative shellfish hatcheries in the world. The major farmed species include: *Venerupis philippinarum* (Manila clams), *Panopea generosa* (geoduck clams), *Mytilus trossulus* (mussels) and the *Ostrea lurida* (oyster). These species are all members of the phylum Mollusca (Waldbusser). Mollusks are arguably the valuable type of economic shellfish for this region. While they are the pillars of the shellfish industry, they are also the most sensitive to changing ocean chemistry (Sea Technology), which has created an extremely threatening situation for those who rely on this industry. The shellfish industry in the Pacific Northwest has been an important cultural and economic part of coastal communities in the Northwest since the beginning of the 1900s. Currently, shellfish farming accounts for \$270 million in economic activity. 3,000 family-wage jobs are dependent on the vitality of the industry in the region (Waldbusser). Major firms in the region include Whiskey Creek Shellfish Hatchery, Taylor Shellfish Hatchery, and Seafood's Hatchery. These major firms combined with smaller hatchery operations produce 40-60 billion shellfish larvae annually. The presence of ocean acidification is expected to significantly drop U.S. shellfish revenues in the next 50 years (Sea Technology).

While most research has been dedicated to the ecological impacts of ocean acidification, estimates of economic cost trajectories are beginning to surface (Narita et al. 2012). As of 2009, Mollusks were valued at \$5 billion U.S. However, if business-as-usual scenarios continue, production loss of mollusks will cost about 6 billion U.S. dollars, with cost ultimately surpassing revenue (Narita et al. 2012). The business-as-usual scenario consist of the ocean's pH level to be reduced by 0.3-0.4 by the end of 21st century, with even more extreme decreases in coastal regions (Narita et al. 2012). Mollusks hold high commercial value as a food source. In addition, human populations in developing countries depend on mollusks for subsistent purposes, as mollusks

contain high concentration of protein (Narita et al. 2012). Demand for shellfish will only increase with continued human population growth. However, ocean acidification has resulted in a shift of the shellfish supply curve to the left, decreasing supply and ultimately raising prices and losing revenue (Narita et al. 2012). Experts estimate that if business-as-usual scenario ensue, a 43% loss in global mollusk production by 2100 is very likely. This estimate consists of a 95% confidence interval (Narita et al. 2012). China has already experienced a \$4 billion U.S. deficit due to mollusk production loss. This global trend will ultimately result in losses in both consumer and producer surplus. (Narita et al. 2012). Currently the global economic cost of sole mollusk loss (not including other commercial shellfish) is estimated to be about \$6 billion U.S. with a constant demand to mollusks (Narita et al. 2012). However, with increased rates of acidification, decreases in mollusk supply, population growth, expected global income rise, and an increased demand this cost could potentially reach \$100 billion U.S. if unaddressed (Narita et al. 2012).

Ocean acidification does not only pose a threat to coastal commercial shellfish operations. Ocean acidification has cultural implications as well. Specifically, for the tribal communities of Puget Sound, ocean acidification poses a severe threat to natural resources that withhold immense use-value to these tribes (Ruckelshaus 2012). Ocean acidification is a significant danger to the continued identity and culture of tribes who rely on wild shellfish harvest for commercial and subsistent uses (Ruckelshaus 2012). As the salmon populations off the coast of Washington have been steadily declining, tribal fishers have become more dependent on shellfish harvests (Ruckelshaus 2012). This growing dependence on shellfish for tribal communities in the presence of ocean acidification puts a tremendous strain on wild shellfish populations.

In addition, Mytilid mussels are extremely at risk for ocean acidification. The example of Mytilid mussels is important because of their ecological and economical importance. They inhabit

rocky tidal niches worldwide (O'Donnell et al. 2012). This specific species contributes to a large portion of marine revenue globally via aquaculture. Globally, these mussels were worth about U.S. \$1.5 billion in 2009 (O'Donnell et al 2012). Ocean acidification degrades the physiological and reproductive processes of Mytilid mussels. The changing chemistry of the ocean is decreasing the integrity of the byssal threads of the Mytilid mussel, an exterior fiber that allows mussels to cling onto and inhabit tidal rocks (O'Donnell et al 2012). The decrease of pH levels is lowering populations of Mytilid mussels, ultimately threatening the stability of coastal rocky ecosystems as well as the global marine economy. This is just one of the many examples of an ecological and economic threat due to decreased mollusk abundance by ocean acidification.

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## METHODS

This section aims to describe the methodological strategies in portraying and analyzing the results derived from various studies regarding ocean acidification and its impact on the shellfish industry in the Pacific Northwest region of the United States. The first section, labeled “Analyzing Mitigation Strategies”, formats how effective states are at initiating local, state, and federal policies and their ability to access assistance from independent agencies such as NOAA.

The section labeled “Sustainability in the Presence of Ocean Acidification” identifies how ocean acidification has effected productivity of shellfish yields in aquaculture firms in the Pacific Northwest, as well as trajectories for worsening acidic conditions.

The section labeled “Profitability in the Presence of Ocean Acidification” presents data derived from specific reports, as well as trajectories of future profit that correlate with a 50-year business-as-usual scenario of ocean acidification’s impact on the shellfish industry.



### *Analyzing Mitigation Strategies*

This research utilizes both qualitative and quantitative assessment of the strategy of state and federal agencies in mitigating the degradation of its seafood industry and marine ecology. This analysis utilizes both “hard systems” and “soft systems” thinking paradigms. The hard systems approach utilizes quantitative assessment of how the available scientific knowledge can be employed in the decision-making process (Srivastava 2009). Quantitative research focuses on where, what who and when questions about a certain phenomenon, such as ocean acidification’s impact, however it fails to holistically answer why and how a phenomenon occurs (Lagos et al 2003). Hard systems thinking assumes that decision-making is top-down and rational (Srivastava 2009). While the hard systems approach is useful in extracting the current use of available science, its assumptions are not always realistic. Hard systems thinking ignores political environments that yield irrational and inefficient outcomes (Srivastava 2009). Special interest groups, PAC contributions, and other influencing factors often shape political agendas that do not always act rational or in the best interest of the populace. The soft thinking paradigm accounts for these shortcomings.

The soft systems thinking paradigm challenges the aspects of the previously mentioned conventional paradigm. That is, it takes into account the uncertainties and conflicts that arise when different stakeholders interact to reach certain goals (Srivastava 2009). Soft systems thinking integrates qualitative data. It mainly focusses on social interaction, a necessity for citizens and stakeholders in a policy analytical process (Srivastava 2009). A policy cannot be deemed equitably successful, for democratic reasons, if it ignores the needs of its citizens and stakeholders.

Soft systems thinking engages qualitative research, an inquiry process of understanding based on distinct methodological traditions of inquiry that explore a social/human problem (Lagos

et al 2003). Qualitative data includes in depth descriptions of circumstances, people, interactions, as well as common beliefs and quotes. The qualitative data in this paper includes content from peer reviewed journals, scientific reports on ocean acidification, and government documents in the form of text. The quantitative data present in this document consists of trajectory models and present reports on shellfish harvests and sales, as well as shellfish firm expenditures. The contents of these texts will be compared and analyzed against one another in order to search for any distinct trends or themes.

The qualitative research approach consists of research categories: contextual, diagnostic, and evaluative. The contextual category aims to identify the form and nature of what exists (Lagos et al 2003). This research will contextualize ocean acidification qualitatively by identifying the attitudes, experiences, and perceptions of the region's populace on the impact of ocean acidification and dwindling shellfish populations as well as identify the threatening elements of ocean acidification on marine ecosystems and economy.

The diagnostic category examines the reasons for the existence of the phenomenon. This research identifies the underlying factors that contribute to the ecological and economical degradation of ocean acidification.

The evaluative approach analyzes the effectiveness of mitigation strategies. This research utilizes the evaluative approach to measure the degree of success of mitigation strategies on inhibiting the increase of ocean acidification.

### *Sustainability in the Presence of Ocean Acidification*

In order to effectively measure how mitigation strategies, limit the ecological and economic impact of ocean acidification on shellfish populations, the ecological and economic impacts must be correlated. Private economic revenue (restaurant sales, harvests, and recreational harvests) from shellfish, as well as job generation and state revenue will be calculated from annual state reports. In addition, the rate of decline of shellfish populations due to ocean acidification will be calculated by investigating ecological shellfish reports and their rates of population decline that is coordinated with decreases in pH levels.

This thesis analyzes and portrays how coastal regions are more prone to higher levels of acidification due to localized events. The rate of pH decline as well as its associated physiological degradation on mollusks is analyzed through a cross examination of different studies. A chart is used to illustrate when physiological functions begin to fail at specific pH levels. This is useful in coordinating future trajectories of mollusk production.

Using information about the economic revenue from shellfish harvests and the ecological state and trend of shellfish populations in the Pacific Northwest, models illustrate ocean acidification's associated risk on the regional shellfish industry (Neuman 2002).

### *Profitability in the Presence of Ocean Acidification*

Data collection, extraction, and analysis plays a central role in relating the ecological and economical effects of ocean acidification on the shellfish industry in the Pacific Northwest. Data is extracted from peer reviewed journal studies, agency reports, trade reports, and government documents regarding the ecological processes and rates of ocean acidification, available direct and indirect jobs in the shellfish industry, annual reported revenues from shellfish hatcheries, and

indirect revenues from industries that rely on shellfish hatcheries. Cross examination of reports is necessary to ensure a homogeneity of data regarding shellfish and its associated industries prior to data analysis (Crowther et al. 2010).

In order to identify industrial trends of the profitability of shellfish, bar graphs illustrate revenue totals for each individual state (Washington, Oregon, and Alaska).

The central question of this thesis aims to correlate the ecological effect of ocean acidification on shellfish organisms and its associated threat to the shellfish industry in the Pacific Northwest of the United States. In order to properly assess this correlation, a regression test is run between the rates of acidification and decrease in total revenues and increase in costs. These results are portrayed visually via line graphs between the independent variable (ocean acidification) and the dependent variable (industrial revenues and costs) to illustrate a relationship between ocean acidification and the economic vitality of the shellfish industry in the Pacific Northwest.

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## RESULTS

The following section presents data derived from various sources. The “Ocean Acidification Impact” section presents data derived from various studies of how the processes of ocean acidification will affect the shellfish productivity and profitability of the shellfish industry in the Pacific Northwest.

The section labeled “Profitability and Costs of Ocean Acidification” identifies the current costs, yields, amount of jobs created, and the revenue of the shellfish industry.

### *OA Impact*

In the past 200 years, there has been an observed and recorded atmospheric carbon dioxide

increase of 36%. About 33% of this increase has diffused into Earth's oceans (Miller et al.) Increased acidification has resulted in calcification rates declining in unison with bicarbonate concentration, creating the current crisis of shellfish production. The bicarbonate to aqueous carbon dioxide ratio has been observed to decrease from 4:1 to 1:1 since the industrial revolution. Reduced export of calcium carbonate from high latitudes has resulted in an increase of ocean carbon dioxide uptake. While this process is reducing atmospheric carbon absorption, it is expected to increase ocean carbon dioxide uptake from 6-13 pentagrams, greatly diminishing organism's ability to calcify (Anthropogenic ocean acidification over 21st century and impact on calcifying organisms)

A study conducted by Whitman Miller and Amanda Reynolds has identified the impact of carbon dioxide on two economically valuable oyster species: *Crassostrea virginica* and *Crassostrea ariakensis*. Larvae of these species were grown under four different carbon regimes: 280, 380, 560, 800 parts per million. These conditions simulated pre-industrial concentrations and future possible concentrations in the next 50-100 years. Larval growth was measured using image analysis and calcification was measured using a chemical analysis of the proportion of calcium content in shells. While the effect on *Crassostrea ariakensis* varied and was not held significant, *Crassostrea virginica* experienced a 16% decrease in shell area as well as a 42% reduction in calcium content of its shells (2009). Under-saturation of the aragonite state occurred in all three carbon regimes. This process is often affiliated with increased periods of upwelling or nutrient accumulation, resulted in immediate deleterious effects of mollusk shell formation. Shell formation of juvenile mollusks was inhibited after only 48 hours of exposure. Adult mollusks also experienced degradation of shell integrity after a 48-hour period of exposure. Diminishing the aragonite saturation state is another consequence of ocean acidification, and as shown in this study,

it can have immediate damaging effects on commercially valuable mollusk populations (Miller and Reynolds 2009).

Aquaculture operations utilize the tides to capture incoming seawater to create an environment to grow larvae. However, the variability of the of incoming seawater chemistry has been identified as a threat to larval growth and development. Coastal zones experience an accelerated rate of acidification compared to open oligotrophic ocean due to upwelling that has diminished the aragonite saturation state, increased nutrient content in addition to the absorption of carbon dioxide from the atmosphere. These processes are expected to cause a 43% loss of mollusks by 2100 due to decreased calcification rates (Narita).

The Pacific Northwest Shellfish industry has experienced significant seed shortages since 2007 (Waldbusser) Whiskey Creek Shellfish hatchery has claimed to have pH levels drop to as low as 7.6 pH. This resulted in an annual production of only 2.5 billion eyed larvae, which is an alarming 75% reduction in normal numbers (Waldbusser) Pacific aquaculture operations account for 48% of the production for total U.S. aquaculture production (Waldbusser and Barton). U.S. domestic shellfish supply greatly depends on the Pacific Northwest region's vitality of shellfish production.

#### ***Current profitability and costs of OA***

Marine mollusks are valued at \$15 billion U.S. and consist of 9% of the global total fishery production, 12% of the total U.S. fishery production, 15% of the totally European Union fishery production, and 20% of China's total fishery production.

Mollusk sales by fishermen alone generate about \$750 million in the Pacific Northwest region (not accounting costs of inputs and labor). However, due to acidity, a study by Cooley and

Doney predicts a 10-25% decrease in mollusk harvests over the next 50 years. This would coincide with a \$200-500 million decrease in sales for mollusk harvesters (2009).

A recent survey study done by Northern Economics assessed the viability of the shellfish aquaculture industry in the Washington and Oregon. Data regarding Alaskan expenditure was unavailable. In Washington, there are currently 330 shellfish growers. 43 (13%) of which responded to the survey. Firms range from hiring zero (self-employed firms) to 400 employees. 14 (33%) of these firms claimed to be self-employed. Nine firms (21%) claimed to hire 1-10 employees. Ten firms (23%) claimed to hire 11-30 employees. Five firms (12%) claimed to hire 31-50 employees. Five firms (12%) claimed to hire 50 employees or more. The minimum employment per farmed acreage was .01 persons per acre, while the maximum employment per farmed acreage was 1 person per acre. Washington's shellfish industry accounts for 1,840 direct jobs statewide, consisting of a ratio of one employee per 100 farmed acres (Northern Economics). Total revenue of shellfish in Washington consisted of \$90.3 million in 2011, with \$89.4 million being derived from shellfish sales.

Production volume of oysters in Washington are just under 25,000,000 pounds. Production volume of clams are 8,250,000 pounds. Production volume of geoducks are 1,500,000. Production volume of mussels are 2,500,000 pounds (Northern economics).

Washington Department of Fish and Wildlife (WDFW) accounts for the amount of harvest pounds per shellfish species harvested in the state. Oysters consisted of 8,736,978 harvest pounds. Clams consisted of 8,207,220 harvest pounds. Geoducks consisted of 1,351,310 harvest pounds. Mussels consisted of 2,947,456 harvest pounds (Northern economics). Total harvest pounds in Washington accounted for 21,242,964 pounds.

There are 29,663 acres of non-tribal permitted shellfish farmed lands in Washington. Growers that own or lease shellfish farms spent a total of \$69.8 million in 2010, with \$56.6 million being spent in the State of Washington itself (Northern Economics).

Three firms (8%) spend greater than \$10 million per year. Seven firms (19%) spend between \$1-10 million per year. Nine firms (25%) spend \$500K-1 million per year. Seven firms (19%) spend \$100K-500K per year. Three firms (8%) spend \$50k-100k per year. Seven firms (19%) spend less than \$25K a year (Northern economics). On average, aquaculture firms in Washington spend about \$3,100 per acre. 37.8% of tidelands are left unfarmed, resulting in a \$4,988 spent per farmed acre.

Current Washington oyster harvests weigh in at 61,000,000 pounds resulting in \$57,750,000 in sales. Current clam harvests weigh in at 9,520,000 pounds resulting in \$19,550,000 in sales. Mussel harvests currently weigh in at 2,750,000 pounds resulting in \$3,162,500 in sales. Geoduck harvest currently weigh in at 1,650,000 pounds resulting in \$20,100,000 in revenue. Larvae and seed account for \$7,000,000 in sales (Barton et al. 2015).

The following data is aquaculture expenditures by type in Washington. Seed and shellfish accounts for 18% of total expenditures. Capital accounts for 10% of total expenditures. Freight accounts for 6% of total expenditures. State and local fees account for 1% of total expenditures. Payroll accounts for 29% of total expenditures. Benefits account for 5% of total expenditure. Federal fees account for 5% of total expenditure. Gas and fuel account for 2% of total expenditure. Leases account for 2% of total expenditure. Insurance accounts for 2% of total expenditure. Other costs account for 2% of total expenditure (Northern economics). This data is visually represented in figure 2 Washington expenditure.

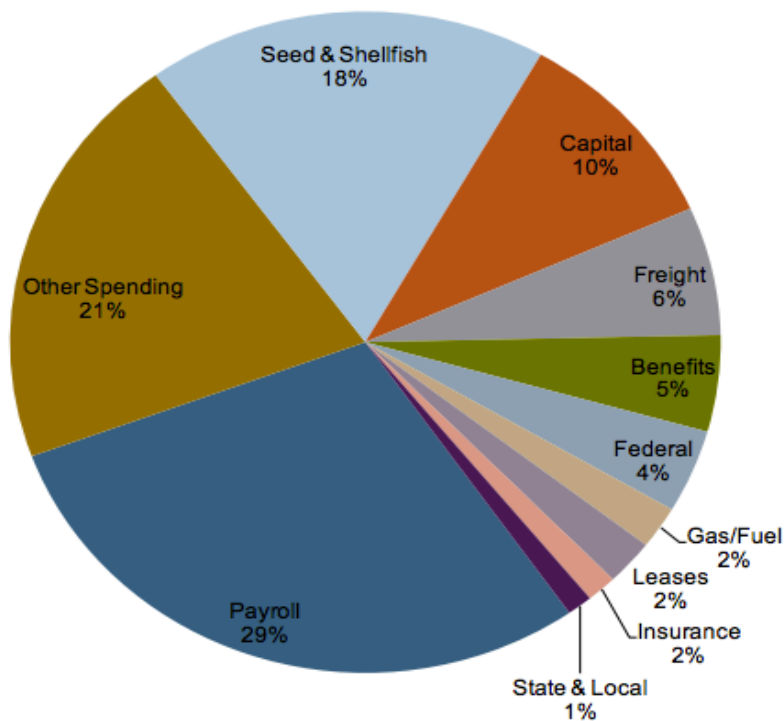


In total, output costs add up to \$184,425,700. Employment costs add up to \$2,710. Labor income adds up to \$77,122,600. \$101.4 million was spent in the Washington economy as a result of shellfish aquaculture operations. It generated a total revenue of \$184 million. Shellfish farms in Washington are responsible for 1,900 direct jobs and influence an additional 810 indirect/induced job activity. Shellfish harvests influence a total of 2,710 jobs in Washington (Northern Economics).

Washington shellfish farmers paid about \$37.3 million in wages in 2010. This economic activity generated an additional labor income of \$39.9 million dollars, with a total of \$77.2 million in labor income (Northern Economics)

FIGURE 1: WASHINGTON EXPENDITURE

Figure 7. Washington Shellfish Aquaculture Expenditures by Type, 2010



Source: Northern Economics, Inc. using PSI Survey responses, 2012

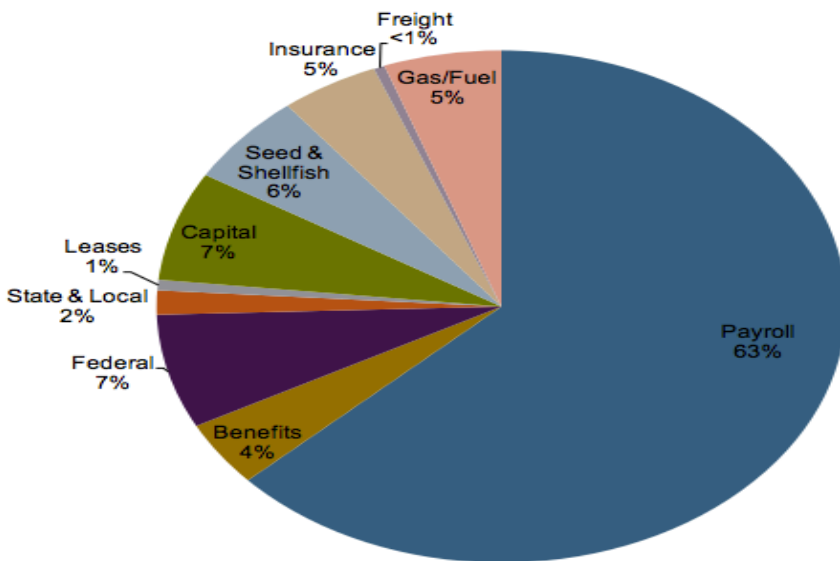
FIGURE 2 WASHINGTON EXPENDITURE

This survey conducted research in Oregon as well, however with a much less response rate (8/23 firms responded). According to the survey, shellfish farms account for 3,043 acres of land, 32% of which are used for farming. There are 107 direct jobs produced from the shellfish aquaculture industry in Oregon, with firms ranging from zero (self-employed) to 85 employees. The employee to acre ratio in Oregon is 1 employee per 23 acres of tideland under cultivation, resulting in 0.04 people per acre (Northern Economics).

Current Oregon harvests weigh in at 2,379,988 pounds resulting in \$2,253,135 in sales. Clams, geoducks and mussels were not available. Shellfish larvae and seeds accounted for \$750,000 in sales (Barton et al. 2015)

There is a reported \$9.7 million worth of total generated revenue from the shellfish industry in Oregon. \$9.3 million worth of revenue directly from shellfish sales in 2011. Expenditure estimates in Oregon are about \$377,000. Payroll accounts for 63% of total expenditure. Benefits account for 4% of total expenditure. Federal fees accounts for 7% of total expenditure. State and local fees account for 2% of total expenditure. Leases account for 1% of total expenditure. Capital accounts for 7% of total expenditure. Seed and shellfish account for 6% of total expenditure. Insurance accounts for 5% of total expenditure. Freight accounts for less than 1% of total expenditure. Gas and fuel accounts for 5% of total expenditure (Northern economics).

**Figure 10. Oregon Shellfish Aquaculture Expenditures by Type, 2010**



Source: Northern Economics, Inc. using PSI Survey responses

**FIGURE 3 OREGON EXPENDITURE**

Current Alaskan oyster harvests weighed in at 206,709 pounds resulting in sales of \$441,781. Current Alaskan clam harvest weighed in at 7,839 pounds and resulted in \$24,841 of sales. Current Alaskan mussel harvests weighed in at 1,988 pounds and resulted in \$6,610 in sales. Alaskan shellfish larvae and seeds resulted in \$126,000 in sales (Barton. Et al. 2015). The Alaskan shellfish industry contributes to \$591,622 in total revenue sales. Alaskan shellfish aquaculture expenditure was unavailable.

In total, the Pacific Northwest region accounts for about \$270 million in revenue for the U.S. shellfish industry.

		Oysters Current*	Clams Current*	Mussels Current*	Geoduck Current*	All Shellfish Larvae and Seed	Total Current
Washington	Pounds	61,000,000	9,520,000	2,750,000	1,650,000		74,920,000
	Sales	\$57,750,000	\$19,550,000	\$3,162,500	\$20,100,000	\$7,000,000	\$107,562,500
California	Pounds	9,270,995	741,463	315,000			10,327,458
	Sales	\$12,361,326	\$830,000	\$945,000		\$2,300,000	\$16,436,326
Oregon	Pounds	2,379,988					2,379,988
	Sales	\$2,253,135				\$750,000	\$3,003,135
Alaska	Pounds	206,709	7,839	1,988			216,536
	Sales	\$441,781	\$24,841	\$6,610		\$126,000	\$599,232
<b>Total</b>	<b>Pounds</b>	<b>72,857,692</b>	<b>10,269,302</b>	<b>3,066,988</b>	<b>1,650,000</b>		<b>87,843,982</b>
	<b>Sales</b>	<b>\$72,806,242</b>	<b>\$20,404,841</b>	<b>\$4,114,110</b>	<b>\$20,100,000</b>		<b>\$117,425,193</b>

FIGURE 4 (BARTON ET AL. 2015) HARVEST WEIGHTS AND SALES

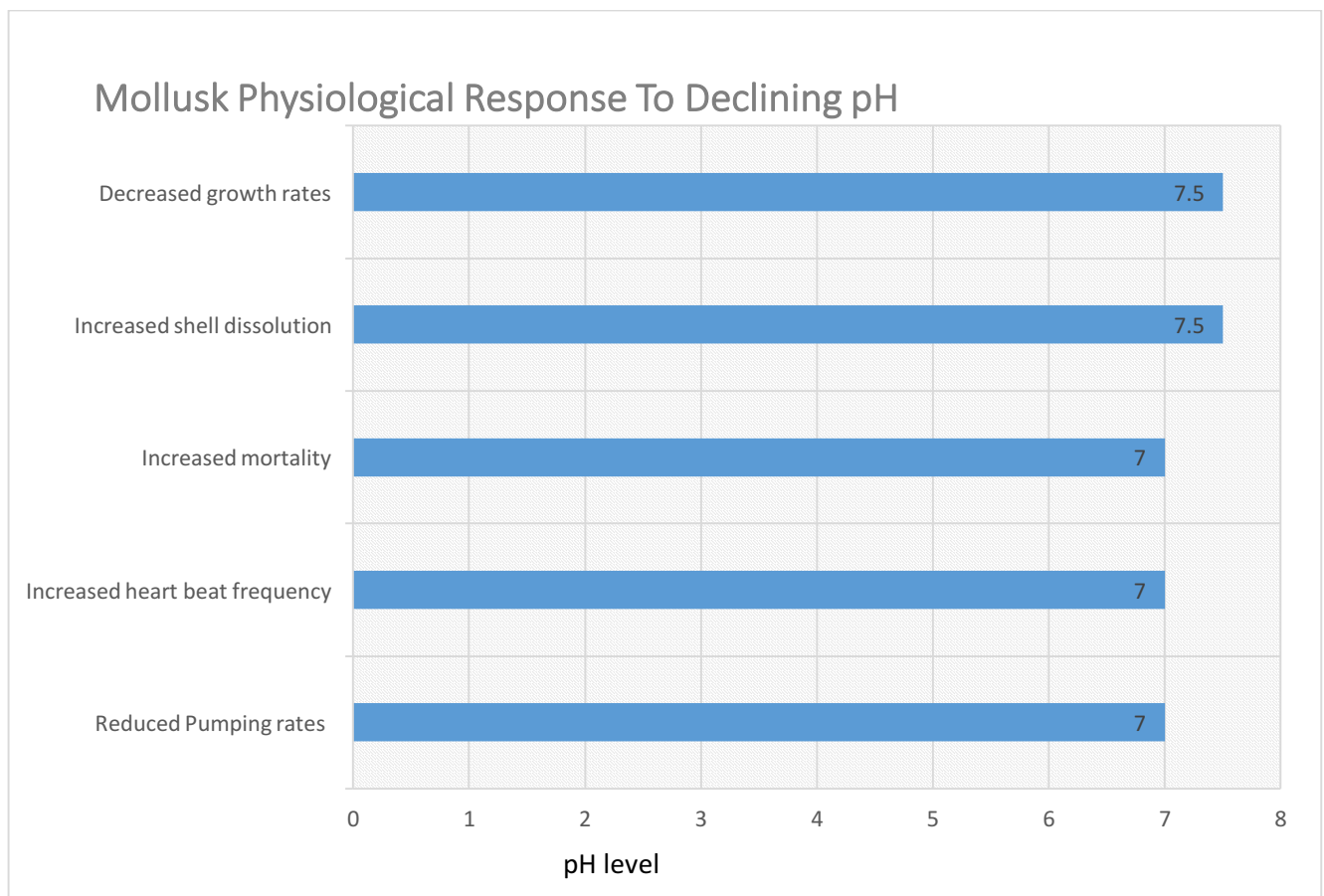
## ANALYSIS OF RESULTS

This section analyzes the impact of ocean acidification in terms of sustainability and profitability. Sustainability focuses on future trajectories of the ability to produce yields as the process of ocean acidification increases. Profitability identifies how the future of ocean acidification will impact total revenues of the industry.

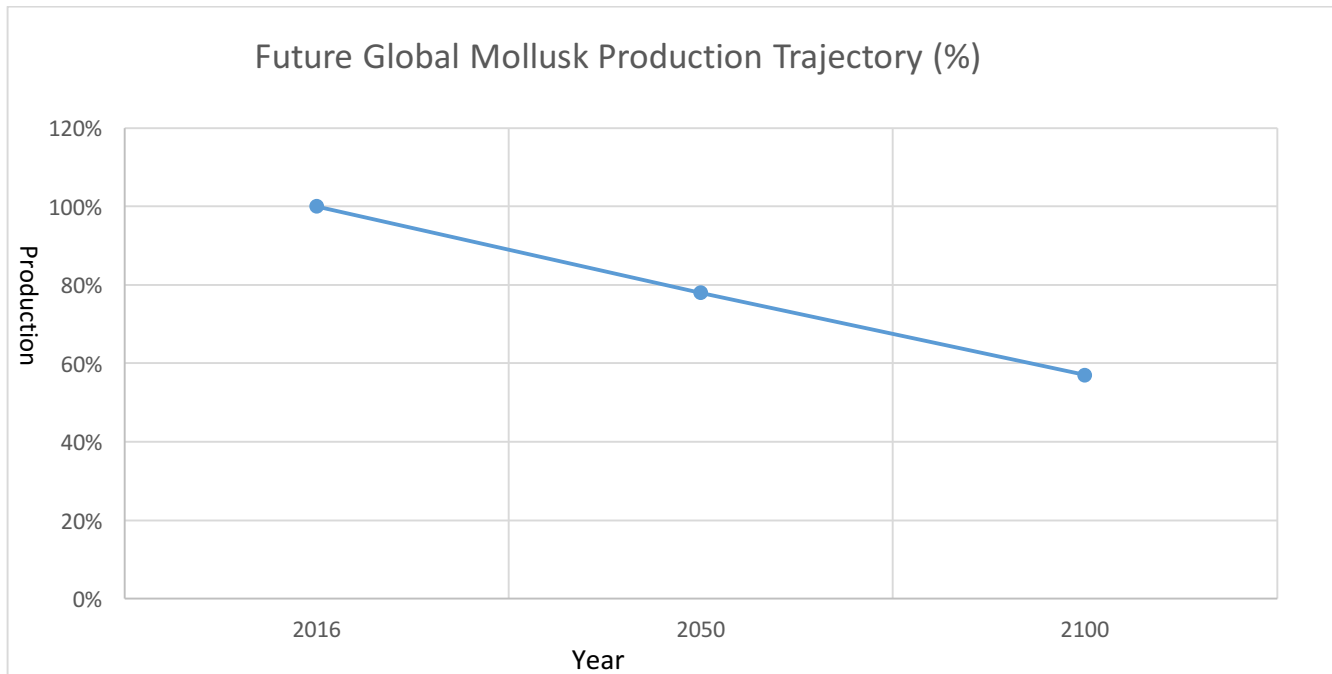
### *Sustainability*

Ocean acidification has a direct deleterious impact on the physiological processes of shelled mollusks. Essentially, increased acidification levels create a corrosive environment for calcifying organisms and can lead to a disturbance in the internal physiological processes of mollusk organisms. A study conducted by Gazeau et al. identified these physiological impacts and the associated pH levels that catalyze these events. At 7.5 pH shell dissolution and decreased growth

rates occur. At 7 pH mollusks experience reduced pumping rates (a feeding mechanism), abnormal behavior, increased heart frequency, and increased mortality. Larvae are particularly at risk at this pH level (Gazeau et al. 2013). The degradation of mollusk physiological processes has essentially resulted in increased mortality rates of mollusks and a decrease in mollusk production for shellfish aquaculture. This is already having an impact on harvest yields and sales. The graph below illustrates at what pH levels do specific physiological responses occur.



**FIGURE 5 MOLLUSK PHYSIOLOGICAL RESPONSE TO DECLINING PH**

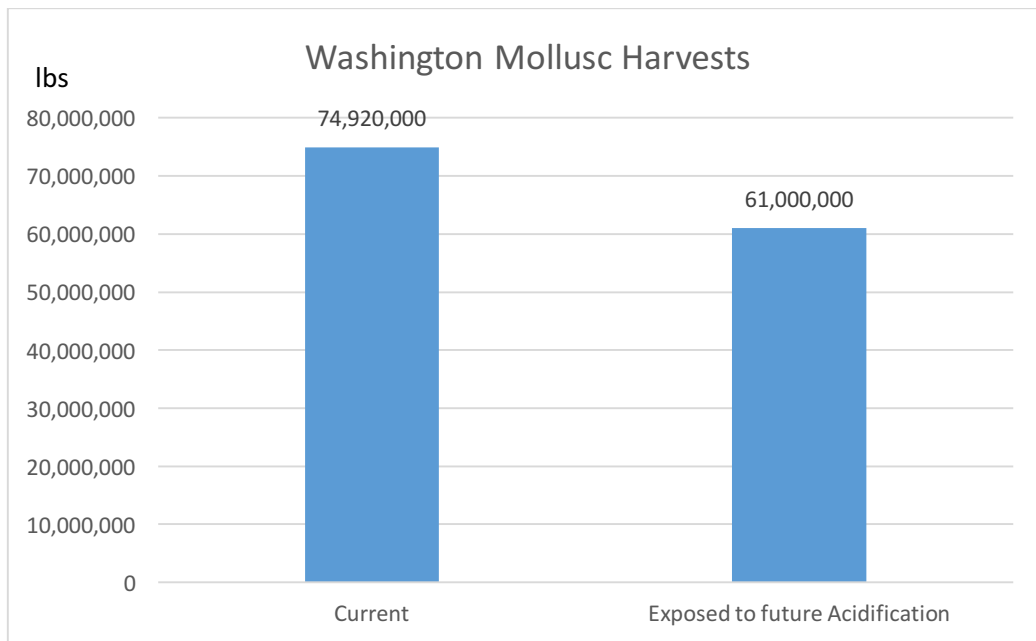


**FIGURE 6 FUTURE GLOBAL MOLLUSK PRODUCTION TRAJECTORY**

With a consistent, business-as-usual scenario trajectory of global carbon emissions and oceanic absorption of carbon dioxide, a study by Narita predicts that shellfish aquaculture firms will experience 43% in global mollusk production by 2100 (Narita). Annually this would be about a 0.5% loss in production.

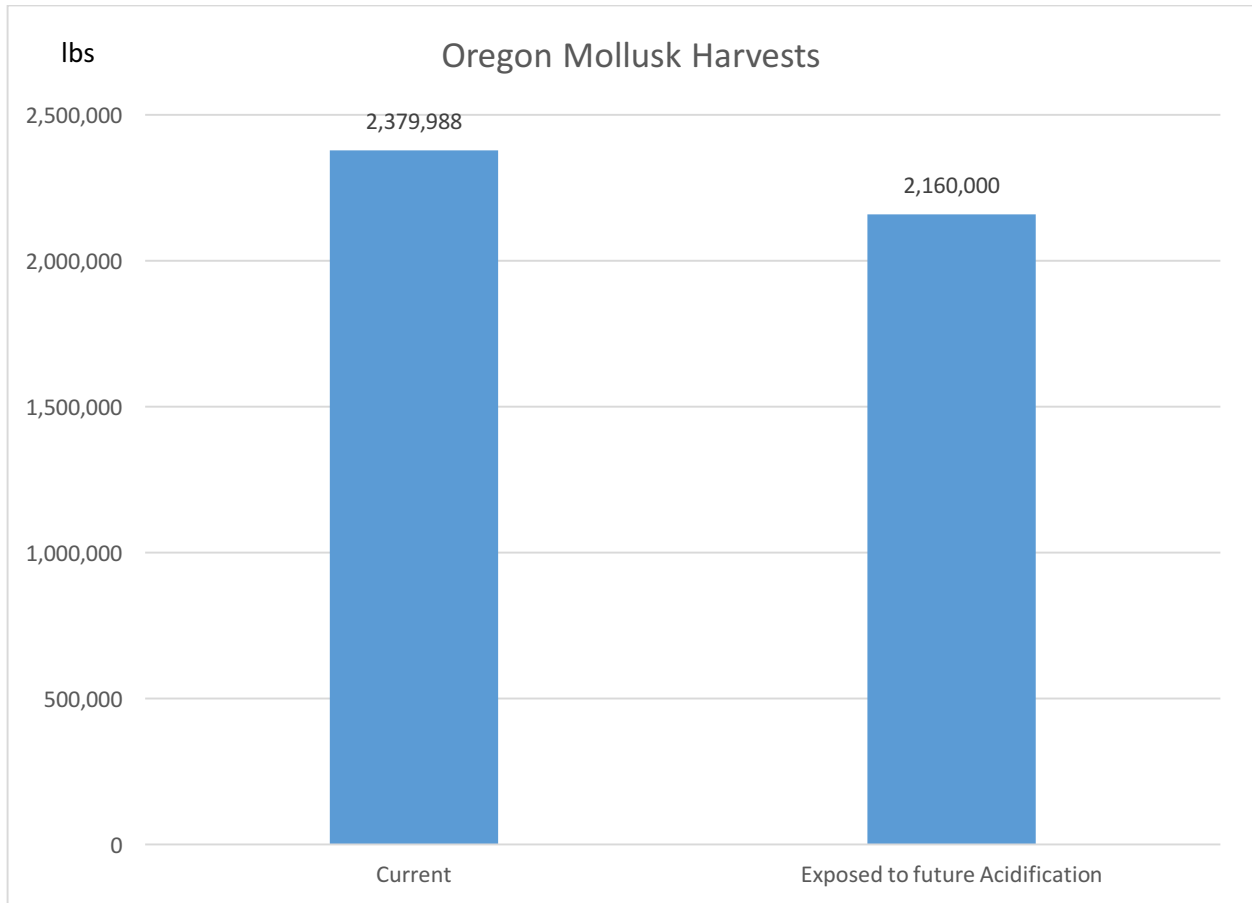
Regional populations, especially that of the U.S. Pacific Northwest, are even more at risk due to localized inputs of additional externalities that amplify and accelerate acidification. A study conducted by Cooley and Doney has identified a 10-25% decrease in mollusk harvests by 2060 due to acidifying oceans as a distinct trajectory. This percentage, as well as its associated implicit cost of decreased harvests, has been applied to the harvest weights and revenues in Washington, Oregon and Alaska (see the Results section) in order to show how ocean acidification is impacting the shellfish industry in the Pacific Northwest. Washington state consists of an annual harvest of 61,000,000 pounds of oysters, 925,200,000 pounds of clams, 1,650,000 pounds of geoducks and

2,570,000 pounds of mussels, totaling to 74,920,000 in mollusk harvests. By applying the predicted decrease in harvests, ocean acidification has the potential to diminish these harvests by a range of 7,492,000-18,730,000 pounds, resulting in mollusk production 67,428,000-56,190,000 pounds of harvested mollusks in the presence of ocean acidification over the next 50 years.



**FIGURE 7 WASHINGTON MOLLUSK PRODUCTION**

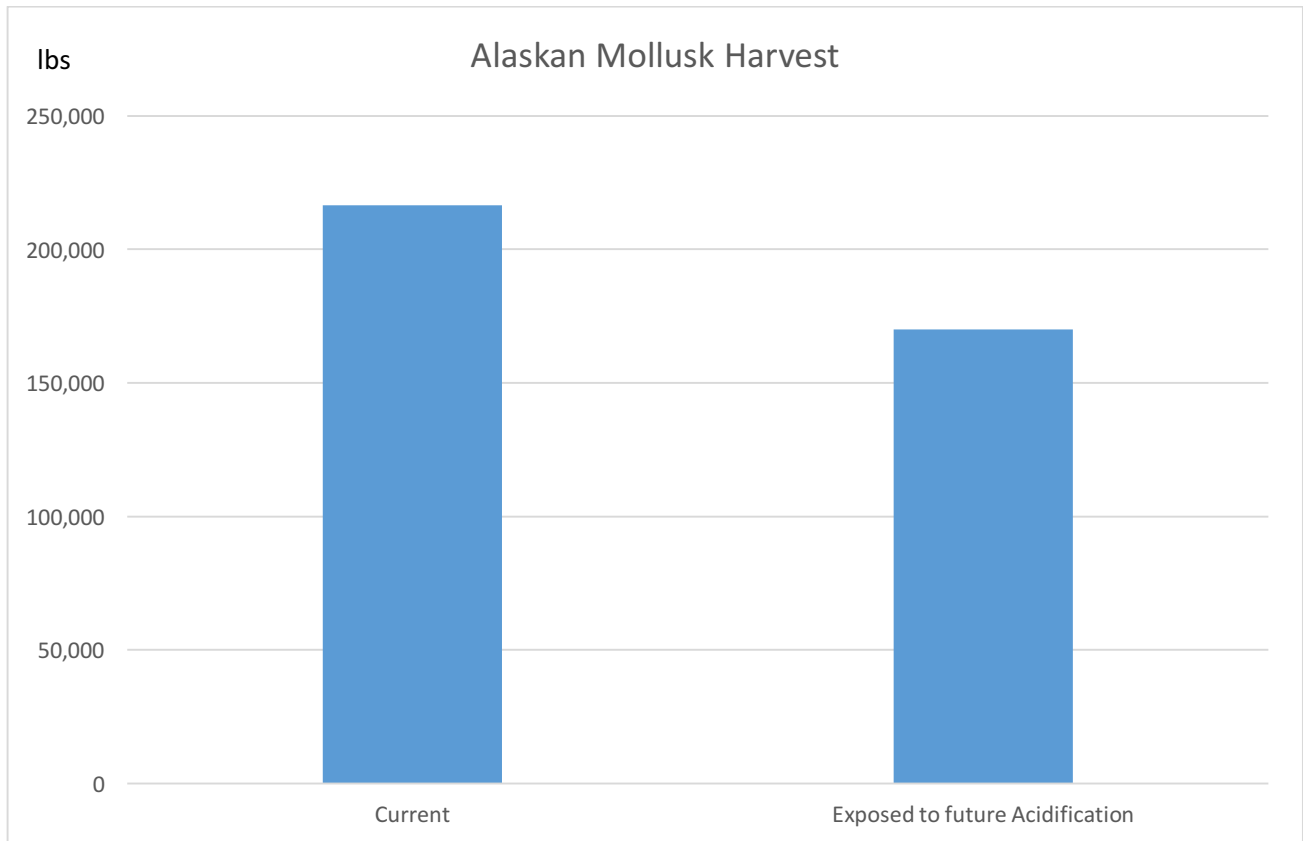
Oregon currently accounts for 2,379,988 harvest pounds of mollusks for the Pacific Northwest Shellfish Industry. In the presence of ocean acidification, low pH values will diminish this yield from 10-25%. This would decrease harvests by 237,998.8-594,997 pounds. Oregon shellfish harvests would drop from 2,379,988 pounds to a range of 2,141,989.2-1,784,991 pounds per annual harvest.



**FIGURE 8 OREGON MOLLUSK PRODUCTION**

Alaskan oyster, clam, and mussel harvests have resulted in a total annual yield of 216,536 harvest pounds. Ocean acidification will present pH scenarios that decrease this yield 21,653.6-54,134 pounds. This would result in annual Alaskan shellfish yields ranging from 194,882.4-162,402 pounds.

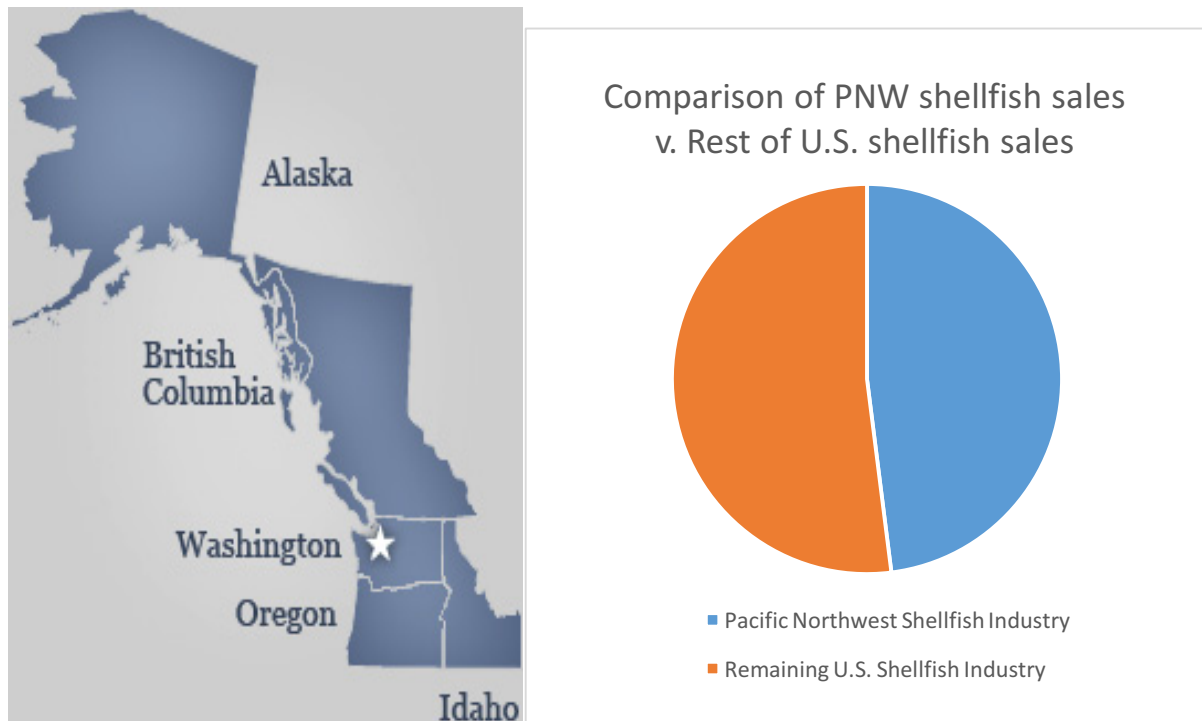




### *Cost of Ocean Acidification*

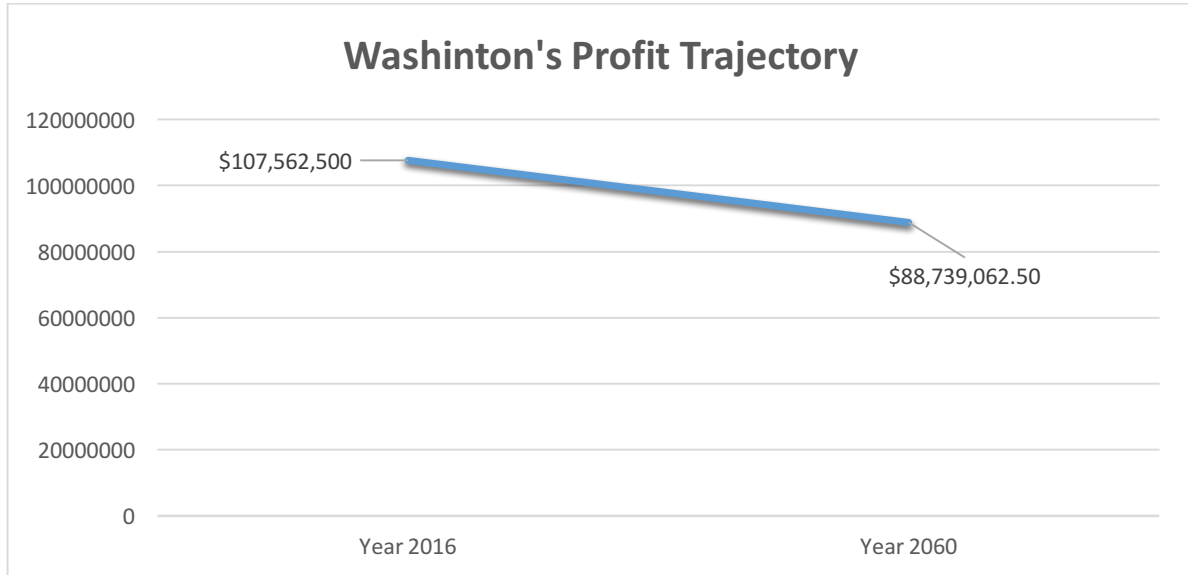
The results from the Cooley and Doney study show a decrease in mollusk harvests due to increased ocean acidification. This is predicted to result in a \$200-500 million decrease in revenue for the U.S. shellfish industry. The Pacific Northwest accounts for about 48% of shellfish production in the U.S., generating about \$2 billion in sales. Ocean acidification in the Pacific Northwest will decrease shellfish sales by \$96-240 million, as the region will account for approximately 48% of total costs experienced by the U.S. shellfish industry. Total sales for aquaculture firms in the Pacific Northwest are expected to decrease sales by a margin of \$1.9-1.6 billion. The U.S. shellfish industry is expected to undergo a 10-25% decrease in sales in the next 50 years. The Pacific Northwest is expected to undergo anywhere from a 1-12% decrease in those

sales.



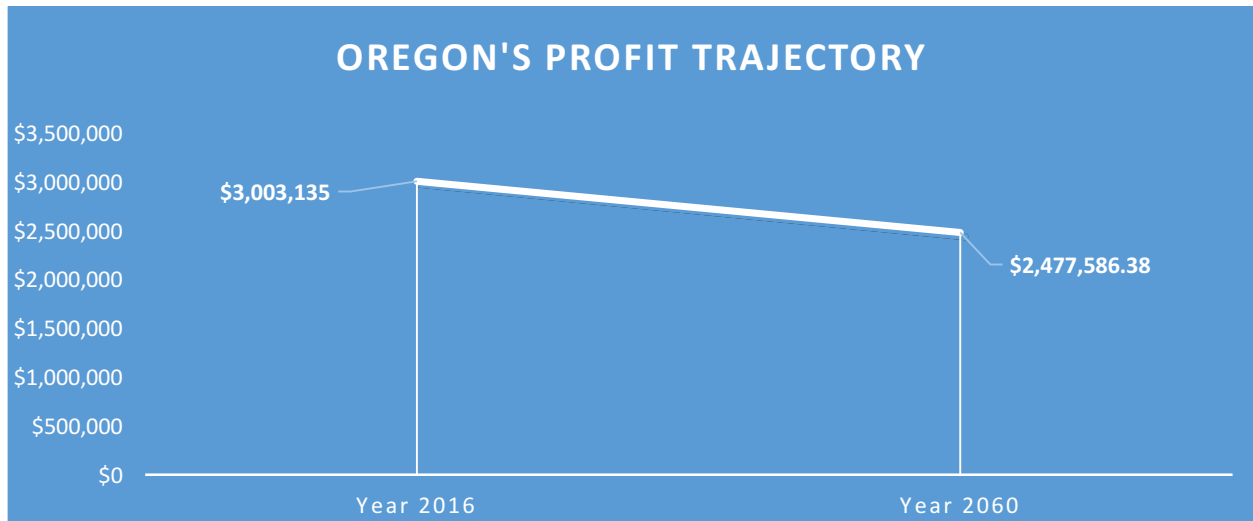
**FIGURE 4 REGION AND SALES**

The figure 4 illustrates the Pacific Northwest's share of the U.S. shellfish industry. While this region generates a large portion of revenue in the U.S. shellfish industry, it also faces much of the oncoming the costs and challenges of ocean acidification, which will be discussed further in the following sections.



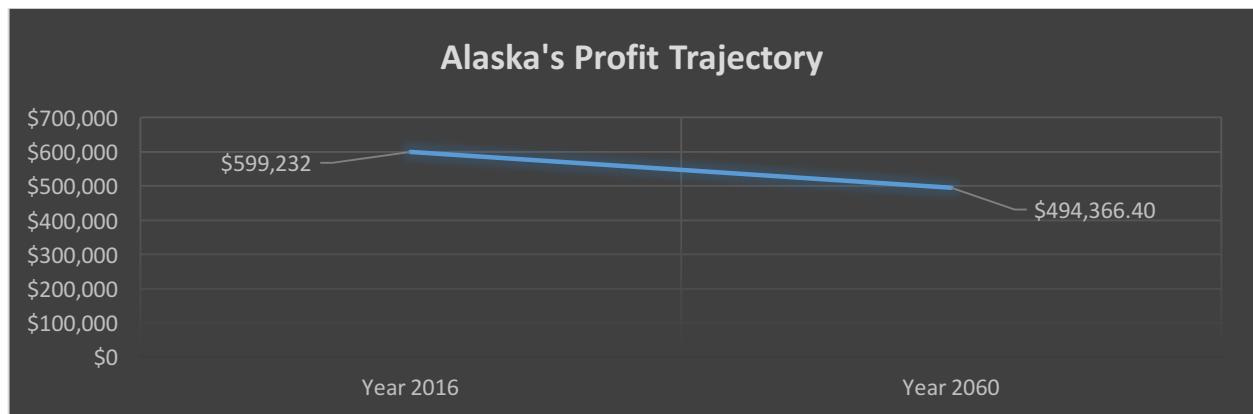
**FIGURE 9 WASHINGTON PROFIT TRAJECTORY**

Current mollusk sales in Washington are at about \$107,562,500 per year (Barton et al. 2015). These sales are expected to drop 10-25% (Narita et al 2010). This would drop annual sales for the Washington shellfish industry to about \$88,739,062.50.



**FIGURE 10 OREGON PROFIT TRAJECTORY**

Current mollusk sales in Oregon account for about \$3,000,195 (Barton et al. 2015). Similar to Washington, these sales are expected to decrease 10-25% in the next 50 years (Narita et al. 2010), resulting in Oregon's shellfish industry to consist of sales of \$2,477,586.38.



**FIGURE 11 ALASKA'S PROFIT TRAJECTORY**

Current mollusk sales in Alaska account for about \$599,232 (Barton et al. 2015). Similar to Washington and Oregon, these sales are expected to decrease 10-25% in the next 50 years (Narita et al. 2010). This would drop mollusk sales in Alaska to about \$494,366.40

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## DISCUSSION

It is evident, based on the data received from multiple reports, that ocean acidification is a direct threat to the health and wellbeing of the shellfish industry in the Pacific Northwest of the United States. Ongoing combustion of fossil fuels will continue to decrease pH levels in oceans, creating a corrosive environment for mollusks and other forms of commercially valuable shellfish. In addition, excessive use of agricultural nutrients and its associated terrestrial run off, seasonal upwelling, and intrusion of brackish water at river-mouths causes a localized acidifying effect on coastal waters that harbor and supply many shellfish aquaculture operations in the Pacific Northwest region.

While ocean acidification is a direct threat to marine organisms, it indirectly threatens entire coastal food webs. Phytoplankton species are severely threatened by acidifying oceans. This will negatively affect juvenile fish species who rely on phytoplankton populations for prey (Doney 2007).

Events such as upwelling, nutrient accumulation, eutrophication, and river discharge may cause a localized spike in ocean acidification. Upwelling in the Pacific Northwest begins in early spring when the Aleutian low pressure system moves to the northwest, causing the Pacific high pressure system to move northward, increasing northwesterly winds. These winds drive surface-water offshore. Upwelling of CO<sub>2</sub> rich waters replace the displaced surface water on the continental shelf. This process lasts until late summer/fall. These waters are rich in carbon content and low in oxygen content and have decreased pH levels to a recorded <7.75 (Feely et al. 2008).

Terrestrial runoff and freshwater discharge also contributes their fair share to ocean acidification. Nutrient pollution causes local acidification due to feedback loops involving

biological growth, metabolism, and decay. These processes deplete oxygen content and create “dead zones” which are rich in carbon dioxide. While this is a short-term effect, it can decrease pH levels up to 0.8 units (Kelly et al. 2012).

These localized events explain why coastal regions experience more extreme acidic conditions and provide implications for policy and mitigation strategy. While The diffusion of atmospheric carbon into the oceans is does not have the same acute effect as localized acidifying events, it is the process that will drive the longevity and continuation of ocean acidification for the foreseeable future.

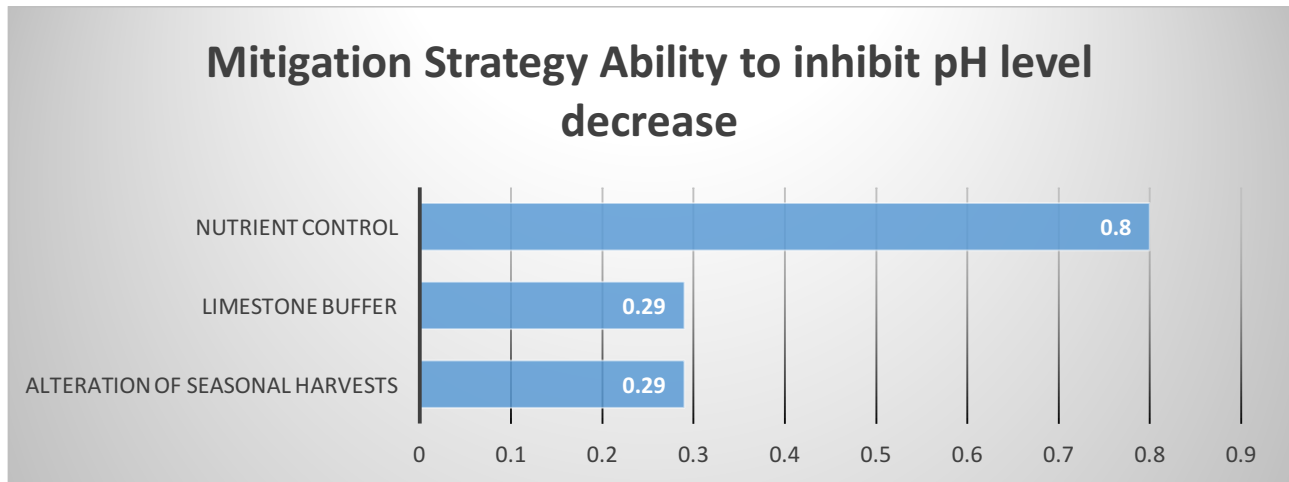
The Pacific Northwest is especially at risk from upwelling due to its geographic location and exposure to the previously mentioned weather patterns. The water chemistry of coastal areas and estuaries, such as Puget Sound, are particularly influenced by upwelling (Adelsman et al. 2012). Mitigation strategies have been developed to offset the spike in acidity that is associated with upwelling. Addition of excess calcium carbonate in the form of powdered limestone has been shown to neutralize the acidity of absorbed CO<sub>2</sub>. This allows for calcium carbonate to stay undissolved and available for the shells of mollusks (Norton).

Another mitigation strategy is seasonal alteration of harvests. Since upwelling occurs during spring and extends into early fall (Feely et al.), aquaculture operations are beginning to use different times of the year to plant their larvae. This knowledge has been observed and made available due to increases in the ability to monitor acidity levels in nearby seawater. Current average ocean pH is about 8.04 +/- 0.3 (Lachkar et al. 2012). Upwelling has said to increase surface water acidity, with pH levels ranging from 7.75 and lower. Upwelling mitigation strategies of alternative seasonal harvests, as well as the addition of a limestone buffer can sustain normal pH

levels during seasonal upwelling. In essence, this can inhibit a 0.29  $\pm$  decrease in pH levels.

Terrestrial runoff containing nutrients from agriculture and organic carbon from natural and anthropogenic sources reduces coastal pH levels and increases acidity. In addition, river discharge of freshwater into coastal saltwater estuaries results in acidification due to its organic matter and nutrient content. These forces often cause local positive feedback loops involving biological growth, metabolism, and decay of organic matter which essentially utilizes oxygen and minimalizes dissolved oxygen content, producing acidic “dead zones.” Nutrient runoff and river discharge has the ability to locally lower pH levels up to 0.8 units, although this is a short-term effect and pH levels will eventually subside to its normal state (Kelly et al. 2012).

Local source reduction in acidification due to nutrient and freshwater pollution may arise from new mandates issuing controls on point and non-point sources of runoff. Firms can effectively be pressured into diminishing their externalization of nutrient pollution by tax imposition per unit of pollution. A more direct approach, a command and control policy, would force firms to internalize all pollutant residuals, or face a fee for breaching policy (Kelly et al. 2012). Successful implementation of these policies can effectively inhibit a 0.8 decrease in coastal pH levels.



**FIGURE 12 MITIGATION STRATEGY**

Shellfish firms have engaged local and regional scientific agencies, specifically NOAA, to implement mitigation strategies that effectively combat the effects of ocean acidification on aquaculture operations in order to produce the necessary yields to meet growing demands for shellfish. NOAA has identified a growing U.S. and global increase in demand for seafood consumption and production. This increase in consumption is likely the result of cultural factors such as awareness of seafood's health benefits and a transition away from terrestrial meat due to its contribution to increased carbon emissions. A newly introduced dieting guideline for Americans has essentially doubled seafood consumption. Wild stocks will not be able to sustain this new cultural demand. This has increased the need for imports from foreign aquaculture as well as an increase in domestic aquaculture (Jewett et al. 2014). While aquaculture operations are now being used in favor of wild stocks, the presence of acidification remains to be an immense threat to the industry and its ability to meet the national demand.

Domestically, the U.S. can benefit from aquaculture in a variety of different ways. Restoration of wild marine species, habitat conservation, nutrient removal, food security, and increased health and nutrition are all possible benefits to aquaculture. Economically, aquaculture



can create jobs as well as enable coastal communities to maintain their cultural identity (Jewett et al. 2014). However, the chemical processes associated with acidification has created an adverse environment for aquaculture production of shellfish. While the entire Pacific Northwest region of the U.S. participate in shellfish farming, Washington state boasts the most productive and lucrative aquaculture operations in the country. Shellfish make up an abundant proportion of Washington's marine fauna, many of which greatly contribute to the state's marine commercial activity. Washington is the top provider of farmed oysters, clams, and mussels in the U.S. (Ruckelshaus 2012). The annual sales of Washington shellfish account for almost 85% of the entire U.S. west coast sales. Shellfish sales are directly responsible for a \$270 million annual economic impact of shellfish aquaculture. This employs about 3,200 people (Ruckelshaus 2012). Wild fisheries of oysters, mussels, and clams (geoducks, razors, and littleneck marina) generate over 2/3 of the total harvest value (Ruckleshaus 2012).

It is important to note that ocean acidification does not solely threaten the revenue generated by shellfish aquaculture operations. The value of on-shore harvests does not include the total economic value of wild and hatchery-based seafood harvests. The influence of revenue of these harvests extend well beyond shellfish sales, including licensing for recreational shellfish harvesting, the seafood industry, and the shipping industry. This generates about \$3 million annually in state revenue (Ruckelshaus 2012). Recreational oyster and clam harvests account for about \$2.7 million dollars in revenue to coastal economies. In addition, the Washington state seafood industry generates about 12,000 jobs (Ruckelshaus 2012). On top of that, the seafood industry generates about \$1.7 billion in gross state product. This is derived from profits from seafood harvests as well as employment and revenue at neighborhood seafood restaurants, distributors and retailers (Ruckelshaus 2012).

Not only do the concerns of ocean acidification pertain to coastal economies. Rather, ocean acidification has cultural implications as well. Specifically, the tribal communities of Puget Sound, ocean acidification poses a severe threat to natural resources that withhold immense use value to these tribes (Ruckelshaus 2012). Ocean acidification is a significant danger to the continued identity and culture of tribes who rely on wild shellfish harvest for commercial and subsistent uses (Ruckelshaus 2012). As the salmon populations off the coast of Washington have been steadily declining, tribal fishers have become more dependent on shellfish harvests (Ruckelshaus 2012). This growing dependence on shellfish for tribal communities in the presence of ocean acidification puts a tremendous strain on shellfish populations.

With increasing ecological, economical, and cultural threats, the issue of ocean acidification has begun to be addressed via legislative mandate. The Federal Ocean Acidification Research and Monitoring Act of 2009 was created to identify the economic, ecological and cultural threats of ocean acidification, as well as construct a strategic plan to mitigate this pressing issue. The federal strategic plan has identified seven priority themes that must be accounted for in order to be successful in mitigation of acidification. The first theme is labeled Research to Understand Responses to Ocean Acidification. This theme focuses on the ecological consequences to ocean acidification. It aims to set clear goals and priorities to understand the physiological responses of marine organisms to ocean acidification, ecological interactions with other stressors associated with climate change, impacts to marine food webs, and new approaches to track and record ecosystem responses to ocean acidification.

The second theme is labeled Monitoring of Ocean Chemistry and Biological Impacts. This theme essentially identifies sampling techniques of data that is relevant to ocean acidification. Focusing the collected data with enhance and prioritize new monitoring systems that are necessary

in monitoring ocean acidification.

The third theme is “Modeling to Predict Changes in Ocean Carbon Cycle and Impacts on Marine Ecosystem.” This aims to develop competent models that accurately predict future trends of ocean acidification as a result of business-as-usual trends, a deduction of carbon emissions, or an increase of carbon emissions. In other words, these models will be utilized to develop certain scenarios regarding anthropogenic emitted carbon and its effect on marine ecosystems and food webs.

The fourth theme is labeled Technology Development and Standardization of Measurements. This theme aims to develop specific goals that improve the ability to measure all required parameters through technology development and adequate data quality via measurement standardization.

The fifth theme, “Assessment of Socioeconomic Impacts and Development of Strategies to Conserve marine organisms and ecosystems essentially focuses on assessing the economic and cultural impacts of ocean acidification on coastal communities, as well as developing strategies that mitigate the negative externalities associated with ocean acidification (Jewett 2014).

In order to successfully mitigate the effects of ocean acidification, cooperative efforts must be made in the local, state, federal, and international levels of governance. Washington state has identified six key early actions that must be immediately addressed and acted upon. These steps can be used as a model for the rest of the Pacific Northwest and the entire U.S. shellfish industry. The first calls for an acceleration on reducing carbon dioxide emissions. This effort must transcend both state and national borders as an effort to globally mitigate the increasing flux of carbon dioxide into the atmosphere. It is essential that leaders in these efforts, domestic and foreign, are

adamant on making significant progress in the mitigation efforts of the threats to ocean acidification (Ruckelshaus 2012).

The next key step addresses the need to find new mechanisms of adaptations to ocean acidification. Ocean acidification is a process that has already begun and will continue to be ongoing due to the immense amounts of carbon that is already in the atmosphere. While it is vital to work on diminishing anthropogenic input, it is also crucial that new adaptive strategies are put into place. One strategy is to use vegetative-type purifiers to utilize nutrients that would otherwise be contents of terrestrial run-off (*Strategic Plan for Federal Research and Monitoring of Ocean Acidification*). Inlets and shellfish areas are where this strategy would be most effective. In addition, shellfish hatchery locations must be constantly monitored for water quality as well as pH. In order to preserve economically viable shellfish populations, Washington state calls for an integration of a commercial-scale water treatment method and/or hatchery design in order to protect valuable larvae from being exposed to the corrosive effects within sea water (Ruckelshaus 2012). In addition, it is important to identify species that are most threatened by ocean acidification, monitor their populations and manage an efficient refuge program that preserves these species for the future.

Washington state in addition aims to increase investments in monitoring and investigating the effects of ocean acidification. An established system of local acidification levels and the associated physiological effects of the inhabited fauna is extremely necessary. This can be attained by accurate estimates that quantify anthropogenic, as well as natural inputs into marine ecosystems. Increasing knowledge on acidifying sources, sinks, and flux rates of carbon and other nutrients that contribute to acidification will enable more accurate estimations. This will enhance short-term corrosiveness forecasts that will reveal corrosive conditions for shellfish hatcheries,

growing areas, and other threatened habitats (Ruckelshaus 2012).

Another key step in addressing ocean acidification is to actively engage and inform all stakeholders who are affected by ocean acidification. The first step is to make information that reaches top level of legislation easily accessible to all stakeholders. The next step is to educate local nearby communities and other stakeholders on the effects and threats of ocean acidification so they are able to play an active role in the policy-formation process. Once stakeholders are properly informed, agricultural firms and business can engage in an active line of dialogue with resource managers in developing necessary actions (Ruckelshaus 2012).

The last key action is the implementation of recommendations. There must be either an existing person in the Governor's cabinet or a formation of a new organization that manages, develops, and implements plans to find solutions to ocean acidification. In addition, there needs to be a formation of an ocean acidification science coordination team that is able to form a dependency of resource management and policy on ocean acidification science (Ruckelshaus 2012).

While it is difficult to determine the exact degree to which future acidity levels will reach due to variability in upwelling and localized terrestrial runoff, as well as in the amount of future carbon emissions, the burdens of ocean acidification are already being experienced by the Pacific Northwest Shellfish industry. Economic degradation of the industry has been identified. Correlating scientific research with the effects of ocean acidification on mollusk populations and production has allowed experts to determine how much production and profit is at risk. The question of future sustainability remains. Regional mitigation strategies initiated by NOAA have given insight to shellfish farmers on how to approach this issue. However, these strategies seem to

only delay and minimize the effects to the industry. If a business-as-usual scenario of carbon emissions continue, the shellfish industry's ability to meet its demand is in serious question.

Scientific and economic experts have provided valuable data that have enabled analysis of the economic impact of ocean acidification, however the perceptions of shellfish farmers play a major role in the implementation of mitigation strategies. A study conducted by Mabardry et al. found that commercial stakeholders who had a greater income dependence on shellfish harvests consisted of a higher awareness of climate change and conservation behavior. Their position in the industry and willingness to work to mitigate ocean acidification has influenced domestic policy for strategy implementation. Currently, shellfish hatcheries in the Pacific Northwest have begun to change the time of production, treat their water, and diversify production overseas to make up for production losses due to increased acidification (2015).

There was an overwhelming response of shellfish farmers (97% of respondents) that perceived ocean acidification to be threatening to their livelihoods. However, there was a general gap in awareness of the processes of ocean acidification. Only 13% of respondents claimed to understand very much, with 54% only understanding somewhat, and 33% not understanding at all (Mabardy et al. 2015). Education is one tool that can be used to assist the industry to be able to address this problem. Increasing awareness of the processes of ocean acidification and how it will impact the viability of mollusk populations can give insight into how to properly harvest shellfish to gain the highest possible yields. Knowledge of water chemistry, timing of harvests, environmental policy, and land-use management may all be used as tools to better prepare the average shellfish farmer.

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## CONCLUSION

For many members of the general public, ocean acidification is an obscure topic. While climate change and its associated impact on global temperature and sea level rise is common knowledge for most, the impact of anthropogenic carbon on ocean chemistry is vastly proportionally misinterpreted. Furthermore, there has been a recognized limitation of knowledge and research on the economic impact of ocean acidification. Ocean acidification has a wide range of direct and indirect effects on marine food webs. The aim of this thesis is to extract data from previous studies to present a clear portrayal of how the ecological degradation of shellfish populations correlates with economic losses in the shellfish industry.

Each state within the Pacific Northwest region of the United States contributes a certain portion of revenue to the U.S. shellfish industry. After reviewing the data, it was clear that Washington state claimed the position of top producer of commercial shellfish. Due to the vastness of Washington's industry, its associated capital, the relationship between industry and research in Washington, and the state's governmental support of mitigation action, Washington state seems most equipped to address the threat of climate change. Oregon and Alaska consist of small-scale aquaculture firms that will experience immense difficulty in retaining economically sustainable yields in the presence of increased acidification.

Local efforts may be effective at temporarily adapting to the issue of ocean acidification, the longevity of the shellfish industry is directly threatened by continued combustion of fossil fuels and the continued oceanic absorption of carbon dioxide. Air pollution has no boundaries and carbon emissions are capable of traveling far distances during their residence time. Carbon that is emitted inland may potentially reach coastal regions. Ocean acidification is not simply a result of

the behaviors and actions of coastal communities regarding air pollution. Nor is it a threat concentrated in coastal areas. Ocean acidification will decrease supply of shellfish locally, regionally, nationally, and globally. Along with an increase in demand of seafood due to altering preferences of meat to seafood and an increasing population, shellfish prices will drastically rise. This may lead to increased consumption of alternative terrestrial food sources that have already played a major role in contributing to climate change.

Mitigation strategies may invoke potential ecological impacts as well. In particular, there is a danger of increasing biological activity via the use of vegetative-type purifiers in an attempt to decrease nutrient content in coastal estuaries. In order to avoid eutrophication, proper disposal of organic matter is essential. If organic matter of decaying biomass is not properly accounted for, bacterial respiration may cause a spike in carbon dioxide levels, as well as deplete oxygen.

While increased monitoring processes may effectively give more insight into the processes and occurrence of ocean acidification, it is necessary that this information is transparent to those who implement policy and legislation. I recommend that in each coastal state, there is a specialist in the governor's office that is responsible for updating and preparing for increases in acidity levels. In essence, there needs to be an increase in utilization of scientific data regarding ocean acidification. Monitoring alone will not solve this issue. Rather, it is necessary to act via state legislature and policy implementation that addresses the data and models that are derived from monitoring.

Many of the adaptive mitigation strategies expand adaptive options for shellfish aquaculture and temporarily address the effects of ocean acidification, none of these strategies act as permanent solution to this issue. In addition, these strategies are purely for the benefit of commercial



aquaculture firms. Recreational wild harvests and local tribal communities that depend on wild harvests for subsistent life do not have the same resources to delay the consequences of ocean acidification. The majority of these mitigation strategies are solely isolated to controlled aquaculture practices. It is extremely difficult to initiate these same strategies in an uncontrolled natural ecosystem.

Owners of aquaculture firms are inherently most at risk of losing their business and its associated revenue to the effects of ocean acidification, there are thousands of jobs, both direct and indirect, that rely on the viability of the shellfish industry in the Pacific Northwest. The livelihood of employees of aquaculture operations, supply manufacturers, and those working in the seafood industry are all, for some to a higher degree than others, threatened by the oceanic chemical alteration of ocean acidification.

Climate change and its processes may initially be perceived as solely an environmental issue; these environmental problems have a direct effect on the vitality of many industries. Industries that require resource extraction are most at risk. The shellfish industry in the Pacific Northwest has already begun to feel the financial burden of this problem. Ocean acidification, although occurs only in specific coastal regions, is a threat that must be addressed and acted on by the global community.

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