THE ECONOMIC IMPACT OF OCEAN ACIDIFICATION ON PACIFIC OYSTERS

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A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

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Fairbanks, Alaska

May 2015

Abstract

Since the start of the Industrial Revolution, our atmosphere has continued to experience increased levels of CO_2 concentrations and with it, changes in seawater carbonate chemistry. These changes in the carbonate chemistry of seawater, a process known as ocean acidification (OA), threaten some species upon which some economies are largely dependent for economic activity. This thesis uses the best available data to summarize the Washington State shellfish economy and estimate potential impacts of OA on Pacific oyster demand. The analysis evaluates the economic impact of OA on demand using an autoregressive distributed lag (ARDL) model approach to estimate short-run and long-run impacts.

Although initial research attempted to assess the impacts of OA on Pacific oyster supply, findings from this study suggest that long-run decreases in carbonate chemistry may negatively impact the demand for Pacific oysters. As the waters used to grow Pacific oysters in Washington State continue to degrade as a result of OA, substantial losses in economic activity from Pacific oysters may be lost. On the west coast, oysters appear to be a luxury good with demand highly responsive to changes in income. Pacific oysters are moderately sensitive to price, indicating demand for oysters is elastic.

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1 Introduction

Ocean acidification (OA) has recently become the topic of many conversations among members of Washington State's coastal communities. Between 2005 and 2009, production of shellfish larvae experienced major failures, signaling a change in seawater conditions used by hatcheries to spawn and rear oyster "seed." Extensive research has since revealed that changes in seawater carbonate chemistry, resulting from increased absorption of carbon dioxide in seawater, has adverse impacts on larvae production (Barton, Hales, Waldbusser, Langdon, & Feely, 2012; Gazeau et al., 2007). If recent emission scenarios from the Intergovernmental Panel on Climate Change (IPCC) prove accurate, changes in seawater carbonate chemistry pose serious global problems, especially for coastal communities that rely on organisms that are most sensitive to the changing conditions.

1.1 Research Objective

This thesis attempts to expand our understanding of impacts associated with OA by analyzing monthly Pacific oyster demand in Washington State between 1996 and 2011.

1.2 Thesis Outline

This thesis includes six chapters. The introduction will inform the reader of the thesis' research objective and relevant information pertaining to OA and Washington State's economic dependence on shellfish production. Chapter two will review existing literature pertaining to the scientific process of OA, carbonate chemistry impacts on specific organisms, and specific modelling techniques previously employed to measure economic impacts as a result of changes to environmental inputs. Chapter three will address the modelling approach employed and specifications. Chapter four describes the data, and their sources, used in the analysis. Chapter five will report empirical model results, interpretations of those results, and their implications. Chapter six will provide a conclusion, along with recommendations for future research.

1.3 Ocean Acidification

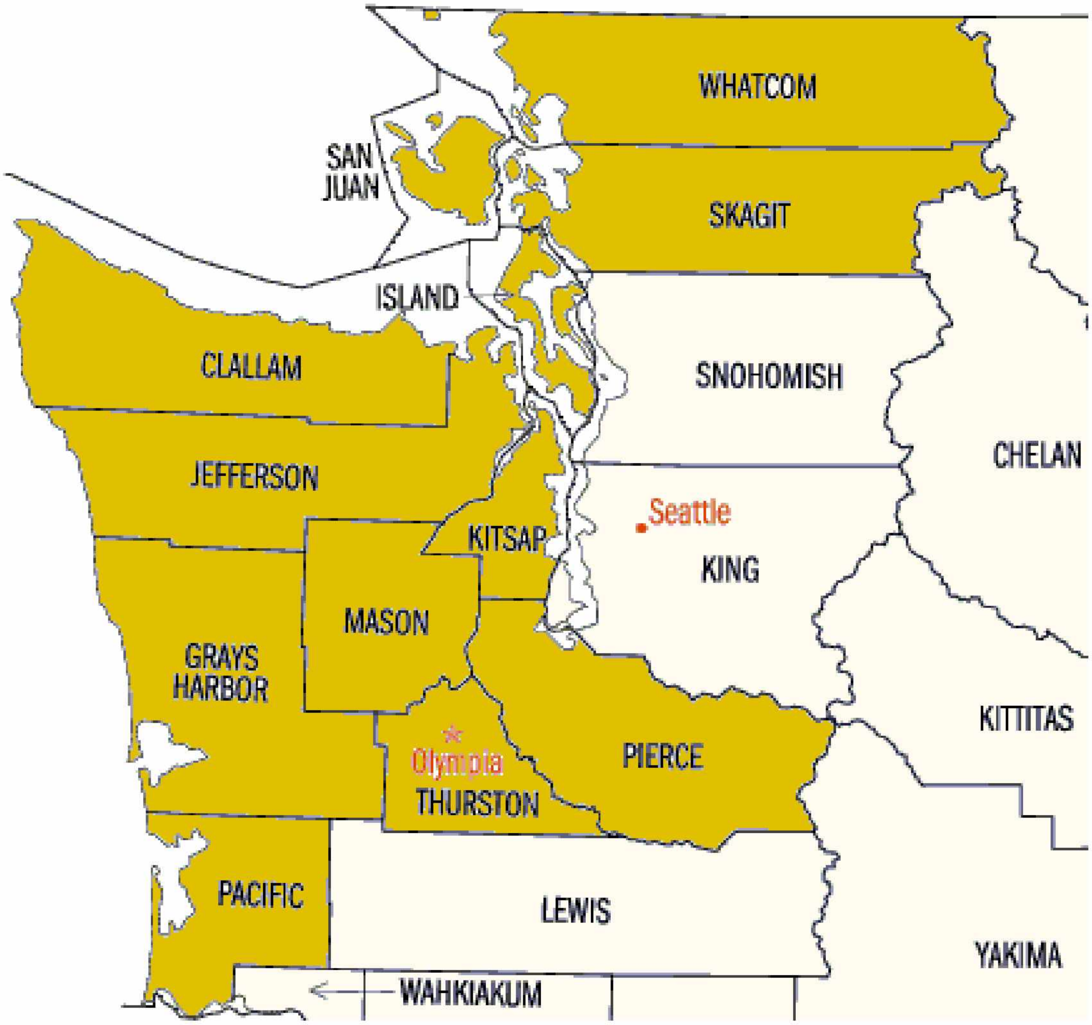
Since the beginning of the industrial revolution, mankind has continued to release carbon dioxide (CO_2) into the atmosphere through industrial and agricultural activities. Since 1750, the average acidity of the ocean has increased 30 percent, with current rates of acidification happening nearly 10 times faster than any time in the past 50 million years (NANOOS, 2015). The ocean absorbs about a quarter of the CO_2 released by mankind into the atmosphere every year. Therefore, as atmospheric CO_2 increases, so do the levels of CO_2 in the ocean (PMEL, 2015). As CO_2 increases in the ocean, concentrations of carbonate ions decrease, creating "corrosive" conditions for organisms producing carbonate ions needed for production. The process of OA and is further discussed in section 2.1.

Marine waters in Washington are particularly vulnerable to ocean acidification as regional marine processes exacerbate the effects of OA. These marine processes impacting carbonate chemistry include: coastal upwelling, nutrient runoff, local CO_2 emissions, and the uptake of nitrogen and sulfur oxides, which are also absorbed from the atmosphere by seawater (NANOOS, 2015). In fact, acidification along the outer coast of Washington and Puget Sound is strongly influenced by coastal upwelling, while acidification in shallow estuaries, including those of Puget Sound, may also be influenced by runoff from fresh water sources that are carrying nutrients from human and natural sources (NANOOS, 2015). Coastal upwelling is a process that occurs when winds blow across the ocean surface, pushing surface water away, which is then replaced with deep ocean water that is rich in CO_2 and low in pH. Wind events leading to upwelling tend to happen seasonally depending on the location and wind direction. As further discussed later, local upwelling events at a shellfish hatchery located in Washington occur during fall and winter months. While this analysis does not capture the effects of local seasonal upwelling events, it does capture gradual changes in carbonate chemistry in the Pacific Ocean's surface seawater as a result of continuous ocean uptake of CO_2.

The deep ocean water being upwelled today is believed to reflect CO_2 generated by biological processes in the ocean as well as CO_2 absorbed from the atmosphere 30 to 50 years ago, when that water was last in contact with the atmosphere. Therefore, CO_2 conditions observed today are likely the byproduct of atmospheric conditions around 1970, when CO_2 concentrations in the atmosphere were much lower (DOE, 2012). As CO_2 concentrations have continued to climb, it is likely upwelled water will continue to exhibit increased acidifying characteristics for decades to come.

1.4 Washington State Shellfish Economy

Shellfish aquaculture in Washington occurs in 12 of 39 counties. Figure 1 highlights those counties actively engaged in shellfish aquaculture.



Source: Northern Economics, Inc. (2013)

Figure 1.Washington State Counties with Shellfish Aquaculture

In 2013, Northern Economics (2013) conducted input-output modelling using survey responses from 43 of the approximately 330 commercial shellfish growers in Washington. Although this accounts for approximately 13 percent, of commercial shellfish growers in Washington State, the 43 responses accounted for 76 percent of total permitted acreage. Table 1 summarizes the survey response rate as a percentage of commercially farmed acres by county. Pacific County reported the largest number of acres surveyed and permitted for Shellfish aquaculture. As shown in Figure 1, Pacific County is located on the Pacific coast of Washington, just below Grays Harbor.

Table 1. Survey Response Rate by Acreage and County

County	Survey Acreage	Total Acreage	Response Rate (%)
Grays Harbor	3,278	2,288	143*
Island	55	87	63
Jefferson	666	1,155	58
Kitsap	25	485	5
Mason	814	4,079	20
Pacific	14,681	17,288	85
Pierce	39	138	28
Skagit	2,233	3,018	74
Thurston	710	1,037	68
Other	-	88	0
Total	22,502	29,663	76

Source: Northern Economics, Inc. (2013)

Note: * Acreage reported for Grays Harbor by survey respondents exceeds total acreage in Washington Department of Health database. PSI confirmed with respondents that the survey total is likely correct and the difference is due to inaccuracies in the WDFW database.

Table 2 summarizes the economic contribution that each county made to the state economy as a whole. As shown, Pacific county accounts for the highest contribution with over $90 million in economic output. The next largest contribution came from Mason County, at a distant second with total output just over $22 million. It should be noted that reported shellfish aquaculture includes oysters, along with geoduck, clams, and mussels.

Table 2. Estimates of Spending by Acre

County	Acres (%)	Output ($)	Employment	Labor Income ($)
Grays Harbor	7.7	11,966,300	210	5,957,500
Island	0.3	455,000	10	226,500
Jefferson	3.9	6,432,900	110	3,007,400
Kitsap	1.6	2,536,600	40	1,262,800
Mason	13.8	22,452,500	370	10,621,000
Pacific	58.3	90,416,800	1,580	45,014,700
Pierce	0.5	721,700	10	359,300
Skagit	10.2	16,045,700	280	7,858,300
Thurston	3.5	5,423,500	90	2,700,200
Other	0.3	460,200	10	229,100
Total	100	156,911,400	2,710	77,236,900

Source: Northern Economics, Inc. (2013)

Note: Labor Income is a subset of Output.

In 2006, The Research Group (2006) also conducted input-output modelling and estimated the economic contribution of Washington State's commercial fisheries at about $312 million. The estimate includes wages and proprietary income earned by captain and crew during harvesting and workers during processing. The report also estimates incomes earned by those working both directly and indirectly for the industry. The Research Group (2006) reports shellfish aquaculture accounted for approximately $57 million, or about 18 percent of the economic contribution of commercial fisheries in Washington State, making it the single largest species contributor,[1] as shown in Table 3.

Table 3. Economic Contribution by Species

Species	Economic Contribution ($ Million)	Percent Contribution
Groundfish	27.0	9%
Pacific Whiting	20.6	7%
Salmon	46.9	15%
Dungeness crab	54.4	17%
Pink Shrimp	4.9	2%
Sardine	11.1	4%
Albacore Tuna	32.6	10%
Shellfish aquaculture	57.1	18%
Other	57.5	18%
Total	312.1	100%

Source: The Research Group (2006)

There is no denying Washington's dependence on shellfish.[2] As such, Washington stands to lose substantial economic activity as a result of OA. The governor convened a Blue Ribbon Panel of leading tribal, state, federal, and local policy makers; scientific experts; public opinion leaders; and industry representatives (DOE, 2012). The Panel was tasked with documenting the current state of scientific knowledge, advancing scientific understanding of OA, recommending actions to respond to increased OA, reducing harmful effects on Washington's shellfish and other marine resources, and suggesting adaptations to the impacts of acidified waters (DOE, 2012). The Blue Ribbon Panel report was released in November 2012. The full report is available at: https://fortress.wa.gov/ecy/publications/publications/1201015.pdf.

1.5 Washington State Oyster Aquaculture

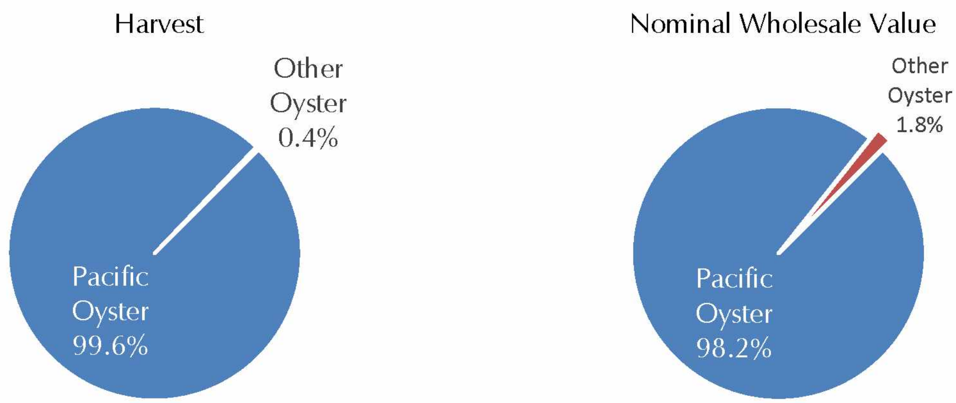
The Pacific Coast Shellfish Growers Association reports nearly 75 million pounds of shellfish is harvested in Washington State annually (PCSGA, 2015).[3] While this estimate includes clams, mussels, and

[1] Excluding the "Other" species group.

[2] Evaluating Washington's full dependence still needs to include impacts to tribal and recreational user groups.

[3] Harvest volumes reported as live weight (in-shell).

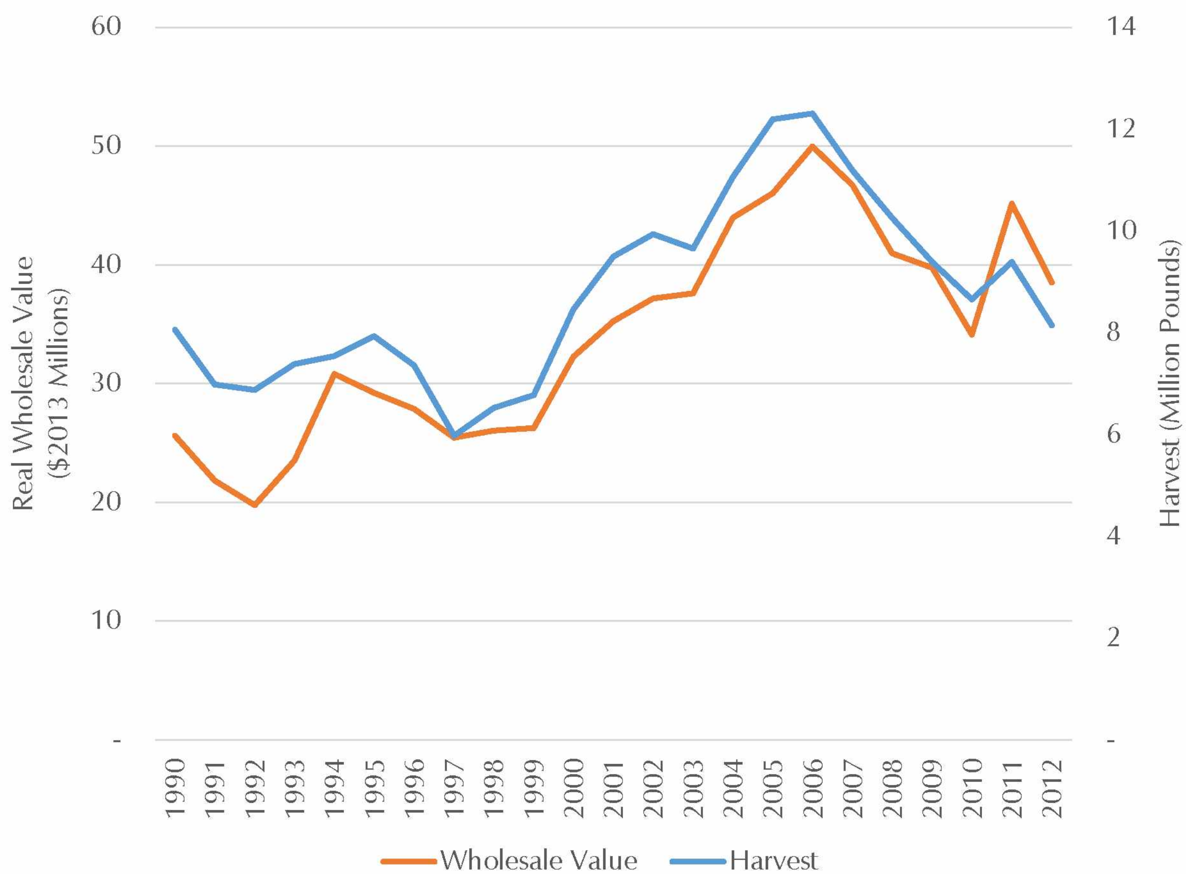
geoduck, over 80 percent (61 million pounds) of production come from oysters. Oysters alone also account for nearly $58 million in sales, over 50 percent of the state's total revenue derived from shellfish. The primary species of Washington State's oyster industry is the Pacific oyster (Crassostrea gigas), first introduced from Japan in 1902 (WDFW, 2015). Figure 2 shows the percentage of oyster production, and value, between 1990 and 2012 by species. As shown, the Pacific oyster accounts for 99.6 percent and 98.2 percent of commercial oyster production and wholesale value in Washington State, respectively. Species of oysters included in the other category include eastern oysters, European flat oysters, and Olympia oysters.



Source: NMFS (2015)

Figure 2.Oyster Production and Wholesale Value by Species in Washington State, 1990-2012

Figure 3 summarizes Pacific oyster production and nominal wholesale value between 1990 and 2013. Small declines in harvest are seen in 1996 and 1997, followed by a sustained decrease in harvests between 2006 and 2012.



Source: NMFS (2015)

Figure 3.Pacific Oyster Harvest and Nominal Wholesale Value in Washington State, 1990-2013

2 Literature Review

Existing literature regarding OA varies between sciences. The chemical process, or mechanism by which seawater becomes more acidic, is universally well understood and agreed upon in the hard sciences. The literature diverges slightly on the biological impacts to different types of marine calcifiers (e.g. mollusks, crustaceans, corals, etc.) and species. Methods for measuring the economic impacts of OA diverge even further. The following section reviews some of the existing literature as it relates to this analysis.

2.1 Mechanism

Existing science literature readily agrees on the process of OA and the resulting environmental mechanism affecting mollusk production. Continued Increases in atmospheric concentrations of CO_2 will decrease the concentrations of carbonate ions (CO_3^{2-}) (Gazeau et al., 2007; Narita, Rehdanz, & Tol, 2011). The series of chemical reactions leading to increased surface seawater as a result of increased atmospheric CO_2 can be found in (Narita et al., 2011). Decreased levels of carbonate ions (CO_3^{2-}) hamper the ability of mollusks to successfully grow shells, which are composed of calcium carbonate ($CaCO_3$).

Oysters grow shells more easily in conditions that promote precipitation of calcium carbonate ($CaCO_3$), or the ability for a substance to be deposited in solid form from a solution. Pacific oysters are presented with a much more difficult time constructing shells with conditions promote dissolution, the process by which a substance forms a solution in a solvent. While it is well agreed upon that oysters are negatively affected by increased exposure to acidifying conditions, the duration and intensity by which oysters can survive varies. The process of dissolution and precipitation of calcium carbonate in seawater can be characterized by the following reaction:

$$CaCO_3 \leftrightarrow {CO_3}^{2-} + Ca^{2+} \tag{1}$$

Where CO_3^{2-} is the dissolved concentration of carbonate ions in seawater, and Ca^{2+} is the dissolved concentration of calcium ions in seawater. Notice the arrow (↔) in the equation (1) denotes that the reaction can take place from left to right, or right to left. The equation read from left to right summarizes the dissolution of carbonate chemistry, while when read from right to left, summarizes the precipitation of calcium carbonate.

The saturation state of seawater with respect to calcium carbonate is calculated as a product of the concentrations of dissolved calcium and carbonate ions in seawater, divided by their product at equilibrium (Narita et al., 2011). When the saturation state equals one ($\Omega = 1$), the seawater is in exact equilibrium with respect to calcium carbonate. The calcium carbonate saturation state is represented by equation (2):

$$\Omega = [CO_3{}^{2-}]\ X\ [Ca^{2+}]/\ [CaCO_3] \qquad (2)$$

Two types of calcium carbonate exists that are relevant to the ability for mollusks to grow shells. Oysters use a method that don't allow them to exert high biological control over calcification directly. Calcium carbonate ($CaCO_3$) is deposited along their inner shell walls, and consequently, they depend on a sufficient ambient carbonate concentration to deposit shells successfully (Cooley & Doney, 2009). Shells developed in this manner are more likely to contain aragonite, which is a more soluble mineral form of calcium carbonate ($CaCO_3$). Species that exert high biological control over calcification directly typically accumulate intracellular stocks of carbonate ions gradually and harden their chitin and protein exoskeletons by depositing calcium carbonate ($CaCO_3$) from within, usually in the less soluble form of calcite (Cooley & Doney, 2009). In addition, water conditions corrosive to aragonite are rapidly expanding into shallower, more biologically sensitive areas at a rate of about five feet per year while conditions corrosive to calcite have remain largely confined to deeper waters (DOE, 2012).Therefore, aragonite is the form of calcium carbonate used in this analysis.

Aragonite saturation state ($\Omega_{aragonite}$) is a metric used to provide an estimate of how readily aragonite dissolves in seawater. When the saturation state of aragonite is equal to one ($\Omega_{aragonite} = 1$), the seawater is in exact equilibrium. This means that aragonite will not dissolve or precipitate. With respect to equation (1), this means the equation is balanced, regardless of which direction it is read. When the $\Omega_{aragonite}$ is less than one ($\Omega_{aragonite} < 1$), the sea water is said to be undersaturated and results in the mineral dissolving. If $\Omega_{aragonite}$ is greater than one ($\Omega_{aragonite} > 1$), the seawater is said to be supersaturated and results in the mineral precipitating (SOEST, 2015d). As seawater becomes more acidic due to elevated concentrations of atmospheric CO_2, carbonate ion ($CO_3{}^{2-}$) concentration will continue to decrease, effectively lowering $\Omega_{aragonite}$, as calcium ion concentration (Ca^{2+}) remains rather constant (Gazeau et al., 2007).

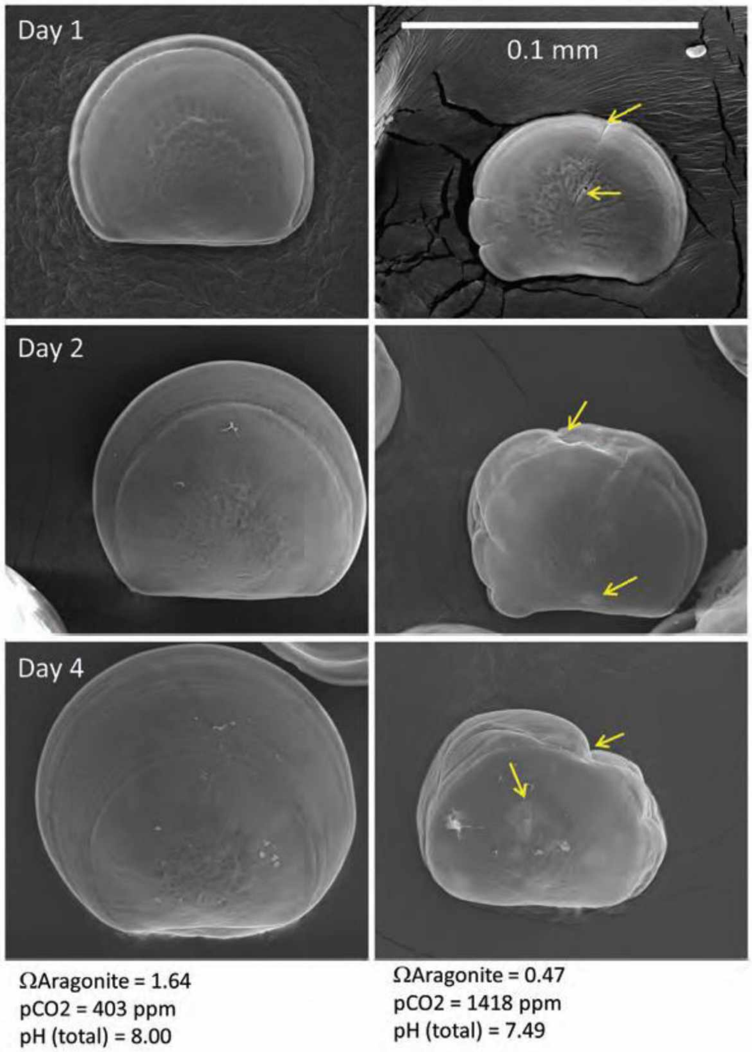
This analysis evaluates the impacts of decreasing trends in $\Omega_{aragonite}$. It is critical to note that the model doesn't explicitly control for any other events that may cause temporary fluctuations in $\Omega_{aragonite}$ and only include changes in open ocean trends. Other events are known to influence variability in carbonate system parameters, especially in shallow, coastally influenced areas. Variables known to influence variability include biological production and respiration, upwelling, ice melt, and river runoff. These variables can cause spatial and temporal variability in carbonate chemistry that is likely to be many magnitudes greater than that observed at open ocean time-series stations (Mathis et al., in press).

2.2 Pacific Oysters

Given the mechanism that relates CO_2 and $\Omega_{aragonite}$, this analysis uses $\Omega_{aragonite}$ as the environmental variable to measure the impact of OA on shellfish production. The extent to how specific species are affected by decreases in $\Omega_{aragonite}$ isn't as precise, mostly due to the inherent complexities of marine biology. However, existing science broadly agrees that increases in OA is likely to negatively impact marine organisms that are highly dependent upon calcium carbonate for development. Strong declines in Pacific oyster calcification rates have been found to be a function of decreasing pH, increasing pCO_2, and decreasing carbonate ion (CO_3^{2-}) (Gazeau et al., 2007). As highlighted by equation (2), decreases in carbonate ion (CO_3^{2-}) decreases $\Omega_{aragonite}$. Using calcification rates calculated from relationships with pCO_2, Gazeau et al. (2007) estimate a 10 percent decrease in Pacific oyster calcification rates following one of IPCC's emission scenarios.

Figure 4 shows Pacific oyster larvae from the same spawn, raised by Taylor Shellfish Hatchery in Dabob Bay, Washington under different conditions. The left column shows the larvae grown under favorable conditions, and the right column under unfavorable conditions. The carbonate chemistry conditions are shown below the columns and represent waters being used to spawn larvae in Dabob Bay. As reported by DOE (2012):

> *The images are Scanning Electron Microscopy of representative larval shells from each condition from one to four days post-fertilization. Because the sampling is destructive, each larva shown is a different organism, and should not be interpreted as the same larva ageing through time. Under more acidified conditions (right column) development of shell is impaired; arrows show defects (creases) and some features (light patches on shell) that are suggestive of dissolution. The extent of deformation shown would result in mortality of larvae were they not sampled; larval shell shape is a commonly used metric of biological fitness for bivalves. The scale bar in the upper right panel is 0.1 mm, or approximately the diameter of a human hair.*



Source: DOE (2012)

Note: Photo credit- Brunner/Waldbusser. Used with permission.

Figure 4.Pacific Oyster Larvae Spawn under Varying Conditions

Barton et al. (2012) found negative correlation between $\Omega_{aragonite}$ in both larval production and midstage growth of Pacific oysters in waters where Pacific oysters were spawned and reared for the first 48 hours after fertilization. Barton et al. (in press) also found that while no significant relationship was established at the time of spawning or early stage growth, significant effects of carbonate chemistry conditions at time of spawn were found on midstage growth, and relative production. These findings suggest a lagged effect of water chemistry on larval development. Since little is understood about the ability of Pacific oysters (or most calcifiers) to respond to changing carbonate conditions, further research will help highlight when organisms are most vulnerable to impacts from OA.

2.3 Economic Modelling

Methods for modelling potential economic impacts resulting from the change in an environmental input are abundant, especially as it concerns to agricultural farming. Leung, Reed, & Geng, (1982) study the economic impacts as a result of crop yield reductions from ambient ozone, an air pollutant, using principle component analysis to model a linear production function. Leung et al. (1982) then evaluate economic welfare impacts using consumer and producer surplus methodology, and regional impacts using input-output analysis. Mjelde, Adams, Dixon, & Garcia, (1984) evaluate similar reductions in crop yields by modelling a translog profit function to estimate the change in profits from ozone.

Not as much research exists on the impacts of OA on shellfish, mostly likely attributable to the relative lack of data required. Previous research by Narita et al. (2011) uses a partial-equilibrium analysis to estimate global, and regional, impacts as a result of reduced mollusk production. Impacts are measured by shifting the supply curve of mollusks to assess the impacts of supply changes to consumers and producers. Cooley & Doney (2009) employ a similar method using mortality estimates from Gazeau et al. (2007), and projecting future harvest trends using IPCC atmospheric CO_2 trajectories. National and regional economic impacts are then measured as a replacement cost, measured by the product of market price and change in quantity. In both studies, the change in shellfish supply is based on previous dose response models. Moore (2011) evaluates the impacts from OA by deriving compensating variation – or the additional amount of money needed to maintain existing utility. Moore (2011) uses a two-stage demand system to estimate utility function parameters needed to derive compensating variation.

Benshoof & Baek (2014) model a production function using an autoregressive distributed lag (ARDL) model to evaluate impacts resulting from changes in policy and environmental characteristics. While Benshoof & Baek (2014) did not evaluate impacts to shellfish, this analysis will utilize the same modelling approach to estimate changes in Pacific oyster demand. This method allows for any changes in Pacific oyster demand to be evaluated using actual transaction data. Assuming the Pacific oyster market is in equilibrium, a general demand equation to be modelled is shown below in equation (3):

$$Q_x^d = \mathrm{f}(\Omega_{aragonite}, P_x, P_y, I) \tag{3}$$

where Q is the quantity of Pacific oysters demanded; $\Omega_{aragonite}$ is the environmental input from OA; P_x is the wholesale price of Pacific oysters; P_y is the price of a similar good; and I is income. Section 3.1

further discusses the model specification for this analysis. Because very little, if any, research has evaluated the economic impacts of OA to Washington State, this analysis will hopefully lend itself to initiating the evaluation of impacts from OA to Washington State, an potentially the entire west coast, for all organisms potentially affected.

Modelling impacts on demand from changes in environmental inputs is largely uncharted. Environmental inputs are only likely to impact demand if consumers observe, or perceive, a correlation to changes in quality. Wessells, Miller, & Brooks, (1995) estimated the economic losses experienced as a result of decreased demand for mussels from toxic algae blooms. The impacts were evaluated using consumer information both prior to, and after, an algae bloom. This analysis will built upon by Dupont, Hall, Calosi, & Lundve, (2014), suggesting decreased sensory quality of shellfish exposed to decreased pH levels; thereby expanding the research on demand impacts as a result of decreased quality from OA. This analysis will combine ARDL modelling methods used by Benshoof & Baek (2014) using a similar demand methodology as Wessells et al. (1995).

3 Method

3.1 The Empirical Model

The ARDL model, developed by Pesaran, Shin, & Smith (2001), is the chosen model specification for this analysis due to the unique characteristics of the data. For example, the ARDL specification can be used to estimate long-run and short-run dynamics, even when the variables being used contain a mixture of stationary (I(0)) and non-stationary (I(1)) time-series processes. The model is "autoregressive" in the sense that the dependent variable is, at least partially explained, by lagged values on itself. The "distributed lag" component refers to additional independent variable lags being used as regressors. Equation (4) represents the specification in a log linear form is chosen for the empirical analysis:

$$lqoyster_t = \alpha_0 + \alpha_1 laragsat_t + \alpha_2 lpoyster_t + \alpha_3 lpbeef_t + \alpha_4 linc_t + \varepsilon_t \tag{4}$$

where $lqoyster_t$ is the demand for Pacific oysters; $laragsat_t$ is the level of aragonite saturation; $lpoyster_t$ represents the price per pound of oyster harvested; $lpbeef_t$ represents the price per pound of beef; $linc_t$ represents the average U.S. disposable household income; and ε_t the error term. These variables will be discussed in further detail in section 4.1.

The ARDL modelling technique is used to evaluate the effects of OA on Pacific oyster demand. The methodology lends itself to evaluating both short-run, and long-run effects of changes in the aragonite saturation state ($\Omega_{aragonite}$). Therefore, as discussed in section 2.1, if decreases in $\Omega_{aragonite}$ lead to more difficult growing conditions for Pacific oysters, a positive coefficient is expected on the aragonite saturation variable. It should be noted that during the timeframe of this analysis, many, if not all, oyster growers did not manage the carbonate chemistry of seawater being used to produce larvae. Since 2012, many oyster hatcheries began treating seawater used for developing larvae with calcium carbonate buffer to ensure optimum carbonate chemistry.[4]

In addition to evaluating the impacts of $\Omega_{aragonite}$ on Pacific oyster demand, the analysis also includes short-run and long-run estimates on the price of Pacific oysters, the price of a similar good (beef), and disposable consumer income. The sign on the coefficients for these variables are expected to vary. The coefficient on the price of Pacific oysters (lpoyster) is expected to be negative, reinforcing the law of demand assuming equilibrium. The coefficient on the price of beef (lpbeef) is expected to be positive as oysters and beef aren't widely viewed as complimenting products. Finally, because oysters aren't a

[4] Calcium carbonate buffer treatments is expected to affect future results.

necessity for many, and often viewed as a delicacy, the coefficient on the disposable consumer income (linc) is expected to be positive. These variables are discussed further in section 4.1.

3.2 The ARDL Approach

To illustrate the ARDL modelling approach, equation (4) is reformulated to an unrestricted error correction equation according to ARDL model procedure, and is shown below in equation (5):

$$\begin{aligned}\Delta \ln \text{qoyster}_t = \beta_1 &+ \sum_{k=1}^{P} \theta\kappa\, \Delta \ln \text{qoyster}_{t-\kappa} + \sum_{k=0}^{P} \theta\kappa\, \Delta \ln \text{aragsat}_{t-\kappa} \\ &+ \sum_{k=0}^{P} \theta\kappa\, \Delta \ln \text{poyster}_{t-\kappa} + \sum_{k=0}^{P} \theta\kappa\, \Delta \ln \text{pbeef}_{t-\kappa} \\ &+ \sum_{k=0}^{P} \theta\kappa\, \Delta \ln \text{income}_{t-\kappa} + \lambda_1 \ln \text{qoyster}_{t-1} + \lambda_2 \ln \text{aragsat}_{t-1} \\ &+ \lambda_3 \ln \text{poyster}_{t-1} + \lambda_4 \ln \text{pbeef}_{t-1} + \lambda_5 \ln \text{inc}_{t-1} + \mu_t \end{aligned} \tag{5}$$

All variables in equation (5) are previously defined. Equation (5) represents the basis of the empirical analysis presented in this thesis. As discussed earlier, regressors on the right side of the equation now include both lagged dependent and independent variables; constituting the characteristics of an ARDL model. Equation (5) is very similar to that of a conventional vector error correction model (VECM). In contrast to an conventional VECM, (5) replaces the conventional error term, that consists of an OLS residual series, with a linear combination of OLS lagged variables (lnqoyster_{t-1}, lnaragsat_{t-1}, lnpoyster_{t-1}, lnpbeef_{t-1}, and lninc_{t-1}). With this approach, short-run dynamics are evaluated as the coefficients following θ signs. These variables reflect the first-differences. The linear combination of lagged level variables represent the long-run relationship, or cointegrating relationship, and are represented by the lambda coefficients (λ1, λ2, λ3, λ4, and λ5). Cointegration among the variables is tested using the F-test to determine joint significance of lagged levels of the variables involved. (Pesaran et al., (2001) provide two sets of asymptotic critical values for the F-test; one set, assumes all variables are I(0) and another set that assumes all variables are I(1). The null hypothesis that no cointegration exists is represented by H0: $\lambda1=\lambda2=\lambda3=\lambda4=\lambda5=0$ against H1: $\lambda1\neq\lambda2\neq\lambda3\neq\lambda4\neq\lambda5\neq0$. The null hypothesis of no cointegration among variables can be rejected if the computed F-statistic is shown to be higher than the upper bound of critical values.[5] Conversely, if the F-statisitc falls within the upper and lower critical

[5] Kremers, Ericsson, & Dolado (1992) have demonstrated that a significant lagged error term is a relatively more efficient way of establishing cointegration.

values, the test is deemed inconclusive and prior information about the order of integration of the variables is needed to infer long-run relationships. It is important to note that the outcome of the bounds test relies upon the choice of lag order. Therefore, this analysis imposes a maximum lag order of 6, using the Akaike Information Criterion (AIC) to select the optimum number of lags.

The ARDL approach was selected as the preferred technique for this analysis to avoid spurious regression results, which may occur when a non-stationary I(1) time series variable is correlated with the dependent variable, despite a causal relationship. If all variables of interest are found to have I(0) processes, OLS regression would likely be a sufficient method. Alternatively, if all time series variables are found to have I(1) processes, conintegration techniques could be employed to establish, and hold constant, any relationships among trending variables; allowing for any relationships to be examined regardless of a time trend. If the I(1) processes are found not to be conintegrated, the variables could be differenced and modelled using OLS.

As mentioned previously, the ARDL modelling approach allows data containing a mix of I(0) and I(1) variables. An ARDL approach also allows partially integrated variables and/or variables whose unit root might not be easily determined. In an instance where the order of integration cannot be determined with great confidence, the ARDL model can be especially useful; especially given the proven weakness of some unit root tests, such as the Dickey-Fuller test. In fact, this weakness is exacerbated in the presence of stochastic trends and can lead to erroneous results when the order of integration is misidentified (Elliott, Rothenberg, & Stock, 1996)

4 Data

4.1 Variable Selection

The complex biological process of OA presents many indicators by which OA can be analyzed. This analysis uses $\Omega_{aragonite}$, as the primary indicator by which to measure OA on Pacific oyster demand. As discussed in section 2.1, $\Omega_{aragonite}$ is critical for the health of many Pacific Northwest Shellfish, including oysters. When the $\Omega_{aragonite}$ is high and conditions are favorable to mineral formation, the $\Omega_{aragonite}$ takes a value greater than 1 ($\Omega_{aragonite} > 1$). When $\Omega_{aragonite}$ is less than 1 ($\Omega_{aragonite} < 1$), the water is considered "corrosive" because dissolution of pure aragonite and unprotected shells will begin to occur (Feely, Sabine, Hernandez, Ianson, & Hales, 2008). This relationship between $\Omega_{aragonite}$ and oyster larvae health, lends itself as one of the best environmental indicators by which to measure the impacts of OA on Pacific oyster demand.

In addition to $\Omega_{aragonite}$, other independent variables include the price of Pacific oysters, the retail price of all-fresh beef, and U.S. disposable personal income per capita. These variables are seen as representing the price elasticity of demand, cross-price elasticity, and the income elasticity of demand, respectively. Also, research presented by Benshoof & Baek (2014) analyzed the effects of the Pacific Decadal Oscillation (PDO) on salmon stocks in Alaska. While not much literature exists concerning the effects of PDO on shellfish, initial modeling efforts included PDO as an independent variable. Due to insignificant results and potential problems with multicollinearity, PDO wasn't included as part of this thesis.

The dependent variable chosen for the analysis is the quantity of Pacific oysters produced, and sold, in Washington State. The price of Pacific oysters is assumed to be an exogenous independent variable as wholesalers are assumed to be price takers, operating in a perfectly competitive market where all product that is harvested is sold. Therefore, it is assumed the price of Pacific oysters is determined independently of Pacific oyster sales. Therefore, equation (5) assumes the equilibrium market price for Pacific oysters determines the quantity of Pacific oysters produced. Table 4 summarizes the variables being used in this analysis.

Table 4. Variable Summary

Name	Variable	Description	Form
LQOYSTER	Dependent	Quantity (meat weight) of Pacific oysters produced	Natural Log
LARAGSAT	Independent	Aragonite saturation state ($\Omega_{aragonite}$)	Natural Log
LPOYSTER	Independent	Real wholesale price of Pacific oysters	Natural Log
LPBEEF	Independent	Retail price of Choice beef ($ cents)	Natural Log
LINCOME	Independent	U.S. disposable income per capita	Natural Log

4.2 Data Sources

Monthly commercial landings and wholesale prices for Pacific oysters in Washington State were taken from National Marine Fisheries Service (NMFS) reports. Landings data do not track the physical location of harvest, but rather the location of the dock where first contact was made or from which was reported. Landing from shellfish are measured in pounds of meat weight, and therefore do not include shell weight.

Wholesale price data is determined by dividing reported nominal landing values by the pounds produced. The nominal wholesale price is then adjusted for inflation, using the Consumer Price Index (CPI), into real ($2013) wholesale price.

Due to federal statutes prohibiting public disclosure, NMFS does not report data that could identify any person (or entity). Therefore, ascertaining specific monthly data can be difficult. However, given the overwhelming production of Pacific oysters in Washington State, and no other indicators that confidential data is being withheld, the author assumes the data to be accurate and the best data available describing Pacific oyster sales in Washington.

Data on $\Omega_{aragonite}$ proved to be the most difficult to find among all variables included in the analysis. Initial efforts focused on obtaining $\Omega_{aragonite}$ data from a shellfish hatchery in Washington to represent changes in the shallow coastal waters where oysters are grown. The data included measurements of $\Omega_{aragonite}$ between March 2010 and July 2012. Although the correct measure ($\Omega_{aragonite}$) was provided, the time series was not long enough to warrant a significant time series analysis.

In a secondary approach to obtain carbonate chemistry data from Washington waters, data provided by Cape Elizabeth, a mooring located approximately 45 nautical miles Northwest of Aberdeen, Washington was analyzed. Cape Elizabeth is operated by the Carbon Dioxide Information Analysis Center (CDIAC) and also provides time-series data on natural variability and temporal trends in the ocean carbon cycle off Washington's coast. The mooring is located near the edge of the continental shelf in approximately 125 m of water, so is well situated to document the upwelling events in the spring and summer (PMEL, 2015b). Cape Elizabeth provides a dataset dating back to June 2006 but does not provide data on $\Omega_{aragonite}$.

Ultimately, monthly data observations used for modelling in this analysis were provided by the Hawaii Ocean Time-series (HOT) Project. HOT started in 1988 with funding from the U.S. National Science Foundation. The primary research objective of the initial 5-year phase of HOT (1988-1993) was to design, establish and maintain a deep-water hydrostation as a North Pacific benchmark for observing and interpreting physical and biogeochemical variability (SOEST, 2015). Site selection for HOT underwent several major criteria considerations. Ultimately, the placement of HOT's sampling site (ALOHA Station) was established at 22' 45'N, 158' 00'W, a location approximately 100 km north of the island of Oahu (SOEST, 2015b).

It is critical to point out the geographical location of the ALOHA station when evaluating the impacts of $\Omega_{aragonite}$ on Pacific oyster demand in Washington. It would certainly be preferable to use $\Omega_{aragonite}$ data taken from an individual hatchery or Cape Elizabeth where Pacific oyster larvae are being produced. However, the analysis uses data provided by HOT, which is located hundreds of miles from Washington State waters where oyster hatcheries operate. In effect, the analysis assumes that trends in $\Omega_{aragonite}$ located at ALOHA Station match trends in $\Omega_{aragonite}$ in Washington State waters used for Pacific oyster larvae production.[6]

Explanatory material, metadata, and notes regarding HOT can be found at: http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2_readme.pdf. For the time series analyzed in this thesis (January 1996 – August 2011), HOT provided 156 $\Omega_{aragonite}$ data observations. A spline was used to bridge 32 missing $\Omega_{aragonite}$ observations. If data was missing for a month where data was available in both the previous and following months, the average $\Omega_{aragonite}$ of the previous and following month was used. If consecutive months were missing, the average $\Omega_{aragonite}$ of the most recent month and following month was used. There were 6 months (3 pairs) of consecutive missing data for which the later spline was employed. There were no instances where data were missing for three consecutive months or more. Although a spline is used to populate missing data, the ALOHA Station provides the longest time series of $\Omega_{aragonite}$ data with minimal interruption.

Nominal monthly retail prices for Choice beef are provided by the U.S. Department of Agriculture (USDA). Price data were adjusted for inflation to represent real dollars.

[6] A total of 18 observations overlap between data from provided by ALOHA Station and hatchery data from Washington. A correlation of 0.06 was calculated, suggesting a positive, yet weak correlation.

Nominal (current) monthly per capita disposable income is reported by the Federal Reserve Bank of St. Louis' Federal Reserve Economic Data (FRED). The data were then adjusted for reflect real per capita disposable income.

4.3 Descriptive Statistics

Table 5 lists descriptive statistics for each of the variables used in equation (5) in level form. There are a total of 188 monthly observations, starting in January of 1996 and ending in August of 2011. Average monthly demand of Pacific oysters was 767,366 pounds, ranging from a minimum of approximately 300,000 pounds, and a maximum of over 1.8 million pounds. Over the length of the analysis, approximately 144 million pounds of Pacific oysters were sold. The number of continuous data observations for Pacific oyster production is the primary constraint to the overall length of the time-series.

Monthly $\Omega_{aragonite}$ averaged 3.65 over the span of the time series, with a range between 3.47 and 3.88. These levels far exceed the value of 1, indicating aragonite stability is very good. As previously noted, the $\Omega_{aragonite}$ sample collection site is located approximately 100 km north of the island of Oahu, and hundreds of miles from Pacific oyster hatchery sites in Washington State. Therefore, the analysis effectively measures the relative change (trend) in $\Omega_{aragonite}$ and assumes a similar trend is $\Omega_{aragonite}$ in Washington State waters. Section 0 summarizes data collected from a specific Washington State shellfish hatchery producing Pacific oyster larvae.

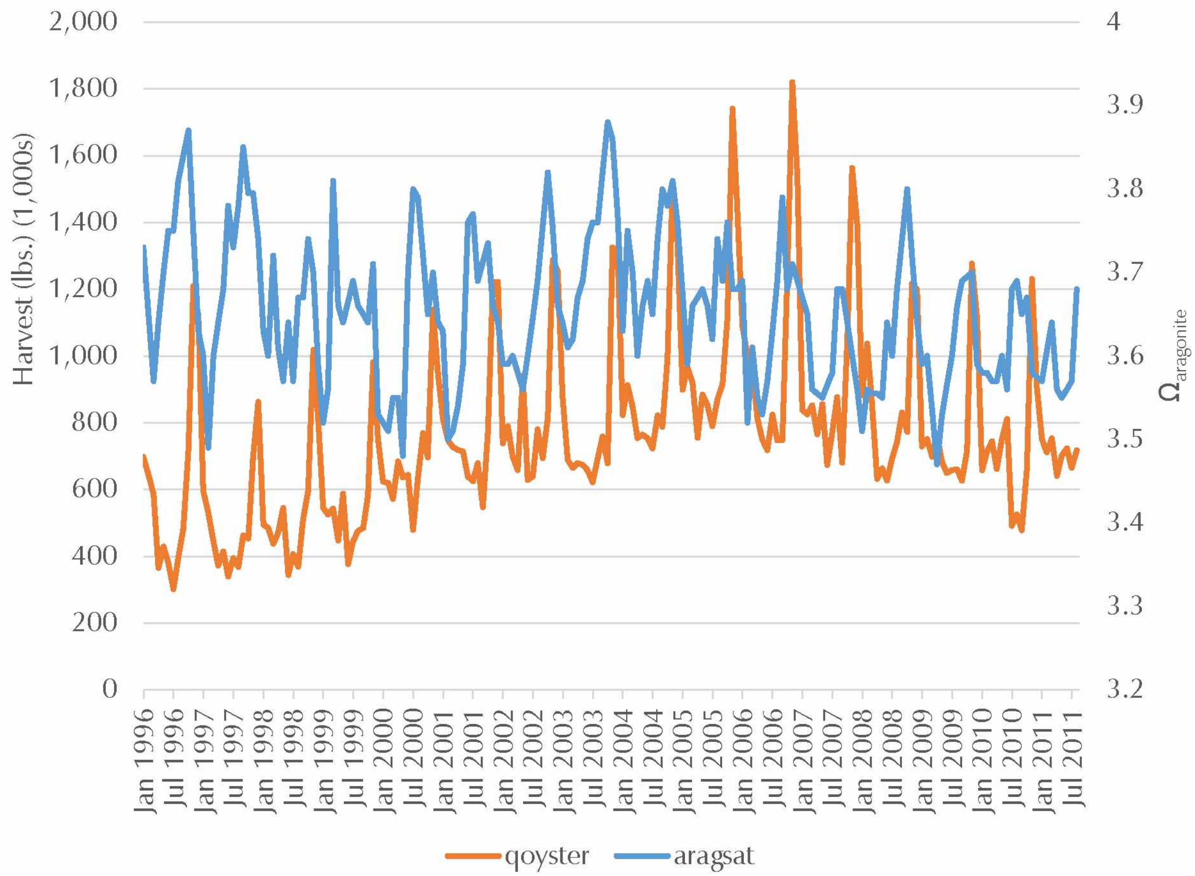
Table 5. Descriptive Statistics

Name	Description	Mean (Standard Deviation)
QOYSTER	Quantity (meat weight) of Pacific oysters produced	767,366 (272,299)
ARAGSAT	Aragonite saturation state ($\Omega_{aragonite}$)	3.65 (0.09)
POYSTER	Real wholesale price of Pacific oysters ($2013)	3.93 (0.39)
PBEEF	Real Retail price of Choice beef ($2013)	5.45 (.22)
INCOME	Real U.S. disposable income per capita ($2013)	29,822 (5,126)

Pacific oyster harvest and $\Omega_{aragonite}$ are graphed in Figure 5. As shown, both Pacific oyster production and $\Omega_{aragonite}$ exhibit large seasonal patterns. $\Omega_{aragonite}$ appears to reach its highest point during the late summer months, just before larvae production tends to peak around November. The lowest levels of

$\Omega_{aragonite}$ appear in late winter and early spring months, typically after the peak in larvae production, when the majority of oyster harvesting occurs.

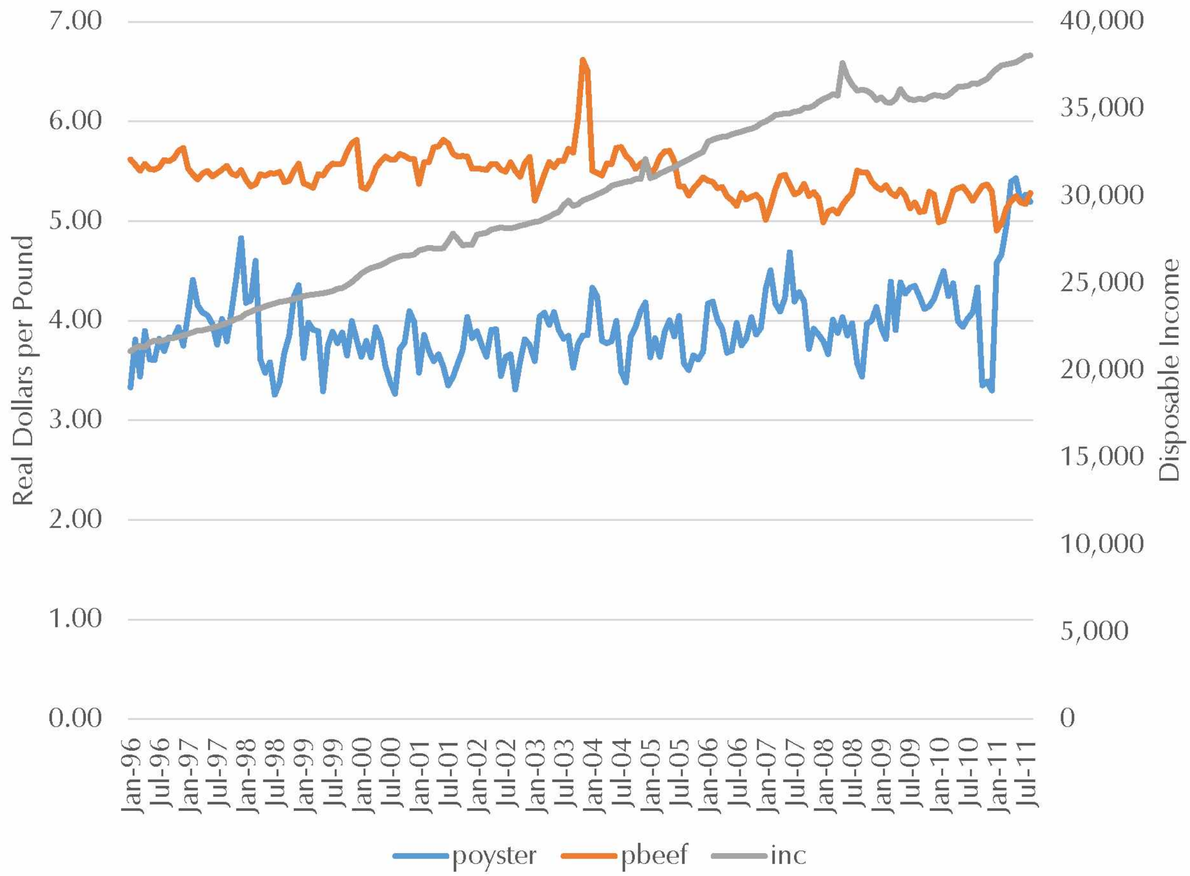
Pacific oyster production appears to track the seasonal trends of $\Omega_{aragonite}$ with a small lag. For instance, the highest levels of production are experienced from September through February, just a few months after $\Omega_{aragonite}$ is at its highest.



Source: NMFS (2015b); SOEST (2015c)

Figure 5.Monthly Pacific Oyster Demand and $\Omega_{aragonite}$ Levels, Jan 1996 – July 2011

Figure 6 summarizes the remaining variables. As shown, real prices for wholesale oysters and all-fresh beef exhibit some seasonality but have remained relatively constant over the period being analyzed. The jump in wholesale oyster price in 2011 coincides with increases in total harvest. In addition, real U.S. disposable income has steadily increased over the period being analyzed.

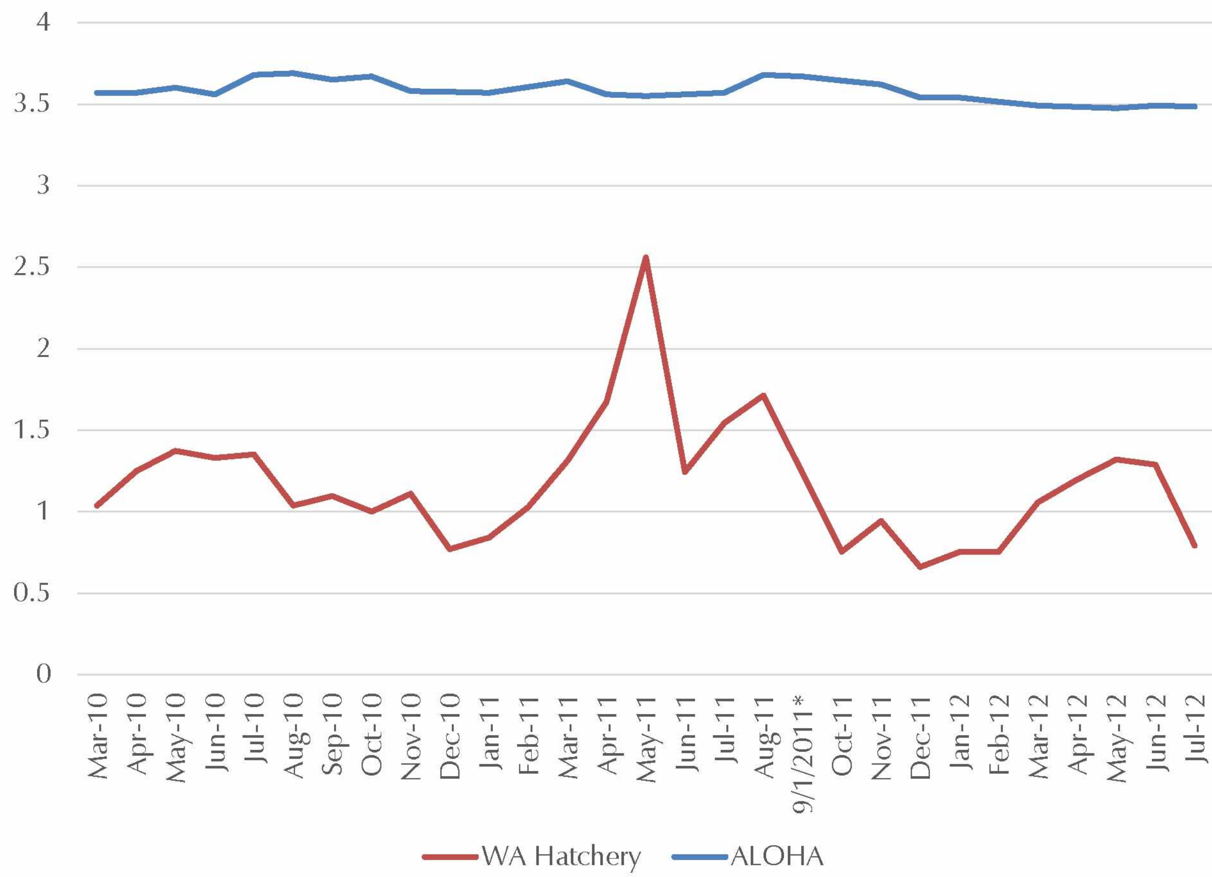


Source: NMFS (2015b); USDA (2015); BEA (2015)

Figure 6.Monthly Pacific Oyster Price, Beef Price, and Disposable Income, Jan 1996 – July 2011

As aforementioned, obtaining a substantial time series dataset for $\Omega_{aragonite}$ proved to be difficult. Because the current analysis uses carbonate chemistry data from the ALOHA station and production data from Washington, it implicitly assumes that trends in carbonate chemistry experienced at the ALOHA station are correlated with trends experienced in Washington's waters. As discussed in section 2.1, shallow coastal environments are likely to exhibit much more volatility in seasonal upwelling. However, research by Bakun (1990) and Snyder, Sloan, Diffenbaugh, & Bell (2003) suggest that upwelling intensity is likely to increase under increased CO_2 concentrations. To attempt to compare $\Omega_{aragonite}$ between the hatchery and ALOHA Station, overlapping data is shown in Figure 7. Only 28 months of observations exist for both locations between March 2010 and July 2012 (one missing observation for September 2011). The overlapping observations reveal a correlation of 0.06, suggesting a positive, but very weak, correlation.

It is important to point out that this exercise is for comparison purposes only, and that further research is needed to understand the relationship, if any, can be established between the two locations.



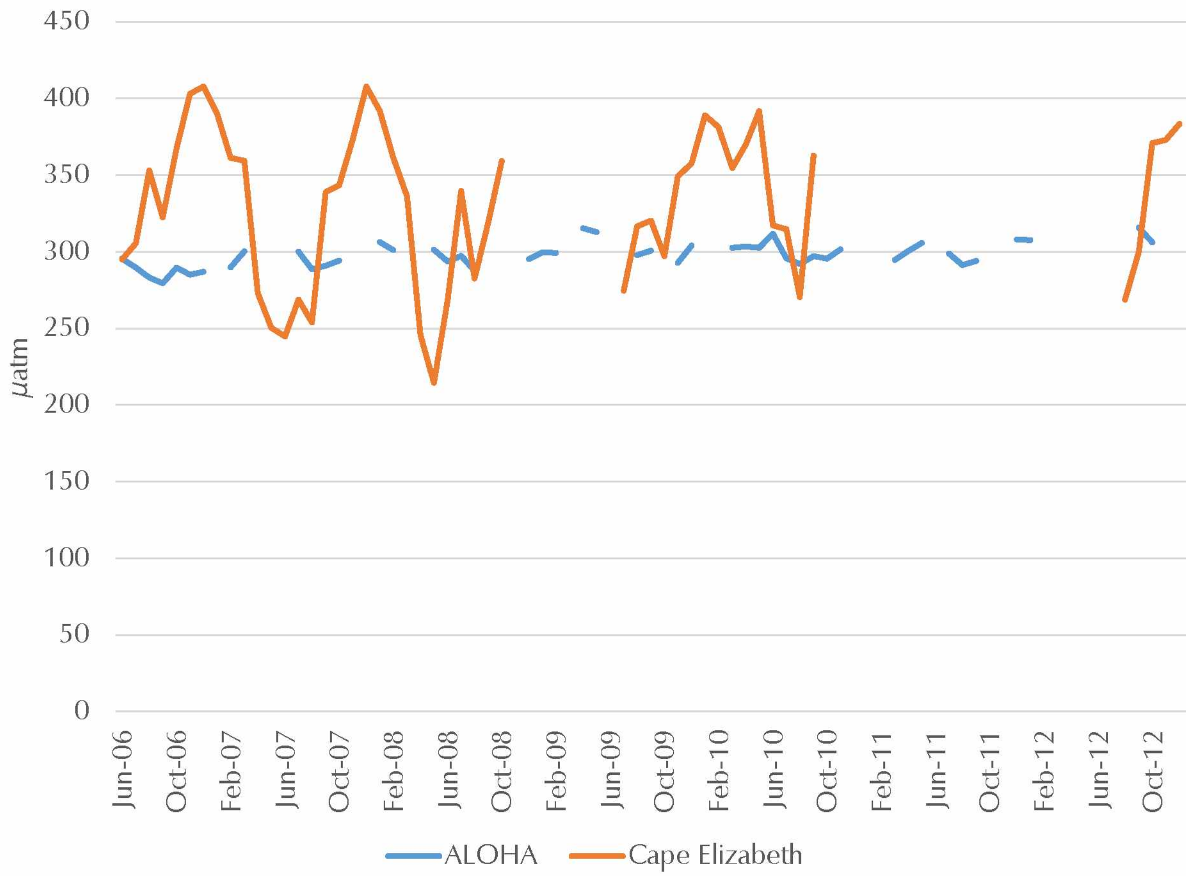
Source: SOEST (2015); Undisclosed WA hatchery.

Figure 7. Washington State Hatchery and ALOHA Station $\Omega_{aragonite}$ Levels, Jan 2011 - July 2012

As shown in Figure 7, both the levels and volatility of $\Omega_{aragonite}$ vary between the two locations. This is expected as the two locations are very different in nature. Shallow coastal conditions experience seasonal upwelling events, as was likely the case in May 2011. Also, the difference in $\Omega_{aragonite}$ naturally decreases with depth as total dissolved CO_2 increases because of biological respiration and cold temperatures in deep seawater (Feely, Doney, & Cooley, 2009). Therefore, levels of $\Omega_{aragonite}$ are much lower than those levels experienced in warmer water conditions located at ALOHA station.

The Carbon Dioxide Information Analysis Center (CDIAC) also provides time-series data on natural variability and temporal trends in the ocean carbon cycle off Washington's coast. Cape Elizabeth is a station moored approximately 45 nautical miles Northwest of Aberdeen, Washington. The mooring is located near the edge of the continental shelf in 125 m of water, so is well situated to document the upwelling events in the spring and summer (PMEL, 2015b).

The Cape Elizabeth station does not provide data on $\Omega_{aragonite}$. Therefore, carbonate chemistry comparisons between ALOHA station and Cape Elizabeth rely on findings that increased atmospheric CO_2 concentrations are reducing carbonate ion concentrations, and thus the level of calcium carbonate saturation, as highlighted in equation (2) (Orr et al., 2005). As such, trends in the partial pressure of CO_2 (pCO_2) are shown for ALOHA and Cape Elizabeth stations in Figure 8. As shown, overlapping data between the two sites is sparse, with no clear indication of any trends. The shallow coastal location of Cape Elizabeth certainly appears to display seasonal swings in pCO_2.



Source: CDIAC (2015); SOEST (2015c)

Figure 8. ALOHA Station and Cape Elizabeth pCO_2 Levels, June 2006 - Oct 2012

While many great efforts are underway to provide better monitoring of waters in Washington State, more time is needed before site specific time-series analyses can be performed. As such, this analysis employs data from ALOHA Station as it is the only source of long-term data on $\Omega_{aragonite}$.

5 Empirical Results

5.1 Unit Root Tests

As mentioned previously in Section 3, the ARDL approach to cointegration can be applied to any combination of I(0) and I(1) variables. Because two sets of critical values are calculated assuming all variables are either entirely I(0) or I(1), Pesaran et al. (2001) claim that unit root pre-testing is not a required. However, Ouattara (2004) has since shown the ARDL technique cannot be conducted using variables of I(2) or higher order processes. Therefore, pre-estimation unit root tests were carried out for all variables in their level and first differenced forms.

To test the order of integration for each variable, the augmented Dickey-Fuller (ADF) test was employed. The ADF test augments the standard Dickey-Fuller test by including lagged changes of the variable being tested. The inclusion of these lags is intended to clean up any serial correlation that may exist in the variable being tested. The results of the ADF tests are shown in Table 6. The null hypothesis of a unit root cannot be rejected for any variable in the level form. Conversely, all variables exhibit unit roots. However, the null hypothesis of a unit root is rejected for variables when first differenced, providing evidence all variables are I(1) processes.

Table 6. Unit Root Tests

Variable	Level (175 observations)	First difference (174 observations)	Decision
	Test statistic	Test statistic	
LQOYSTER	-0.093	-5.614***	I(1)
LARAGSAT	-2.046	-6.039***	I(1)
LPOYSTER	-1.867	-4.933***	I(1)
LPBEEF	-2.815	-3.797**	I(1)
LINC	-1.2	-3.664**	I(1)

Note: ***, ** and * denote significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

5.2 Results of ARDL Model

The number of lags chosen for the model were based on Akaike Information Criterion (AIC). AIC is a commonly used method for fitting the underlying data without producing biased results. Six periods was the maximum length allowed in the model and was estimated using the Microfit software package.

To test for long-run conintegration in the ARDL model, a standard F-test tests for joint significance among variables. The F-statistic of 16.78 was produced exceeds the 95 percent upper bound of (4.05), which suggest long-run conintegration between variables.[7] Subsequently, the ARDL approach can be used to estimate both the short- and long-run coefficients.

Coefficients and corresponding significance levels for long-run relationships is shown in Table 7. The effect of $\Omega_{aragonite}$ on oyster demand is found to be statistically significant (alpha=.01 level). The coefficient is found to be positive, as expected, suggesting that increases in $\Omega_{aragonite}$ lead to increased demand for oysters. Results suggest that with all else held constant, a one percent decrease in $\Omega_{aragonite}$ is predicted to decrease demand by 5.5 percent. This is expected as previous research suggests that decreasing $\Omega_{aragonite}$ adversely impacts shellfish production (Gazeau et al., 2007; Barton et al., in press).

The coefficient on the price of oysters is negative and represents the price elasticity of demand. Therefore, as the price of oysters increases one percent, demand for oysters is predicted to fall approximately 1.1 percent, suggesting an elastic demand curve. More importantly, the negative coefficient on the price of oysters aligns with the law of demand which states that in equilibrium, with all else equal, the quantity demanded of a good decreases when its price increases, and vice versa.

The coefficient on the price of beef captures the cross price elasticity between beef and oysters. This measures the responsiveness of the demand for oysters compared to changes in price of a beef. The coefficient is positive, and the model predicts a one percent change in the price of beef will increase demand for oysters by approximately 2.3 percent. The positive coefficient would suggest that beef and oysters are substitute products.

Finally, the coefficient on income captures the income elasticity of demand. Income elasticity of demand measures the responsiveness of demand due to changes in consumer income. The coefficient on income is positive and suggests a one percent increase in consumer income will increase oyster demand by approximately 1.6 percent. Since the change in oyster demand is greater than the change in income, the model suggest oysters are a luxury good.

[7] Critical values for the F-statistic are calculated by stochastic simulations using 20,000 replications.

Table 7. Estimated Long-Run Coefficients using the ARDL Approach

Regressor	Coefficient (Standard Error)
LARAGSAT	5.552 (2.023)***
LPOYSTER	-1.098 (0.433)**
LPBEEF	2.309 (1.117)**
LINC	1.571 (0.197)***
Constant	-22.916 (8.073)***
R^2	0.70963
Adjusted R^2	0.67756

Note: ***, ** and * denote significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

Short-run coefficients in the ARDL model measure the immediate impacts to oyster demand given a change in the variable. Table 8 reports short-run effects of each variable and their corresponding significance levels. Results indicate that all explanatory variables contain at least one significant first-differenced coefficient. Income (linc) and the price of beef (lpbeef) are highly significant (alpha=.01 level). The wholesale price of Pacific oysters (lpoyster) and quantity of Pacific oysters (lagged dependent variable) are significant at the five percent level (alpha=.05 level). And $\Omega_{aragonite}$ (laragsat) is significant at the ten percent level (alpha=.10 level). However, interpretation of the lagged coefficients can be difficult due to the nature of short-run dynamics; and it is not uncommon to observed unexpected signs in the short-run analysis.

The error correction term is found to be highly significant ((alpha=.01 level) and its coefficient falls within the appropriate range, confirming the existence of a long-run relationship. The error correction term signifies the amount of time it takes for the system to adjust from disequilibrium (during which short-run coefficients are effective) to equilibrium (after which long-run coefficients are in effect). The error correction term is interpreted as a percentage of the data interval—which in this analysis is one month—that the system remains in disequilibrium after being shocked. Therefore, the coefficient of -0.55 implies that 55 percent of any disequilibrium in Pacific oyster demand is corrected within one month; and would return to equilibrium after nearly two months.

Table 8 also includes chi-squared statistics from testing for no serial correlation, no functional form misspecification, normality, and homoscedasticity.

Table 8. Estimated Short-Run Coefficients using the ARDL Approach

Regressor	Coefficient
$\Delta LQOYSTER_{t-1}$	0.167 (0.084)**
$\Delta LQOYSTER_{t-2}$	0.054 (0.082)
$\Delta LQOYSTER_{t-3}$	0.152 (0.079)*
$\Delta LARAGSAT$	-0.448 (0.93)
$\Delta LARAGSAT_{t-1}$	-1.921 (0.979)*
$\Delta LPOYSTER$	-0.109 (0.223)
$\Delta LPOYSTER_{t-1}$	0.539 (0.25)**
$\Delta LPOYSTER_{t-2}$	0.555 (0.23)**
$\Delta LPBEEF$	2.797 (0.739)***
$\Delta LPBEEF_{t-1}$	-0.653 (0.832)
$\Delta LPBEEF_{t-2}$	-1.730 (0.779)**
$\Delta LPBEEF_{t-3}$	0.289 (0.738)
$\Delta LPBEEF_{t-4}$	-1.610 (0.683)**
$\Delta LINC$	0.864 (0.153)***
ecm_{t-1}	-0.550 (0.081)***
X^2_{SC} (1)=0.0441[0.834], X^2_{FF} (1)=0.159 [0.690], X^2_N (2)=0.099 [0.952], X^2_H (1)=2.060 [0.151]	

Note: ***, ** and * denote significance at the 1 percent, 5 percent, and 10 percent levels, respectively. Parentheses are t-statistics. Brackets in diagnostic tests are p-values. X2SC (1), X2FF (1), X2N (2), and X2H (1) denote chi-squared statistics to test for no serial correlation, no functional form misspecification, normality and homoscedasticity, respectively with p-values given in brackets.

6 Conclusion

6.1 Summary Results

Initial efforts to research the economic impacts from OA on Pacific oysters were concentrated on modeling supply and cost functions. However, the data needed to undertake those methodologies proved to be extremely difficult to ascertain. Such efforts are certainly an area for future research as data on the ocean's carbonate chemistry continue to be collected.

Instead, this analysis approached the economic impact of OA from the viewpoint of demand. As previously noted, recent literature points to the decline in quality of oysters produced in low pH conditions (Dupont et al. 2014). Building upon findings from Dupont et al. (2014) and methodology used by Wessells et al. (1995), this analysis evaluates the economic impact of OA on Pacific oyster demand as a result of decreased quality.

This study found that long-run decreases in $\Omega_{aragonite}$ negatively impact the demand for Pacific oysters. As the waters used to grow Pacific oysters in Washington State continues to degrade as a result of OA, substantial demand for Pacific oysters may be lost as a result of poor quality. Results indicate that for every one percent decrease in $\Omega_{aragonite}$, demand decreases approximately 5.5 percent, holding all else equal. These findings suggest that communities dependent upon species sensitive to change in OA, such as Washington State, could face large economic losses given changes in seawater chemistry as a result of OA.

On the west coast, oyster demand appears to be a luxury good and highly responsive to changes in income. Pacific oysters are moderately sensitive to price, indicating demand for oysters is elastic. These findings are similar in sign to those estimated by Cheng & Capps (1988).

Due to unprecedented research on the impacts of OA on shellfish demand, it is the hope that this thesis pioneers further research into not only the economic impacts of OA of shellfish supply and production, but also the potential economic impacts as a result of decreased quality from OA.

6.2 Future Research

Adverse impacts on Pacific oyster demand from OA will undoubtedly have an impact on consumers and producers. Using the findings presented in this thesis, deriving impacts on social welfare as a result of OA would be the next logical step. Social welfare impact measurements could include changes in consumer surplus or compensation variation. In addition to analyzing the impacts of OA on Pacific oysters, the methodology presented in this thesis pertaining to the use of $\Omega_{aragonite}$ as an indicator of the change in environmental input could also be used to model economic impacts resulting from adverse impacts on other marine calcifiers. However, continuous monitoring of seawater carbonate chemistry is needed to attempt such analyses.

In addition, as the availability of data pertaining to OA improves, efforts to model economic impacts as a result of OA on supply and/or production could be evaluated. Other approaches could also include the estimation of revenue, cost, or profit functions. However, such approaches are likely to require intense data acquisition to match existing carbonate chemistry data sources.

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