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Productivity Growth and Product Choice in Fisheries: the Case of the Alaskan pollock Fishery Revisited

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Abstract
Many fisheries worldwide have exhibited marked decreases in profitability and fish stocks during the last few decades as a result of overfishing. However, more conservative, science- and incentive-based management approaches have been practiced in the US federally managed fisheries off Alaska since the mid 1990's. The Bering Sea pollock fishery is one such fishery and remains one of the world's largest in both value and volume of landings. In 1998, with the implementation of the American Fisheries Act (AFA) this fishery was converted from a limited access fishery to a rationalized fishery in which fishing quota were allocated to cooperatives who could transfer quotas, facilitate fleet consolidation, and maximize efficiency. The changes in efficiency and productivity growth arising from the change in management regime have been the subject of several studies, with a few focusing on the large vessels that both catch and process fish onboard (catcher-processors). In this study we modify existing approaches to account for the unique decision making process characterizing catcher-processor's production technologies. In particular, we focus on sequential decisions regarding what products to produce and the factors that influence productivity once those decisions are made using a multiproduct revenue function. The estimation procedure is based on a latent variable econometric model and departs from and advances previous studies since it deals with the mixed distribution nature of the data. Our productivity growth estimates are consistent with increasing productivity growth since rationalization of the fishery, even in light of large decreases in the pollock stock. These findings suggest that rationalizing fishery incentives can help foster improvements in economic productivity even during periods of diminished biological productivity.

Key Words: Fisheries, Revenue function, Productivity, Environmental Factors

1. Introduction

The common property characteristic of many fisheries and the nature of the regulations that have been imposed to deal with the resulting depressed fish stocks and profitability in several countries around the world have had negative consequences on the economic performance of fisheries and paradoxically on the fish stocks as well. Regulations have often been based on direct output or input constraints that are ineffective in minimizing the side effects of common-property management such as over-capitalization. When restrictions are placed on a subset of the inputs used in fishing, the regulations often induce increased use of unregulated inputs to maintain or increase fishing power and catch share, promoting the so called race-for-fish or "input stuffing". As a consequence harvesting efficiency and profits can be severely impaired with continued pressure on fish stocks.

These consequences, while ironic, have been widely discussed in the literature and several authors have stressed and measured the efficiency impacts associated with alternative types of management such as the allocation of access privileges and the use of rational incentives (Arnason 2012, Wilen 2009, Abbott et al. 2010, Weninger and Waters 2003, Tingley and Pascoe 2005, Vestergaard 2005, Orea et al. 2005, Felthoven 2002, Grafton et al 2000*)*. However, there are few examples in the literature (e.g. Paul et al. 2009) that have focused on investigating the financial implications of these new types of management both in terms of enhanced revenue due to increased processing productivity as well as flexibility in the timing and coordination of fishing to support processing decisions. Specifically, the hypothesis we test in our research is whether and to what extent eliminating the race for fish has augmented processors' abilities to control the rate at which fish enter the processing chain and to adapt their product choices in response to prices as well as other regulatory and environmental factors. We examine this hypothesis in the context of processing revenue and productivity aboard vessels that jointly conduct fishing and processing.

In line with the study performed by Paul et al., this paper focuses on the revenue patterns of the North Pacific pollock fishery which operates in the Eastern Bering Sea off Alaska. This fishery is one of the largest in the world in terms of both volume and value (NMFS 2011) and makes an interesting study case since after the implementation of the Alaskan Fisheries Act (AFA) in 1998 it changed from a limited access fishery to a cooperative-based fishery in which quota were allocated to vessel owners who could then sell or lease their quota to other vessel owners. Harvest quota were allocated to three sectors: the inshore sector (comprised of vessels that delivered to onshore processing plants), the mothership sector (comprised of vessels that delivered to floating processors) and the offshore sector, the focus of this paper (comprised of catcher-processor vessels).

Paul et al. analyzed production in this fishery over the time period 1994-2004 and concluded that the effects of the AFA induced better coordination between catching and in-vessel processing, better catch screening (e.g. more time to search for higher quality, more uniform fish) and handling (smaller tows and less bruising), which collectively led to a more valuable product mix. In other words, the AFA appeared to generate greater productivity and thus revenue per unit of fish caught, even when controlling for price fluctuations and changes in product composition.

One of the caveats in their modeling effort was the large number of zeros in the left-hand-side of the supply equations jointly estimated with the revenue function. Many vessels did not produce one or more of the outputs (e.g., surimi) over the span of the data, so for vessels that had never produced a given product, it was assumed that the relevant processing technology wasn't available and dummy variables were created to eliminate particular products as choices in specific observations within the dataset. While the high number of zeroes did not preclude econometric estimation, it did raise some questions about whether there were more rigorous and holistic ways of modeling the joint decision of what products to produce, the trade-offs among the various factors of production, and the resulting productivity. But these questions require technical considerations regarding the correct distribution of the data and resulting econometric specification.

Zeroes associated with a given processed product may appear in the database for several reasons, many of which may be unknown to the researcher. For example, the vessel may not have had the processing equipment onboard at some times (e.g. surimi), or nature or the environment may dictate whether or not a given product is available during that portion of the season (e.g. roe). Market prices of outputs may also play a role since unfavorable prices may induce the vessel to not process a specific product. In fact, the existence of so many zeroes for some products suggests that there is a discrete nature underlying the data generating process – to either process or not process a given type of product. This nature however is not purely discrete since once the output value appears greater than zero it can take any value within a considerably large range. This leads us to conclude that econometric estimation methods based on mixed distributions and combine discrete and continuous features would better accommodate the nature of these data.

In this context, the present paper's goal is to build an empirical and testable econometric framework which takes into account the mixed nature of the distribution of our data. More specifically, on the theoretical side we derive a multiproduct revenue function model and on the empirical side we build a testable model based on a flexible functional form for the revenue and derived supply functions. Econometric estimations are carried out by applying a two-step latent variable model and with them we analyze impacts on productivity and revenue before and after implementation of the AFA, accounting for large changes in the fish stock that occurred in the post-AFA period.

1.1. The Pollock fishery: Location, Vessels and Targeted Species

The Alaskan Pollock fishery encompasses a large area in the Bering Sea between Russia and Alaska (Figure 1). This fleet is comprised of vessels whose catch is almost entirely made up of pollock[1]and who either deliver to shoreside or floating processors, or catch and process the fish themselves. The focus of this study is on this last category of vessels: catcher-processors. The vessels are on average 100 meters long, with an average capacity 1800 gross tons, operating with 6000 horsepower on average. They all use similar trawl gear and the targeted specie is pollock, a pelagic whitefish from which the vessels produce several products.

2. The Basic Theoretical Model

The model is based on a multiproduct short-run revenue function which represents the maximum attainable revenue for a vessel given prices, fishing and processing inputs and technology, and environmental conditions. In general, the function takes the form of

$$R(\mathbf{P},\mathbf{Z},\mathbf{T}). \qquad (1)$$

Where **P** is a vector of *M* output prices, **Z** a vector of *L* input levels, and **T** a vector of *J* fishing conditions (weather, technological factors and fish biomass).

[1] "Sideboard" or non-pollock species are allowed to be caught but they comprise a small percentage of the total catch.

Measuring productivity involves characterizing changes in revenue associated with the factors recognized in the model—often just conventional factors of production, output prices and time. The resulting residual measure of revenue, net of input change and output prices over time is typically interpreted as productivity growth but is also often recognized to be a "measure of our ignorance" (Abramovitz [1956]). The more productive factors that are explicitly represented in the function representing the technology, and thus whose productive contributions can be separately measured and interpreted, the less output change is relegated to the unexplained residual.

More specifically, the traditional productivity residual is represented by growth in revenue not explained by (weighted) changes in input use and output prices. The productive impacts of other determinants of the production or transformation relationship can also be evaluated if data on such factors are available and the weights representing their productive contributions to revenue can be measured via revenue elasticities.

Formally, growth over time (*t*) in revenue is attributed to the production determinants included as arguments of the function through the total differential:

$$\frac{dR}{dt} = \sum_m \frac{\partial R}{\partial P_m}\frac{dP_m}{dt} + \sum_l \frac{\partial R}{dZ_l}\frac{dZ_l}{dt} + \sum_{j(j\neq t)} \frac{\partial R}{dT_j}\frac{dT_j}{dt} + \frac{\partial R}{\partial t} \qquad (2)$$

Rearranging, we can define revenue change not explained by output prices (P), input use (Z), and other environmental impacts (Z) as:

$$\frac{\partial R}{\partial t} = \frac{dR}{dt} - \sum_m \frac{\partial R}{\partial P_m}\frac{dP_m}{dt} + \sum_l \frac{\partial R}{dZ_l}\frac{dZ_l}{dt} + \sum_{j(j\neq t)} \frac{\partial R}{dT_j}\frac{dT_j}{dt}$$

(3)

Or, in percentage or proportional terms (log-changes):

$$\frac{\partial \ln R}{\partial t} = \frac{d \ln R}{dt} - \sum_m \frac{\partial \ln R}{\partial \ln P_m} \frac{d \ln P_m}{dt} + \sum_l \frac{\partial \ln R}{d \ln Z_l} \frac{d \ln Z_l}{dt} + \sum_{j(j \neq t)} \frac{\partial \ln R}{d \ln T_j} \frac{d \ln T_j}{dt} \tag{4}$$

Which can be expressed in terms of elasticities and observed changes in the data as

$$\varepsilon_{R,t} = \frac{\partial \ln R}{\partial t} = \frac{d \ln R}{dt} - \sum_m \varepsilon_{R,P_m} \frac{d \ln P_m}{dt} + \sum_l \varepsilon_{R,Z_j} \frac{d \ln Z_l}{dt} + \sum_{j(j \neq t)} \varepsilon_{R,T_j} \frac{d \ln T_j}{dt} \tag{5}$$

Assuming vessels are price taking firms[2], from (1) we can derive the conditional supply functions associated with each of the processed products using Hotelling's lemma. That is,

$$Y_m = \partial R/\partial P_m \,, \tag{6}$$

where Y denotes the output quantity and m the specific product. R is convex in **P.** Further revenue function properties are homogeneneity in **P** and non-decreasing in **P** and **Z**. Outputs can be either substitutes or complements depending on their cross-price effects. These properties are empirically testable.

More specifically, first-order revenue elasticities with respect to the components of the **P**, **Z**, and **T** vectors can be derived to estimate (5) above by computing logarithmic derivatives with respect to the revenue function, where

$$\varepsilon_{R,P_m} = \frac{\partial \ln R}{\partial \ln P_m} = \frac{\partial R}{\partial P_m} \frac{P_m}{R} = \frac{Y_m P_m}{R} \tag{7}$$

reflects the marginal revenue share of product m, which must be positive for the products exhibiting supply responsiveness.

The input elasticities are given by

$$\varepsilon_{R,Z_l} = \frac{\partial \ln R}{\partial \ln Z_l} = \frac{\partial R}{\partial Z_l} \frac{Z_l}{R} = \frac{W_l Z_l}{R} \tag{8}$$

[2] This fishery produces a majority of the world supply of pollock in most years, along with Russian stocks, but the global price of pollock is considered to be driven by the entirety of the whitefish market, which includes several other species and stocks worldwide. Thus, the price taking assumption is probably reasonable for any particular vessel or firm in this fishery.

where W_l is the marginal shadow value of input l, reflect the shadow shares. These must be positive for productive inputs. The elasticities with respect to the **T** factors,

$$\varepsilon_{R,T_j} = \frac{\partial \ln R}{\partial \ln T_j} = \frac{\partial R}{\partial T_j}\frac{T_j}{R} \qquad (9)$$

similarly reflect the revenue contribution of T_j and may be either positive or negative.

Collectively, these elasticities and changes in prices, input use, and environmental factors can be used to compute Equation (5), economic productivity growth in terms of the trend in revenues not explained by other productive factors in the model, $\varepsilon_{R,t} = \partial \ln R / \partial t = \frac{\partial R}{\partial t} / R$, which may also be positive or negative and exhibit different values in each period.

3. Data and Empirical Implementation.

The data contain weekly observations for catcher-processors in the North Pacific pollock fishery during 1994-2009 obtained from the U.S. National Marine Fisheries Service federal observer program, weekly production reports, and vessel characteristic data combined from federal, Alaska state, and U.S. Coast Guard vessel registration files. Overall the sample contains 544 observations that were aggregated to the seasonal level ("A" is the winter and "B" is the summer) since roe an important product in the industry is rarely present in pollock in the summer and therefore practically infeasible in the B season for many years in our model.

In this fishery, over all years in our data present in TABLE 1, an average of 88% of the total annual revenue earned by this fleet comes from 4 processed pollock products: regular fillets (*F*), deep skin fillets (*D*), surimi (*S*) and roe (*R*). Besides theses products, vessels produce other pollock products (*O*) such as mince or meal and oil, in order to utilize the leftovers after making the former primary products. A small amount of other non-pollock (*N*) products (mostly flatfish and Pacific cod fillets) are produced, but the amount is limited to through the allocation by fishery managers (even more strictly so in the post-AFA years); in earnest, these vessels target pollock while fishing. Therefore the *M* processed outputs are comprised by *F*, *D*, *S*, *R*, *O* and *N*. In equation (1), **P** includes the prices for the *M* pollock processed products. **Z** includes variables representing fishing effort and includes weekly crew size (*C*), number of days fished (*DA*), vessel characteristics (gross tonnage (*G*) and horsepower (*H*)) and two additional dimensions of fishing effort – towing duration (*DU*) and number of tows (*TO*). *DU* represents the actual time spent with gear in the water to obtain the observed catch. *TO* represents how many times a vessel puts the trawl gear in the water and extracts fish. These latter two dimensions of fishing effort have changed in the post-AFA period and it is purportedly due to the regulatory change (Wilen and Richardson 2008). As the race for fish ended as a result of the AFA, vessels often take more tows screening for better quality fish of a consistent size, and the resulting hauls are often lower to discourage bruising and retain product quality.

The net result is a greater number of shorter tows and heightened product value. In other words, changes in *DU*, *TO* and *DA* embody the regulatory impacts on revenue and product mix. **T** contains a time trend (*t*), and a measure of average annual surface air temperature (*SA*), that may affect revenue, as an indicator of environmental conditions. Higher values of *SA* are consistent with better fishing conditions. **T** also contains a measure of pollock stock (*K*) which is the estimated EBS pollock, age 3+ biomass measured in millions of fish, which represents the pollock that are annually recruited into the fishery (younger, smaller fish are not targeted by the fleet and do not contribute to the catchable fish biomass). For summary statistics of these variables and a description of their interpretation, see Tables 2 and 3 below. To facilitate a broad view of the data trends we have presented a summary over the entire period as well as for the pre- and post-AFA periods. As noted earlier, the data used in the regressions were based upon data aggregated over each season in each year.

For the revenue function in (1) we assume a fully flexible generalized Leontief:

$$
\begin{aligned}
R_{it} = R_{it}(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}) \equiv & \sum_m \sum_n \alpha_{mn} P_{mit}^{.5} P_{nit}^{.5} + \sum_m \sum_l \delta_{ml} P_{mit} Z_{lit} + \sum_m \sum_j \delta_{mj} P_{mit} T_{jit} \\
& + \sum_m P_{mit} (\sum_l \sum_q \delta_{lq} Z_{lit} Z_{qit} + \sum_j \sum_k \delta_{jk} T_{jit} T_{kit} + \sum_l \sum_j \delta_{lj} Z_{lit} T_{jit} \quad ,
\end{aligned}
\tag{10}
$$

for vessel i at time t. Subscripts m, n denote output price, l,q input levels and j,k fishing conditions. The functional form for the supply equations is then derived accordingly to (6), that is

$$
\begin{aligned}
Y_{mit} = \frac{\partial R_{it}(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it})}{\partial P_{mit}} \equiv & \sum_n \alpha_{mn} P_{nit}^{.5} / P_{mit}^{.5} + \sum_l \delta_{ml} Z_{lit} + \sum_j \delta_{mj} T_{jit} \\
& + \sum_l \sum_q \delta_{lq} Z_{lit} Z_{qit} + \sum_j \sum_k \delta_{jk} T_{jit} T_{kit} + \sum_l \sum_j \delta_{lj} Z_{lit} T_{jit} \quad ,
\end{aligned}
\tag{11}
$$

4. Estimation

In Paul et al. the parameters of the revenue function represented by (10) are estimated jointly in a system along with the supply equations represented by (11), using seemingly unrelated regression (SUR) techniques. As discussed in the introduction, the presence of numerous zero-valued supply observations reflect that the data generating process may be mixed: partially discrete and partially continuous. Several econometric models have been developed to deal with this problem for single equation models, for example the double hurdle models and their variants (Blundell and Meghir (1987), Cragg (1971), Heckman (1976) and Amemya (1974)). Since we have a system of censored equations we follow an alternative modeling approach based on a two-step procedure proposed originally by Heien and Wessells (1990) and later refined by Shonkwiler and Yen (1999).

Vessel operators derive benefits (or positive net revenue) by deciding to process each product *m*, $m \in M$. The decision process is represented by a pair (d^*_{mit}, w^*_{mit}) of latent benefit random variables, where d^*_{mit} is the one associated with the decision of the i^{th} vessel to process product *m* in time *t*, and w^*_{mit} with the decision of how much of product *m* to be processed by the i^{th} vessel in time *t*.

The first step of the modeling process is defined as,

$$d^*_{mit} = g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m) + e_{mit}$$
$$d_{mit} = \begin{cases} 1 & \text{if } d^*_{mit} > 0 \\ 0 & \text{otherwise} \end{cases} , \qquad (12)$$

And the second step is defined as

$$w^*_{mit} = h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m) + u_{mit}$$
$$Y_{mit} = d_{mit} w^*_{mit} \qquad (13)$$

In which (d^*_{mit}, w^*_{mit}) are real valued pairs of the latent variables, $g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)$ is the functional form for the equation describing the discrete decision to process or not to process product *m,* and $h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m)$ is the functional form for the equation describing how much of output *m* is being processed; $\mathbf{P}_{it}, \mathbf{Z}_{it}$ and $\mathbf{T}_{it}$ are described in Section 3 and $\boldsymbol{\beta}_m$ and $\boldsymbol{\gamma}_m$ are vectors of parameters associated with each product *m*; e_{mit} and u_{mit} are random errors.

Assuming for each product *m* that e_{mit} and u_{mit} are bivariate normally distributed with

$cov(e_{mit}, u_{mit}) = \delta_m$, the conditional mean of Y_{mit} can then be defined as

$$\mathrm{E}(\mathrm{Y}_{\mathrm{mit}} | \mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}; \mathrm{e}_{\mathrm{mit}} > -g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)) =$$

$$h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m) + \delta_m \frac{\varphi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m))}{\Phi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m))}. \quad (14)$$

In which, $\varphi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m))$ and $\Phi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m))$ are respectively the normal *pdf* and *cdf* evaluated at $g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)$.

Now, given that $\mathrm{E}(\mathrm{Y}_{\mathrm{mit}} | \mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}; \mathrm{e}_{\mathrm{mit}} \leq -g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)) = 0$, the unconditional mean of Y_{mit} is then defined as

$$\mathrm{E}(Y_{mit} | \mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}) =$$

$$\Phi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)) h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m) + \delta_m \varphi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)). \quad (15)$$

To implement the model empirically, in the first step, probit estimates of $\boldsymbol{\beta}_m, \hat{\boldsymbol{\beta}}_m$, are calculated and then introduced into (15). The supply function, Y_{mit}, is then modeled as

$$\mathrm{Y}_{\mathrm{mit}} = \Phi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \hat{\boldsymbol{\beta}}_m)) h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m) + \delta_m \varphi(g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \hat{\boldsymbol{\beta}}_m)) + \mathrm{v}_{\mathrm{m}}. \quad (16)$$

For $g(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\beta}_m)$ it is assumed the linear functional form $\alpha_m + \sum_m \gamma_m P_{mit} + \sum_l \gamma_l Z_{lit} + \sum_j \gamma_j T_{jit}$, and for $h(\mathbf{P}_{it}, \mathbf{Z}_{it}, \mathbf{T}_{it}, \boldsymbol{\gamma}_m)$ the functional form comes from (11). In the second step the M equations of the system in (16) plus the revenue equation as defined in (10) are estimated jointly by SUR techniques.

As already shown by Shonkwiler and Yen (1999) and Tauchman (2005) the error term in (16) is heteroscedastic. To overcome this problem we set up a FGLS estimator by using the residual covariance matrix, the weighting matrix and the covariance matrix of the transformed residuals of the system of the censored equations (which include the Probit estimates). The estimation process is then carried out as follows: the disturbances of the model are assumed to be independent across observations, but to have free covariance across observations. A consistent estimate of this covariance matrix is formed and used to weight the observations when the equations are re-estimated. Since the diagonal elements of the covariance matrix are not necessarily identical, heteroscedasticity is taken into account across units.

5. Results

The Estimation and Measures

Individual parameter estimates from our models have limited intuitive content for these flexible functional forms,[3] therefore the analyses rely on first-order elasticities fitted at the sample mean and statistically tested against zero using standard errors computed by the Krinsky-Robb method (Krinsky and Robb, 1986), as our elasticities are non-linear. In Table 4 we present the first-order elasticities, that is, the computed values for equations (7), (8) and (9), calculated separately for the whole period as well as pre-AFA and post-AFA periods.

The results indicate that the value of fish biomass has the expected positive (and statistically significant) impact on revenue. Considering the whole period, a 1% increase in pollock fish stock increases revenue by 0.58% . The stock impact was higher in the pre-AFA (1.39%) period than after the AFA was implemented(0.39%), suggesting that stock declines in the derby period had a greater impact on revenues, *ceteris paribus*, than in the rationalized fishery. In earlier work (Paul et al.) the stock variable was not included in the final specification due to lack of model significance of the stock variable. Here, however, an updated database on stock and a longer temporal horizon of the fishery are utilized, encompassing greater variation in stock sizes (in particular, large stock declines in most recent years). Statistical tests for the stock

[3] Also due to lack space we do not present them here. They can be obtained however upon request to the corresponding author.

variable lead us to conclude that in our current specification, stock is indeed a significant determinant of both catch and revenue productivity in pollock BSAI fishery.

Moreover our measure of productivity, as given by the revenue elasticity with respect to the time trend, shows a highly statistically significant ε_{Rt} of 0.08, indicating a strong growth in economic productivity including harvesting *and* processing. This is approximately the same rate found by Paul et. al (2009) using a shorter time series and slightly different model specification. Although very few economic productivity studies have been conducted for other U.S. fisheries, this is an impressive rate of productivity in comparison. In the Northeast Groundfish fishery, Jin et. al (2002) found an average rate of productivity growth of around 4%, albeit over a longer time period (from 1964-1993). Another important and striking result is that the fishery was able to keep up this productivity level, comparing both pre- and post-AFA periods, even after the considerable stock declines we have observed in the last several years in this fishery. This provides strong evidence that the flexibility in both harvesting and processing product choices in a rationalized fishery have substantively contributed to the economic performance of the North Pacific pollock fishery.[4]

Looking at other revenue impact measures, the elasticities of revenue with respect to output prices are all positive (considering all 544 observations) and statistically significant considering all products (roe, deep, regular fillets, surimi, other pollock and non-pollock products). The largest estimated share is with surimi (29.3%) followed by roe (28%), deep-skin fillets (18.2%) and regular fillets (14.3%). This pattern is consistent across the pre- and post-

[4] This productivity residual pattern is different than the one found in Paul et al. which presented a higher productivity growth rate in the pre-AFA period. We believe, however, that by accounting for pollock stock changes across time, using a larger data time span and the more accurate model to reflect product selection and better characterize the technology, our estimators are more consistent and estimates more precise. Given the relatively high stock sizes in the pre-AFA period and the way our model accounts for revenue changes attributable to stock changes, the differences in our current results relative to the earlier work would be expected.

AFA periods with the exception of the regular fillets, for which the elasticity estimate was not statistically significant in the pre-AFA period.

Elements of the **Z** vector which are often used to calculate returns to scale (RTS) in dual models, by summing over their shadow values, include horsepower, crew size, days fishing, and gross tonnage. The variables are all positive and statistically significant over the sample, and the mean RTS changed from a pre-AFA value of 1.58 to a post-AFA value of 1.15, reflecting the increased catch levels of the smaller fleet and their ability to capitalize on increasing returns to scale. The regressors that were included in order to capture changes in fishing strategy (number of tows and duration of tows), are positive, as expected, and statistically significant at 5%, considering the whole sample.

The most notable changes we observe for input shadow values beyond scale changes are that in the pre-AFA period, days fished and number of tows had a relatively higher and statistically significant impact on revenue compared to the post-AFA period, when their elasticity became smaller in magnitude and barely or not at all statistically significant. We attribute this change to the way in which rationalization and ending the race for fish has changed fishing. Specifically, longer seasons and a greater number of tows per vessel, often employed as test tows to ensure the optimal quality and size for fish targeted for roe and fillet processing, have diminished the marginal product of each. We also observed that the shadow value of horsepower increased, and that of crew size decreased, in the post-AFA period. The horsepower trend likely reflects the change in the composition of the fleet (the decommissioned vessels were generally shorter and less powerful) and their greater rate of productivity, while it is possible that the reduction in the shadow value of additional crew members reflects a diminishing marginal product of crew, as average crew size is much higher in the post-AFA period.

Greater towing duration for a given amount of tows, fishing days, and other factors of production was not found to be statistically significant contributor to revenue over the sample or in the post-AFA period. However, there was a negative and (barely) statistically significant relationship between revenue and towing duration in the pre-AFA period, which could be explained by longer towing times being associated with poorer fishing conditions (for a given amount of tows and days at sea). While we have attempted to control for fishing conditions with stock estimates and other environmental variables that may affect productivity, there are likely other unmeasured or immeasurable factors that affect fishing proficiency in a given year. Related to this issue, fishing conditions and associated revenue measured by the annual air surface temperature and measured by $\varepsilon_{R,T_{SA}}$ did appear to be more favorable in warmer periods, *ceteris-paribus,* over the entire sample.

In Table 5 we show the results for own- and cross-price elasticities for all products (estimates statistically significant at 5% are in bold). As expected the own-price elasticities are all positive for the primary products: roe, deep skin fillets, regular fillets and surimi(statistically significant, however, only for regular fillets and surimi). For the secondary products (other pollock and others non-pollock) these elasticities are negative (and statistically significant at 5% for other non-pollock), a result which is counter to what one might expected, but not particularly surprising. We believe this is in part due to the full retention requirements, which require the pollock vessels to process the entire fish, creating ancillary products like meal or oil or mince. After the AFA was implemented, and nine vessels left the fishery due to the buyout, the remaining vessels produced a greater share of the sector's catch, including the ancillary products, which were required to be produced regardless of the price of those products. Here we are likely observing the impacts of regulatory requirements that lead production decisions to be decoupled from price signals/trends. A similar rationale explains the production patterns we see for the small production of the non-pollock species. We would expect to see (and have seen) very little price sensitivity in non-pollock species, as they are relatively valuable to the fleet and available in limited quantities to the fleet by fishery managers in order to preclude effort from spilling out of the pollock fisheries beyond management defined thresholds. Decreased catch and production of these non-pollock species throughout our sample (drive largely by heightened post-AFA restrictions on non-pollock catch) in the presence of significant price increases leads to the negative relationship we observed for non-pollock price elasticities. We believe this to be an artifact of the constraints on non-pollock catch and not a lack of rational production decisions by the catcher-processor fleet.

Looking at the cross-price elasticities, the products that are most responsive to other products' prices, either in magnitude or statistical significance, are regular fillets, surimi and others non-pollock. Results conform to our expectation that fillet production is sensitive to the price of surimi, as they are biological substitutes in that one cannot retrieve a fillet if the bulk of the fish is used to create surimi. Roe does not seem to be highly responsible to any other product's prices, as there is no biological substitute product to be created from the roe, its price far exceeds all other products, and as a result, boats concentrate their efforts to procure it during Season A so long as the prices cover operating costs. As expected, secondary products (either the ancillary other-Pollock or the bycatch represented by other non-Pollock) tend to be complements to all other primary products, except for surimi. On the other hand, primary products tend to be substitutes among one another (with the exception of surimi and roe).

6. Concluding Remarks

In this article we have used a multi-product revenue function to analyze the revenue and productivity patterns for the catcher-processor fleet targeting pollock in the North Pacific. The period under study includes the implementation of the American Fisheries Act (AFA), which transformed the fishery from a limited access, derby style regime to a rationalized industry that employs transferable harvest quotas. This system has allowed vessel operators to improve product quality and value through better coordination of harvesting and processing activities, exploit economies of scale, and to conduct their activities more cooperatively within the fleet.

In contrast to previous studies we have used a latent variable model to estimate a system of equations, some of which are censored, to take into account the mixed nature of the data. Our modeling framework allows for interactions among all arguments of the revenue and supply functions, including inputs (crew, vessel characteristics, and fishing methods) and environmental factors (weather and fish stock). This econometric approach allows for consistent estimation of the parameters without the potential bias that can arise when working with censored data.

The results of the study reflect the contributions of a broad range of market, technological, regulatory, and environmental factors on revenue and productivity in the industry. We have quantified and examined the productive relationships for inputs and outputs in the production process. We find the greatest level of price responsiveness for those outputs that compete for the flesh of the pollock (surimi and fillets), with less price sensitivity occurring for those that do not (roe) and non-conventional relationships for management dictated or highly constrained products (ancillary pollock and non-pollock products). Our measures of input use and fishing strategies show similar expected (positive) values in their estimated shadow values, albeit with different values in the pre- and post-AFA periods.

In particular the marginal contribution of days fished and number of tows have changed, reflecting differential fishing and processing strategies present in the pre- and post-AFA periods. Although increases in these factors still contribute positively (and statistically significantly) to revenue, the marginal value has decreased after rationalization, reflecting that time has become less binding and other dimensions of effort, such as product form and product recovery rate, are more important drivers of value in the fishery.

Our productivity residual, which controls for wide range of factors affecting revenues in this fishery, is strongly positive and found to be higher in the post-AFA period that in previous studies. We attribute this difference to our explicit accounting of the contribution of fish stock sizes to catch levels and the marked decrease in the number of pollock available to the fleet in recent years. Our results thus reflect that productivity growth appears to be higher in a rationalized environment, even in the face of diminishing environmental productivity, which is a fairly striking result and display of ingenuity by the fleet.

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Figure 1 – Bering Sea

Figure 2 – The Typical Vessel

Figure 3 – Alaska Pollock (Theragra chalcogramma)

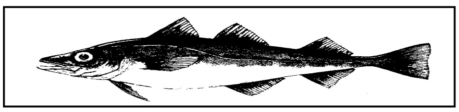

TABLE 1 – Yearly Revenue Shares (%) by Pollock Product

	Roe Pollock	*Boneless Fillet*	*Deep Skin Fillets*	*Surimi*	*Other Pollock*	*Non-Pollock*
1994	5.5	48.5	23.4	9.2	4.2	9.2
1995	10.6	44.4	30.6	2.5	3.6	8.4
1996	15.3	37.1	28.6	2.6	4.3	12.1
1997	11.8	46.7	29.2	0.6	3.0	8.7
1998	15.9	39.7	17.2	12.9	6.5	7.9
1999	29.4	35.4	22.5	3.0	4.6	5.0
2000	17.7	30.5	38.3	4.2	5.8	3.6
2001	14.1	23.1	38.6	13.1	8.9	2.4
2002	13.6	25.2	33.1	18.3	7.0	2.8
2003	18.1	20.9	31.7	19.5	6.5	3.3
2004	17.6	19.0	35.2	17.8	7.2	3.2
2005	18.0	26.0	28.3	17.0	6.3	4.4
2006	16.5	22.9	23.6	22.9	8.8	5.3
2007	20.0	24.2	21.7	20.4	8.3	5.5
2008	15.1	32.7	18.7	21.1	7.1	5.2
2009	22.5	21.4	16.2	23.3	10.7	5.8

Table 2 – Descriptive Statistics – Whole, Pre-AFA and Post-AFA Samples

	Whole Sample				*Pre-AFA Sample*				*Post-AFA Sample*			
Variables	*mean*	*std. Error*	*min.*	*max.*	*mean*	*std. error*	*min.*	*max.*	*mean*	*std. error*	*min.*	*max.*
Pollock Stock	9428.92	2264.54	4393	12883	10777.35	1171.47	9627	12883	8734.05	2376.77	4393	11974
Crew Size	103.39	25.94	30	165	95.5	27.14	30	165	107.45	24.36	43	162
Horsepower	5678.93	1648.03	2250	8800	5596.21	1654.16	2250	8800	5721.55	1645.56	2250	8800
Number of Days	84.9	27.24	24	180	69.1	25.55	24	180	93.04	24.37	32	175
Number of Tows	301.6	91.03	60	721	275.9	101.33	60	673	314.84	82.31	116	721
Gross Tonnage	1706.22	812.19	530	3198	1708.7	807.89	530	3198	1704.94	815.52	530	3198
Towing Duration	919.32	363.05	161	2461	887.33	376.27	161	2461	935.81	355.46	200	2413
Surface Air Temp	2.69	0.87	1	4.03	2.74	0.66	2.19	3.99	2.67	0.97	1	4.03
Roe Quantity	269.25	296.48	0	1197	162.18	204	0	1115	324.43	320.87	0	1197
Roe Price	13248.58	2940.84	7912	20524	11825.79	2444.88	7912	14967	13981.77	2908.68	10167	20524
Regular Fillets Quantity	801.06	977.66	0	4582	175.42	443.27	0	2664	1123.46	1020.91	0	4582
Regular Fillets Price	2362.35	633.02	1327	3983	2070.5	254.13	1327	2502	2512.74	712.67	1457	3983
Deep Skin Fillets Quantity	754.94	773.77	0	4092	324.21	596.82	0	2718	976.91	761.42	0	4092
Deep Skin Fillets Price.	2928.68	520.29	2377	4389	2752.98	228.1	2482	3103	3019.22	599.74	2377	4389
Surimi Quantity	1697.43	1254.35	0	5144	1411.55	1083.97	0	4127	1844.74	1310.93	0	5144
Surimi Price	2290.11	663.07	1569	4409	2259.34	263.1	1894	2583	2305.98	794.06	1569	4409
Other Pollock Quantity	812.34	665.04	0	3872	439.98	393.53	0	2405	1004.23	694.73	0	3872
Other Pollock Price	1041.32	416.07	392	3063	724.13	249.34	392	2953	1204.77	389.67	448	3063
Other Non Pollock Quantity	588.93	1204.3	0	8126	765	1396.44	0	8126	498.19	1083.18	0	6085
Other Non Pollock Price	1944.27	1739.08	378	11751	1615.48	997.07	489	4385	2113.71	1997.91	378	11751
Time	8.32	4.55	1	16	3.15	1.39	1	5	10.98	3.09	6	16

Table 3 – Variables Definition and Units of Measurement

Time	Time counter (t=1,2,…)
Number of Days	Number of days fished in each week by each vessel, summed over all weeks in a year.
Horsepower	Horsepower of the vessel.
Crew Size	Average number of crew aboard each vessel (weekly number of crew aboard each vessel summed over all weeks in a year divided by the number of weeks).
Pollock Stock	Millions of 3+ year old spawning pollock from December 2011 stock assessment (NPFMC, 2011).
Number of Tows	Number of times trawl is hauled out of the water in each week summed over all weeks in a year.
Towing Duration	Number of hours trawled in each week summed over all weeks in a year.
Surface air Temperature	Calculated as deviations from a 1950-2003 base.
Gross Tonnage	A measure of a vessel's volume in cubic meters
Quantity of Processed Pollock and Non-Pollock Products	Tons of product, or an aggregate of products, produced by a vessel in a given year.
Price of Processed Pollock and Non-Pollock Products	US$ per ton, derived as total revenues divided by tons produced per . For aggregates such as "other pollock" or "non-pollock" products, we summed total revenue in each class and divided by total tons produced, effectively weighting the prices by volume produced.

Table 4: First Order Revenue Elasticities

Products			Z Factors			T Factors		
Full Sample	Estimate	t-stat		Estimate	t-stat		estimate	t-stat
ε_{R,P_R}	**0.276**	*13.68*	ε_{R,Z_c}	**0.427**	*6.22*	$\varepsilon_{R,T_{SA}}$	**0.317**	*6.71*
ε_{R,P_F}	**0.143**	*10.24*	ε_{R,Z_H}	**0.402**	*7.13*	$\varepsilon_{R,t}$	**0.080**	*13.05*
ε_{R,P_D}	**0.182**	*15.27*	ε_{R,Z_G}	**0.156**	*4.50*	ε_{R,T_K}	**0.578**	*4.74*
ε_{R,P_S}	**0.293**	*32.35*	$\varepsilon_{R,Z_{DA}}$	**0.234**	*2.34*			
ε_{R,P_o}	**0.066**	*18.44*	$\varepsilon_{R,Z_{TO}}$	**0.204**	*2.32*			
ε_{R,P_N}	**0.061**	*10.10*	$\varepsilon_{R,Z_{DU}}$	0.014	*0.26*			
Pre-AFA	Estimate	t-stat		Estimate	t-stat		estimate	t-stat
ε_{R,P_R}	**0.329**	*10.81*	ε_{R,Z_c}	**0.667**	*5.58*	$\varepsilon_{R,T_{SA}}$	**0.472**	*5.14*
ε_{R,P_F}	-0.013	*-0.35*	ε_{R,Z_H}	**0.292**	*2.38*	$\varepsilon_{R,t}$	**0.083**	*4.37*
ε_{R,P_D}	**0.178**	*5.32*	ε_{R,Z_G}	**0.300**	*5.07*	ε_{R,T_K}	**1.395**	*3.00*
ε_{R,P_S}	**0.439**	*18.04*	$\varepsilon_{R,Z_{DA}}$	**0.324**	*2.13*			
ε_{R,P_o}	**0.047**	*8.09*	$\varepsilon_{R,Z_{TO}}$	**0.630**	*4.02*			
ε_{R,P_N}	**0.129**	*7.65*	$\varepsilon_{R,Z_{DU}}$	**-0.191**	*-2.38*			
Post-AFA	Estimate	t-stat		Estimate	t-stat		estimate	t-stat
ε_{R,P_R}	**0.300**	*15.09*	ε_{R,Z_c}	**0.371**	*4.69*	$\varepsilon_{R,T_{SA}}$	**0.284**	*5.27*
ε_{R,P_F}	**0.195**	*19.33*	ε_{R,Z_H}	**0.447**	*7.88*	$\varepsilon_{R,t}$	**0.082**	*10.13*
ε_{R,P_D}	**0.192**	*21.17*	ε_{R,Z_G}	**0.120**	*3.31*	ε_{R,T_K}	**0.385**	*4.45*
ε_{R,P_S}	**0.266**	*35.38*	$\varepsilon_{R,Z_{DA}}$	**0.214**	*1.81*			
ε_{R,P_o}	**0.078**	*22.98*	$\varepsilon_{R,Z_{TO}}$	0.078	*0.80*			
ε_{R,P_N}	**0.048**	*9.55*	$\varepsilon_{R,Z_{DU}}$	0.074	*1.19*			

(*)Numbers in bold mean statistically significant at 5%.

Table 5: Own and Cross-Price Elasticities

M	$\varepsilon_{Y_R P_m}$	*t-stat*	$\varepsilon_{Y_F P_m}$	*t-stat*	$\varepsilon_{Y_D P_m}$	*t-stat*	$\varepsilon_{Y_S P_m}$	*t-stat*
R	0.048	*0.34*	-0.181	*-0.86*	-0.242	*-1.40*	0.141	*1.27*
F	-0.096	*-0.87*	**1.40**	*2.84*	-0.606	*-1.47*	**-0.459**	*-2.88*
D	-0.151	*-1.40*	-0.708	*-1.47*	0.313	*0.61*	-0.039	*-0.24*
S	0.153	*1.27*	**-0.943**	*-2.88*	-0.069	*-0.24*	**0.650**	*3.71*
O	0.034	*1.38*	**0.264**	*2.53*	0.062	*0.67*	**-0.182**	*-4.24*
N	0.011	*0.27*	**0.167**	*2.05*	**0.542**	*6.49*	**-0.111**	*-3.46*

M	$\varepsilon_{Y_O P_m}$	*t-stat*	$\varepsilon_{Y_N P_m}$	*t-stat*
R	0.146	*1.38*	0.032	*0.27*
F	**0.590**	*2.53*	**0.275**	*2.05*
D	0.163	*0.67*	**1.046**	*6.49*
S	-0.835	*0.07*	**-0.375**	*-3.46*
O	-0.160	*-1.13*	0.070	*1.55*
N	0.095	*1.55*	**-1.049**	*-9.19*