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Estimation of multi-output production functions in commercial fisheries ☆

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ABSTRACT

Measuring the productivity of vessels in a multi-species fishery can be problematic. Typical regression techniques are not capable of handling multiple outputs while Data Envelopment Analysis (DEA) tends to ignore the stochastic nature of production. Applied economists have devoted considerable time to this problem and have developed several methods of dealing with the issue of multiple output technologies in commercial fisheries. Our paper contributes to this literature by providing another method for estimating production functions of vessels operating in multi-species fisheries. We utilize a two-stage model – with data from the West Coast Limited Entry Groundfish Trawl Fishery – using DEA to aggregate output in the first stage. This aggregate index is then used as the dependent variable in a regression framework, allowing for the estimation of the return to different inputs in fisheries production. This provides information that may be particularly important for fisheries managers.

1. Introduction

The Magnuson-Stevens Fisheries Conservation and Management Act (MSA) established a legislative mandate for fisheries managers in the U.S. to consider the economic implications of management actions. In response, resource economists have built a large body of research around the issue of developing metrics to assess the economic performance of commercial fishing operations. The frequent omission of reliable input prices from fisheries data has led to the emergence of technical efficiency and related primal productivity measures as important performance metrics for commercial fisheries. The recent move by NOAA to adopt a policy of promoting catch-share management wherever feasible has renewed interest in the topic of performance metrics. In order to fulfill their responsibilities under MSA, and evaluate impacts of newly instituted catch-share programs on producers, it is important for policy makers to have reliable estimates of key performance indicators, such as technical efficiency.

Evaluation of technical efficiency for fisheries in which production technologies are characterized by multiple outputs can involve an uncomfortable choice between deterministic methods (such as Data Envelopment Analysis (DEA)), which remain faithful to the multi-output nature of the technology but lack a statistical foundation addressing the inherent stochasticity of commercial fishing, and regression-based models (such as Stochastic Frontier Analysis (SFA)), which respects the uncertainty underlying fishing but is ill-equipped to model production of multiple outputs. Our study reconciles this dichotomy by leveraging a newly developed empirical technique [9] to estimate efficiency among harvesters in California's multi-species Groundfish Trawl Fishery. The CJR model has been shown to recover the true inefficiency from simulated data. Moreover, the method permits identification and estimation of key parameters of the production function. This is a potentially valuable development for fisheries managers as estimated marginal input productivities and output elasticities can have important implications for fisheries managers.[1] This study provides the first policy-relevant, empirical application of the CJR model.

2. Literature review

Measuring vessel performance in a multi-species fishery is complicated by the frequent lack of input price data and the multi-output nature of the production function. Typical regression techniques are not capable of handling multiple outputs. Thus, regression analysis struggles to accurately measure the productivity

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[1] One way that marginal productivities can be informative for fisheries managers is in the context of input controls (see [11,22,30] for discussion of input controls in fisheries management). If regulated and unregulated inputs can be easily substituted for one another, this may erode the efficacy of input controls.

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of vessels in a multi-species fishery, unless input or output prices are known. The issue of estimating productivity, technical efficiency and/or harvesting capacity in a multi-species fishery in the absence of input or output prices is a familiar one and the one in which applied economists have invested considerable resources [35,39,19,20].

One approach to handle multiple outputs is to specify an output aggregate that can then be incorporated as the dependent variable in a regression model. One simple measure of aggregate output is the average (or sum) of all relevant species in a fishery (see e.g. [13]). Such an aggregate assumes the marginal rate of technical substitution is constant (and equal to one), implying a constant opportunity cost regardless of the output mix. This measure violates standard microeconomic principles.

A popular alternative to the regression based approaches is Data Envelopment Analysis (DEA), a linear programming model that evaluates each production possibility relative to a piecewise linear frontier. DEA, coined by Charnes et al. [7], built on the pioneering work of Farrell [17] by allowing multiple inputs and outputs assuming constant returns to scale. Banker et al. [3] extended DEA to the variable returns to scale technology of Afriat [1]. See [23,24] for recent survey articles. In addition to allowing multiple outputs, the approach is axiomatic and hence does not require *a priori* specification of the production function. One limitation; however, is that the approach is deterministic and does not allow statistical noise. In this paper, we apply the two-stage model of Collier et al. [9]. In the first stage, DEA is applied to obtain an index of aggregate output. In the second stage, regression is used. This approach allows consideration of statistical noise and multiple outputs.[2]

Finally, approaches based on the directional technology distance function [6,14,8,15] have emerged in recent years as popular methods for representing multi-output production technologies. Using a directional distance function approach, multi-output production functions can be estimated with standard econometric techniques. Applications of the directional distance function ([27,18]); however, have highlighted some important practical challenges, such as the difficulty of dealing with zeros in the output vector with a directional distance function model. This issue can be particularly limiting in the context of commercial fishing, where it can be common for fishermen to target particular species or species aggregates within a multi-species fishery.

Our paper contributes to the applied production economics literature by providing another method for estimating production functions of vessels operating in multi-species fisheries. We utilize a recently developed DEA technique that transforms multiple outputs into an aggregate output index without forcing the production frontier to have a constant marginal rate of technical substitution [9]. This aggregate index is used as the dependent variable in a regression framework to estimate the return to effort and technical efficiency in fisheries production. We apply this model to data from the West Coast Limited Entry Groundfish Trawl Fishery. The paper proceeds as follows: in Section 2 we discuss the data and some background on the West Coast Limited Entry Groundfish Trawl Fishery, Section 3 explains the methodology, Section 4 discusses the results and Section 5 concludes.

3. Methodology

Assume that each of n vessels employs a vector $x=(x_1,\ldots,x_m)$ of m inputs to produce a vector $y=(y_1,\ldots,y_s)$ of s outputs according to the technology set $T=\{(x,y): x \text{ can produce } y\}$. Input and output vectors for vessel j $(j=1,\ldots,n)$ are given by $(x_{1j},\ldots,x_{mj})$ and $(y_{1j},\ldots,y_{sj})$. The output set $P(x)$ is defined as $P(x)=\{y:(x,y)\in T\}$. An output set consistent with microeconomic theory is presented in Fig. 1, where for convenience we assume only two outputs are produced. We observe a convex output set consistent with increasing opportunity costs. Three possibilities A–C are observed producing maximum output (with different mixes) given input usage. In the case of different types of catch, the increasing costs could reflect costs of relocation and/or that some inputs are better suited for certain species of fish.

Past research has aggregated output by adding (or averaging) the various outputs. This implicitly assumes constant costs with an arbitrary weighting scheme. The problem of aggregating with this approach is revealed in Fig. 2, where the production set from Fig. 1 is replicated. As shown, it appears that production possibility A is producing less aggregate output than possibility C, which is itself observed producing less output than production possibility B. This contradicts the assumption that each observation is technically efficient, producing the maximum feasible output given the same input usage. This arises because of the improper linear aggregation.

An alternative aggregation consistent with microeconomic theory was recently developed by Collier et al. [9]. Instead of assigning arbitrary weights, aggregate output is estimated non-parametrically using linear programming.[3] Aggregate production is measured relative to a fixed isoquant. We illustrate the approach in Fig. 3, where we now assume that 5 vessels A–E are observed producing (catching) two species of fish, y_1 and y_2. Since the approach is nonparametric, it is not necessary to choose a particular functional form nor assign weights *a priori*. Similar to our previous figures, vessels A–C are operating efficiently on the isoquant of the output set.

Two vessels, D and E are observed producing less output than vessels A–C. Vessel D (E) is producing $100y_{1D}/y_{1G}(100y_{1E}/y_{1G})$ percent as much aggregate output. There are two possibly explanations for why D and E produce less output: inefficiency or smaller input usage. Collier et al. [9] measured aggregate output (AY_i) for vessel i (i=1 to n) using the following linear programming model:

$$
\begin{aligned}
&AY_i^{-1} = Max\ \theta \\
&\text{s.t.} \\
&\textstyle\sum_{j=1}^{n}\lambda_j y_{kj} \ge \theta y_{ki} \quad \forall\ k=1,\ldots,s \\
&\textstyle\sum_{j=1}^{n}\lambda_j = 1 \\
&\lambda_j \ge 0 \quad \forall\ j.
\end{aligned}
\tag{1}
$$

The model seeks the maximum radial expansion (theta) of vessel i's output while maintaining the assumption of convexity. This is achieved via convex combinations, where λ_J is the weight placed on observation j's output vector and convexity is defined by maintaining that each λ_J is non-negative and they sum to one. The model is equivalent to a data envelopment model without constraints on inputs. One can view this as an additional assumption that all vessels are using the same amount of each input. Aggregate output is the inverse of the maximum radial expansion; for a given output mix, lower levels of output will lead to higher expansions. The resulting index $AY_i \le 1$.

Solution of (1) using the data from Fig. 3 results in $AY_A = AY_B = AY_C = 1$, implying that vessels A–C are achieving the highest aggregate output. Unlike the simple linear aggregation methods, this approach properly evaluates aggregate output.

[2] An interesting extension beyond the scope of this paper would be to consider imposing the Ultra Passum law [29].

[3] This necessarily assumes that production is output homothetic, which allows us to generate any output isoquant from a base isoquant. The distance between isoquants is only a function of the inputs. See Shephard [36] for a formal proposition and proof.