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# Efficiency Gains and Cost Reductions from Individual Transferable Quotas: A Stochastic Cost Frontier for the Australian South East Fishery

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## *Abstract*

In this paper efficiency gains and associated cost reductions from increases in traded quota are estimated with a stochastic cost frontier for the Australian South East Trawl Fishery (SETF). Estimation of this frontier also provides key information on the relative importance of input costs in the SETF, returns to scale, variations in costs as a result of trade in quota and the economic performance of each fishing vessel, year to year. Final estimations indicate that increases in the volume of quota traded have resulted in considerable efficiency gains and cost reductions in the SETF, ranging from 1.8 to 3.5 cents per kilogram for surveyed vessels for every 1% increase in the volume of quota traded, or 1–2.4% of total variable costs, with considerable gains also accruing to crew and skipper in the form of larger share payments. Mean vessel efficiency is relatively high in the SETF, estimated at over 90%, and increases further to 92% over the sample period with increased trades in quota.

**JEL Classification:** Q22, Q28

**Keywords:** individual transferable quotas, stochastic cost frontier, fishery efficiency

## 1. Introduction

Since the early 1990s there has been a trend in fisheries management toward the adoption of individual transferable quotas (ITQs). Although not necessarily applicable to every fishery, the rationale for the use of ITQs is clear. Tradeable quotas to catch, based on a total allowable catch (TAC), in principle, both protect resource stocks and provide the incentives for a relatively more efficient use of fishery resources. The volume of quota allocated (based on TAC) can be adjusted season-to-season to suit the changing stock-recruitment characteristics of the fishery, while the transferability of quota allows for a shift of fishing entitlements and fishing effort from relatively high to low marginal cost boats and provides vessels an opportunity to obtain quota in cases where catch exceeds prior quota holdings.

There are at least two necessary conditions for ITQs to be efficiency enhancing in a fishery. First, a well-organized market for the transfer of quota must be established, at relatively low transactions costs.[1] Second, quota holders must participate in this market and in a manner that transfers quota from high to low marginal cost producers and allows for an ex post transfer of quota among vessels to compensate for catches that are larger or smaller than planned or prior quota holdings. Kompas and Che (2001) found that the market for leased quota trades in the South East Trawl Fishery (SETF) is active, indicating that transactions and information costs are not sufficient to prevent substantial volumes of trade. In the current paper efficiency gains and associated cost reductions from enhanced trade in quota are estimated for the SETF, using Australian Fisheries Management Authority (AFMA) and Australian Bureau of Agricultural and Resource Economics (ABARE) survey data on 47 vessels in an unbalanced panel data set (of 131 observations) for the period 1997–2000. It employs a technique which specifies a stochastic frontier cost function in order to decompose the variation among vessels in the cost of harvesting fish due to unbounded random effects from those that result in differences in efficiency among fishing vessels in the industry. Estimation of this frontier also provides key information on the relative importance of input costs in the SETF, returns to scale, variations in costs as a result of trade in quota and the economic performance of each fishing vessel, year to year.

Although stochastic frontier production functions have been the subject of considerable econometric research during the past two decades, originating with a general discussion of the nature of inefficiency in Farrell (1957), there are very few examples (given their difficulty and the considerable data requirements) of applied cost frontier analyses.[2] Fortunately, for the SETF input costs can be calculated from existing data sets and are seen, as required for the stochastic cost frontier, to vary across vessel types and sizes.

Section 2 of the paper briefly reviews the literature. Section 3 describes the Australian South East Fishery, a lucrative fishery in which the value of total catch in 1999–2000 is estimated at $78 million (ABARE, 2001). The volume and characteristics of trade in lease and permanent quota are also detailed. Section 4 provides the theoretical context for the stochastic cost frontier and associated inefficiency model used in the estimations. Section 5 describes the data and variables to be estimated.

There are three important points to note at the outset. First, like most fisheries, the SETF uses a combined wage and share payment system for crew and skipper. In many cases the skipper is also the owner of the boat. Survey data does not decompose total payments to labour (crew and skipper) by share and standard wage payments and thus total labour payments reflect both costs and what might naturally be considered as profit payments, at least from the point of view of returns to the fishery as a whole. In this paper, estimates are thus performed on both total labour payments as reported and on arbitrarily adjusted labour payments to account for potential share amounts and the resulting effects on costs from trades in ITQs. The data and estimates clearly suggest that part of the cost savings due to enhanced trade in quota accrue as added share payments to crew and skipper. Second, there is no adequate data available for quota prices in the SETF, leased or permanent, so expenditures on quota cannot be included in estimates of the cost function. Any implied cost savings to individual vessels (as opposed to the fishery as a whole) from trades in quota must thus be evaluated with this in mind. Finally, although quantitative assessments of (biomass) stocks in the SETF are either very limited or do not exist, it is generally recognized that many species are under considerable pressure, particularly orange roughy, eastern gemfish and blue warehou (AFFA, 2002). Since many large boats target these species the effects of trawl type and boat weight are estimated in the inefficiency model in an attempt to account for these stock effects. Potential decreases in fish stocks will also be accounted for by increases in fuel expenditures and other components in the frontier cost function. However, once trawl type and boat weight are accounted for in the specification (for large boats that target species thought to be under pressure) there was little change in coefficient values. Continued stock depletion (if any) thus appears to have had little or no effect on the estimates over the period 1997–2000.

Section 6 sets out the specification of the stochastic cost frontier and inefficiency model to be estimated and presents the results. Without specific cost functions for each vessel and listed trades of quota from vessel to vessel it is impossible to determine whether quota is sold from high to low marginal cost producers directly. Instead, the effects of traded quota on efficiency and costs are estimated indirectly in the inefficiency model. Section 7 concludes. An appendix collects technical details.

## 2. Previous Studies

Although many more general assessments exist (e.g., Kaufmann et al., 1999), few studies examine the economic effects of transferable harvesting rights in fisheries. Of those available, fisheries characterized by a single high valued species appear to have yielded the largest efficiency gains from the adoption of ITQs. For example, early analysis of Australia's Southern Bluefin Tuna industry by Geen and Nayar (1989) found substantial efficiency gains from the adoption of ITQ management. Gauvin et al. (1994) examine conditions in the US wreckfish fishery prior to and immediately after the introduction of ITQs. They suggest that higher average and more stable prices, along with apparent reduction in capital and effort, following the move to ITQs is consistent with an increase in efficiency. Similarly, Weninger (1998) finds significant efficiency gains from the adoption of ITQs in USA clam fisheries. Grafton et al. (2000), for the British Columbia halibut fishery, shows that although substantial long-term gains in efficiency can be jeopardized by preexisting regulations, the gains form ITQs occur not just in terms of cost efficiency but also include important benefits in revenue and product form.

Evidence for the performance of ITQs in multi-species fisheries is more mixed. Arnason (1993) finds strong evidence for gains in economic efficiency in the move to ITQs in Iceland's fisheries, some of which are multi-species trawl fisheries. Campbell and Lindner (1990) estimate significant efficiency gains across a variety of New Zealand fisheries, including multi-species cases. Dupont and Grafton (2001) found that ITQs in the multi-species Scotia-Fundy mobile gear ground-fishery have encouraged vessels to better allocate their catches over the fishing season and increased the quality and price of their product. On the other hand, Squires and Kirkley (1996), find that the potential economic gains from applying ITQs in a U.S.A. mixed trawl fishery could be small. A primary reason for that finding is existing excess capacity in a fishery. Lipton and Strand (1992) also find excess capacity at the time of adoption of ITQs as limiting efficiency gains.

With the exception of Weninger (1998) and Grafton et al. (2000), none of the above papers test for efficiency gains from ITQs in a stochastic frontier setting and neither Weninger (1998) or Grafton et al. (2000) provide a direct test of a stochastic cost frontier. However, Grafton et al. (2000) do obtain dual cost frontier efficiency measures from estimates of a Cobb–Douglas stochastic production frontier and nicely decompose allocative and technical efficiency measures on this basis.

## 3. The Australian South East Fishery

The South East Fishery (SEF) is a complex, multi-species, trawl and non-trawl fishery situated off the south east coast of Australia. The fishery, targeting about 118 species of finfish and deep-water crustaceans, provides the major (scale) fresh fish requirements to south east Australia. The value of catch in 1999–2000 is estimated at $78 million, accounting for 19% of the total catch in Commonwealth fisheries (ABARE, 2001).

The trawl sector of the SEF in Australia is a multi-species fishery extending south from Barrenjoey Point in NSW, around Victoria and Tasmania, to Cape Willoughby in South Australia. The fishery includes over 100 species of finfish and deep-water crustaceans. The majority of catches are taken using three types of trawl method: otter board, Danish seine and mid-water trawl.[3] The major species landed are orange roughy, blue grenadier, ling and tiger flathead. The value of the trawl sector catch in 1999–2000 alone is estimated to be $72 million (ABARE, 2001).

Prior to 1992, the SEF was managed by a series of input controls, with the exception of an ITQ system for eastern gemfish. The ITQs were further extended in 1992 (covering an additional 15 species) as a result of concerns about stock sustainability, falling profitability and the apparent failure of input controls to reduce effort and fishing capacity in the fishery. Each fishing year AFMA allocates seasonal quotas based on each operator's permanent quota holdings together with any adjustment for under- or over-catch from the previous season. Operators have the option of changing their quota mix by leasing allotted quota from other operators at any time during the fishing year. Quota transactions occur through a broker or directly between operators. All transfers of quota are recorded by AFMA, although it is not a requirement to report the price at which quota is traded. In the Danish seine sector, a holding company pools the seasonal allocations of individual operators at the beginning of the season and allocates quota back to operators as catches are made. Permanent quota trading was restricted from March 1992 to January 1994 such that only full quota buy-outs were permitted. Overall, the volume of permanent quota transfers increased from 1346 tonnes in 1992 to a peak of 6119 tonnes in 1994 and has since declined to 1615 tonnes in 1999 (Table 1). Most quota trade in the SEF continues to be through lease transactions (Figure 1). Including orange roughy, where the allowable quota has been substantially reduced since 1993 (TAC for most other species in the SETF is not binding), the annual volume of lease trade has nonetheless increased considerably from 18,400 tonnes in 1992 to 27,172 tonnes in 2000 (Table 2). Most of the increase in lease trades has occurred since 1996 (Figure 1). On average, 21,100 tonnes of quota have been leased out each year between 1992 and 2000.

## 4. Theoretical Context

Since our concern is with a panel data set, index vessels by $i$ and time periods by $t$. Following Schmidt and Lovell (1979), define a stochastic production frontier as

$$Q_{it} = A\left[\prod_{j=1}^{n}(x_{jit})^{\alpha_j}\right]e^{(v_{it}-u_{it})}, \tag{4.1}$$

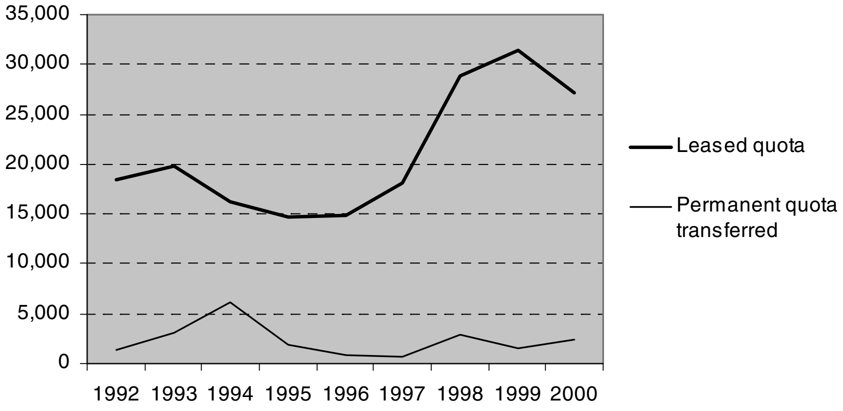

*Figure 1.* Permanent quota and leased quota transferred, 1992–2000 (tonnes).

*Table 1.* Permanent quota transfers (tonnes).

| | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|
| Blue eye trevalla | 3.3 | 12.3 | 27.8 | 5.8 | 3.5 | 0.4 | 7.1 | 0.6 | 9.4 |
| Blue grenadier | 181.1 | 465.0 | 1459.4 | 266.5 | 172.5 | 13.3 | 1,893.5 | 915.9 | 683.5 |
| Blue warehou **(a)** | 0.0 | 144.9 | 234.1 | 189.1 | 4.5 | 46.3 | 45.0 | 10.9 | 66.9 |
| Flathead | 161.6 | 280.1 | 503.1 | 291.7 | 224.5 | 38.5 | 221.7 | 174.3 | 277.2 |
| Gemfish eastern | 13.9 | 17.3 | 34.9 | 7.0 | 0.9 | 9.3 | 19.0 | 1.7 | 7.1 |
| Gemfish western | 1.0 | 47.1 | 5.1 | 20.3 | 1.4 | 50.0 | 2.3 | 0.0 | 58.6 |
| Jackass morwong | 141.5 | 171.9 | 349.0 | 120.9 | 46.9 | 29.5 | 113.4 | 47.8 | 74.4 |
| John dory | 9.2 | 30.7 | 55.1 | 7.2 | 0.9 | 36.1 | 26.7 | 1.3 | 9.3 |
| Ling | 47.8 | 58.9 | 192.6 | 51.9 | 49.4 | 90.9 | 46.1 | 34.6 | 70.2 |
| Mirro dory | 22.6 | 87.1 | 107.1 | 45.5 | 14.6 | 24.3 | 84.2 | 24.4 | 35.5 |
| Ocean perch | 15.7 | 10.7 | 102.3 | 35.2 | 2.1 | 34.4 | 30.2 | 3.8 | 17.4 |
| Orange roughy east | 116.8 | 135.7 | 352.8 | 178.5 | 78.1 | 0.0 | 134.5 | 163.7 | 251.0 |
| Orange roughy south | 3,04.0 | 904.1 | 1,069.0 | 100.3 | 47.8 | 0.8 | 57.9 | 0.0 | 67.2 |
| Orange roughy west | 79.0 | 137.0 | 310.6 | 28.7 | 37.5 | 0.0 | 16.2 | 2.7 | 104.6 |
| Redfish | 39.5 | 77.9 | 178.4 | 99.0 | 17.4 | 5.2 | 75.0 | 1.1 | 45.8 |
| Royal red prawn | 9.7 | 38.4 | 13.3 | 6.3 | 1.0 | 9.7 | 43.9 | 19.5 | 0.2 |
| School whiting | 13.4 | 160.1 | 515.8 | 210.2 | 91.7 | 62.9 | 56.3 | 163.3 | 214.2 |
| Silver trevally | 24.6 | 48.9 | 131.7 | 27.8 | 0.8 | 10.2 | 39.3 | 0.0 | 30.2 |
| Spotted warehou | 161.4 | 291.1 | 477.2 | 230.9 | 73.2 | 165.7 | 44.8 | 49.2 | 214.2 |
| Total | 1,346 | 3,119 | 6,119 | 1,923 | 869 | 628 | 2,957 | 1,615 | 2,443.6 |

*Source*: AFMA quota monitoring system; (**a**) blue and spotted warehou treated as a single species in 1992.

where $Q_{it}$ is output of boat $i$ at year $t$, $x_{jit}$ is the amount of input $j$ used by boat $i$ at year $t$, $n$ is number of inputs used, $\alpha_j$ is the share parameter of input $j$ in the fishing production function, $A$ is total factor productivity and $(v_{it} - u_{it})$ a composite error term, for $v$ a random stochastic variable and $u$ a measure of inefficiency. The dual stochastic cost frontier (see Appendix A) is given by

$$C_{it} = r\left[\frac{Q_{it}\prod_{j=1}^{n} p_j^{\alpha_j}}{A\prod_{j=1}^{n}\alpha_j^{\alpha_j}}e^{-(v_{it}-u_{it})}\right]^{\frac{1}{r}} \tag{4.2}$$

or in log form

$$\ln C_{it} = \alpha_0 + \frac{1}{r}\ln Q_{it} + \frac{1}{r}\sum_{j=1}^{n}\alpha_j \ln p_j - \frac{1}{r}(v_{it} - u_{it}) \tag{4.3}$$

*Table 2.* Leased quota transfers (tonnes).

| | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|
| Blue eye trevalla | 64.5 | 87.5 | 81.2 | 85.1 | 96.4 | 115.9 | 108.7 | 107.2 | 119.9 |
| Blue grenadier | 2,352.0 | 3,004.7 | 2,214.3 | 1,534.2 | 2,395.6 | 4,829.4 | 11,584.4 | 14,350.6 | 8,792.7 |
| Blue warehou **(a)** | – | 564.3 | 577.3 | 583.5 | 752.8 | 702.0 | 689.9 | 322.8 | 499.1 |
| Flathead | 514.7 | 1,810.6 | 1,988.4 | 2,226.2 | 1,926.4 | 2,203.9 | 4,020.8 | 4,691.1 | 4,634.3 |
| Gemfish eastern | 85.3 | 30.9 | 23.0 | 18.6 | 12.0 | 85.1 | 180.7 | 132.2 | 92.1 |
| Gemfish western | 104.5 | 144.3 | 47.3 | 61.0 | 114.7 | 85.9 | 99.1 | 185.0 | 317.8 |
| Jackass morwong | 479.4 | 641.8 | 508.3 | 478.1 | 577.9 | 902.3 | 843.2 | 780.4 | 752.9 |
| John dory | 53.7 | 60.9 | 75.5 | 69.6 | 69.1 | 51.6 | 105.3 | 88.6 | 112.2 |
| Ling | 261.8 | 467.5 | 537.2 | 780.6 | 901.1 | 780.5 | 1370.4 | 1446.3 | 1661.1 |
| Mirro dory | 155.5 | 205.0 | 171.4 | 201.4 | 290.3 | 363.6 | 376.8 | 260.0 | 292.5 |
| Ocean perch | 64.9 | 107.7 | 185.5 | 131.8 | 162.4 | 199.4 | 281.7 | 191.7 | 267.2 |
| Orange roughy east | 5,379.3 | 1,312.6 | 1,152.9 | 1,512.7 | 1,410.3 | 1,532.8 | 1,918.7 | 2,134.0 | 1,999.2 |
| Orange roughy south | 5,432.1 | 7,163.1 | 4,638.2 | 2,024.8 | 1,084.9 | 1,823.9 | 505.1 | 421.0 | 609.3 |
| Orange roughy west | 1,568.4 | 1,047.7 | 730.5 | 984.8 | 1464.2 | 551.5 | 920.0 | 675.1 | 826.0 |
| Redfish | 220.6 | 255.4 | 378.9 | 619.2 | 534.2 | 926.6 | 1529.5 | 864.0 | 530.9 |
| Royal red prawn | 50.5 | 59.3 | 107.0 | 136.6 | 112.3 | 78.7 | 152.3 | 247.2 | 277.9 |
| School whiting | 708.0 | 1,387.1 | 1,246.0 | 1,698.9 | 1,216.5 | 1,285.7 | 1,606.1 | 1,308.1 | 1,441.3 |
| Silver trevally | 56.8 | 92.0 | 169.0 | 212.1 | 160.9 | 160.0 | 204.1 | 143.0 | 175.3 |
| Spotted warehou | 848.9 | 1,360.2 | 1,309.8 | 1,397.1 | 1,602.6 | 1,434.0 | 2,311.3 | 2,993.4 | 3,770.2 |
| Total | 18,400 | 19,803 | 16,142 | 14,756 | 14,885 | 18,113 | 28,808 | 31,345 | 27,172 |

*Source*: AFMA quota monitoring system, 1997–2002; **(a)** blue and spotted warehou treated as a single species in 1992.

for

$$\alpha_0 = \ln r - \frac{1}{r}\sum_{j=1}^{n} \alpha_j \ln \alpha_j - \frac{1}{r}\ln A, \tag{4.4}$$

where $p_j$ is the factor price of input $j$ and

$$r = \sum_{j=1}^{n} \alpha_j \tag{4.5}$$

is a measure of returns to scale. Throughout, the term $v$ represents a random stochastic variable, with the usual properties, or $v \sim N(0, \sigma_v^2)$, accounting for effects on output and costs beyond vessel control. The term $u$ is a non-negative inefficiency effect, assumed to be drawn from a normal distribution truncated at zero. In the case, where $u_{it} = 0$ across all vessels and time periods, equations (4.1) and (4.2) revert to the standard production and cost function implying that all vessels are fully efficient. For any $u_{it} > 0$ output is lower and costs are larger and thus harvest is inefficient. The value $u_{it}$ can be further restricted by

$$u_{it} = u(z_{it}; \delta), \tag{4.6}$$

where $z$ accounts for the effects of fishery and vessel-specific terms that influence efficiency and $\delta$ are parameters to be estimated. Equation (4.6) can also include a random stochastic variable. The measure of efficiency $E_{it}$ is given by

$$E_{it} = e^{-u_{it}} \tag{4.7}$$

and is clearly bounded between zero and one.[4]

Although total input payments for each factor of production are listed in the data set, exact input price data is not available for the SETF. The cost function thus has to be expressed in terms of total payments ($\varepsilon_{jit}$) to each input. However, when constant returns to scale holds, or $r = 1$, equation (4.2) is equivalent (see Appendix B) to

$$C_{it} = Q_{it}\left[\frac{\prod_{j=1}^{n}\left(\frac{\varepsilon_{jit}}{Q_{it}}\right)^{\alpha_j}}{\prod_{j=1}^{n}(\alpha_{jit})^{\alpha_j}} e^{-(v_{it}-u_{it})}\right] \tag{4.8}$$

or, in log form

$$\ln C_{it} = \tilde{\alpha}_0 + \ln Q_{it} + \sum_{j=1}^{n}\alpha_j \ln\left(\frac{\varepsilon_{jit}}{Q_{it}}\right) - (v_{it} - u_{it}) \tag{4.9}$$

for

$$\tilde{\alpha}_0 = -\sum_{j=1}^{n}\alpha_j \ln \alpha_j \tag{4.10}$$

and noting that

$$\tilde{\alpha}_0 = \alpha_0 - \ln A. \tag{4.11}$$

With constant returns to scale (CRS), or when $r = 1$, estimates of Equations (4.3) and (4.9) are thus equivalent, except for the change in the constant. In particular, the coefficients $\alpha_j$ are the same. Parameter estimates for equation (4.9) are obtained through maximum likelihood estimates (MLE), where the maximum likelihood function is based on a joint density function for the error term $-(v_{it} - u_{it})$ (Stevenson, 1980). Efficiency can be calculated for each individual firm or vessel per year by

$$E[\exp(u_{it}) \mid -(v_i - u_i)] = \frac{1 - \Phi(\alpha_a + \gamma(v_{it} - u_{it})/\sigma_a)}{1 - \Phi(\gamma(v_{it} - u_{it})/\sigma_a)} \exp\left[-\gamma(v_{it} - u_{it}) + \sigma_a^2/2\right] \tag{4.12}$$

for $\sigma_a = \sqrt{\gamma(1-\gamma)\sigma^2}$, $\sigma^2 \equiv \sigma_u^2 + \sigma_v^2$, $\gamma \equiv \sigma_u^2/\sigma^2$ and $\Phi(\cdot)$ the density function of a standard normal random variable (Battese and Coelli, 1988). The value of $\gamma = 0$ when there are no deviations in costs due to inefficiency and $\gamma = 1$ implies that no deviations in costs result from stochastic random effects with variance $\sigma_v^2$.

## 5. Data and Variables

The unbalanced panel data set used in this paper consists of 47 vessels over the period 1997–2000, or 131 observations with 57 missing observations (Table 3). The original database was drawn from annual surveys and statistics for the SETF fleet carried out and compiled by ABARE and AFMA. The raw database includes measures of output (value and quantity of total fish landed), type of fishing (otter trawl and Danish seine), length of vessels, under-deck tonnage, engine power, fishing hours, boat composition (wood, steel, etc.), boat value, boat depreciation, average number of crew onboard, labour costs, fuel costs, gear costs, material costs (including costs for oil, grease, boat and gear repair, bait, ice, and packing materials). Fishing logbook data obtained from AFMA includes data for all vessels for the period 1997–2000, including the number of fishing hours (effort) and other vessel characteristics. Of the roughly 103 vessels operating in the SETF during the sample period, the 47 vessels in the unbalanced panel data set represent more than 50% of the total catch of fish in the area each year.

A summary list of all specific variables is contained in Table 4 and associated summary statistics are given in Table 5. All values are indexed by base year 1997. Output variables are available for both quantity and value. Total fish volume sold for all species was provided from ABARE surveys. The value of fish landed or total income from fish sold was derived as the difference between the total value of fish sold and the expenditures for fish marketing and transportation. Based on raw cost variables, cost expenditure components were derived including those for four major groups: capital, labour, fuel, gear and materials. The value of boat capital is the market value of boat, hull, engine and onboard equipment (excluding quota and endorsement values) as of July during the survey year. Capital costs are defined by the user cost of capital calculated as a sum of depreciation cost, the annual opportunity cost of the total capital value and the difference in boat value between season opening and closing time in a given year. Vessel depreciation is based on the discrete diminishing value method used in ABARE surveys.[5] The opportunity cost for vessel capital was derived as the multiple of the nominal interest rate and vessel capital value. Fuel cost was calculated as total fuel expenditures used for fishing for the financial year. Gear cost was calculated as total expenditures for gear (purchasing, maintaining and repairing) used for fishing each year. Material costs are calculated as a sum of the costs for boat repairs (the most important part of material costs), bait and ice, packing materials and other material costs. The factor price for capital, labour and fuel is derived as the cost required to produce a dollar value of output. Since gear and material costs generally depend on fish volume trawled (regardless of the value of fish) this measure is derived as the cost required for trawling a kilogram of fish. Expenditures for labour (crew and skipper) are obtained from ABARE surveys and generally include both wage and share payments.

*Table 3.* Unbalanced panel data used for estimations (SETF).

| Boat No | 1997 | 1998 | 1999 | 2000 | Total observation |
|---|---|---|---|---|---|
| 1 | * | * | * | * | 4 |
| 2 | * | * | * | * | 4 |
| 3 | * | * | * | * | 4 |
| 4 | * | * | na | na | 2 |
| 5 | * | * | * | * | 4 |
| 6 | * | * | * | * | 4 |
| 7 | na | na | * | * | 2 |
| 8 | * | * | na | na | 2 |
| 9 | * | * | * | * | 4 |
| 10 | na | * | * | * | 3 |
| 11 | * | * | * | * | 4 |
| 12 | * | * | na | na | 2 |
| 13 | na | * | * | * | 3 |
| 14 | * | * | na | na | 2 |
| 15 | * | * | na | na | 2 |
| 16 | * | * | na | na | 2 |
| 17 | * | * | na | na | 2 |
| 18 | * | * | na | na | 2 |
| 19 | na | na | * | * | 2 |
| 20 | na | na | * | * | 2 |
| 21 | na | na | * | * | 2 |
| 22 | * | * | * | * | 4 |
| 23 | * | * | na | na | 2 |
| 24 | * | * | na | na | 2 |
| 25 | * | * | * | * | 4 |
| 26 | * | * | * | * | 4 |
| 27 | * | * | * | * | 4 |
| 28 | * | * | na | na | 2 |
| 29 | * | * | * | * | 4 |
| 30 | * | * | * | * | 4 |
| 31 | na | na | * | * | 2 |
| 32 | * | * | * | * | 4 |
| 33 | * | * | na | na | 2 |
| 34 | * | * | na | na | 2 |
| 35 | * | * | * | * | 4 |
| 36 | * | * | * | * | 4 |
| 37 | * | * | na | na | 2 |
| 38 | * | * | na | na | 2 |
| 39 | * | * | na | na | 2 |
| 40 | * | * | na | na | 2 |
| 41 | * | * | na | na | 2 |
| 42 | na | * | * | * | 3 |
| 43 | na | na | * | * | 2 |
| 44 | na | na | * | * | 2 |
| 45 | na | na | * | * | 2 |
| 46 | * | * | * | * | 4 |
| 47 | na | na | * | * | 2 |
| Total | 35 | 38 | 29 | 29 | 131 |

*Table 4.* Description of outputs, inputs and vessel specific variables (47 vessels for the period 1997–2000).

| Variables | Description | Sources |
|---|---|---|
| Q | Total fish sold (kg) | ABARE |
| Y | Gross value from fish sold ($ ) | ABARE |
| TYPE | Type of fishing operation:<br>Trawl =1; Danish = 0 | AFMA log book |
| TIME | Year of observation<br>1997=1; 1998=2; 1999=3; 2000=4 | |
| SIZE | Vessel length (m) | AFMA log book |
| WEIGHT | Under deck tonnage | AFMA log book |
| POWER | Registered engine power (kw) | AFMA log book |
| EFF | Fishing hours (h) | AFMA log book |
| HULL | Boat material, e.g., wood, steel and aluminum | AFMA log book |
| K | Boat value ($ ) | ABARE |
| DK | Boat depreciation ($ ) | ABARE |
| LAB | Average number of crew on boat (no) | ABARE |
| LCOST | Labour costs ($ ) | ABARE |
| FCOST | Fuel costs ($ ) | ABARE |
| GCOST | Gear costs ($ ) | ABARE |
| MCOST | Other costs including costs for oil grease, repairs for boat, cost gear, bait, packing materials, ice and other materials | ABARE |

*Table 5.* Summary statistics for key variables in the SETF (Unbalanced panel data: 131 observations for 47 vessels, 1997–2000).

| | | Average | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Total fish landed | kg | 208,881 | 174,567 | 5,000 | 1,171,634 |
| Total value of fish sold | $ | 453,067 | 537,058 | 25,000 | 4,984,615 |
| Size | m | 19.4 | 5.0 | 12.8 | 45.7 |
| Weight | tonnes | 73.4 | 58.2 | 13.0 | 371.0 |
| Power | kw | 243.0 | 136.3 | 82.0 | 888.0 |
| Effort | h | 1,050 | 526 | 43 | 2,819 |
| Boat capital value | $ | 182,505 | 153,445 | 21,153 | 784,468 |
| Capital cost | $ | 28,055 | 22,974 | 3,326 | 108,875 |
| Labor | persons | 3.3 | 1.1 | 2.0 | 9.0 |
| Labor costs | $ | 168,716 | 164,097 | 16,140 | 1,528,848 |
| Fuel cost | $ | 79,560 | 103,218 | 5,284 | 791,048 |
| Gear cost | $ | 28,304 | 38,521 | 500 | 220,000 |
| Material costs and services | $ | 187,589 | 225,334 | 13,580 | 1,597,816 |

## 6. Empirical Results

Prior to testing the cost frontier, a production function for the SETF is estimated to test for returns to scale. In log form the specification of equation (4.1) is

$$\ln Q_{it} = \gamma_0 + \gamma_1 K_{it} + \gamma_2 \mathrm{LAB}_{it} + \gamma_3 F_{it} + \gamma_4 M_{it} + \gamma_5 G_{it} + v_{it} - u_{it} \qquad (6.1)$$

for $Q$ the value of output, $K$ capital, or boat value, LAB labour, or the average number of crew on board, $F$ fuel, $M$ material and $G$ gear expenditures.. All dollar values are measured in 1997 prices. Estimated coefficients are reported in Table 6.[6] Table 7 reports log likelihood ratio tests[7] for equation (6.1), indicating that the null hypothesis of a Cobb Douglas form of the production function and CRS cannot be rejected.

With CRS, estimates of each $\alpha_j$ in equations (4.3) and (4.9) are equivalent. For the SETF equation (4.9) is thus specified as

$$\ln C_{it} = \breve{\alpha}_0 + \ln Q_{it} + \sum_{j=1}^{n} \alpha_j \ln\left(\frac{\varepsilon_{jit}}{Q_{it}}\right) - (u_{it} - v_{it}) \tag{6.2}$$

for $C$ costs, $Q$ output (or harvest) and input expenses ($\varepsilon_{jit}$) for capital, labour (total labour costs including skipper), fuel, materials and gear per unit of output, indexed for vessel $i$ and time period $t$.[8] The cost inefficiency model, or equation (4.6), is given by

$$u_{it} = \delta_0 + \delta_1 \ln qt + \delta_2 trawl + \delta_3 \ln weight + \omega_{it} \tag{6.3}$$

for $qt$ the volume of (net) lease quota traded, $trawl$ the type of trawl method used (a binary variable with zero for Danish seine and one for inshore and offshore otter trawlers), $weight$ vessel weight and $\omega_{it}$ a random stochastic variable for $\omega_{it} \sim N(0, \sigma_{\omega}^2)$.[9] Since this is a 'share payment' fishery various values for payments to labour are trialed, ranging from reported ABARE data (which includes all pay-

*Table 6.* Parameter estimates of the production function (equation (6.1)).

| | Coefficient | Asymptotic $T$-ratio |
|---|---|---|
| Constant | 1.69***<br>(0.48) | 3.48 |
| Capital | 0.02<br>(0.03) | 0.34 |
| Labour | 0.65***<br>(0.05) | 12.32 |
| Fuel | 0.16***<br>(0.03) | 4.49 |
| Material | 0.12***<br>(0.03) | 3.26 |
| Gear | 0.04**<br>(0.02) | 1.73 |
| Sigma-squared | 0.11***<br>(.029) | 4.16 |
| Gamma | 0.785***<br>(.064) | 12.22 |
| ln (likelihood) | 20.20 | |

*Notes:* *, ** and *** denote statistical significance at the 0.10 level, 0.05 and 0.01 level, respectively. Numbers in parentheses are asymptotic standard errors.

*Table 7.* Generalized likelihood ratio tests.

| Null hypothesis | Model 1 $\chi^2$–statistic | Model 2 $\chi^2$–statistic | $\chi^2_{0.99}$–value | Decision |
|---|---|---|---|---|
| Production function is Cobb Douglas (equation (6.1)) | | | | |
| $\beta_6 = \beta_7 = \cdots = \beta_{15} = 0$ | 3.68 | N/A | 24.049 | Cannot Reject H$_0$ |
| Production function exhibits constant returns to scale (equation (6.1)) | | | | |
| $\beta_1 + \beta_2 + \cdots + \beta_5 = 1$ | 0.22 | N/A | 16.07 | Cannot Reject H$_0$ |
| Parameter tests of the stochastic cost frontier and technical inefficiency models (equations (6.2) and (6.3)) | | | | |
| $\gamma = \delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$ | 81.34 | 101.46 | 16.074 | Reject H$_0$ |
| $\delta_1 = \delta_2 = \delta_3 = 0$ | 18.8 | 66.62 | 12.483 | Reject H$_0$ |
| $\delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$ | 57.82 | 103.86 | 14.325 | Reject H$_0$ |
| $\gamma = 0$ | 71.10 | 111.72 | 8.273 | Reject H$_0$ |
| No time trend in the stochastic cost frontier (equation (6.2)) | | | | |
| $\beta_{\mathrm{TIME}} = 0$ | 0.40 | 0.80 | 8.27 | Cannot Reject H$_0$ |
| No time trend in the efficiency model (equation (6.3)) | | | | |
| $\beta_{\mathrm{TIME}} = 0$ | 0.10 | 0.20 | 8.27 | Cannot Reject H$_0$ |

*Notes:* (i) The critical values for the hypotheses are obtained from Table 1 of Kodde and Palm (1986); (ii) the coefficients $\beta_6, \beta_7, \ldots, \beta_{15}$ are parameters indicating pairs of translog relationships among capital, labour, fuel, material and gear; and (iii) the coefficients $\beta_1, \beta_2, \ldots, \beta_5$ are the estimated share parameters of capital, labour, fuel, material and gear, respectively.

ments to labour and skipper, composed of standard wages and share payments for labour per unit of output sold on each vessel (or model 1) to cases where total labour costs, including skipper costs, are arbitrarily divided by 2 (model 2), 2.5, and 3 to account for a potential difference between wage and share payments. A precise decomposition is not reported in the data set.[10]

The specification given by equations (6.2) and (6.3) was determined on the basis of generalized likelihood ratio tests, with the relevant test statistic given by

$$LR = -2\{\ln[L(H_0)] - \ln[L(H_1)]\}, \tag{6.4}$$

where $L(H_0)$ and $L(H_1)$ are the values of the likelihood function under the null and alternative hypotheses. Likelihood ratio tests are reported in Table 7 with critical values for the test statistic drawn from a mixed $\chi^2$ distribution as reported in Kodde and Palm (1986). The null hypotheses of a time trend in the cost frontier and technical inefficiency models is rejected. The null hypothesis that technical inefficiency effects are absent ($\gamma = \delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$) and that vessel-specific effects do not influence technical inefficiencies ($\delta_1 = \delta_2 = \delta_3 = 0$) in equation (6.3) are both rejected as is $\delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$. Finally, the null hypothesis that $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2) = 0$, or that inefficiency effects are not stochastic, is also rejected. All results indicate the stochastic and inefficiency effects matter so that usual OLS estimates are not appropriate in this study.

The MLE for the stochastic cost function (equation 6.2) and the inefficiency model (equation 6.3) are reported in Table 8 for the case of wages that include all

*Table 8.* Parameter estimates of the stochastic cost frontier and technical inefficiency models, (equations (6.2) and (6.3)).

| | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Coefficient | Asymptotic $T$-ratio | Coefficient | Asymptotic $T$-ratio |
| Stochastic cost frontier | | | | |
| Constant | 1.18*** | 19.86 | 1.30*** | 15.25 |
| | (0.059) | | (0.08) | |
| Output | 1.00*** | 209.35 | 1.00*** | 132.35 |
| | (0.005) | | (0.075) | |
| Capital price | 0.08*** | 9.29 | 0.11*** | 12.33 |
| | (0.008) | | (0.086) | |
| Labor price | 0.51*** | 27.97 | 0.33*** | 16.36 |
| | (0.02) | | (0.020) | |
| Fuel price | 0.12*** | 16.66 | 0.17*** | 16.60 |
| | (0.007) | | (0.010) | |
| Material price | 0.20*** | 16.15 | 0.27*** | 20.55 |
| | (0.012) | | (0.013) | |
| Gear price | 0.04*** | 9.44 | 0.05*** | 8.92 |
| | (0.004) | | (0.005) | |
| Inefficiency model | | | | |
| Constant | 7.34** | 2.19 | 14.10** | 2.52 |
| | (3.34) | | (5.599) | |
| Quota traded | −1.05** | 2.30 | −1.70*** | 2.56 |
| | (0.45) | | (0.66) | |
| Type of trawl | 0.70** | 1.94 | 0.69** | 2.51 |
| | (0.36) | | (0.273) | |
| Boat weight | 0.47*** | 2.87 | 0.45*** | 2.95 |
| | (0.16) | | (0.153) | |
| Sigma-squared | 0.10*** | 2.49 | 0.117*** | 2.78 |
| | (0.04) | | (0.042) | |
| Gamma | 0.997*** | 673.80 | 0.995*** | 3.77 |
| | (0.001) | | (0.003) | |
| ln (likelihood) | 187.44 | | 172.27 | |
| Mean technical efficiency | 91.91% | | 91.65% | |

*Notes:* *, ** and *** denote statistical significance at the 0.10 level, 0.05 and 0.01 level, respectively. Numbers in parentheses are asymptotic standard errors. Numbers in parentheses are asymptotic standard errors.

share payments (model 1) and the case in which half of the wage rate is assumed to be a share payment and thus excluded from costs (model 2). In both cases the largest component of costs in the stochastic cost frontier is the price of labour although (not surprisingly) its value falls from 0.51 to 0.33 in model 2. The price of materials and fuel are the next largest components. The low coefficient value on capital is a likely consequence of using a ‘book value’ measure of capital in the data set. All estimates are significant at the 1% level, with standard errors in parentheses.[11]

*Table 9.* Estimated results for sensitivity analysis on labour costs.

| | Parameter for the price of labour the stochastic cost frontier model | | Parameter for the volume of lease quota traded in the inefficiency model | |
|---|---|---|---|---|
| | Coefficient | Asymptotic $T$-ratio | Coefficient | Asymptotic $T$-ratio |
| Model 1 | 0.51*** | 27.97 | −1.05** | 2.30 |
| Total payments to labour/value of output | (0.02) | | (0.45) | |
| Model 2 | 0.33*** | 16.36 | −1.70*** | 2.56 |
| Total payments to labour/2/value of output | (0.020) | | (0.66) | |
| Model 3 | 0.28*** | 13.20 | −2.12** | 1.64 |
| Total payments to labour/2.5/value of output | (0.02) | | (1.29) | |
| Model 4 | 0.24*** | 11.01 | −2.41** | 2.02 |
| Total payments to labour/3/value of output | (0.02) | | (1.19) | |

*Notes:* *, ** and *** denote statistical significance at the 0.10 level, 0.05 and 0.01 level, respectively. Numbers in parentheses are asymptotic standard errors.

Of particular interest in the inefficiency model is the estimated coefficient on the volume of quota traded. In both models, the sign on this coefficient is negative indicating that an increase in the volume of quota traded (in tonnes of fish) results in enhanced efficiency and a consequent decrease in costs. Again, not surprisingly, this value rises from −1.05 to −1.70 in model 2 since adjusted wage rates are now half of their previous value. Positive values for coefficients on trawl and boat weight indicate that inshore and offshore otter trawlers (larger boats) are less cost efficient. The reason for this is clear in the SETF. Offshore otter trawlers, which are typically made of steel, fish more than 50 km offshore, principally targeting orange roughy, eastern gemfish and blue warehou.[12] However, stocks of these fish are thought to have declined considerably over the past 20 years (AFFA, 2002) indicating longer fishing trips and higher costs for offshore vessels.[13] Danish seine vessels are typically smaller vessels made of wood and target closer to shore on species that are relatively more abundant.

The value of $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ is high in both models indicating that differences in efficiency dominate stochastic random effects, a likely characteristic of an ITQ fishery, where fishing days can be reserved for favorable weather conditions and the specific targeting of each species depending on quota holdings. Mean technical efficiency is also roughly the same in both models but rises from 90.42 (89.29) in model 1 (model 2) in 1997 to 92.12 in both models in the year 2000, reflecting the efficiency gains from increased trades in quota.

Sensitivity results for different values of labour costs are reported in Table 9 and confirm expectations. The lower are labour costs (and hence the higher are

*Table 10.* Impact of ITQs on the fishery costs.

| | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| Total fishing cost for the industry ($ million) | | | | |
| 1997 | $35,935 | $27,834 | $26,214 | $25,134 |
| 1998 | $39,786 | $30,949 | $29,181 | $28,003 |
| 1999 | $53,655 | $42,263 | $39,985 | $38,466 |
| 2000 | $53,572 | $43,126 | $41,036 | $39,644 |
| Cost savings per kilogram fish landed with a 1% increase in the total volume of quota traded | | | | |
| 1997 | $0.020 | $0.025 | $0.030 | $0.033 |
| 1998 | $0.021 | $0.027 | $0.032 | $0.035 |
| 1999 | $0.020 | $0.026 | $0.030 | $0.033 |
| 2000 | $0.018 | $0.023 | $0.028 | $0.030 |

potential share payments) the lower is the estimated coefficient on the price of labour and the larger is the coefficient on the volume of quota traded. Removing potential share payments from labour costs thus increases the measure of efficiency or the cost savings from having trades in quota. Model 3 is the case where labour costs are divided by 2.5 and in model 4 by 3. The coefficient on the volume of quota traded ranges from $-1.05$ to $-2.02$. The impact on cost savings for the surveyed fishery from trade in ITQs is substantial. Table 10 indicates total fishing costs and cost savings per kilogram of fish landed that result from a 1% increase in the total volume of quota traded, for the years 1997–2000. Depending on the amount of total payments to labour, cost savings range from 1.8 to 3.5 cents per kilogram. Even in the case where total payments to labour are not adjusted for potential share payments (model 1), cost savings range from 1.8 to 2.1 cents per kilogram, or 1 to 2.4% of total variable costs, with total cost savings (based on actual catch) to the surveyed fishery in 1999, for example, of $110,000. In all four models, cost savings fall slightly from 1998 to 2000. The reason for this is unclear, although it is possible that efficiency gains are dissipating over time as the volume of quota trade increases.

## 7. Concluding Remarks

Few studies exist on the direct benefits of ITQs in fisheries. Using a stochastic cost frontier and associated inefficiency model, this paper estimates the efficiency gains and cost reductions associated with enhanced trades in ITQs in the Australian south east trawl fishery. It is impossible to determine whether or not trades literally occur from high to low marginal cost producers. Instead, this paper accounts for efficiency gains and cost reductions by estimating a cost frontier and inefficiency model for 47 vessels directly, in an unbalanced data set over the years 1997–2000. Cost reductions thus occur not only as a result of transfers from high to low marginal costs producers, but also to vessels that obtain catch in excess of prior quota holdings through lease trades.

Estimated efficiency gains and cost reductions are considerable. Even in the case, where all share payments to labour are considered as costs items, ITQs result in a cost savings of 1.8 to 2.1 cents per kilogram for every 1% increase in the volume of quota traded. In the year 1999, for example, total cost savings in the surveyed fishery amount to approximately $110,000, with cost reductions ranging (depending on the size of labours share) from 1 to 2.4% of total variable costs. Considerable gains also undoubtedly accrue to crew and skipper in the form of larger share payments. Mean vessel efficiency levels are relatively high in the SETF, estimated at over 90%, increasing further to 92% over the sample period with increased trades in quota.

As future survey data on quota prices becomes available, further research intends to examine the 'wedge' between the price of lease quota and the market price of fish to determine the exact extent to which quota trades decrease transactions costs in the SETF. A knowledge of quota prices (as a weighted average across species or as independent variables in the cost frontier) would also allow for a more direct test of any potential stock depletion, since a decline in stocks would partially be reflected in higher quota prices.

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## Notes

1. On the problems with 'thin' markets, or markets with few participants and infrequent transactions, thus leading to high transactions costs (see Squires, et al., 1995).
2. Schmidt and Lovell (1979), Parikh et al. (1995), Ray (1997) and Gropper et al. (1999) are among the few and notable papers that estimate cost frontiers. Green (1993) and Forsund et al. (1980) are useful surveys of both cost and production frontiers.
3. Danish seiners are small low-powered vessels which typically target flathead and whiting in relatively shallow shelf waters. The Danish seine fleet mainly operates out of Lakes Entrance in Victoria and nearly all fishing activity takes place in Bass Strait and Eastern Zone B. In 1995, Danish seiners accounted for 75 and 29% of the total landings of school whiting and tiger flathead, respectively, in the trawl sector (Sachse and O'Brien, 1996). Danish seiners also catch small quantities of a number of other quota species including, most importantly, john dory and jackass morwong (Hogan et al., 1999).

   Inshore otter trawlers are smaller trawlers which generally operate in the shallow continental shelf and upper shelf waters to a depth of 500 m and catch a variety of species. Inshore trawlers operate out of Ulladulla and Eden in New South Wales and Portland in Victoria. Most fishing activity occurs in the Eastern A, Eastern B and Western management zones, although a small quantity of fish is taken in the Bass Strait (Hogan et al., 1999).

Offshore otter trawlers are larger vessels which mainly operate in the deeper continental slope waters of the western and eastern Tasmania management zones. These vessels usually work in depths between 600 and 1000 m targeting orange roughy and winter spawning aggregations of blue grenadier (Geen et al., 1993).

4. The complications of a systems estimate with first-order conditions for optimal input use by factor of production are avoided in this paper, as is a decomposition between technical and allocative efficiency (see Coelli et al., 1998; Schmidt and Lovell, 1979) and scale economies, including short run measures of efficiency (see Grafton et al., 2000). It is worth noting that there is a dimension of allocative efficiency, that is, the choice of the total amount of effort applied to the fishery, that cannot be captured directly by the analysis of individual boat data.
5. The diminishing value method is based on current replacement cost, or $V$, and the age of each capital item. The depreciation value ($D$) in the initial period is given by $D_0 = \delta V_0$ and thus at year $t$, $D_t = \delta(V_{t-1} - D_{t-1})$ for $V_{t-1}$ the boat value in the previous year. The depreciation rate ($\delta$) is the standard rate allowed by the Australian Tax Office.
6. Results for the stochastic production frontier are reported for simplicity in 'errocomponent form', or without a specification of an inefficiency model, since the test for constant returns to scale is the primary concern. Including an inefficiency model (results available from the authors on request) results in only a slight change in coefficients. In all cases the null hypothesis of CRS cannot be rejected.
7. The relevant test statistic is given by equation (6.4).
8. Unfortunately there are no useful data for quota prices available for use as an independent variable in equation (6.2). Although quota prices are evidently available for 1998 (see Bose, et al., 2000) it is not possible to match this data to boats and quota trades in the data set for the period 1997–2000. The AFMA data set provides detailed quota trades by species but not by price. The ABARE survey data has limited records on quota prices for the years 1999 and 2000, but these are inadequate for purposes of estimation. Additional supplementary survey data in this regard is planned for the future.
9. Including permanent quota trades in the measure of $qt$ does not alter the results. In any case, lease trades are the preferred measure since these are more directly tied to potential cost reductions, particularly for vessels that target a given species.
10. Total wage payments (wage and share payments) in the data set vary from \$27 to \$394 per person per boat-day, with an average of \$143. An alternative to the arbitrary division of wage costs into wages and share payments is the attempt to measure the opportunity cost of labour by market or award rates for comparable occupations. Supplementary survey questions are planned in the future in an attempt to determine the opportunity cost of crew and skipper in the SETF.
11. The results for the estimates of the cost frontier were confirmed using a 'random coefficients approach', following Kalirajan and Obwona (1994), allowing for the possibility of non-neutral shifts in the frontiers.
12. More recently, these otter trawlers have moved to the inshore sector.
13. As mentioned there is no adequate stock assessment data available for the quota species in the SETF. An attempt to account for stock declines in the overall regression with year dummies and a split sample shows that with trawl type and boat size included (for large boats that target species thought to be under pressure), as given in equation (6.3), there was little change in coefficient values. For example, adding a year dummy in the cost frontier for 1997 generates a coefficient of $-0.001$ with low significance. Testing for years separately also resulted in little change in the coefficient on quota traded, although the share coefficient on fuel expenditures increased slightly in the last year of the sample. The effect of including trawl type and boat size in the inefficiency model thus appears to adequately account for any suspected stock declines over the sample period. Leaving orange roughy, eastern gemfish and blue warehou aside, the final results suggest little effects from stock decline from 1997 to 2000 in the overall (when accounting for all sixteen quota species) regression. Including the dummy variable for trawl type in the cost frontier instead of the

inefficiency model also leaves the final results in Table 8 unchanged. All results are available from the authors upon request.

## Appendix A: Formation of the Stochastic Cost Frontier

Following Schmidt and Lovell (1979), the minimum value cost ($C_{it}$) function of boat $i$ at year $t$ is

$$C_{it} = \min_{x_{jit}} \sum_{j=1}^{n} p_j x_{jit}, \tag{A1}$$

where $p_j$ is the factor price of input $j$, $x_{jit}$ is the amount of input $j$ used by boat $i$ at year $t$, and $n$ is number of inputs used. The problem is to minimize equation (A1) subject to a production technology given by

$$Q_{it} = A \left[ \prod_{j=1}^{n} (x_{jit})^{\alpha_j} \right] e^{(v_{it} - u_{it})}, \tag{A2}$$

where $Q_{it}$ is output of boat $i$ at year $t$, $\alpha_j$ is the share parameter of input $j$ in the fishing production function, $A$ is total factor productivity and $(v_{it} - u_{it})$ a composite error term, for $v$ a random stochastic variable and $u$ a measure of inefficiency. First-order conditions are

$$p_j - \lambda \alpha_j (x_{jit})^{-1} \left[ A \left( \prod_{j=1}^{n} (x_{jit})^{\alpha_j} \right) e^{(v_{it} - u_{it})} \right] = 0 \tag{A3}$$

for all $j$, or

$$p_j = \lambda \alpha_j x_{jit}^{-1} Q_{it}, \tag{A4}$$

ignoring the composite error.

Dividing equation (A4) by $p_1$ and solving for $x_{jit}$ as a function of $x_{1it}$ gives

$$x_{jit} = x_{1it} \frac{p_1}{p_j} \frac{\alpha_j}{\alpha_1} \tag{A5}$$

and using equation (A2) obtains

$$Q_{it} = A \left[ \prod_{j=1}^{n} \left( x_{1it} \frac{p_1}{p_j} \frac{\alpha_j}{\alpha_1} \right)^{\alpha_j} \right] e^{(v_{it} - u_{it})}. \tag{A6}$$

Denoting returns to scale as $r = \sum_{j=1}^{n} \alpha_j$ implies that

$$Q_{it} = \left[ A (x_{1it})^r \left( \frac{p_1}{\alpha_1} \right)^r \frac{\prod_{j=1}^{n} \alpha_j}{\prod_{j=1}^{n} p_j} \right] e^{(v_{it} - u_{it})} \tag{A7}$$

and solving for $x_{1it}$ as a function of $Q_{it}$ and using equation (A5) gives

$$x_{jit} = \frac{\alpha_j}{p_j}\left[\frac{Q_{it}\prod_{j=1}^{n} p_j^{\alpha_j}}{A\prod_{j=1}^{n}\alpha_j^{\alpha_j}}e^{-(v_{it}-u_{it})}\right]^{\frac{1}{r}} \tag{A8}$$

for all $j$.

Finally, substituting equation (A8) into (A1) obtains the stochastic cost frontier

$$C_{it} = r\left[\frac{Q_{it}\prod_{j=1}^{n} p_j^{\alpha_j}}{A\prod_{j=1}^{n}\alpha_j^{\alpha_j}}e^{-(v_{it}-u_{it})}\right]^{\frac{1}{r}} \tag{A9}$$

or equation (4.2). In log form, this gives

$$\ln C_{it} = \alpha_0 + \frac{1}{r}\ln Q_{it} + \frac{1}{r}\sum_{j=1}^{n}\alpha_j \ln p_j - \frac{1}{r}(v_{it}-u_{it}) \tag{A10}$$

for

$$\alpha_0 = \ln r - \frac{1}{r}\sum_{j=1}^{n}\alpha_j \ln \alpha_j - \frac{1}{r}\ln A \tag{A11}$$

as in equations (4.3) and (4.4).

## Appendix B: CRS and the Stochastic Cost Frontier with Total Input Payments

With CRS equation (A9) becomes simply

$$C_{it} = \left[\frac{Q_{it}\prod_{j=1}^{n} p_j^{\alpha_j}}{A\prod_{j=1}^{n}\alpha_j^{\alpha_j}}e^{-(v_{it}-u_{it})}\right]. \tag{B1}$$

Let total expenses to each input $j$ be given by

$$\varepsilon_{jit} = p_j x_{jit} \tag{B2}$$

for boat $i$ at year $t$. Solving for input prices $p_j$ and substituting into equation (B1) lets the cost function be expressed as

$$C_{it} = \left[ \frac{Q_{it} \prod_{j=1}^{n} (\varepsilon_{jit})^{\alpha_j}}{\left( A \prod_{j=1}^{n} (x_{jit})^{\alpha_j} \right) \left( \prod_{j=1}^{n} (\alpha_{jit})^{\alpha_j} \right)} e^{-(v_{it} - u_{it})} \right]. \tag{B3}$$

Given a production function

$$Q_{it} = A \left[ \prod_{j=1}^{n} (x_{jit})^{\alpha_j} \right] \tag{B4}$$

and noting that

$$\sum_{j=1}^{n} \alpha_j \ = 1, \tag{B5}$$

equation (B3) becomes

$$C_{it} = \left[ \frac{Q_{it} \left[ \prod_{j=1}^{n} \left( \frac{\varepsilon_{jit}}{Q_{it}} \right) \right]^{\alpha_j}}{\prod_{j=1}^{n} (\alpha_j)^{\alpha_j}} e^{-(v_{it} - u_{it})} \right]. \tag{B6}$$

In log form, this gives

$$\ln C_{it} = \breve{\alpha}_0 + \ln Q_{it} + \sum_{j=1}^{n} \alpha_j \ln \left( \frac{\varepsilon_{jit}}{Q_{it}} \right) - (v_{it} - u_{it}) \tag{B7}$$

or equation (4.9), for

$$\breve{\alpha}_0 = - \sum_{j=1}^{n} \alpha_j \ln \alpha_j. \tag{B8}$$

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