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

Tuong Nhu Che
Australian Bureau of Agricultural and Resource Economics

Tom Kompas
National Centre for Development Studies
Australian National University
tom.kompas@anu.edu.au
and
Australian Bureau of Agricultural and Resource Economics
tom.kompas@abare.gov.au

Abstract

In this paper efficiency gains and associated cost reductions from increases in quota leased or traded are estimated for the South East Trawl Fishery (SETF), using Australian Fisheries Management Authority logbook data and Australian Bureau of Agricultural and Resource Economics survey data on 47 vessels in an unbalanced panel data set (of 131 observations) for the period 1997 to 2000. Estimated results indicate that increases in the volume of quota traded (either leased or sold, in tonnes of fish) 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 one per cent increase in the volume of quota traded. Mean vessel efficiency levels also increased over the sample period with increases in quota traded.

†Acknowledgments: Paper presented at the eleventh biannual International Institute of Fisheries Economics and Trade Conference, Wellington New Zealand, August 2002. The authors would like to thank Steve Beare, Debbie Brown and Peter Gooday for helpful comments on this work and the nature of the Australian south east fishery in general. Financial support from the Fisheries Resources Research Fund is gratefully acknowledged. The views expressed herein are those of the authors and do not necessarily reflect the views of ABARE.

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 quotas to catch allows for a shift of fishing entitlements and fishing effort from relatively high to low marginal cost fishing firms or vessels.

Fisheries dominated 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, Ward and Burgess (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.

Evidence for the performance of ITQs in multi-species fisheries is 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. 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 USA 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.

There are at least two necessary conditions for individual transferable quotas 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. Kompas and Che (2001) show that the market for leased quota trades in the South East Trawl Fishery (SETF) as a whole is essential, 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) logbook data 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 to 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

[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.

discussion of the nature of inefficiency in Farrell (1957), there are very few examples (given 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 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 3 provides the theoretical context for the stochastic cost frontier and associated inefficiency model used in the estimations. Section 4 describes the data and variables to be estimated. There is one important point to note at the outset. 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 thus 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. The estimates suggest that part of the cost savings due to enhanced trade in ITQs may accrue as added share payments to crew and skipper. Section 5 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 trades in quota literally pass from high to low marginal cost producers. Instead, the effects of traded quota on efficiency and costs are estimated directly in the inefficiency model. Section 6 offers some concluding remarks.

2. 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 per cent 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

[2] Schmidt and Lovell (1979) is a notable exception. Green (1993) and Forsund, Lovell and Schmidt (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 per cent 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 roughy, blue grenadier, ling and tiger flathead. The value of the trawl sector catch alone in 1999-2000 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. Individual transferable quotas were further extended in 1992 (covering an additional fifteen 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 1,346 tonnes in 1992 to a peak of 6,119 tonnes in 1994 and has since declined to 2,443 tonnes in 1999. Nevertheless, most quota trade in the SEF continues to be through lease transactions. 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 has increased considerably from 18,400 tonnes in 1992 to 27,172 tonnes in 2000. Most of the increase in lease trades has occurred since 1996. On average, 21,047 tonnes of quota have been leased out each year between 1992 and 1999.

3. Theoretical Context

Since our concern is with a panel data set, index vessels by i and time periods by t. In general terms, the stochastic cost frontier takes the form

$$\ln C_{it} = C(Q_{it}, w_{it}; \beta) + v_{it} + u_{it} \tag{3.1}$$

for C the cost of harvest, Q output, w input prices and β parameters to be estimated. The term v represents a random stochastic variable, with the usual properties, or $v \sim N(0, \sigma_v^2)$, accounting for effects on costs beyond vessel control. The term u is a non-negative cost 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, equation (3.1) reverts to standard (minimum) cost function implying that all vessels are fully efficient. For any $u_{it} > 0$ costs are larger and harvest inefficient. The value u_{it} can be further restricted by

$$u_{it} = u(z_{it}; \delta) \tag{3.2}$$

and upper shelf waters to a depth of 500 metres 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 600m to 1000m targeting orange roughy and winter spawning aggregations of blue grenadier (Geen, *et al.*, 1993).

where z accounts for the effects of fishery and vessel-specific terms that influence efficiency and δ are parameters to be estimated. Equation (3.2) can also include a random stochastic variable.

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. However, when constant returns to scale holds, equation (3.1) can be transformed to give a cost function of the form

$$C_{it} = \alpha_0 Q_{it} \left[\prod_j \left(\frac{p_{ijt} x_{ijt}}{Q_{it}} \right)^{\alpha_i} \right] e^{(v_{it} + u_{it})} \tag{3.3}$$

accounting for total payments to inputs. In log form, parameter estimates for (3.3) 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

$$E[\exp(u_i) \mid v_i + u_i] = \frac{1 - \Phi(\alpha_a + \gamma(v_i + u_i)/\sigma_a}{1 - \Phi(\gamma(v_i + u_i)/\sigma_a)} \exp\left[\gamma(v_i + u_i) + \sigma_a^2/2\right] \tag{3.4}$$

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 σ_v^2.

4. Data and Variables

The unbalanced panel data set used in this paper consists of forty-seven vessels over the period 1997 to 2000, or 131 observations with fifty-seven missing observations. The original database was drawn from annual surveys and statistics for the SEFT 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 SEFT during the sample period, the forty-seven vessels in the unbalanced panel data set represent more than 50 per cent of the total catch of fish in the area each year.

All values in the data set 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 approach. 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, labor 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 are obtained from ABARE surveys (split by labour type between skipper, crew and family members) and generally include both wages and share payments.

5. Empirical Results

Prior to testing the cost frontier, a production function for the SETF was estimated. Coefficients in error components form (for convenience) for capital, labour, gear, material inputs and gear are .01, .65, .044, .11, .16. A Wald test with a null hypothesis of no constant returns to scale is rejected, with critical value 39.0 > 16.07. Thus, with constant returns to scale, the estimate of equation (3.3) for the SETF is specified by

$$\ln C_{it} = \beta_0 + \beta_1 \ln Q_{it} + \beta_2 \ln p^k_{it} + \beta_3 \ln p^l_{it} + \beta_4 \ln p^f_{it} + \beta \ln p^m_{it} + \beta_6 \ln p^g_{it} + (v_{it} - u_{it}) \tag{5.1}$$

for C and Q costs and output (or harvest) and input prices p^k, p^l, p^f, p^m and p^g for capital, labour (total labour costs including skipper per unit of the value of output), fuel (cost per unit of the value of output), materials and gear (per unit of fish caught by weight), all indexed for each vessel i and time period t. The inefficiency model, or equation (3.2), is given by

$$u_{it} = \delta_0 + \delta_1 \ln qt + \delta_2 trawl + \delta_3 \ln weight + \omega_{it} \tag{5.2}$$

for qt the volume of 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 ω_{it} a random stochastic variable for $\omega_{it} \sim N(0, \sigma^2_\omega)$. Since this is a 'share payment' fishery various values for payments to labour are trialed, ranging from reported ABARE data (which includes all payments to labour and skipper, composed of standard wages and share payments for labour per unit of output sold on each vessel) to cases where total labour costs, including skipper costs, are arbitrarily divided by 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.

The specification given by equations (5.1) and (5.2) was determined on the basis of generalized likelihood ratio tests, with the relevant test statistic given by

$$LR = -2\{\ln[L(H_0)] - \ln[L(H_1)]\} \tag{5.3}$$

where $L(H_0)$ and $L(H_1)$ are the values of the likelihood function under the null and alternative hypotheses. The null hypotheses of a translog cost function and a time trend in either the cost frontier or inefficiency model were both rejected at the 5 per cent level of significance. 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 (5.2) 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 maximum likelihood estimates for the stochastic cost function (equation 5.1) and the inefficiency model (equation 5.2) are reported in the attached table for the case of wages that include all 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. All estimates are significant at the 1 per cent level, with standard errors in parentheses. Coefficients in the stochastic cost frontier roughly correspond to those given in the estimates of the production function for the SETF.

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 are (generally speaking) 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 kms offshore, principally targeting orange roughy.[4] However, orange roughy stocks have declined considerably indicating longer fishing trips and higher costs for offshore vessels. 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 confirm expectations. The lower are labour costs (and hence the higher are 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. 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, with total cost savings (based on actual catch) to the surveyed fishery in

[4] More recently, these otter trawlers have moved to the inshore sector.

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.

6. 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 to 2000. Cost reductions thus occur not only as a result of quota 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 one percent 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) ranging from 1 to 2.4 per cent 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 per cent, increasing further to 92 per cent over the sample period with increased trades in quota. Further work 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 decease transactions costs in the SETF.

REFERENCES

ABARE (Australian Bureau of Agricultural and Resource Economics), 2001, *Australian Fisheries Statistics*, Canberra.

AFMA (Australian Fisheries Management Authority) 1999, *Annual Report 1998-99*, Canberra.

AFMA, 2001a, Southern Shark and South East Non-Trawl Fisheries Bycatch Action Plan: Background Paper, Canberra.

AFMA, 2001b, Great Australian Bight Trawl Fishery Bycatch Action Plan: Background Paper, Canberra.

AFMA, 2001, South East Trawl Fishery Bycatch Action Plan: Background Paper, Canberra.

Arnason, R., 1993, 'Iceland's ITQ system,' *Marine Resource Economics*, 8: 201-18.

Battese, G. E. and Coelli, T. J., 1988, "Prediction of firm level technical inefficiencies with a generalized frontier production function," *Journal of Econometrics*, 38: 387-99.

Caton, A. and McLoughlin, K. (eds.) 2000, *Fishery Status Reports 1999: Resource Assessments of Australian Commonwealth Fisheries*, Bureau of Rural Sciences, Canberra.

Coelli, T., Prasada Rao, D. S. and Battese, G. E., 1998, *An Introduction to Efficiency and Productivity Analysis*, Boston: Kluwer.

Dupont, D. P. and Grafton, R. Q., 2001, "Multi-Species Individual Transferable Quotas: The Scotia-Fundy Mobile Gear Ground-fishery," *Marine Resource Economics*, 15: 205-220.

Farrell, M. J., 1957, "The measurement of productive efficiency," *Journal of the Royal Statistical Society, Series A*, CXX: 253–290.

Forsund, F., Knox Lovell, C. A. and Schmidt, P., 1980, "A survey of frontier production functions and of their relationship to efficiency measures," *Journal of Econometrics*, 13: 5–25.

Geen, G., Nielander, W. and Meany, T. F., 1993, "Australian experience with individual transferable quota systems: The use of individual quotas in fisheries management", OECD, Paris.

Geen, G. and Nayar, M. 1989, *Individual Transferable Quotas and the Southern Bluefin Tuna Fishery: Economic Impact*, Occasional Paper 105, ABARE, AGPS, Canberra.

Gauvin, J. R.., Ward, J. M.. and Burgess, E. E.., 1994, 'Description and evaluation of the wreckfish (Polyprion americanus) fishery under individual transferable quotas,' *Marine Resource Economics*, 9: 99-118.

Green, W. H., 1993, "The econometric approach to efficiency analysis," in H. O. Fried, C. A. K. Lovell and S. S. Schmidt (eds.), *The Measurement of Productive Efficiency: Techniques and Applications,* New York: Oxford University Press, 68–119.

Hogan, L., Thorpe, S. and Timcke, D., 1999, *Tradeable quotas in fisheries management: implications for Australia's south east fishery*, ABARE, Canberra.

Kodde, D. A. and Palm, F. C., 1986, "Wald criteria for jointly testing equality and inequality restrictions," *Econometrica*, 54: 1243–1248.

Kompas, T. and Che, N., 2001, *Factors Influencing the Volume of Lease Trades in Individual Transferable Quota Markets: The Australian South East Trawl Fishery*, ABARE, Canberra.

Sachse, M. and O'Brien, C., 1996, *South East Trawl Fishery Logbook Data Summary 1986 to 1995*, September, AFMA/BRS, Canberra.

Schmidt, P. and Knox Lovell, C. A., 1979, "Estimating technical and allocative inefficiency relative to stochastic production and cost frontiers," *Journal of Econometrics,* 9: 343–366.

Squires, D., Kirkley, J. and Tisdell, C. A., 1995, "Individual transferable quotas as a fisheries management tool', *Reviews in Fisheries Science*," 3: 141-69.

Squires, D. and Kirkley, J. 1996, "Individual transferable quotas in a multiproduct common property industry," *Canadian Journal of Economics*, 29: 318-42.

Stevenson, R. E., 1980, "Likelihood function for generalized stochastic frontier estimation," *Journal of Econometrics*, 13: 57-66.

Tilzey, R. 1998, *The South East Fishery 1998*, Fishery Assessment Report compiled by the South East Fishery Assessment Group, Australian Fisheries Management Authority, Canberra.

Weninger, Q., 1998, "Assessing efficiency gains from individual transferable quotas: an application to the mid-Atlantic surf clam and ocean quahog fishery," *American Journal of Agricultural Economics*, 80: 750-64.

Table: Parameter estimates of the stochastic cost frontier and technical inefficiency models, (equations 5.1 and 5.2)

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