Catch, Effort and the Management of the Australian Northern Prawn Fishery

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Abstract

This paper is a study of the production technology and relative efficiency of vessels harvesting banana and tiger prawns in the Northern Prawn Fishery (NPF), one of Australia's largest and most lucrative fishing areas. It is based on an unbalanced panel data set of 226 observations among thirty-seven vessels for the years 1990–1996 and employs a technique which specifies a stochastic frontier production function in order to decompose the variation among vessels in the harvest of prawns due to unbounded random effects beyond firm control from those that result in differences in technical inefficiency among fishing vessels in the industry. In other words, variations in maximum expected output can occur either as a result of stochastic effects (e.g., good and bad weather states), or from the fact that vessels in the industry may be operating at various levels of inefficiency due to mismanagement, poor incentive structures, less than perfectly competitive behaviour or inappropriate input levels or combinations. Estimation of this output frontier also provides key information on the relative importance of inputs in the production of banana and tiger prawns, output elasticities, returns to scale, possible variations in stock size and the economic performance of each fishing vessel, year to year.

Likelihood ratio tests confirm that both stochastic effects and the extent of technical inefficiency matter, thus making traditional OLS estimates inappropriate. The level of technical inefficiency is shown to depend positively on gear headrope length and negatively on either the number of A-units or fuel expenditures. The point is especially relevant since A-unit restrictions over vessel size and engine power in the fishery during this period appear to

have resulted in a substitution toward less efficient but unregulated inputs, such as gear headrope length.

In this regard, the recent introduction of gear headrope length restrictions may be justified on two counts: both as a device to limit effort or catch and protect prawn stocks and as a way, given the final estimates in this paper, of improving economic performance by increasing the technical efficiency of vessels remaining in the industry. Nevertheless, it is important to emphasize that restrictions on an existing inefficient input may result in far smaller reductions in effort than projected, since the technical efficiency of vessels in the fishery will rise. With an increase in technical efficiency, gear-restricted fishing firms will harvest at points closer to their output frontiers. Moreover, with the removal of A-unit restrictions, 'effort creep' in the form of larger vessels and more powerful engines may more than compensate for any decrease in effort due to gear reduction.

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1. Introduction

The management of open or limited access fisheries is a difficult challenge. For most cases, the harvesting capacity of the fishing fleet exceeds the biological capacity of the resource to regenerate. As a result some type of control with the aim of reducing catch or harvesting capacity is seen as necessary. Ideally, regulation should both enhance economic performance and guarantee the biological sustainability of fish stocks for future generations. Unfortunately, open or limited access fisheries are generally characterized by severe economic inefficiencies, often resulting in excess effort among firms, over-capitalization (e.g., too many firms and overly large boats, engines and net size) and quickly depleted stocks. In addition, some regulatory measures, partly designed to correct these problems, often generate unwanted effects, such as the substitution of regulated inputs for more inefficient but unconstrained inputs in order to maintain catch.

This paper is a study of the production technology and relative efficiency of firms producing banana and tiger prawns in the Northern Prawn Fishery (NPF), one of Australia's largest and most lucrative fisheries. It employs a technique which specifies a stochastic frontier production function in order to decompose the variation among vessels in the harvest of fish due to unbounded random effects (e.g., weather) from those that result in differences in technical efficiency among fishing vessels in the industry. Estimation of this frontier also provides key information on the relative importance of inputs in the production of banana and tiger prawns, output elasticities, returns to scale, variations in stock size and the economic performance of each fishing vessel, year to year.

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).[1] In traditional economic theory, efficiency is generally assumed as an outcome of price-taking, competitive behavior. In this context (and assuming no uncertainty), a production function shows the maximum level of output that can be obtained from given inputs and the prevailing technology. However, variations in maximum output can also occur either as a result of stochastic effects (e.g., good and bad weather states), or from the fact that firms in the industry may be operating at various levels of inefficiency due to mismanagement, poor incentive structures, less than perfectly competitive behavior or inappropriate input levels or combinations. The econometric technique used in this paper, developed by Battese and Coelli (1988), allows for a decomposition of these effects and a precise measure of technical inefficiency defined by the ratio of observed output to the corresponding (estimated) maximum output defined by the frontier production function, given inputs and stochastic variation.

Recently, there has been widespread application of stochastic production frontiers to assess firm inefficiencies in various agricultural and industrial settings (e.g. Battese and Coelli, 1992, Coelli and Battese, 1996 and Kong, Marks and Wan, 1999), but few studies have been directed toward renewable resource-based industries. For fisheries, Kirkley, Squires and Strand (1995) and Sharma and Leung (1999) are among the few exceptions. However, the first paper simply estimates a stochastic production frontier for sea scallop vessels in the Mid-Atlantic fishery over a three year period for 10 vessels in a two-step procedure. No vessel-specific technical inefficiency effects are included. Sharma and Leung (1999) estimate technical inefficiencies for 122 vessels in the Hawaiian longline fishery, but with only cross-sectional data. Fortunately, for the NPF in Australia both time series and vessel-specific data are available. The present study contains a panel of 226 observations for banana prawns and 228 observations to tiger prawns across thirty-seven vessels (accounting for nearly 40 per cent of industry prawn output) for the years 1990–1996, allowing for both a time-dependent stochastic output frontier and technical inefficiency effects to be appropriately estimated in a single step.

Section 2 of the paper provides a summary of the theoretical framework for stochastic production frontiers. Section 3 briefly describes the Australian NPF and the banana and tiger prawn fisheries in particular. It is important to note two things at the outset. First, along with other effects, banana prawn catch is highly dependent on seasonal weather patterns, with poor catches generally following lower than average rainfalls in the preceding summer. This is indeed reflected in the final estimations. Second, the industry as a whole (for both banana and

[1] Green (1993) and Forsund, Lovell and Schmidt (1980) are useful surveys.

tiger prawn harvesting) has been subject to regulations designed to control effort levels and protect stocks. A-unit restrictions over vessel size and engine power are especially relevant during the sample period and appear to have resulted in a substitution (given final estimates for technical inefficiency effects over time) toward less efficient but unregulated inputs.

Section 4 describes the data set and the relevant variables used in the estimations. The raw data set includes values for both banana and tiger (grooved and brown) prawn output, but since the two fisheries are effectively separate, with different fishing seasons and characteristics, this paper concentrates on banana and tiger prawns as separate harvesting processes. The alternative to this is to measure all output in value terms (e.g., Sharma and Leung, 1999), given the relative price of banana to tiger prawns and average price changes over the sample years, and form estimates based on all aggregate values. In this case, however, the specified output frontier would no longer literally represent a production function and would (of course) be subject to price variability. Moreover, given the high dependence on seasonal weather effects and the purported weak relationship between catch and future stock abundance for banana prawns—both of which apparently do not apply, or at least not to the same extent, to tiger prawn production—it seems best to separate the two production processes on principle alone. In addition, although seasonal weather patterns effect the abundance of banana prawns there are no clear estimates of the stock-recruitment relationship for this species. For tiger prawns this relationship has been estimated and forms an important part of the econometric specification.

A number of factors are likely to affect the output of banana and tiger prawns in the NPF, including the size of boat, engine size and power, net size, effort, weather, and fishing skill. In addition, many of these factors are more than coincident (e.g., engine size can be correlated with net and vessel size). After excluding various specifications by likelihood ratio tests, sections 5.1 and 5.3 provide the econometric specifications used in this study. Weather-dummies are included for banana prawn output to provide proper estimates of output elasticities and additional likelihood ratio tests for both banana and tiger prawns confirm that stochastic effects and the extent of technical inefficiency matter, indicating that traditional OLS estimates are inappropriate.

Sections 5.2 and 5.4 summarize the overall results and section 6 provides a further discussion. In particular, Section 6.1 details technical inefficiencies for each vessel in the fishery and reports mean values sample-wide and in terms of average annual measures. Section 6.2 discusses the factors which affect the level of technical inefficiency. Some care has to be taken with the interpretation here. In general terms, economic inefficiency can be decomposed into allocative and technical inefficiency (see Farrell, 1957). The first implies that input proportions are incorrect and the second that input levels are not optimal. However, with both restricted and unregulated inputs and time series effects in the measure of technical inefficiency (with possible changes in mean input levels over time), the distinction between the two becomes much less clear. In some sense both effects can occur simultaneously and the data appears to suggest this.[2] Section 7 concludes.

2. Theoretical Framework

Stochastic production frontiers were first developed by Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977). The specification allows for a non-negative random component in the error term to generate a measure of technical inefficiency, or the ratio of actual to expected maximum output, given inputs and the existing technology. The idea can be readily applied to panel data. Indexing (fishing) firms by i, the specification can be expressed formally by

$$Y_{it} = f(X_{it}, \beta, t)e^{v_{it}-u_{it}} \tag{2.1}$$

for time t, Y_{it} output (or catch), X_{it} a vector of inputs and β a vector of parameters to be estimated. As usual, the error term v_{it} is assumed to be independently and identically distributed as $N(0, \sigma_v^2)$ and captures random variation in output due to factors beyond the control of firms, such as weather. The error term u_{it} captures technical inefficiency in production, assumed to be firm-specific, non-negative random variables, independently distributed as non-negative truncations (at zero) of the distribution $N(\mu_{it}, \sigma_u^2)$, where, following Battese and Coelli (1995),

$$\mu_{it} = \delta_0 + z_{it}\delta \tag{2.2}$$

defines an inefficiency distribution parameter for z_{it} a vector of firm-specific effects that determine technical inefficiency and δ is a vector of parameters to be estimated. Firm-specific effects for a fishery could include the size of vessel, length of gear, engine power, a hired skipper versus an owner-operator, skipper experience, and so on. Input variables may be included in both equations (2.1) and (2.2) as long as technical inefficiency effects are stochastic, say for random variable ω_{it} (see Battese and Coelli, 1995).

The condition that $u_{it} \geqq 0$ in equation (2.1) guarantees that all observations lie on or beneath the stochastic production frontier. A trend can also be included in equation (2.2) to capture time-variant effects.[3] Following Battese and Corra (1977) and Battese and Coelli (1993), variance terms are parameterized by replacing σ_v^2 and σ_u^2 with $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$.

[2] Huang and Liu (1994) arrive at a similar conclusion and use a systems maximum likelihood estimate to generate a non-neutral shift in the output frontier, implying that both the productivity of inputs and marginal rates of substitution change.

In strict technical terms, a precise decomposition of technical and allocative efficiency can only be obtained using a stochastic cost frontier, with measures of input prices for all variables (see Schmidt and Knox Lovell, 1979). For the NPF such data is not readily available but the matter is being pursued by the authors in a study of the south-east fishery in Australia.

[3] For the specification in section 5, likelihood ratio tests (not reported) reject a time trend in the technical inefficiency model, so the effect is ignored here.

For the basic case, the technical efficiency (TE) of the i-th firm in the t-th period can be defined as

$$TE_{it} = \frac{E(Y_{it} \mid u_{it}, X_{it})}{E(Y_{it} \mid u_{it} = 0, X_{it})} = e^{-u_{it}} \tag{2.3}$$

for E the usual expectations operator. The measure of technical efficiency is thus based on the conditional expectation given by equation (2.3), given the values of $v_{it} - u_{it}$ evaluated at the maximum likelihood estimates of the parameters in the model, where the expected maximum value of Y_{it} is conditional on $u_{it} = 0$ (see Battese and Coelli, 1988). The measure TE_{it} clearly must have a value between zero and one. If $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2) = 0$ the expected value of TE is one since there are no deviations due to technical inefficiency, or $\sigma_u^2 = 0$. If $\gamma = 1$ deviations in output are due entirely to technical inefficiency effects or σ_u^2. Thus, for $0 < \gamma < 1$, output deviations are characterized by the presence of both technical inefficiency and a random (stochastic) error. The overall mean technical efficiency of firms is

$$TE = \left\{ \frac{1 - \phi[\sigma_u - (\mu/\sigma_u)]}{1 - \phi(\mu/\sigma_u)} \right\} e^{-\mu + \frac{1}{2}\sigma_u^2} \tag{2.4}$$

where $\phi(\cdot)$ represents the density function for the standard normal variable. For the more complicated case in which at least some input variables appear in both equations (2.1) and (2.2), the technical efficiency of the i-th firm is given by

$$TE_{it} = (\bar{x}_{it}\beta - u_{it})(\bar{x}_{it}\beta)^{-1} \tag{2.5}$$

where $\bar{x}_{it}$ represents the vector-mean of the relevant input variables and β is a vector of the associated input coefficients. Mean technical efficiency now becomes

$$TE = 1 - \left\{ \mu + \frac{\sigma_u \phi(-\mu/\sigma_u)]}{1 - \phi(-\mu/\sigma_u)} \right\} (\bar{x}\beta)^{-1} \tag{2.6}$$

where $\bar{x}$ is the vector mean of the input levels of all firms in the industry.

3. The Australian Northern Prawn Fishery

The northern prawn fishery (extending from Cape Londonderry in Western Australia to Cape York in Queensland) is the largest and one of Australia's most valuable fisheries. First established in the late 1960's, more than fifty species of prawn inhabit the fishery, but brown and grooved tiger prawns and white banana prawns currently account for over 80 per cent of the commercial landings (ABARE, 2001). The gross value of prawn production in the NPF in 1999–2000 is estimated to be A$107 million with a total harvest of about 5,600 tons (AFMA, 2001). Nearly 90 per cent of all prawn output is exported to Japan and Asia.

In 2000, 115 vessels actively participated in the NPF. All vessels are purpose built twin gear otter trawls and generally range in size from 14 to 29 meters, with the most common boat size between 18 and 25 meters (AFMA, 2001). Most boats operate between 80 and 90 percent of the time available for fishing, with breakdowns and unloadings (to mother-ships) accounting for much of the remaining time. The fleet is technologically advanced, employing modern packing and freezing capabilities and sophisticated fishing aids such as echo sounders and satellite global positioning systems and plotters.

The banana prawn fishery is primarily located in the eastern waters of the Gulf of Carpentaria, in isolated grounds along the Arnhemland coast and in Joseph Bonaparte Gulf. Annual catches since 1983 range from 2,200 to 6,600 tons per year (Caton and McLoughlin, 2000). The white banana prawn accounts for over 80 per cent of all banana prawn catch. The spawning of banana prawns generally occurs in offshore areas, while recruitment of prawns to the fishery usually takes place in late spring. Banana prawns form dense aggregations (boils), which are easily spotted, allowing for rapid harvesting. The fishing season (with mostly daytime catch) starts around April and lasts for only a few weeks. Single aggregations of prawns usually contain 4 to 180 tons, but can be as high as 400 tons. Highest seasonal catches generally follow higher than average rainfall during the preceding summer (see Staples and Vance, 1986). Given the ease in harvesting, trawls for banana prawns are typically of a short, ten to twenty minute duration. Total effort attributed to the banana prawn fishery in 1998 was approximately 5,298 boat days (Caton and McLoughlin, 2000).

Although it is clear that potential catch is highly dependent on weather patterns, the relationship between catch and future stock size for banana prawns is not. As yet, there is no conclusive evidence that effort affects future stock abundance in this fishery (see Staples and Maliel, 1994), although recent catches below expectations have caused concern. In fact, the maximum sustainable yield for banana prawns is estimated to be 4,000 tons, which is roughly equivalent to the average catch over the past decade (Taylor and Die, 1999).

The tiger prawn fishery is concentrated in waters adjacent to coastal seagrass beds in the southern and western Gulf of Carpenteria and along the Arnhemland coast. Tiger prawns are fished at night, with trawlers targeting tiger prawns as catch rates in the banana prawn fishery begin to decline. Unlike banana prawns, tiger prawns do not form easily spotted, dense aggregations (boils), which are quickly harvested. The effective fishing season is thus much longer and takes a disproportionate amount of the total fishing effort applied in the NPF. Average annual catches of all tiger prawns range from 3,300 to 5,300 tonnes per fishing season, with a maximum sustainable yield estimated to be around 4,000 tonnes (ABARE, 2001). Yearly tiger prawn numbers are not nearly as dependent on weather patterns as banana prawns, which as mentioned can vary considerably with rainfall in the preceding summer. Nevertheless, recent stock assessments suggest that tiger prawn stocks are overfished with falls in landings over the past decade and recent tiger prawn catches (2,811 tonnes in 1997, 2,795 tonnes in 1998 and 2,195 tonnes in 1998) well below estimated maximum sustainable yield

(ABARE, 2001), and continue so to the end of 2000 (Dichmont, 2001).

Over the years the NPF as a whole has been subject to policy management, based on granted units over entry and inputs defined by a Statutory Fishing Right (SFR), to address concerns over the level of fishing effort and the biological sustainability of stocks. The fishery is managed by the Australian Fisheries Management Authority (AFMA). A number of measures to control effort have been used, including mid-seasonal and area closures (since 1987), gear restrictions (twin gear only, since 1987) and most recently gear headrope length restrictions (ABARE, 2001). Of particular concern for the period of this study (1990–1996) are the presence of restrictions on vessel size and engine power (defined A-units). A-unit controls have been in place in this fishery since 1987. An aggressive target for reductions was set for 1993 through an enhanced buy-back scheme designed to literally surrender A-units. The target was not met in 1993 and an additional compulsory pro rata surrender of A-units across remaining boat operators came into effect in April 1993, forcing the number of units to the target level (see Dann and Pascoe, 1994).

4. Data and Variables

4.1. Data set

The unbalanced panel data set used in this paper consists of thirty-seven vessels over the period 1990 to 1996, or 226 observations in total, with thirty-three missing values for banana prawns (Table 1) and 228 observations with thirty-one missing values for tiger prawns (Table 2).[4] The original database was drawn from surveys and statistics for the NPF fleet carried out and compiled by ABARE surveys and the CSIRO. The raw database includes measures of output by species (banana, brown and grooved prawn), crew size, revenue, boat variable costs (not available by species), capital costs and gear. Fishing logbook data obtained from the CSIRO includes data for all fishing firms for the period 1988–97, including the number of fishing days (effort). The CSIRO also holds data on vessel size and characteristics and skipper employment and experience. Of the roughly 130 vessels operating in the NPF during the sample period, the thirty-seven vessels in the unbalanced panel data set are among the largest that operate, representing almost 40 per cent of the total catch of prawns in the area each year.

4.2. Variables and variable construction

A brief description of the main variables of interest and their sources is contained in Table 3. Summary statistics for the key variables for the thirty-seven vessels studied are listed in Table 4 for banana prawns and Table 5 for tiger prawns.

[4] Final stock-recruitment estimates for tiger prawns for the years 1997-2000 are not yet available. Data for all vessels in the NPF to the year 2000 is available but does not contain all of the variables used in the specifications in this paper.

The output of banana prawns is measured in kilograms per year, with considerable variance from year-to-year. Average catch per boat for 1990–1996 is 41,333 kg/year with an average of 56.7 fishing days/year, as the usual proxy for fishing effort. The output of tiger prawns is 7,451 kg/year with an average of 119.4 fishing days per year. For the entire sample, the size of vessel in meters varies from seventeen to thirty meters, with a standard deviation of two meters and an average of twenty-three meters. Crew number averages 6.6 per boat and the average number of fishing days per year is 56.7 for banana and 119.4 days for tiger prawns. Skipper is a binary variable and indicates whether the boat is owner-operated (zero) or a skipper (one) is employed. Skipper experience is measured in years.

Since vessel trawling capacity is an important determinant of catch, headrope gear length is used as a proxy for trawling capacity throughout. Average gear length in the panel is measured at 27 meters, with a slightly smaller standard deviation for tiger relative to banana prawns. Input expenditures average $47,522 per year, indexed by fuel prices in base year 1989, and include fuel, oil, and grease. Among these, fuel expenditures are clearly the most important and serve as a reasonable proxy for engine power and size.[5] Average fuel expenditures are much higher for tiger prawns, or $150,803 per year. Finally, the value of A-units, as a sum of one A-unit for every cubic meter of hull volume and one A-unit for each kilowatt of engine power, is used as a rough measure of fishing capacity. A-units averaged 508 in the panel data set.

5. Empirical Results

5.1. Econometric specification: banana prawns

Generalized likelihood ratio tests are used to help confirm the functional form and specification. The correct critical values for the test statistic from a mixed χ-squared distribution (at the 5% level of significance) are drawn from Kodde and Palm (1986). As a pre-test, the null hypothesis of a Cobb-Douglas form of the production function was tested against a general translog specification by setting the relevant parameters for squared and interaction terms in the translog form equal to zero. The resulting test statistic was $\chi^2_{10} = 9.4$ compared to a critical value of 19.7. A Cobb-Douglas functional form was thus selected for banana prawns.[6]

[5] See NPFAMP (2000). To some extent, fuel is also related to the size of vessel. In the data set, boat fuel expenditures are available only as an aggregate over tiger and banana prawn output. The measure of fuel used for banana prawns is thus obtained by multiplying total all input expenditures (mostly fuel) by effort days in banana prawn production as a fraction of total effort days in banana and tiger prawn production.

[6] It is important to note that although translog production functions allow more scope for substitution, the input restrictions used in the NPF (notwithstanding the tendency to substitute regulated with unconstrained inputs, at least to some extent) make conventional measures of elasticities of substitution (which can be difficult to calculate in any case) inappropriate (see

Accordingly, equation (2.1) for the unbalanced panel data set (1990–1996) for banana prawns is specified by a production function in log-linear Cobb-Douglas form, or

$$\begin{aligned}\ln Y_{it} &= \beta_0 + \beta_1 \ln \text{crew}_{it} + \beta_2 \ln \text{effort}_{it} + \beta_3 \ln \text{gear}_{it} + \beta_4 \ln \text{fuel}_{it} + \\ &\quad \beta_5 d90 + \beta_6 d92 + \beta_7 d94 + \beta_8 T + v_{it} - u_{it} \qquad (5.1)\end{aligned}$$

where Y_{it} is the output of banana prawns, crew is crew number per boat, including the skipper (or owner-operator), and effort is the average number of fishing days. Fuel represents all input expenditures (fuel, oil, and grease). The values $d90$, $d92$ and $d94$ are year-dummies for 1990, 1992 and 1994 and T is a time trend.[7] A specific measure of capital (e.g., the relatively crude measure of A-units as the linear combination of vessel size and engine power) is not included here since fishing days already embody a certain degree of capital (and other materials) and, moreover, there is clear evidence that fuel expenditures are strictly related to engine (and vessel) size and power (see NPFAMP, 2000). As usual, crew labour services are assumed to be proportional to crew size.[8]

The vessel-specific factors used in the technical inefficiency distribution parameter, or equation (2.2), are A-units, gear length and the binary variable skipper,

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Dupont, 1991).

[7] As mentioned, the stock of banana prawns available for catch (or fishery recruitment) is largely affected by weather conditions, particularly rainfall in the previous summer. Equation (5.1) was 'tested down' with various choices for dummy variables. The years 1990, 1992 and 1994 proved to be significant and correspond exactly to the years with abnormally low rainfall levels in the summer prior to harvest. In the Carpentaria region, rainfall in the summer months (December to March) in the years 1990, 1992 and 1994, obtained from the CSIRO, was 2654, 3445 and 3550 millimeters compared to average for all other years in the sample period of 4550 millimeters. The specification given by (5.1) rightly assumes that weather effects, as normally distributed and unbounded random variables, are accounted for (with adjustments to coefficient values for inputs through the choice of relevant dummy variables) in the disturbance term v_{it}, rather than in the technical inefficiency model, or equation (5.2).

There is no data available on current stock abundance (or recruitment) to include as an input in equation (5.1), although weather-dummies clearly account for some changes in fishery recruitment. In addition, although there is some doubt about the issue, it appears that catch and future stock abundance may in fact be largely independent for banana prawns (see Staples and Maliel, 1994 and Timcke, *et al.*, 1999). Including a trend to (presumably) capture stock effects through time leaves the question open.

[8] Equation (5.1) is comparable to the approaches used in Kirkley, Squires and Strand (1995) and Sharma and Leung (1999). Given the available data, the first paper uses days at sea, stock abundance and labour to estimate sea scallop production in the Mid-Atlantic and the second paper uses trip days, crew size and other inputs (fuel, bait, ice, etc.) to estimate output in the longline fishery in Hawaii.

It should be mentioned that Kirkley, Squires and Strand (1995) use a two-step procedure to estimate technical inefficiency, rather than estimating the stochastic production frontier and technical inefficiency effects directly in a single step. The latter provides more efficient estimates (see Battese and Coelli, 1995 and Kumbhakar, Gosh and McGuckin, 1991) and, moreover, the two-step procedure is inconsistent with the assumption of indentically and independently distributed technical inefficiency effects.

so that

$$\mu_{it} = \delta_0 + \delta_1 \ln \text{A-units} + \delta_2 \ln \text{gear} + \delta_3 \text{skipper} + \omega_{it} \tag{5.2}$$

where the absence of a skipper (one) designates an owner-operator (zero). A-units are explicitly included at this point to gauge the effects on technical efficiency from the introduction of A-unit targets and restrictions in the NPF and roughly measures boat fishing capacity.[9] As mentioned, gear can be included in both equations (5.1) and (5.2) as long as technical inefficiency effects are stochastic (see Battese and Coelli, 1995). The overall structure is similar to a 'non-neutral' stochastic frontier production function (see Huang and Liu, 1994 and Coelli, *et al.*, 1998). In this context, it is assumed that A-units and gear may not be at their 'optimal' levels (or proportions), and particularly so given possible responses to input restrictions in the fishery, thus generating less than their maximum or best (expected) possible effect.[10]

Additional likelihood ratio (LR) tests are summarized in Table 6. The relevant test statistic is

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

where $L(H_0)$ and $L(H_1)$ are the values of the likelihood function under the null and alternative hypotheses respectively. The null hypothesis of no time trend in equation (5.1) is rejected.[11] 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 strongly rejected. All results indicate the stochastic effects and technical inefficiency matter and that usual OLS estimates are not appropriate in this study.

5.2. Results: banana prawns

Maximum likelihood estimates of the model were obtained using FRONTIER 4.1 (Coelli, 1996). The program itself follows a three-step procedure. OLS estimates are first obtained, followed by a grid search that evaluates a likelihood function for values of γ between zero and one, with adjustments to OLS estimates of β_0 and σ^2. All other values of β are restricted to be zero in this step. Finally, the best likelihood values selected in the grid search are used as starting values in

[9] Since A-units and fuel expenditures (which are known to vary by engine size and power) are clearly correlated, both variables cannot be included together. Nevertheless, replacing fuel with A-units gives comparable final estimates in all cases.

[10] See Forsund, Knox Lovell and Schmidt (1980) for a general discussion of the use of input variables in a technical inefficiency model.

[11] The null hypothesis of no time trend in the technical inefficiency model (not reported) cannot be rejected at the 5% level of significance but is rejected at the 1% level.

a quasi-Newton iterative procedure to form maximum likelihood estimates at a point where the likelihood function obtains its global maximum.

Results for the model (equations 5.1 and 5.2) are reported in Table 8. All input variables in the stochastic frontier production function are significant, except crew number, as are time trend and year-dummy variables. Estimates also show that inputs for banana prawn output in order of importance are fishing effort (fishing days), fuel (as a proxy for engine size and power), headrope gear length and crew number. All input share coefficients sum to 0.75. OLS estimates are also reported and as expected vary from frontier estimates for all input variables.

Results for the technical inefficiency model indicate that A-units and gear length are both significant. A-units have a significant negative effect on technical inefficiency (hence a positive effect on technical efficiency) and gear length has a positive effect on inefficiency. The hire of a skipper estimates as non-significant but has the expected sign. Incentive effects for owner-operated boats should likely result in an increase in technical efficiency relative to a hired skipper.[12]

Finally, the value of $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ is 0.806 and highly significant. A good measure of the residual variation is thus due to inefficiency effects, although variance in v_{it} still clearly matters.

Although banana prawn catch is highly dependent on seasonal weather effects, the relationship between catch and future stock abundance, as mentioned, is not clear. In fact, it is argued that future stock size is largely independent of the amount of fishing effort on adult stock, with the escape of spawners highly resilient to recruitment overfishing (see Staples and Maliel, 1994). Nevertheless, recent catches below expectations have generated concern that stock size may be falling. The estimates presented in Table 5 lend some support to this concern. After allowing for weather effects, the time trend for catch is highly significant and an order of magnitude of -0.05, indicating a 5 per cent negative growth rate in output over the period 1990–1996. Admittedly this study is over a period of time that may be too short to draw a definite inference about stock changes, but it is difficult to attribute the fall in output to anything else.[13] Moreover, the negative time trend was found to be robust to virtually dozens of alternative specifications.

5.3. Econometric specification: tiger prawns

Once again, generalized likelihood ratio tests are used to help confirm the functional form and specification. Stock assessments are available for tiger prawns

[12] Sharma and Leung (1999) obtain a similar result for the skipper effect.

[13] The decrease in average technical efficiency (see section 6.2) is clearly not sufficient to account for the size of the negative time trend. It should also be added that although the vessels studied in this paper represent only 40 per cent of industry output, changes in output during the sample period among these firms and the industry in total are roughly the same.

In general, stock-recruitment relationships can be difficult to quantify. The only available studies for the NPF is Wang and Die (1996) and Dichmont (2001).

and a resulting stock-recruitment estimate is included in the specification of the production function. As a pre-test, the null hypothesis of a Cobb-Douglas form of the production function was tested against a general translog specification by setting the relevant parameters for squared and interaction terms in the translog form equal to zero. The resulting test statistic was $\chi^2_{10} = 12.4$ compared to a critical value of 19.7. A Cobb-Douglas functional form was thus again selected. Equation (2.1) for the unbalanced panel data set (1990–1996) for tiger prawns is specified by a production function in log-linear Cobb-Douglas form, or

$$\ln Y_{it} = \beta_0 + \beta_1 \ln \text{effort}_{it} + \beta_2 \ln \text{fuel}_{it} + \beta_3 \ln \text{stock}_{it} + v_{it} - u_{it} \tag{5.4}$$

where Y_{it} is the output of tiger prawns, effort is the average number of fishing days, fuel represents all input expenditures (fuel, oil, and grease) and stock is the measure of stock abundance or recruitment to the fishery.

The firm-specific factors used in the technical inefficiency model, or equation (2.2), for tiger prawns are fuel expenditures, gear length, skipper experience (years) and the binary variable skipper, so that

$$u_{it} = \delta_0 + \delta_1 \ln \text{fuel} + \delta_2 \ln \text{gear} + \delta_3 \text{skipexp} + \delta_4 \text{skipper} + \omega_{it} \tag{5.5}$$

where the absence of a skipper (one) designates an owner-operator (zero).[14] As mentioned, fuel expenditures can be included in both equations (5.4) and (5.5) as along as technical inefficiency effects are stochastic (see Battese and Coelli, 1995) and are a proxy for engine size and power.

Additional likelihood ratio (LR) tests are summarized in Table 7. The null hypothesis of no time trend in equation (5.4) and (5.5) is rejected. The null hypothesis that technical inefficiency effects are absent ($\gamma = \delta_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$) and that vessel-specific effects do not influence technical inefficiencies ($\delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$) in equation (5.5) are both rejected, as is $\delta_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$. 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 strongly rejected. All results again indicate the stochastic effects and technical inefficiency matter and thus that traditional OLS estimates are not appropriate in this study.

5.4. Results: tiger prawns

Results for the model (equations 5.4 and 5.5) are reported in Table 10. All input variables in the stochastic frontier production function are significant, and by order of importance for tiger prawn output are: stock (.43), effort (.30) and fuel (.26). Input share coefficients sum to 0.99 and a Wald test (not reported) confirms that constant returns to scale cannot be rejected.

[14] The use of A-units rather than fuel expenditures in the technical inefficiency model for tiger prawns gives similar results. Although there is no apparent evidence in the data, fuel expenditures were used at this point to allay possible concerns over the false reporting of A-unit capacity.

All variables in the technical inefficiency model test as significant. Gear length has a significant (8.14) positive effect on technical inefficiency (hence a negative effect on technical efficiency), whereas fuel, skipper experience and the presence of a skipper have a positive effect on technical efficiency. Finally, the value of $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ is 0.95 and highly significant. A good measure of the residual variation is thus due to inefficiency effects, although variance in v_{it} still clearly matters. The negative sign on the coefficient for skipper is surprising, although since tiger prawns are much more difficult to locate than banana prawns, a hired skipper (as opposed to an owner-operator) may imply added expertise in the fishery.

6. Discussion

6.1. Technical efficiency and frontier output

Using the measures contained in section 2, the predicted technical efficiencies for vessels in this study range considerably from 0.19 to 0.93, with a mean technical efficiency of 0.725 for banana prawns, and from 0.31 to 0.96, with a mean technical efficiency of 0.773 for tiger prawns. The frequency distribution of estimated efficiencies is depicted in figure 1 for banana prawns and figure 3 for tiger prawns. For banana prawns the majority of vessels, 77 in total (or 34 per cent), have a technical efficiency index between 0.71 and 0.80, 71 boats lie in the range from 0.71 to 0.80, 46 (20.35 per cent) from 0.61 to 0.70, 18 (8 per cent) from 0.50 to 0.60 and 12 boats (5.31 per cent) have a technical efficiency index of less than 0.50. Only two boats have an index greater than 0.9.[15] For tiger prawns the majority of vessels range from 0.81 to 0.90. Predicted technical efficiencies for each vessel for the years 1990–1996 are listed in Table 9 for banana prawns and table 11 for tiger prawns, and graghed on yearly averages in Figure 4 for tiger prawns. Technical efficiency clearly falls from 1992 onwards in the fishery.

Figure 2 depicts average (over all vessels) annual output and estimated frontier output for banana prawns in the sample.[16] The low values for average annual output in the years 1990, 1992 and 1994 conforms with the estimated results on weather-dummy variables in table 5. All coefficient values for these years are negative, relatively large in magnitude and highly significant. Weather effects are clearly a large part of the story for banana prawn output and matter most in the final estimations during 'bad weather' draws.[17] Including weather-dummies

[15] Comparable cross-sectional measures for 122 Hawaiian longline vessels, given by Sharma and Leung (1999), are 42% with a technical efficiency index of 0.9 or above, 34% within the range of 0.8 to 0.9, 12% from 0.7 to 0.8, 7% from 0.6 to 0.7, 3.3% from 0.5 to 0.6 and 2.2% percent of the boats have an index of less than 0.5. The mean in this study is 0.84. Kirkley, Squires and Strand (1995) obtain a mean value of 0.75 in the mid-Atlantic sea scallop fishery, across ten vessels.

[16] Since this is drawn from panel data with a few missing observations some care has to taken with the interpretation of an average across all vessels.

[17] When included in the estimated equation, the year 1991, with a large average output, has

in the stochastic production frontier, equation (5.1), thus clearly conditions both estimated output elasticities and the level of estimated maximum efficient output. The output frontier accordingly generates low average annual values in the years 1990, 1992 and 1994.

6.2. Technical efficiency effects

The difference between average annual output and frontier output in figure 2 also depicts the measure of mean technical efficiency for banana prawn vessels for the years 1990–1996. The value of mean technical efficiency varies little over the sample period, but there is a significant difference between pre-1993 and the 1993–1996 measures. Average technical efficiency before 1993 is 74.6 per cent, but from 1993–1996 the average falls to 71.2 per cent. Similar results are obtained for tiger prawns (figure 4), with a fall from 83 per cent in 1992 to 76 per cent in 1996. Given the estimated results for technical inefficiency in table 8 and 10 (negative for either A-units or fuel expenditures and positive for gear length), the fall appears to be the result of policy measures designed to decrease the number of A-units in this fishery (with target of 54,000 class A-units by 1993) and the corresponding increase in gear length as vessels apparently substituted toward the relatively inefficient but unregulated input (figure 5). Average vessel values generally confirm the result. A-units fall through most of the sample period, but particularly so before 1993.[18] However, gear length increases steadily from 1993, with average values of 26.12, 27.17, 27.44 and 27.72 meters in each successive year for banana prawns and 26.91, 27.17, 27.30 27.72 for tiger prawns.[19] Average gear length for the entire fishery is depicted in figure 5, rising dramitically from 1993. Average technical inefficiency between the two periods thus decreases as the proportion of gear length to A-units rises.

7. Concluding Remarks

This paper represents a study of the production technology and relative efficiency of firms producing banana and tiger prawns in the Northern Prawn Fishery (NPF), one of Australia's largest and most lucrative fishing areas, based on a unbalanced panel data set of 226 observations among thirty-seven vessels for the years 1990–1996. On average, vessels in this panel study are shown to be reasonably technically efficient, but with considerable variance. The level of

a positive sign but is statistically insignificant. Evidently the years 1990, 1992 and 1994 are decreasing the measured average output of banana prawns considerably.

[18] For example, A-units in 1990 are 27.45 and in 1993, 26.12. The vessel buy-back scheme designed to surrender A-units does not apply in this study only in the sense that the same thirty-seven vessels appear in the panel data set from 1990–1996. A-unit reduction in the sample was thus achieved through physical limits on engine power and speed, which are thought to be especially difficult to monitor and enforce.

[19] In the unbalanced panel data set the value for gear length rises for each of the thirty-seven vessels, for all observed values.

technical inefficiency is shown to depend positively on gear headrope length and negatively on either A-units or fuel expenditure. The point is especially relevant since A-unit restrictions over vessel size and engine power in the fishery during this period appear to have resulted in a substitution toward less efficient but unregulated inputs, such as gear length.

In this regard, the recent introduction of gear headrope length restrictions (see Chapman and Beare, 2001) may be justified on two counts: both as a device to limit effort or catch and protect prawn stocks and as a way, given the final estimates in this paper, of improving economic performance by increasing the technical efficiency of vessels remaining in the industry. Nevertheless, it is important to emphasize that restrictions on an existing inefficient input may result in far smaller reductions in effort than projected, since the technical efficiency of vessels in the fishery will rise. With an increase in technical efficiency, gear-restricted fishing firms will harvest at points closer to their output frontiers. Moreover, with the removal of A-unit restrictions, 'effort creep' in the form of larger vessels and more powerful engines may more than compensate for any decrease in effort due to gear reduction.

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Table 1: Summary of panel of observations, banana prawns *(*=observed, na= not observed)*

Year/ Vessel number	1990	1991	1992	1993	1994	1995	1996	Total observations
1	*	*	*	*	*	*	*	7
2	*	*	*	*	*	na	na	5
3	*	*	*	*	*	*	*	7
4	*	*	*	*	*	na	na	5
5	*	*	*	*	*	*	*	7
6	*	*	*	*	*	*	na	6
7	*	*	*	*	*	*	*	7
8	*	*	*	*	*	*	*	7
9	*	*	*	*	*	*	*	7
10	*	*	*	*	*	*	*	7
11	*	*	*	*	*	*	*	7
12	*	*	*	*	*	*	*	7
13	*	*	*	*	*	*	*	7
14	*	*	*	*	*	*	*	7
15	*	*	*	na	na	*	*	5
16	*	*	*	na	*	na	na	4
17	*	*	*	*	*	*	*	7
18	na	na	*	na	*	*	*	4
19	na	na	na	*	*	na	na	2
20	na	na	*	*	*	*	*	5
21	na	na	*	*	*	*	*	5
22	na	na	*	*	*	*	*	5
23	*	*	*	*	*	*	*	7
24	*	*	*	*	*	*	*	7
25	*	*	*	*	*	*	*	7
26	*	*	*	*	*	*	*	7
27	*	*	*	*	*	*	*	7
28	*	*	*	*	*	*	*	7
29	*	*	*	*	*	*	*	7
30	*	*	*	*	*	na	*	6
31	*	*	*	*	*	*	*	7
32	*	*	*	*	*	*	*	7
33	*	*	*	*	*	*	*	7
34	*	*	*	*	*	*	*	7
35	na	na	*	*	*	*	*	5
36	na	na	na	*	*	*	*	4
37	na	na	na	*	*	*	*	4
Total	**29**	**29**	**34**	**34**	**36**	**32**	**32**	**226**

Table 2: Summary of panel of observations, tiger prawns *(*=observed, na= not observed)*

Year/ Vessel number	1990	1991	1992	1993	1994	1995	1996	Total observations
1	*	*	*	*	*	*	*	7
2	*	*	*	*	*	na	na	5
3	*	*	*	*	*	*	*	7
4	*	*	*	*	*	na	na	5
5	*	*	*	*	*	*	*	7
6	*	*	*	*	*	*	na	6
7	*	*	*	*	*	*	*	7
8	*	*	*	*	*	*	*	7
9	*	*	*	*	*	*	*	7
10	*	*	*	*	*	*	*	7
11	*	*	*	*	*	*	*	7
12	*	*	*	*	*	*	*	7
13	*	*	*	*	*	*	*	7
14	*	*	*	*	*	*	*	7
15	*	*	*	na	na	*	*	5
16	*	*	*	na	*	na	na	4
17	*	*	*	*	*	*	*	7
18	*	*	*	na	*	*	*	6
19	*	*	na	*	*	na	na	4
20	na	na	*	*	*	*	*	5
21	na	na	*	*	*	*	*	5
22	na	na	*	*	*	*	*	5
23	*	*	*	*	*	*	*	7
24	*	*	*	*	*	*	*	7
25	*	*	*	*	*	*	*	7
26	*	*	*	*	*	*	*	7
27	*	*	*	*	*	*	*	7
28	*	na	*	*	*	*	*	6
29	*	*	*	*	*	*	*	7
30	*	*	*	na	*	na	*	5
31	*	*	*	*	*	*	*	7
32	*	*	*	*	*	*	*	7
33	*	*	*	*	*	*	*	7
34	*	*	*	*	*	*	*	7
35	na	na	*	*	*	*	*	5
36	na	na	na	*	*	*	*	4
37	na	na	na	*	*	*	*	4
Total	**31**	**30**	**34**	**33**	**36**	**32**	**32**	**228**

Table 3: Description of inputs and vessel specific variables, Northern Prawn Fishery
(37 vessels for the period 1990-96)

Variables	Description	Sources
• Crew	Number of crew on boat and skipper	ABARE
• Fishing effort	Nominal fishing days for banana prawns	CSIRO
• Vessel A-unit	The sum of one A-unit for every cubic meter of hull volume and one A-unit for each kilowatt of engine power	CSIRO
• Input expenditures	Fuel, oil and grease and expenditures measured in 1989 prices	ABARE
• Gear length	Headrope length of gear (meters)	CSRIO
• Boat size	Vessel length (meters)	CSIRO
• Skipper	Hired skipper (1), owner-operated vessel (0)	CSIRO
• Banana prawn output	Banana prawns (kilograms)	ABARE
• Skipper experience	Skipper experience with plotters (years)	CSIRO
• Stock	Tiger prawn stock assessment data	CSIRO
• Tiger prawn output	Tiger prawns (kilograms)	ABARE

Table 4: Summary statistics for key variables for banana prawns *(Unbalanced panel data: 226 observations for 37 vessels, 1990-96)*

		Average	Stdev	Min	Max
Output	*kg/year*	41,333	26,417	4,931	125,235
Crew number/boat	*Persons*	6.6	1.1	5.0	9.0
Fishing days/year	*Days*	56.7	31.4	6.0	158.0
Input expenditures (1989 prices)	*$AUS*	47,522	33,738	4,181	202,460
Gear length	*Meters*	27.0	2.7	24.0	32.0
Vessel A-unit	*A-units*	508	80	330	694

Source: *Constructed from statistics and surveys compiled by ABARE and CSRIO*

Table 5: **Summary statistics for key variables for tiger prawns** *(Unbalanced panel data: 228 observations for 37 vessels, 1990-96)*

		Average	Stdev	Min	Max
Output	*kg/year*	7,451	1,345	6,291	9,912
Crew number/boat	*persons*	6.61	1.13	5.00	9.00
Fishing days/year	*days*	119.4	44.5	2.0	188.0
Fuel expenditures (1989 prices)	*$AUS*	150,803	35,299	57,984	259,334
Gear length	*meters*	27.2	2.0	18	32
Skipper experience	*years*	3	2	0	9

Source: *Constructed from statistics and surveys compiled by ABARE and CSRIO*

Table 6: Generalised likelihood ratio tests for parameter restrictions in the stochastic production frontier and technical inefficiency models, banana prawns (equations 5.1 and 5.2)

Null hypothesis	χ^2-statistic	$\chi^2_{0.95}$-value	Decision
No time trend in equation (5.1)	6.66	2.70	reject H_0
$\gamma = \delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$	15.24	10.37	reject H_0
γ=0	17.44	2.70	reject H_0
$\delta_0 = \delta_1 = \delta_2 = \delta_3 = 0$	14.90	8.76	reject H_0
$\delta_1 = \delta_2 = \delta_3 = 0$	14.18	7.04	reject H_0

Note: *The critical values for the hypotheses are obtained from Table 1 of Kodde and Palm (1986).*

Table 7: Generalised likelihood ratio tests for parameter restrictions in the stochastic production frontier and technical inefficiency models, tiger prawns (equations 5.4 and 5.5)

Null hypothesis	χ^2-statistic	$\chi^2_{0.95}$-value	Decision
Time trend in the stochastic production frontierl	4.94	2.71	reject H_0
Time trend in the technical inefficiency model	6.66	2.71	reject H_0
$\gamma = \delta_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$	46.09	10.37	reject H_0
γ=0	46.04	2.71	reject H_0
$\delta_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$	26.40	8.76	reject H_0
$\delta_1 = \delta_2 = \delta_3 = \delta_4 = 0$	26.31	7.05	reject H_0

Note: *The critical values for the hypotheses are obtained from Table 1 of Kodde and Palm (1986).*

Table 8: Parameter estimates of the stochastic production frontier and technical inefficiency models, banana prawns (equations 5.1 and 5.2)

	MLE		OLS	
	Coefficient	Asymptotic T-ratio	Coefficient	Asymptotic T-ratio
Stochastic production frontier				
Constant	6.42*** *(0.97)*	6.59	5.57*** *(1.04)*	5.32
Crew	-0.10 *(0.19)*	0.51	0.11 *(0.20)*	0.57
Effort	0.38*** *(0.15)*	2.40	0.30** *(0.17)*	1.80
Gear length	0.20* *(0.11)*	1.88	0.18 *(0.15)*	1.22
Fuel	0.27** *(0.13)*	2.18	0.32*** *(0.14)*	2.33
Time trend	-0.05** *(-0.02)*	2.24	-0.06*** *(0.023)*	2.73
Year 1990	-0.62*** *(0.13)*	4.87	-0.68*** *(0.14)*	4.76
Year 1992	-0.57*** *(0.10)*	5.90	-0.57*** *(0.11)*	5.26
Year 1994	-0.62*** *(0.09)*	6.84	-0.61*** *(0.09)*	6.43
Technical inefficiency model				
Constant	2.91 *(3.78)*	0.77		
A-unit	-1.52** *(0.95)*	1.60		
Head rope length of gear	1.53** *(0.85)*	1.80		
Skipper	0.73 *(0.92)*	0.79		
Sigma-squared	0.647*** *(0.12)*	5.58		
Gamma	0.806*** *(0.065)*	12.32		
Ln (likelihood)	-149.71			-158.43
Mean Technical Efficiency	0.725			

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

Figure 1: Frequency distribution of technical efficiencies by number of vessels, banana prawns

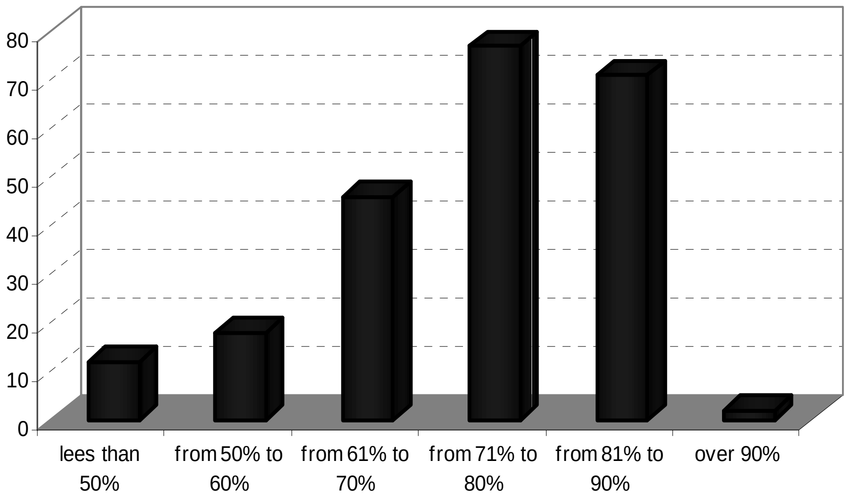

Figure 2: Average annual output and frontier output for banana prawns

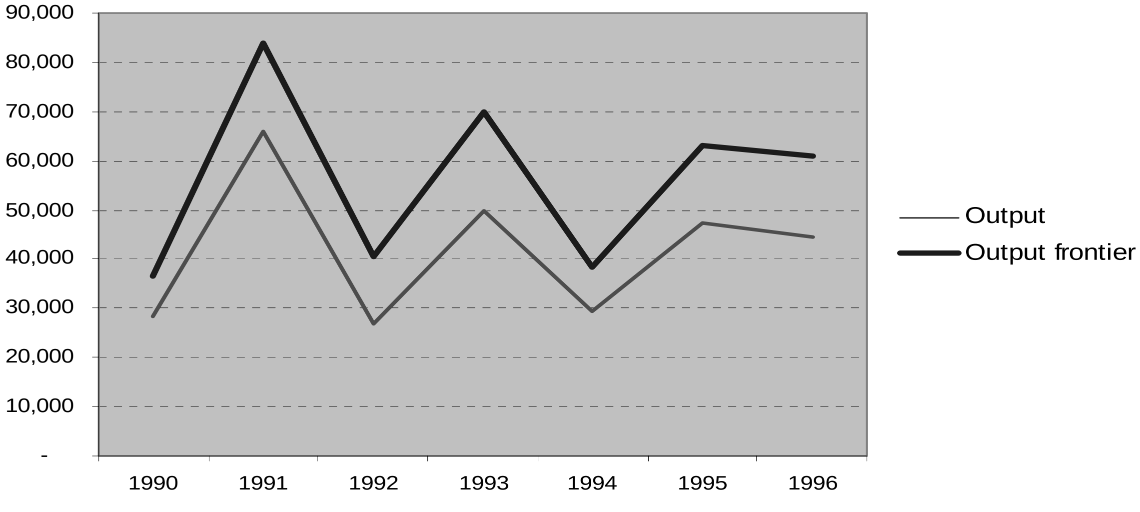

Table 9: Predicted technical inefficiencies for banana prawn vessels in the Northern Prawn Fishery 1990-96

Year/ Vessel number	1990	1991	1992	1993	1994	1995	1996
1	0.81	0.84	0.70	0.78	0.66	0.81	0.77
2	0.70	0.82	0.76	0.72	0.68	na	na
3	0.57	0.88	0.59	0.73	0.55	0.81	0.46
4	0.63	0.88	0.86	0.80	0.73	na	na
5	0.84	0.82	0.73	0.71	0.81	0.62	0.73
6	0.64	0.81	0.52	0.63	0.54	0.73	na
7	0.83	0.84	0.83	0.70	0.49	0.85	0.67
8	0.83	0.83	0.74	0.66	0.79	0.63	0.89
9	0.77	0.84	0.60	0.73	0.81	0.85	0.75
10	0.72	0.89	0.77	0.63	0.86	0.64	0.88
11	0.77	0.82	0.72	0.72	0.70	0.81	0.73
12	0.81	0.85	0.82	0.67	0.81	0.81	0.81
13	0.66	0.77	0.84	0.40	0.67	0.73	0.80
14	0.64	0.83	0.74	0.63	0.83	0.82	0.78
15	0.67	0.86	0.78	na	na	0.70	0.84
16	0.72	0.80	0.75	na	0.51	na	na
17	0.56	0.74	0.67	0.42	0.33	0.84	0.80
18	na	na	0.68	na	0.74	0.66	0.75
19	na	na	na	0.66	0.54	na	na
20	na	na	0.73	0.72	0.78	0.71	0.63
21	na	na	0.72	0.72	0.83	0.80	0.80
22	na	na	0.83	0.65	0.56	0.67	0.76
23	0.59	0.70	0.75	0.69	0.75	0.83	0.70
24	0.57	0.73	0.70	0.27	0.90	0.87	0.82
25	0.63	0.72	0.70	0.62	0.75	0.81	0.76
26	0.80	0.75	0.82	0.76	0.82	0.89	0.75
27	0.93	0.32	0.70	0.73	0.71	0.77	0.76
28	0.88	0.65	0.69	0.79	0.83	0.83	0.78
29	0.90	0.60	0.83	0.81	0.84	0.88	0.82
30	0.86	0.83	0.90	0.93	0.90	na	0.71
31	0.73	0.79	0.80	0.72	0.73	0.20	0.59
32	0.70	0.77	0.75	0.75	0.82	0.19	0.37
33	0.57	0.64	0.86	0.71	0.67	0.21	0.56
34	0.60	0.75	0.65	0.68	0.61	0.56	0.29
35	na	na	0.77	0.71	0.77	0.64	0.80
36	na	na	na	0.79	0.84	0.84	0.83
37	na	na	na	0.77	0.81	0.86	0.78

Table 10: Parameter estimates of the stochastic production frontier and technical inefficiency models, tiger prawns (equations 5.4 and 5.5)

	Maximum Likelihood Estimate	
	Coefficient	Asymptotic T ratio
Stochastic production frontier		
Constant	2.06 *(1.97)*	1.04
Effort	0.30*** *(0.12)*	2.49
Fuel	0.26* *(0.14)*	1.81
Stock	0.43*** *(0.16)*	2.65
Technical inefficiency model		
Constant	3.13*** *(1.21)*	2.58
Fuel expenditures	-3.03* *(1.68)*	1.80
Head rope length of gear	8.14** *(4.29)*	1.90
Skipper experience	-0.15** *(0.08)*	1.96
Skipper	-3.95* *(2.51)*	1.57
Sigma-squared	2.63* *(1.67)*	1.57
Gamma	0.95*** *(0.03)*	29.26
Ln (likelihood)	140.17	
Mean Technical Efficiency	0.773	

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

Figure 3: Frequency distribution of technical efficiencies by number of vessels, tiger prawns

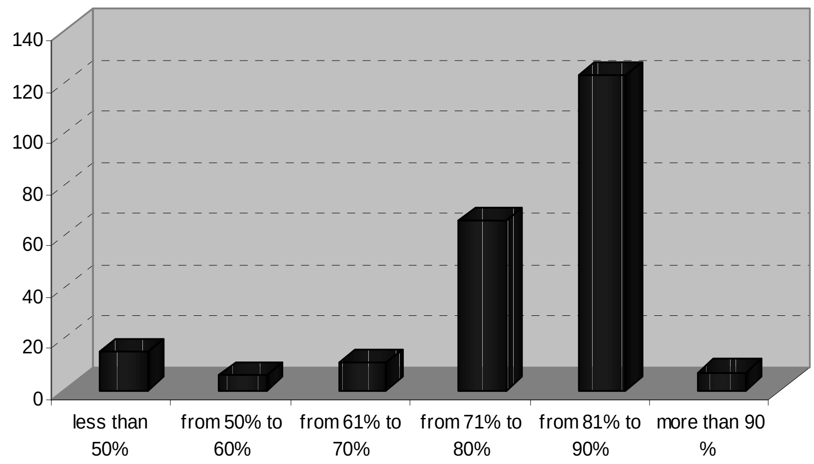

Figure 4: Mean efficiency, tiger prawns 1990-96

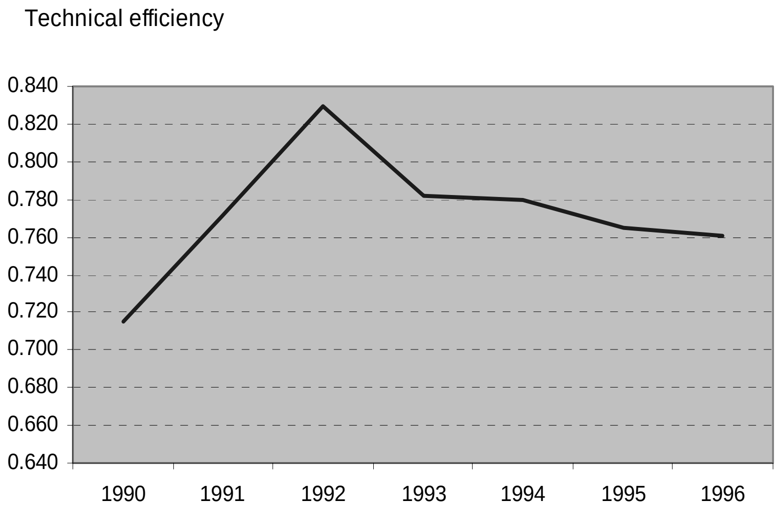

Table 11: Predicted technical inefficiencies for tiger prawn vessels in the Northern Prawn Fishery, 1990-96

Year/ Vessel number	1990	1991	1992	1993	1994	1995	1996
1	0.69	0.65	0.86	0.79	0.83	0.86	0.86
2	0.82	0.82	0.85	0.79	0.80	na	na
3	0.82	0.78	0.86	0.80	0.85	0.87	0.86
4	0.74	0.75	0.86	0.81	0.79	na	na
5	0.81	0.83	0.86	0.79	0.79	0.87	0.78
6	0.81	0.73	0.84	0.77	0.83	0.86	na
7	0.42	0.78	0.85	0.79	0.85	0.83	0.83
8	0.34	0.80	0.83	0.77	0.84	0.86	0.60
9	0.82	0.82	0.87	0.86	0.82	0.07	0.85
10	0.81	0.80	0.85	0.82	0.82	0.88	0.77
11	0.80	0.76	0.85	0.82	0.80	0.86	0.83
12	0.51	0.81	0.84	0.78	0.84	0.84	0.86
13	0.81	0.79	0.81	0.81	0.83	0.83	0.85
14	0.14	0.47	0.79	0.73	0.62	0.82	0.81
15	0.80	0.77	0.85	na	na	0.68	0.79
16	0.71	0.74	0.87	na	0.77	na	na
17	0.82	0.78	0.82	0.87	0.89	0.80	0.84
18	0.86	0.91	0.87	na	0.75	0.83	0.86
19	0.92	0.90	na	0.86	0.84	na	na
20	na	na	0.88	0.81	0.82	0.85	0.91
21	na	na	0.87	0.84	0.86	0.87	0.87
22	na	na	0.86	0.85	0.92	0.87	0.87
23	0.82	0.81	0.82	0.68	0.82	0.88	0.77
24	0.82	0.79	0.83	0.85	0.81	0.89	0.81
25	0.78	0.82	0.80	0.80	0.70	0.52	0.85
26	0.66	0.85	0.79	0.68	0.81	0.87	0.77
27	0.79	0.80	0.78	0.76	0.84	0.87	0.79
28	0.82	na	0.77	0.74	0.79	0.54	0.41
29	0.84	0.83	0.85	0.83	0.83	0.89	0.39
30	0.64	0.57	0.58	na	0.15	na	0.14
31	0.80	0.76	0.83	0.96	0.76	0.77	0.77
32	0.77	0.74	0.84	0.67	0.82	0.84	0.89
33	0.81	0.80	0.84	0.95	0.82	0.75	0.81
34	0.77	0.69	0.84	0.74	0.80	0.76	0.91
35	na	na	0.82	0.35	0.26	0.48	0.40
36	na	na	na	0.73	0.85	0.31	0.79
37	na	na	na	0.63	0.81	0.88	0.79

Figure 5: Average gear length per boat, Northern Prawn Fishery, 1990-96 (meters)