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Abstract

The paper provides the first *ex-post* estimates of the effects on technical efficiency of input controls in a fishery. Using individual vessel data from the northern prawn fishery of Australia for the years 1990–1996 and 1994–2000, a stochastic production frontier is estimated to analyse the efficiency impacts of input controls on engine and vessel size. The results indicate that technical efficiency is *increasing* in a measure of vessel size and engine capacity that was controlled by the regulator from 1985 to 2001, and *decreasing* in an unregulated input, gear headrope length. The study shows that fishers have substituted from regulated to unregulated inputs over the period 1990-2000 and technical efficiency has declined coincident with increasing restrictions on vessel size and engine capacity. The decline in technical efficiency indicates that the goal of the regulator to increase economic efficiency has not been realised.

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"—we cannot necessarily simply limit "effort" (a multidimensional notion) by, say, limiting tonnage or vessel numbers, or numbers of fishermen. With flexibility fishermen have the option to, and may, in fact, simply readjust other factors in their control to expand effort and subvert any imposed restrictions."

J.E. Wilen (1979) pp. 855-856.

1 Introduction

Input controls and restrictions on vessel gear are the principal methods of controlling effort in many developed fisheries.[1] This is despite a large literature that outlines the potential for fishers to substitute to unregulated inputs and circumvent controls on overall fishing effort.[2] Although fishery managers are aware of the possibility of input substitution, this paper is the first to measure *ex-post* changes in individual technical efficiency associated with input controls and to estimate the direct effects of the controlled input on average vessel technical efficiency.[3] The results are important as they provide a confirmation that input controls may have a deleterious effect on efficiency and provide support for alternative methods of regulation, such as individual output controls, in fisheries where efficiency is viewed as an important goal of management.

Our study uses data from Australia's northern prawn fishery (NPF) which is managed by the Australian Fisheries Management Authority (AFMA) with the objective of ensuring ecological sustainability and economic efficiency (ABAREa 2000). To prevent overfishing, AFMA has limited fishing effort by regulating vessel and gear capacity. To assess the economic effects of these input controls and input substitution from regulated to unregulated inputs we estimate changes in technical efficiency using a stochastic frontier production function.[4] This method decomposes the variation in the output of fish due to unbounded random effects, such as weather, from variation in technical efficiency that can be explained by differences in vessel or skipper characteristics.[5] Such an approach also provides key information on the relative importance of inputs in production of banana prawns and the economic performance of each fishing vessel, year to year.

Various applications of stochastic production frontiers to assess firm inefficiencies exist in agricultural and industrial settings and include Battese and Coelli (1992), Coelli and Battese (1996) and Kong, Marks and Wan (1999). The first technical efficiency study in fisheries was by Hannesson (1983) who assumed a single input and estimated a deterministic frontier. In a seminal paper, Kirkley, Squires and Strand (1995) were the first to use a stochastic frontier in fisheries and predicted the possible effects on technical efficiency of changes in limited entry and input restrictions. The stochastic frontier approach has also been employed by Pascoe and Coglan (2002) in a study of the contribution of unmeasurable inputs to overall technical efficiency in the English Channel fishing fleet, by Grafton, Squires and Fox (2000) to evaluate the efficiency effects of output controls in the British Columbia halibut fishery and by Sharma and Leung (1999) to investigate the effects of vessel characteristics and targeted species on vessel technical efficiency in the Hawaiian longline fishery.

The purpose of the paper is to empirically estimate the effects of fishery inputs controls on efficiency. The following section describes the fishery used in this study and its management regulations. Section 3 provides a summary of the theoretical framework for stochastic production frontiers used to estimate individual vessel technical efficiency. Section 4 describes the different data used in the analysis and the econometric specification of the stochastic production frontiers. Section 5 evaluates the results and efficiency effects of inputs controls in the fishery. Section 6 uses the results of the study to provide insights about fisheries management and the use of input controls and section 7 concludes.

2 The Australian Northern Prawn Fishery

The northern prawn fishery (extending from Cape Londonderry in Western Australia to Cape York in Queensland) and covering almost one million square kilometers is the largest and one of Australia's most valuable fisheries. First established commercially in the late

1960s, 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). Annual catches since 1983 range from 2,200 to 6,600 tons per year (AFFA, 2000) with the white banana prawn accounting for over 80% 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.

The gross value of prawn production in the NPF in 1999–2000 was some 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. The potential catch is highly dependent on weather patterns, but the relationship between catch and future stock size for banana prawns is less certain. As yet, there is still no conclusive evidence that effort effects future stock abundance in this fishery (see Staples and Maliel, 1994), although very recent catches below expectations have caused concern (ABAREb, 2000 and Timcke *et.al.*, 1999). 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 prawn fishery can be prosecuted from April to November with a mid-season closure in June and July to protect spawning stocks. Most fishers focus their efforts on banana stocks before the mid-season closure and then switch to targeting tiger and other prawn species. The fishers employ twin rig otter trawls and use advanced technologies to locate fish that include color echo sounders, GPS navigation, on-board computers, and satellite communications.

The fishing season (with mostly daytime catch) starts around April and lasts for only a few weeks. Single aggregations of banana prawns usually contain 4 to 180 tons, but can be as high as 400 tons. The highest seasonal catches generally follows higher than average rainfall during the preceding summer (Staples and Vance, 1986) and lower catches are associated with abnormally lower rainfall in the same year. Given the ease in harvesting, the trawling time for banana prawns is typically of a short, ten to twenty minute duration.

2.1 Management Regulations

The fishery is managed by AFMA—an Australian federal agency. Over the years, the NPF has been regulated to address concerns over the level of fishing effort and its impact on the biological sustainability of stocks. Since 1977 the fishery has been regulated by limited entry controls to prevent overharvesting that have restricted the number of vessels in the fishery. Initially the goals of regulation were to ensure a sustainable biomass and stock of prawns, but since 1991 it has also included the objective of economic efficiency.

To address concerns over prawn stocks due to an increased number of vessels and excessive fishing effort, the regulator implemented limited-entry restrictions in 1977. At the time, 292 vessel licences were allocated although there were only 193 active vessels. These licences were transferable and trading resulted in their allocation to newer and larger vessels. In addition, more fishers took up their fishing entitlements and by 1981 there was an almost 50 percent increase in the number of active vessels. Concerns about the increased fishing effort in terms of the prawn stocks[6] led to a series of regulatory changes to control the inputs used by fishers.

In 1985, a boat replacement policy was introduced that was designed to reduce the capacity of the fishing fleet. Under the policy, vessel owners wishing to improve their vessels, or use a newer vessel, were required to surrender "A-units" equal to the number of A-units on the upgraded or new vessel, less 375. These A-units were defined as the sum of the kilowatt of engine power and hull size in cubic metres and represented a measure of fishing capital. The boat replacement policy required vessel owners to acquire A-units from other licence holders and was designed to prevent further increases in capacity within the fleet. The policy was changed in 1993 such that vessel owners wishing to upgrade or introduce a new vessel were obliged to surrender A-units and a vessel licence, such that at least one other vessel was removed from the fishery.

The regulator has also initiated voluntary buy-back of A-units with the goal of reducing the number of A-units in the fleet to 70,000 units. The first buy-back scheme was introduced in 1985 and was funded by a $A450 levy on each vessel based on the number A-units held, but it failed to meet its target. In 1991, a second voluntary buy-back scheme was implemented with the goal of reducing the number of A-units from 96,300 to 54,000 by 1993 using $A45 million financial assistance from the government. The buy-back scheme reduced the number of A-units to 76,000 by 1992 and, to achieve the target, a pro-rata reduction of A-units was imposed in 1993. To be in compliance with the A-unit regulations, vessel owners were obliged to reallocate their A-units among the vessels they owned or purchase A-units from other fishers who then exited the fishery (Dann and Pascoe 1994). The end result was that by 1996 there were 127 active fishing vessels in the fleet with a total capacity of 52,000 A-units (Die and Bishop 1998). In addition to A-units regulations, various other measures have been used to control fishing effort. These measures include seasonal closures (to protect spawning resource stocks), gear restrictions that limit the gear to two trawl nets, and a gear length limit that restricted the average total headrope length to 24 fathoms (subsequently removed in 1993).

Concerns over the ability of input controls to limit fishing effort and its negative implications for economic efficiency have led to discussions over the possible use of individual output controls. To date, the introduction of individual harvesting rights has been strongly opposed by the fishers, especially operators with larger vessels, who believe they can generate higher returns under the present regulations.

3 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 approach can be readily applied to an unbalanced panel. Indexing (fishing) firms by i, the specification can be expressed formally by

$$Y_{it} = f(X_{it}, \beta, t)e^{v_{it} - u_{it}} \tag{1}$$

for time t, where Y_{it} is output (or catch), X_{it} is a vector of inputs and β is a vector of parameters to be estimated. The error term v_{it} is commonly 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. The common assumption is that the error term is firm-specific, non-negative and independently distributed as non-negative truncations (at zero) of the distribution $N(\mu_{it}, \sigma_u^2)$. Following Battese and Coelli (1995), the technical inefficiency term can be specified as

$$\mu_{it} = \delta_0 + z_{it}\delta + \omega_{it} \tag{2}$$

where ω_{it} is distributed as $N(0, \sigma_\omega^2)$, z_{it} is a vector of firm-specific effects that determine technical inefficiency and δ is a vector of parameters to be estimated. Firm-specific factors that might affect technical efficiency include vessel size, length of gear, engine power, a hired skipper versus an owner-operator, skipper experience, among others. Input variables may be included in both equations (1) and (2) provided that technical inefficiency effects are stochastic (Battese and Coelli, 1995).

The condition that $u_{it} \geq 0$ in equation (1) guarantees that all observations lie on or beneath the stochastic production frontier. A trend can also be included in equation (2) to capture time-variant effects.[7] 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 $\gamma =$

$\sigma_u^2/(\sigma_v^2 + \sigma_u^2)$.

The technical efficiency of the i-th firm in the t-th period can be defined as

$$TE_{it} = \frac{E(Y_{it} \mid u_{it}, X_{it})}{E(Y_{it} \mid u_{it} = 0, X_{it})} = e^{-u_{it}} \tag{3}$$

where E is the expectations operator. Thus the measure of technical efficiency is based on the conditional expectation given by equation (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} has a value between zero and one and the overall mean technical efficiency of firms is

$$TE = \left\{ \frac{1 - \phi[\sigma_u - (\mu/\sigma_u)]}{1 - \phi(\mu/\sigma_u)} \right\} e^{-\mu + \frac{1}{2}\sigma_u^2} \tag{4}$$

where $\phi(\cdot)$ represents the density function for the standard normal variable.

4 Data and Model

The unbalanced panel data used to estimate the stochastic frontiers for the NPF comes from two different data sets. Data on a larger set of variables is available for an unbalanced panel of thirty-seven vessels over the period 1990 to 1996, or 228 observations with thirty-one missing values, and for a smaller set of variables for the entire fleet over the period 1994-2000 for a total of 844 observations with 122 missing values. Details of the variables in each data set are summarised in tables 1a and 1b with summary statistics provided in tables 2a and 2b.

The vessels included in the 1990-96 data harvested almost 40 per cent of the total catch of banana prawns each year and are drawn from surveys and statistics for the NPF fleet carried out and compiled by the Australian Bureau of Agricultural and Resource Economics (ABARE) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

The data includes measures of output by species (banana, brown and grooved prawn), crew size, revenue, boat variable costs (not available by species), capital costs, nominal fishing days for banana prawns and vessel characteristics (hull units, engine power, A-units, gear length, boat size). The 1994-2000 data comes from CSIRO and is limited to boat or vessel characteristics (hull units, engine power, A-units, gear length, boat size), landings of banana prawns and nominal fishing days for banana prawns.

4.1 Variables and variable construction

The output of banana prawns is measured in kilograms per year, with considerable variance from year-to-year, and an average per boat for 1990–1996 of 41,333 kg/year and for 1994–2000 of 29,074 kg/year. For the entire fleet, vessel size varies from thirteen to thirty metres, with a standard deviation of nine metres and an average of twenty-two metres. Crew size averaged 6.6 persons per vessel in the period 1990–1996 and the average number of fishing days per year, the usual proxy for fishing effort, was 56.7 for the same period.

Due to the nature of fishing in the NPF, vessel trawling is an important determinant of catch and, thus, headrope gear length is used as a proxy for trawling capacity. Average gear length in the panel is measured at 13 metres. Fuel expenditures averaged $47,522 per year for the period 1990–1996, indexed by fuel prices in base year 1989, and include fuel, oil, and grease.[8] For the entire fleet, over the period 1994–2000, A-units per vessel had a mean value of 418.

4.2 Econometric specification

Generalized likelihood ratio tests are used to help confirm the functional form and specification of the estimated models. The correct critical values for the test statistic come from a mixed χ-squared distribution (at the 5% level of significance) and are drawn from Kodde and Palm (1986). A translog specification was initially estimated, but a pre-test with the null hypothesis of the Cobb-Douglas as the correct functional form could not be rejected.[9]

Given differences in the available variables for the two unbalanced panels, two different stochastic production frontiers were estimated. Using the 1990–1996 data, the inputs into the harvesting process can be specified as flows with the exception of a proxy for trawling capacity proxied by headrope length. For the 1994–2000 data, the number of variables is more restricted and, with the exception of the number of fishing days, is limited to the levels of capital variables that includes engine power and headrope length.

For the 1990–1996 data set, the estimated stochastic production function is given below,[10]

$$\begin{aligned}\ln Y_{it} &= \beta_0 + \beta_1 \ln \mathsf{crew}_{it} + \beta_2 \ln \mathsf{effort}_{it} + \beta_3 \ln \mathsf{gear}_{it} + \beta_4 \ln \mathsf{fuel}_{it} + \\ &\quad \beta_5 d90 + \beta_6 d92 + \beta_7 d94 + \beta_8 T + v_{it} - u_{it} \qquad (5)\end{aligned}$$

where Y_{it} is the output of banana prawns by observation i in period t, crew is number of persons 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). Gear is the vessel's head-rope length and is a measure of trawling capacity. The variables $d90$, $d92$ and $d94$ are year-dummies for 1990, 1992 and 1994 to account for weather related anomalies that represent years of abnormally low rainfall prior to harvest which reduces the fishing stock of prawns.[11] The time trend given by T captures non-specific effects on harvest because there is no data available on current stock abundance (or recruitment) to include as an input in equation (5), although weather-dummies clearly account for some changes in fishery recruitment.[12]

A specific measure of capital, such as A-units, is not included because fishing days already embody a certain degree of capital (and other materials), there is evidence that fuel expenditures are strictly related to engine (and vessel) size and power (see NPFAMP, 2000) and because we wish to ensure inputs are represented as a flow of services.[13] In this set up, crew labour services are assumed to be proportional to crew size.

Using the 1994–2000 data, the estimated stochastic production function is given by,

$$\begin{aligned} \ln Y_{it} &= \beta_0 + \beta_1 \ln \mathsf{effort}_{it} + \beta_2 \ln \mathsf{engine}_{it} + \beta_3 \ln \mathsf{gear}_{it} + \\ &\quad \beta_4 d94 + \beta_5 d00 + \beta_6 T + v_{it} - u_{it} \end{aligned} \tag{6}$$

where engine is defined as kilowatts of power and year dummies for 1994 and 2000 are included for weather anomalies.

The vessel-specific factors in the technical inefficiency distribution parameter, using the 1990–1996 data are A-units, gear length and the binary variable skipper given below,

$$\mu_{it} = \delta_0 + \delta_1 \mathsf{A} - \mathsf{units} + \delta_2 \mathsf{gear} + \delta_3 \mathsf{skipper} + \omega_{it} \tag{7}$$

where the ω_{it} is an error term to account for random differences in efficiency across vessels and the absence of a skipper (one) designates an owner-operator (zero). For the 1994-2000 data, the technical inefficiency model is given by,

$$\mu_{it} = \delta_0 + \delta_1 \mathsf{gear} + \delta_2 \mathsf{hullunits} + \delta_3 \mathsf{effort} + \delta_4 \mathsf{engine} + \omega_{it} \tag{8}$$

where hull units are measured in cubic metres and A-units correspond to the sum of hull units and engine power.

Gear can be included in both equations (5) and (7) and (6) and (8), and effort and engine power in both (6) and (8) provided that technical inefficiency effects are stochastic (see Battese and Coelli, 1995).[14]

Hypothesis tests for the stochastic frontiers and the inefficiency models are summarised in tables 3a and 3b and represent generalized likelihood ratio (LR) tests. The null hypothesis of no time trend in equations (5) and (6) is rejected. The null hypothesis that technical inefficiency effects are absent ($\gamma = 0$ and $\delta_i = 0$ for all i) and that vessel-specific effects do not influence technical inefficiencies ($\delta_i = 0$ for all $i > 0$) in equations (7) and (8) are both rejected, as is $\delta_i = 0$ for all i. The null hypothesis that $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2) = 0$ in (5) and (6), or that inefficiency effects are not stochastic, is also rejected. Thus the results indicate that for the two estimated models for 1990–1996 and 1994–2000 that stochastic effects and technical inefficiency are important factors explaining vessel performance.

5 Empirical Results

Maximum likelihood estimates of the model were obtained using FRONTIER 4.1 (Coelli, 1996).[15] The program itself follows a three-step procedure. OLS estimates are first obtained and then a grid search is used to evaluate 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 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 using 1990-1996 data (equations (5) and (7)) are reported in table 4a while results using the 1994-2000 data (equations (6) and (8)) are given in table 4b. All input variables for the stochastic frontier production function in table 4a are significant at the 10% level with the exception of crew size. All inputs in the stochastic production frontier in table 4b are significant at the 1% level.

Given the fecundity and short-lived nature of prawns managers of the NPF have assumed 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 (Staples and Maliel, 1994). Nevertheless, recent catches below expectations have generated concern by the regulator that stock size may be falling. The estimates presented in tables 4a and 4b lend some support to this concern. After allowing for weather effects, the time trend for the catch of banana prawns is highly significant for both (5) and (6), indicating a 5% and 8% negative growth rate in output over the period 1990–1996 and 1994–2000. This decline is suggestive of a declining resource stock and is robust to alternative specifications of the models.

Results for the technical inefficiency model indicate that A-units and gear length are both significant at the 5% level for the 1990-1996 data, but the variable skipper is not. A-units have a significant negative effect on technical inefficiency or a *positive* effect on technical efficiency while gear length has a *negative* effect on technical efficiency. The results are similar using the 1994-2000 data where the components of A-units, hull units and engine power are both significant and negative implying they have a *positive* effect on technical efficiency. Fishing effort, defined as the number of fishing days, also has a significant and positive effect on technical efficiency while the head-rope gear length has a significant and *negative* effect on technical efficiency. For both (5) and (6) the value of $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ exceeds 0.80 and is significant at the 1% level—implying that a substantial proportion of the variation across vessels in both periods is due to technical inefficiency.

5.1 Efficiency Effects

Figures 1a and 1b depict average (over all vessels) annual output and estimated frontier output for banana prawns in the sample. The figures illustrate the decline in mean technical efficiency over the two samples. The low values for average annual output in figure 1a for the years 1990, 1992 and 1994 conforms with the results on weather-dummy variables in Table 4a. All coefficient values for these years are negative, relatively large in magnitude and highly significant. A similar result is found in figure 1b for the years 1994 and 2000 suggesting that weather effects are important explanatory variables in banana prawn production. In other words, weather-dummies in the stochastic production frontiers given by equations (5) and (6), condition 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 from equation (5) and for 1994 and 2000 from equation (6).

Both data sets provide similar levels of mean technical efficiency of 0.725 and 0.774 for the periods 1990-1996 and 1994-2000. Very few boats in either data set have technical efficiencies in excess of 0.90 and most vessels lie in the range 0.61–0.80. More importantly, in terms of the effects of input controls, is the decline in mean technical efficiency over the sample periods. Given the estimated results for technical inefficiency in table 4A (an *increase* in A-units will increase technical efficiency while an increase in gear length will *decrease* technical efficency), 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). In turn, this has led to an unintended increase in a non-regulated input—gear length—that has reduced technical efficiency.

The deleterious effects of A-unit controls is supported by the results using the 1994-2000 data for the entire fleet. Technical efficiency trends downwards over this period falling from 75.1% in 1994 to 68.2% in 2000. Moreover, technical efficiency is, on average, lower the smaller the A-units of vessels, as shown in table 5. In addition, the average A-units per vessel fell through the 1990-1996 period that coincides with the buy-backs and *pro rata* reductions instituted by the fisheries regulator. In other words, attempts to control fishing capital in the fishery by reducing A-units has prevented fishers from increasing their technical efficiency.

Following the reductions in the controlled input (A-units), it also appears that fishers have substituted engine power and hull size for increased gear head-rope length. For instance, in every year from 1993 the average head-rope length has risen and rose from 23.12 meters in 1993 to 26.06 meters in 2000. Thus, regulatory imposed restrictions on A-units prevented fishers from increasing technical efficiency while input substitution to unregulated gear has had the effect of reducing technical efficiency. Combined, the input regulations have resulted in increased fishing power for the fleet over the 1990-2000 period, but reduced technical efficiency.

6 Input Controls and Efficiency

The notion that input controls can result in substitution was observed by Wilen (1979) a quarter of century ago. Subsequently, empirical studies using data from the New England otter trawl fishery (Squires 1987), VIII division of the European anchovy fishery (Del Valle, Astorkiza and Astorkiza 2003), the British Columbia salmon fishery (Dupont 1991), Tasmanian rock lobster fishery (Campbell 1991) and the English beam trawl fishery (Pascoe and Robinson 1998), among others, have shown the ability of fishers to substitute among inputs. In the case of the British Columbia salmon fishery, input controls and limited entry have resulted in rent dissipation (Dupont 1990) and there is evidence this has contributed to stagnation in productivity growth in the New England groundfish fishery over the period 1983–1993 (Jin *et al.* 2002). Pascoe and Robinson (1998) have also shown that restrictions on engine size on vessels in inshore waters provided an incentive for vessels of a certain size to change their fishing location.

Two important studies that have focused on technical efficiency and regulatory structure in fisheries include Kirkley, Squires and Strand (1995) and Pascoe and Coglan (2002). The former study used data from ten vessels over the period 1987–1990 to predict the impact of limited entry and input restrictions on the mid-Atlantic sea scallop fishery. They found that restrictions on crew size and an annual days-at-sea limit could increase average technical efficiency while restrictions on dredge size would leave technical efficiency unaffected. Pascoe and Coglan (2002) find that unmeasurable inputs in the form of differences in skipper and crew skill explain a substantial part of the variation in technical efficency across vessels. They also observe that limits on days-at-sea, or other means to limit fishing effort, may be circumvented by improvements in skipper competency.

The results from the NPF, however, are the first to show that average technical efficiency was directly *constrained* by input controls (A-units) and that technical efficiency *declined* due to input substitution (to gear headrope length). The study provides convincing evidence of the potentially negative effects of input controls on technical efficiency, even in the absence of input substitution, and the necessity for testing the influence of inputs on vessel-level performance. In general, the findings support alternative forms of regulation, such as individual output controls or a mix of input and output controls, that permit fishers to choose their input mix and levels while maintaining the sustainability of stocks.

7 Concluding Remarks

The paper provides the first ever *ex-post* estimates of the effects on technical efficiency of input controls in a fishery. Using individual vessel data from the northern prawn fishery of Australia for the years 1990–1996 and 1994–2000, a stochastic production frontier is estimated to analyse the efficiency impacts of input controls on vessel capacity (engine and vessel size).

The results indicate that technical efficiency depends *negatively* on an unregulated input, gear headrope length, but *positively* on a measure of vessel size and engine power that is used to control fishing effort. This finding is significant because restrictions over vessel size and engine power were used in the fishery during the 1990–2000 period to reduce fishing effort so as to prevent overharvesting.

The study is important because it shows that the substitution to unregulated inputs (gear headrope length) from regulated inputs (vessel size and engine power) has contributed to a decline in overall technical efficiency. It suggests that the use of input controls, especially limits on engine and hull size, have been contrary to the stated objective of the fishery regulator to maximise economic efficiency. In general, the paper finds that fishery managers need to pay particular attention to the inputs that are controlled, and to the possibilities of input substitution and their effects on technical efficency when regulating a fishery. An important implication is that if economic efficiency is a goal of fisheries management then alternatives to input controls, such as individual transferable quotas or a mix of input and individual output controls, are worthy of consideration.

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End Notes:

1. Alam, Omar and Squires (2002) analyse the issue of licence limitation, especially area licences, in the context of tropical fisheries.

2. A classic survey of the evidence is provided by Townsend (1990).

3. The first empirical measures of input substitution in fisheries using flexible functional forms was by Squires (1987). Empirical studies that have assessed the impact of input controls have measured the level of input substitution and rent dissipation (Dupont 1991), input substitution from regulated to unregulated inputs (Campbell 1991; Del Valle, Astorkiza and Astorkiza 2003) and the contribution of unmeasurable inputs to efficiency (Pascoe and Coglan 2002).

4. We are prevented from estimating allocative efficiency in this fishery because of lack of data on input prices. We note that technical efficiency is necessary, but not sufficient, to ensure economic efficiency.

5. Green (1993) and Forsund, Lovell and Schmidt (1980) are useful surveys of the stochastic frontier approach. Kumbhakar and Knox Lovell (2000) is also highly recommended.

6. This is especially true for tiger prawns, but the tiger and banana prawns fisheries are treated as a single fishery for management purposes.

7. For the specifications in section 4, likelihood ratio tests (not reported) reject a time trend in the technical inefficiency model, so the effect is ignored here.

8. See NPFAMP (2000). Fuel is related to engine power and to a lesser extent to vessel size. 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 fuel expenditures by effort days in banana prawn production as a fraction of total effort days in banana and tiger prawn production.

9. Results from the translog and the pretest are available from the authors upon request. It should also be noted that although the translog allows more scope for substitution, the input restrictions used in the NPF make conventional measures of elasticities of substitution inappropriate (Dupont, 1991).

10. Equation (5) 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 labor 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 identically and independently distributed technical inefficiency effects.

11. 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, 3550 millimeters compared to average for all other years in the sample period of 4550 millimeters.

12. The specification given by (5) 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. Managers at AFMA also believe that there has been a downward trend in the stock of prawns over the 1990s, but do not have the data to test their hypothesis.

13. A-units and fuel expenditures (which are known to vary by engine size and power) are correlated and thus both variables are not included together. Nevertheless, replacing fuel with A-units gives comparable final estimates in all cases.

14. Diagnostic tests, available from the authors, also indicate that if the input variables are included in levels in equations (7) and (8), there is no specification error.

15. Identical estimates were also obtained using GAUSS. The GAUSS program was also used to derive diagnostic tests.

Table 1a: Description of inputs and vessel specific variables 1990-1996 data

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 metre 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 (metres)	CSIRO
• Boat size	Vessel length (metres)	CSIRO
• Skipper	Hired skipper (1), owner-operated vessel (0)	CSIRO
• Banana prawn output	Banana prawns (kilograms)	ABARE

Table 1b: Description of inputs and vessel specific variables 1994-2000 data

Variables	Description
• Output	Output of banana prawn (kg)
• Fishing effort	Nominal fishing days for banana prawns (days)
• Hull units	Under deck tonnage
• Engine power	Registered engine power (kw)
• Vessel A-unit	The sum of one A-unit for every cubic metre of hull volume and one A-unit for each kilowatt of engine power
• Gear length	Headrope length of gear (metres)
• Boat size	Vessel length (metres)

Source: CSIRO

Table 2a: Summary statistics for key variables for banana prawns in the Northern Prawn Fishery (1990-1996 data)

		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 CSIRO*

Table 2b: Summary statistics for key variables for banana prawns in the Northern Prawn Fishery (1994-2000 data)

		Average	Stdev	Min	Max
• Output	*kg/year*	29 074	65 486	372	125 390
• Fishing effort	*days*	40	68	1	134
• Hull units		108	77	26	179
• Engine power	*kw*	309	216	95	526
• Vessel A-unit	*A-units*	418	292	121	705
• Boat size	*meters*	21.7	8.5	12.8	29.8
• Gear length	*meters*	25.4	4.2	14.0	36.0

Source: *Constructed from statistics by CSIRO*

Table 3a: Generalised likelihood ratio tests of hypotheses for parameters of the stochastic production frontier and technical inefficiency models (equations (5) and (7)) using 1990-1996 data

Null hypothesis	χ^2-statistic	$\chi^2_{0.95}$-value	Decision
No time trend in equation (7)	6.66	2.70	fail to reject H_0
$\gamma=\delta_0=\delta_1=\delta_2=\delta_3=0$	15.24	10.37	reject H_0
$\gamma=0$	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 3b: Generalised likelihood ratio tests of hypotheses for parameters of the stochastic production frontier and technical inefficiency models (equations (6) and (8)) using 1994-2000 data

Null hypothesis	χ^2-statistic	$\chi^2_{0.95}$-value	Decision
No time trend in equation (8)	8.43	3.86	fail to reject H_0
$\gamma=\delta_0=\delta_1=\delta_2=\delta_3=\delta_4=0$	117.76	12.59	reject H_0
$\gamma=0$	20.48	2.7	reject H_0
$\delta_0=\delta_1=\delta_2=\delta_3=\delta_4=0$	187.9	11.07	reject H_0
$\delta_1=\delta_2=\delta_3=\delta_4=0$	111.44	9.49	reject H_0

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

Table 4a: Parameter estimates of the stochastic production frontier and technical inefficiency models (equations (5) and (7)) using 1990-1996 data

	Coefficient	Asymptotic T-ratio
Stochastic production frontier		
Constant	6.42*** *(0.97)*	6.59
Crew	-0.10 *(0.19)*	0.51
Effort	0.38*** *(0.15)*	2.40
Gear length	0.20* *(0.11)*	1.88
Fuel	0.27** *(0.13)*	2.18
Time trend	-0.05** *(-0.02)*	2.24
Year 1990	-0.62*** *(0.13)*	4.87
Year 1992	-0.57*** *(0.10)*	5.90
Year 1994	-0.62*** *(0.09)*	6.84
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	
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.*

Table 4b: Parameter estimates of the stochastic production frontier and technical inefficiency models (equations (6) and (8)) using 1994-2000 data.

	Coefficient	Asymptotic T-ratio
Stochastic production frontier		
Constant	5.09*** *(0.42)*	11.99
Effort	0.74*** *(0.03)*	27.03
Engine power	0.25*** *(0.09)*	2.72
Head rope length of gear	0.62*** *(0.13)*	4.82
Year 1994	-0.85*** *(0.04)*	19.78
Year 2000	-0.13*** *(0.05)*	8.96
Time trend	-0.08*** *(0.01)*	8.96
Technical inefficiency model		
Constant	14.74*** *(3.76)*	3.91
Head rope length of gear	3.00* *(1.60)*	1.88
Hull units	-1.96*** *(0.58)*	2.23
Fishing effort	-1.64*** *(0.47)*	3.46
Engine power	-1.78*** *(0.78)*	2.26
Sigma-squared	0.82*** *(0.28)*	2.90
Gamma	0.93*** *(0.03)*	34.54
Ln (likelihood)	310.33	
Mean Technical Efficiency	0.774	

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 5: Size of boat and average technical efficiency (equations (6) and (8)) using 1994-2000 data

A-Units	TE	No of observations
Less than 375	0.62	234
From 375 to 475	0.79	408
Greater than 475	0.81	207

Figure 1a: Average annual output (kg) and frontier output (equations (5) and (7)) for banana prawns using 1990-1996 data

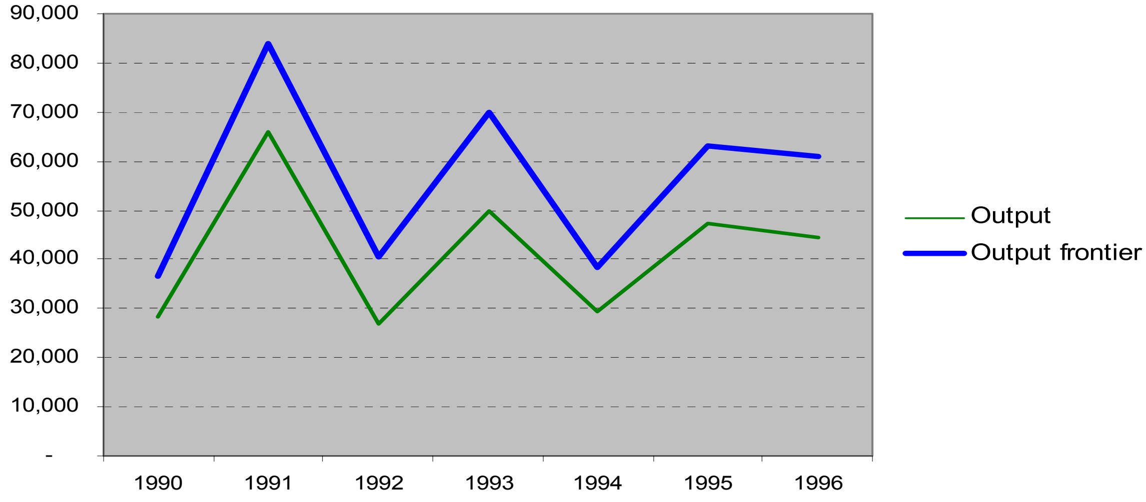

Figure 1b: Actual annual output (tons) and frontier output (equations (6) and (8)) for banana prawns using 1994-2000 data