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Measuring environmental-economic efficiency in the Karapiro catchment, New Zealand

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Abstract: New Zealand's success in raising agricultural productivity has been accompanied by higher input use, leading to adverse effects on the environment. Until recently, analysis of farm performance has tended to ignore such negative externalities. However the current emphasis on environmental issues has led dairy farmers to target improvements in both environmental performance and productivity. Therefore measuring the environmental performance of farms and integrating this information into farm productivity calculations should assist informed policy decisions which promote sustainable development.

Nitrogen discharge from dairy farming is major source of nonpoint pollution in the Karapiro catchment. Incorporating farm nitrogen discharges into farm production measures helps to identify farms which are efficient both economically and environmentally. However this is a challenging process since conventional environmental efficiency measures are usually based on simple input and output flows but nitrogen discharge is a complex process which depends on climate variability, pasture and cow physiology and geophysical variability. Furthermore the outdoor, pastoral nature of New Zealand farming means that it is difficult to control input and output flows, particularly of nitrogen.

Therefore this paper proposes a novel approach to measure environmental and economic efficiency of dairy farms using a spatially micro-simulated virtual population data. The methodology used for empirical analysis is a two stage process. The first stage involves solving a data envelopment analysis (DEA) problem. In the second stage, the efficiency scores from the first stage are regressed on other explanatory variables using the maximum likelihood approach.

Technical, economic, environmental and combined efficiency are measured. Achieving environmental efficiency costs on average $757 per ha. Moving from an economically efficient nitrogen discharge level to an environmentally efficient discharge level reduces the mean nitrogen discharge by 38 percent. Analysis of environmental efficiency variation suggests that 44 percent of the variation is explained by topography, cow production potential, stocking rate and feeding practices. Given the cross sectional nature of the data, the fit can be considered reasonable.

These environmental-economic efficiency measures should not be directly interpreted as representing the amount of environmental harm caused by farms, since the location of farms in relation to a water body may influence the damage to the water body. In addition, some farms could be taking measures to abate nitrogen discharges through the adoption of best management practices such as nitrification inhibitors and winter stand-off pads. Therefore an extension of the model to incorporate these could be of interest. Given adequate data, this approach can be extended to analyse other environmental issues such as agricultural greenhouse gas emissions.

Keywords: *Data Envelopment Analysis, Economic, Efficiency, Environment*

1. INTRODUCTION

Measuring the environmental performance of dairy farms and integrating this information into farm productivity calculations is important for informed policy decisions which promote sustainable development. To date, analysis of dairy farm performance in New Zealand has ignored undesirable effects on the environment (Jaforullah & Whiteman, 1999; Neal, 2004). This study incorporates farm nitrogen discharges into farm production measures to identify farms which are efficient economically and environmentally. Efficient farms can be used to benchmark progress and help in the design of policy that promotes farm efficiency sustainably.

2. METHOD OF ANALYSIS

This paper proposes a novel approach to measure environmental and economic efficiency of dairy farms using spatially micro-simulated virtual population data. The methodology used for empirical analysis is a two stage process. The first stage involves solving a data envelopment analysis (DEA) problem. In the second stage, the efficiency scores from the first stage are regressed on other explanatory variables using the maximum likelihood approach to identify the reasons for differences in performance.

DEA has been used in many studies to analyse environmental oriented efficiencies (Coelli, Lauwers, & Van Huylenbroeck, 2007; Fare, Grosskopf, & Pasurka Jr, 2007; Tyteca, 1996; Wossink & Denaux, 2006). It does not require the assumption of functional form to specify the relationship between inputs and outputs and the distributional assumption of the inefficiency term. This avoids unnecessary restrictions about functional form, which are likely to distort efficiency measures (Coelli, 1995). The approach can, however, be criticised for not accounting for the possible influence of measurement error and other noise in the data (Coelli, Rao, O'Donnell, & Battese, 2005). Since a virtual population of farms is used to construct the frontier in this study, it is not necessary to consider sampling variability - the data can be considered to be noise free. In fact, in this study efficiency is measured rather than estimated.

3. MODELLING ENVIRONMENTAL PERFORMANCE

The incorporation of environmental impact information into production process analysis provides an opportunity to measure environmental performance and changes in performance under environmental constraints. Environmental effects are often brought into the model as either undesirable outputs or undesirable inputs. In recent literature two novel approaches have been adopted. One approach (Coelli, Lauwers, & Van Huylenbroeck, 2007) uses the concept of nutrient surplus to derive environmental efficiency in agricultural applications. Nutrient surplus is simply calculated as a linear function of input and output using the material balance concept. When output is fixed, nutrient surplus is minimized by decreasing the nutrient content in the inputs. In the second approach (Asmild & Hougaard, 2006), enhancing the nutrient content of the output is modelled as a mean of minimizing nutrient into environment. It measured economic and environmental efficiency by incorporating economic output variables along with the nutrient content of the output in the output matrix. Since the nutrient content of the output is an extra variable, it is likely to suffer from the dimensionality problem as increasing the number of variables inflates the efficiency.

The applications of environmental efficiency measures described above rely on simple input and output flow. However, the environmental impact of New Zealand dairy farms on water quality is a complex process which depends on climate variability, pasture and cow physiology and geophysical variability. In addition to this, the outdoor, pastoral nature of New Zealand farming means that it is difficult to control input and output flows, particularly of nitrogen. The measurement of environmental efficiency in this paper combines the merits of the efficiency measures described by Renihard et al (2000), Asmild & Hougaard (2006) and Coelli et al (2007) in order to apply to New Zealand farming context.

In this study farm nitrogen discharges are modelled with the following function:

$$z = f(Fertiliser\,N, StockingRate, Feed, Soiltype, Topography) \qquad (1)$$

where *z*- indicates the nitrogen discharge per ha. To estimate nitrogen discharges, the Overseer nutrient budget software (V5.3.1) is used. In calculating nitrogen discharges, winter management and effluent disposal practices are assumed to be on a par with industry recommendations, and an average rainfall of 1100 mm for the Waikato region is used. Input oriented approaches are useful in situations where the environmental focus is on reducing pollution while maintaining production (Wossink & Denaux, 2006). The mathematical formulation for input oriented *technical efficiency* under variable returns to scale. *z* is the vector nitrogen discharge. This formulation computes input oriented technical efficiency as the ability of a farm to reduce input, including nitrogen discharges, for a given level of output.

$$Min_{\theta,\lambda}\theta \text{ subject to } -q_j+Q\lambda\geq 0,\ \theta x_j - X\lambda \geq 0\ ,\ \theta z_j - Z\lambda = 0 \text{ and } \lambda \geq 0 \qquad (2)$$

Economic efficiency is formulated as the ability to minimize farm expenses (x^*) for a given level of other variables. The mathematical formulation is similar to Equation 3. It is measured as the ratio of minimum cost to observed cost.

$$Min_{\lambda,x_i^*} c_i x_i^* \text{ subject to } -q_j+Q\lambda\geq 0,\ x_j^* - X\lambda \geq 0,\ z_j - Z\lambda = 0 \text{ and } \lambda \geq 0 \qquad (3)$$

Environmental efficiency is defined as the ratio of minimum nitrogen discharge to observed nitrogen discharge, conditional on observed levels of the desirable output and the conventional inputs. This is achieved by minimizing the nitrogen discharge for a given level of output and other conventional inputs.

$$Min_{\theta,\lambda}\theta \text{ subject to } -q_j+Q\lambda\geq 0,\ x_j - X\lambda \geq 0,\ \theta z_j - Z\lambda = 0 \text{ and } \lambda \geq 0 \qquad (4)$$

Environmental–economic efficiency is modeled as minimizing nitrogen discharge and farm expenses simultaneously, given output level and other inputs. This overcomes the dimensionality problem in Ashmild's approach,

$$Min_{\theta,\lambda}\theta \text{ subject to } -q_i+Q\lambda\geq 0,\ \theta x - X\lambda \geq 0,\ \theta z_j - Z\lambda = 0,\ \lambda \geq 0 \qquad (5)$$

A two stage process is adopted to model economic improvements and then environmental improvement. In the first stage, economic improvement potential is calculated by maximizing the farm income for a given level of other inputs including nitrogen discharges. Farm income is derived by multiplying milksolids produced by the payout received. The output orientation is used as it is easy to get the estimates for the subsequent stage, where economic efficiency is followed by environmental efficiency.

$$Max\ \theta \text{ subject to } -\theta(p*q_i)+Q\lambda\geq 0\ ,\ x - X\lambda \geq 0\ ,\ z_i - Z\lambda = 0 \text{ and } \lambda \geq 0 \qquad (6)$$

Farms are first made economically efficient through multiplying economic output (farm income) by economic efficiency scores. Then in the second step the environmental efficiency is derived using economically efficient output, similar to that specified in Equation 6. Finally, two the step analysis carried out perform environmental improvements followed by economic improvement here farms are first made environmentally efficient by using the environmental efficiency scores. Then in the second step economic efficiency is derived using adjusted environmental output.

The above DEA efficiency measures are calculated using an open source software package, FEAR (Version 1.1) by Wilson (2008). It is implemented on R, which is a language and environment for statistical computing and graphics. The routines included in FEAR 1.1 allow computation of DEA estimates of technical, allocative and overall efficiency while assuming either variable, non increasing, or constant returns to scale.

Analysis of environmental efficiency variation

Environmental efficiency is affected by many factors such as management, input use, topography, and soil type. Tobit regression using the maximum likelihood approach is used for regressing such variables on the efficiency estimates. This two stage approach was preferred for a number of reasons: its ability to accommodate multiple continuous and categorical variables; the requirement of no prior assumptions regarding the direction of influence of environmental variable and statistical inference on the influence upon efficiencies; computational convenience and transparency.

The explanatory model can then be written as Equation 7

$$Y^* = X\ \beta + \mu \qquad (7)$$

where *Y* is a DEA efficiency score, rescaled between 0 and 100, and used as a dependent variable. *X* is a vector of independent variables related to farm specific attributes. β is the unknown parameter vector associated with the farm specific attributes, and μ_i is an independently distributed error term assumed to be normally distributed with 0 mean and constant variance, σ^2. Tobit regression is implemented in Stata 10 (StataCorp., 2007).

4. EMPIRICAL ANALYSIS

The data used in this study consists of 210 virtual farms in the catchment. Physical and financial farm variables and estimated nitrogen discharges are used for analysis. In the Waikato 90% of farm revenue on average is derived from the sale of milksolids, according to the DairyNZ's Economic Farm Survey for 2003/04 and 2004/05, It is reasonable therefore to treat milksolids as the sole economic output of the farms. Given the virtual nature of the data, particular care was taken in the selection and definition of variables. Land, building and plant and machinery variables were avoided as they may not be representative of the farms in the catchment. Land prices in particular are influenced by location as well as economic productivity, and variations in plant and machinery are affected by the particular type in use. The economic farm surplus variable was not used, as depreciation, labour, runoff and stock may not be applicable to the virtual population.

The choice of variables has to be limited to avoid the problems of dimensionality that can affect DEA analysis. Due to the nature of the technique the number of model variables may affect DEA results. DEA efficiency rating depends on the number of farms and the number of inputs and outputs specified (Ondersteijn, Lansink, Giesen, & Huirne, 2002). Adding more model variables for a given sample size can yield higher efficiency scores for units in the sample. However, omitting necessary input or output may lead to misspecification of the production model. Therefore various inputs belonging to the same category and measured in the same physical units have been aggregated. Major types of supplementary feeds were aggregated using the energy content of the major ingredient in terms of Megajoules. Farm expenses are specified by aggregating variable and fixed costs. Farm expenses defined here are on average less than 20 percent of the average farm expenses reported in the Economic Farm Survey of Dairy Farms. This is due to the exclusion of some variables which would have been difficult to assign to farms in a virtual population. For the same reason dairy farm income also excludes other dairy income and net stock income.

Table 1 presents summary statistics of the variables for farms used in the efficiency analysis. Table 2 lists the variables used in the regression analysis. The geophysical environment which is likely to affect the nitrogen discharges is represented by dummies for soil type and topography. These dummy variables categories were merged into larger groups when there were only a small number of observations in a category, and they were similar in terms of nitrogen discharge potential. The market value of cows was used as a proxy for genetic merit and resultant feed conversion efficiency. It was assumed that the market value of stock included only the milking cows.

Table 1 Descriptive statistics of the data used in the efficiency analysis

Variable	Units	Mean	Stdev	Minimum	Maximum
Milksolids	Kg	97,870	52,699	30,891	350,957
Farm size	Ha	107	63	26	570
Milking cows	No	284	167	99	1200
Nitrogen discharge	Kg	4133	2606	836	21090
Farm expenses	$	260,560	141,851	82,607	855,459
Farm income	$	434,541	233,982	137,155	1,558,249

Table 2 Explanatory variables used in Tobit regression

Variable	Units	Mean	Stdev	Minimum	Maximum
Maize silage/cow	Tones	0.21	0.29	0.00	1.33
Market value/cow	$	989.00	158.50	491.00	1224.49
Milksolids per cow	No	351.07	45.46	246.37	464.49
Stocking rate	Kg	2.72	0.48	1.80	4.51
Fertiliser nitrogen	$	135.22	64.00	20.00	290.00
Geo-physical variables *Podzol –rolling, Volcanic –easy, Pumice-rolling, Pumice-easy*					

5. RESULTS AND DISCUSSION

Scale efficiency of farms was examined in terms of technical efficiency. The mean scale efficiency was 0.96, so farms are considered to face constant returns to scale. New Zealand dairy farms are characterised by constant returns to scale in other studies as well (Jaforullah & Whiteman, 1999; Neal, 2004). Therefore constant returns to scale are assumed in estimating the final model specification.

Table 3 DEA efficiency scores

Efficiency measure	*Efficient farms*	*Mean*	*Stdev*	*Min*	*Max*
Technical efficiency	16	0.82	0.09	0.57	1.00
Economic efficiency	13	0.72	0.13	0.49	1.00
Environmental efficiency	3	0.64	0.12	0.42	1.00
Environmental-economic efficiency	12	0.80	0.11	0.55	1.00
Economic efficiency followed by environmental efficiency	19	0.75	0.10	0.57	1.00
Environmental efficiency followed by economic efficiency	10	0.78	0.08	0.67	1.00
Allocative efficiency	5	0.89	0.19	0.41	1.00

Figure1 shows the frequency distributions of the different efficiency measures. Approximately 80 percent of farms achieved less than 80 percent environmental efficiency. In contrast, more than 60 percent of farms achieved more than 80 percent technical efficiency. Environmental-economic efficiency seems to be similar to technical efficiency.

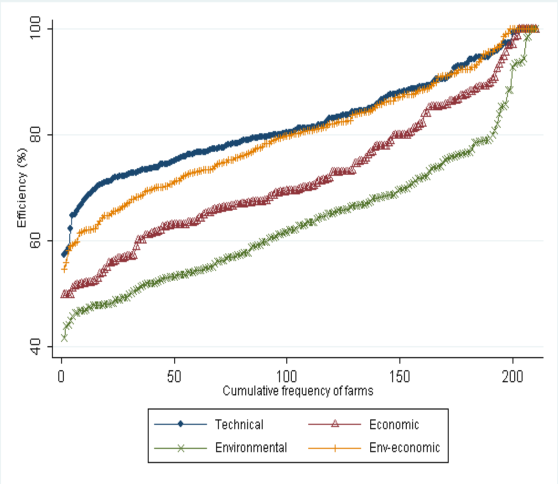

Figure 1 Cumulative distribution of efficiency

Efficiency measures are computed according to DEA models specified in Equations 1 to 6. The results are summarized in Table 3. Substantial differences are found in efficiencies among farms. The average level of technical efficiency of 0.82 means that in principle the farms can reduce their input use by 1- 0.82 (18 percent) and still maintain the existing level of output. In effect, the level of output can be enhanced by keeping the level of inputs constant. However, the perceptions of risk and the skill level of farmers might have an impact on their ability and desire to achieve this sort of efficiency. The measure of technical efficiency found here is similar to the technical efficiency of dairy farms (0.83) estimated by Jaforullah & Whiteman in 1999. Mean economic efficiency of 0.72 suggests that the average farm could reduce costs by 28 percent and still produce the same output. This economic efficiency is largely the result of technical inefficiency. The mean allocative efficiency is quite high, at 0.89. This suggests that most farms are using an input mix that approximates the cost minimizing the input mix. The high mean allocative efficiency scores are most likely due to the production technology, which is well known and adopted by farms (Coelli et al, 2007).

The DEA results indicate the potential for very significant nitrogen discharge reduction in dairy farming, without any need to find extra and expensive new technologies for pollution reduction. However, there is a cost associated with operating at the emission minimizing point. Table 4 shows average nitrogen discharge and expenditure in relation to economic and environmental efficiency. Achieving environmental efficiency costs on average \$757 per ha. Moving from an economically efficient nitrogen discharge level to an environmentally efficient discharge level reduces the mean nitrogen discharge by 38 percent. This information can be used to determine the shadow cost, which is (2534-1777)/(39-24)= \$50.50 per kg for this nitrogen discharge reduction. Appropriate environmental policies may be required in order to move farms towards an environmentally efficient point.

Table 4 Average nitrogen discharge and expenditure for economic and environmental efficiency

	Economic efficiency	*Environmental efficiency*
Nitrogen discharge (kg/ha)	39	24
Farm expenses ($/ha)	1777	25340

Environmental efficiency variation

Factors affecting environmental efficiency are shown in Table 5. The pseudo R^2 of 0.068 reported may not be the best measure of fit, so R^2 is based on predicted and observed efficiency values. The calculated value is 0.44, which is similar to OLS R^2. The model, therefore, explains 44 percent of the variation. Given the cross sectional nature of the data, the fit can be considered reasonable. As might be expected, stocking rate has a negative and significant effect on environmental efficiency, indicating that lowering the stocking rate has the potential to significantly improve environmental efficiency. The effect of the production potential of each dairy cow is positive but not significant, which may simply reflect that there is little variation in production potential. The market value of cows has been used as a proxy for breed quality and seems to have a slight positive effect on efficiency. Reinhard, Lovell, & Thijssen (2002) also showed that a more productive breed of cows could contribute to environmental efficiency by reducing the stocking rate and increasing the feed conversion efficiency. Maize silage has a positive effect on efficiency but it is not significant, which may be due to low levels of usage (on average 0.2 tons per head). According to farm trials feeding maize silage tends to reduce nitrogen discharge by 10 percent because of a higher conversion of nitrogen to milk in low protein supplementary feed (Ledgard, Penno, & Sporsen, 1999). There are concerns over feeding maize silage, however, because feed cost is higher and there are additional nitrogen discharges from growing the extra maize. The Podzol soil group is used as the base to interpret the coefficients on the dummy variables. It is represented by the regression intercept. The estimates on the three dummy variables thus measure the proportionate difference in environmental efficiency in relation to Podzols. The effect of pumice soil on environmental efficiency is significant and negative, since pumice soils are prone to nitrogen leaching. However, the negative impact of volcanic and Podzol soils is less pronounced than with pumice soils, showing the importance of considering geophysical variations when designing policies for water quality improvement.

Table 5 Parameter estimates for environmental efficiency

Variables	Estimate	Standard error	t-value	p-value
Intercept	85.45	8.57	9.97	0.000
Production environment				
Maize silage/cow	0.61	2.74	0.22	0.82
Market value/cow	0.02	0.01	3.34	0.01
Milksolids per cow	-0.01	0.01	-0.77	0.44
Stocking rate	-4.39	1.51	-2.92	0.00
Physical environment				
Dummy variables				
Volcanic-easy*(0.24)+	-17.10	2.77	-6.18	0.00
Volcanic-rolling*(0.18) +	-19.16	2.89	-6.63	0.00
Pumice_rolling*(0.33) +	-25.39	2.69	-9.37	0.00
Pumice_easy* (0.14) +	-25.19	2.97	-8.54	0.00
Ó	10.05	0.50		
Pseudo R^2	0.07	* Podzol- rolling is used as base and captured by the intercept term		
Log-likelihood	-772.12	+ The values in parenthesis behind the dummy variables indicate the percentage of the total observations that are described by each dummy variable.		
Number of observations	210			

6. IMPLICATIONS

This paper presents an analytical framework to measure environmental and economic efficiency. The second stage parameter estimates reflect the impact of variables that can guide policy to improve environmental efficiency. The farms studied are shown to be technically efficient producers, but there is still significant room for improvement in terms of environmental efficiency. In order to realize the environmental improvement potential, it would be useful to identify the characteristics of those farms that are environmentally efficient. Economic efficiency can be viewed as a private good for farms. Environmental efficiency, on the other hand, is a public good, important from a social point of view. It may, therefore, be necessary to provide further incentives through regulatory initiatives (Asmild & Hougaard, 2006).

In the efficiency measurements, it is assumed that farms do not adopt any best management practices. A range of such options are proposed, such as limiting external nitrogen input, increasing nitrogen use efficiency via lower protein feed resources, reducing farm dairy effluent losses, avoiding direct deposition of excreta to land in autumn/winter by using grazing off or feed pad systems or herd homes and nitrification inhibitors. However, these best management practices may need additional inputs such as extra capital for building feed pads or herd homes.

Finally, farm level environmental-economic efficiency scores should not be directly interpreted as representing the amount of environmental harm caused by farms, since the location of farms in relation to a water body may influence the damage to the water body. In addition, some farms could be taking measures to abate pollution through the adoption of best management practices such as using nitrification inhibitors and winter pads. Therefore an extension of the model to incorporate these could be of interest, given ready availability of data on abatement activity.

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