

Assessing dairy farming eco-efficiency in New Zealand: A two-stage data envelopment analysis

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Abstract

The dairy industry is a significant contributor to the New Zealand economy. Improving dairy productivity while meeting appropriate environmental standards is necessary if the New Zealand economy is to grow sustainably. In this paper, a two-stage data envelopment analysis (DEA) technique was employed to assess the combined environmental and economic performance of dairy farms (i.e., eco-efficiency). A sample of 108 farms from a survey carried out in 2011-12 across all regions of New Zealand was used to analyse the eco-efficiency of dairy farms. Survey data on milk solid production was used to estimate economic performance, while data on greenhouse gas (GHG) emissions and nutrient leaching were used to estimate environmental performance. Other information in the survey such as geophysical characteristics and management practices that could indirectly affect the eco-efficiency of the dairy farms was also incorporated in the analysis. In the first stage of our analysis, an eco-efficiency score for each farm was estimated using directional distance function with restrictions in environmental outputs. In the second stage, the effect of the geophysical characteristics and management practices on the calculated eco-efficiency scores were then estimated using an integrated truncated regression and bootstrapping procedure. The results show that, on average, a reduction of 27% in environmental externalities was possible while maintaining the same level of output. GHG emissions, nitrogen leaching, and phosphorous loss were excessive and inefficient. Adopting irrigation and on-farm management practices (e.g., feed-pad, in-shed feeding, and wintering-pad) improved efficiency. The few dairy farms located on hilly or sloped land were found to be less efficient than those on flat land. Environmental policies applied to dairy sector have the potential to reduce GHG emission, nitrogen leaching, and phosphorous loss by 3.45 million tonnes, 20,610 tonnes, and 366 tonnes, respectively.

Keywords

Productivity analysis – Dairy industry – data envelopment analysis – New Zealand

1. Introduction

Enhancing agricultural productivity without eroding natural resources is essential to sustain economic development (Koochafkan et al., 2012). In New Zealand, several studies have shown the environmental consequences of agricultural activity and its effects on social wellbeing (Monaghan et al., 2007; Daigneault et al., 2016; Fernandez & Daigneault, 2017). Public regulatory bodies have established enabling legislation, such as the Resource Management Act 1991 and Climate Change Response Act 2002, to ensure effective management of natural resources and to meet New Zealand's international environmental obligations (MFE, 2017).

Dairy is one of the most important industries in New Zealand. It contributes around \$7.8 billion (3.5%) to New Zealand's total GDP, exports \$13.6 billion worth of products, and employs more than 40,000 individuals (NZIER, 2017). Although the dairy industry plays a vital role in the New Zealand economy, it also generates significant environmental externalities. The percentage of greenhouse gas (GHG) emissions, nitrogen (N) leaching, and phosphorous (P) loss in New Zealand due to dairy farming is estimated at 36.8%, 35%, 11.4%, respectively of NZ's total emissions and nutrient leaching, despite using just 7% of the land area (Daigneault et al., 2016). Environmental pressures that result from the dairy sector economic activities could, therefore, greatly affect surrounding ecosystem services and biodiversity. As such, improving the industry's economic and environmental performance could have a tangible effect on New Zealand's economic growth.

Policies that aim to reduce the environmental impact of dairy production have often focused on pathways that can lead to more efficient use of resources. Obviously, this policy question can be best addressed using the efficiency (frontier) technique (Oude Lansink, 2014). In New Zealand, some studies have analysed the productivity and efficiency of the dairy sector but none of these studies have considered the environmental externalities of the production process. For instance, Jiang and Sharp (2015) employed a stochastic meta-frontier model to assess the technical efficiency and technological gap of New Zealand dairy farming. They also analysed the cost efficiency of dairy farming in New Zealand using a stochastic frontier analysis, SFA (Jiang and Sharp, 2014). Rouse et al. (2009) conducted a two-stage data envelopment analysis (DEA) to estimate the technical and scale efficiency of milk solid production. In the first stage, the efficiency score for each farm was estimated. That was followed, in the second stage, by analysing the impact of several indirect factors, related to climate and farm geophysical characteristics, on efficiency. Jaforullah & Whiteman (1999) and Jaforullah & Premachandra (2003) investigated a methodological approach that compares the accuracy of the estimated efficiency scores of dairy farms using three frontier techniques, namely, corrected ordinary least squares (COLS), SFA and DEA.

The objective of this study is, therefore, to estimate the environmental inefficiency of the dairy sector and to determine its causes. This will help to evaluate current environmental policies and design new policies that aim to reduce environmental pollutants while maintaining the current production level. In section two, the two-stage data envelopment analysis technique that is used to measure inefficiency will be illustrated. In section three, results will be presented, while in section four, policy implications of the analysis will be discussed.

2. Methods

First stage: data envelopment analysis

We assume that the production technology set on a sample datum i is defined by a combination of economic value-added vector $v \in \mathbb{R}_+^M$ of M output dimensions and environmental pollutants $p \in \mathbb{R}_+^K$ of K output dimensions. The technology (T) is given by:

$$T = \{(v, p) \in \mathbb{R}_+^M \times \mathbb{R}_+^K \mid v \text{ can be generated by } p\} \quad (1)$$

The eco-efficiency scores are estimated for each farm i by first identifying the ratio between economic value added and environmental pollutants:

$$\frac{\text{Economic value added}}{\text{Environmental pollutants}} = \frac{v_i}{D(p_i)} \quad (2)$$

The economic value added (v_i) can either be collected in the survey data or estimated from data on the production inputs and outputs, and prices. The environmental pollutant $D(p_i)$ is an integrated measure that is estimated as a weighted average of the pollutants (p_1, \dots, p_k) generated by the production of farm i (Kuosmanen and Kortelainen, 2005). Kuosmanen and Kortelainen (2005) suggested using DEA as an objective weighting technique to avoid any bias in weighting the relative importance of different environmental pollutants. Instead of using the maximization problem to estimate the eco-efficiency scores, the dual formulation (i.e., minimization of eco-efficiency), could be used to avoid the technical complexities of solving the non-linearity present in the maximization problem. As such, the linearization of the reciprocal formulation of the maximization problem could be defined as (Kuosmanen and Kortelainen 2005; Picazo-Tadeo et al. 2011; Urdiales et al., 2016):

$$\text{Minimize Eco-efficiency}_i^{-1}(\theta_i, z_i) = \theta_i'$$

$$\text{Subject to} \quad (3)$$

$$v_i' = \sum_{i=1}^z z_i p_{ki}, \text{ where } k = 1, \dots, K,$$

$$z_i \geq 0, \quad \text{where } i = 1, \dots, N$$

where z_i is the weight that is used to identify the reference point on the eco-efficiency frontier for each farm i . The DEA eco-efficiency score which solves this problem for farm i , θ_i , can be interpreted as the maximum potential proportional reduction in all environmental pressures that could be achieved while maintaining the present level of economic activity. Mathematically, this eco-efficiency score is between 0 and 1, where 1 represents the farms on the frontier.

In addition to the above mentioned (traditional Farrell) eco-efficiency that considers reducing all pollutants proportionally, we also estimated pollutant-specific eco-efficiency which account for slacks of each pollutant. The pollutant-specific eco-efficiency was estimated as follows (Picazo-Tadeo et al. 2011):

$$\text{Pollutant specific eco - efficiency} = \theta_i' - \frac{S_k}{e_k}$$

where S_k is the slack of pollutant k , and e_k is the efficient level of pollutant k .

The second stage: Truncated Regression

Using a truncated regression, the eco-efficiency scores was regressed on a set of geophysical characteristics and management practices factors (z_j) as follows (Simar and Wilson, 2007):

$$\text{Eco - efficiency} = a + z_j\delta + \varepsilon_j, \quad j = 1, \dots, n,$$

where

$$\varepsilon_j \sim N(0, \sigma_\varepsilon^2), \text{ such that } \varepsilon_j \geq 1 - a - z_j\delta, j = 1, \dots, n$$

The truncated regression ensures that values of the eco-efficiency scores ranged between zero and one. The error term (ε_j) is assumed to be normally distributed with zero mean and unknown variance (σ_ε^2) and a left truncation at $1 - a - z_j\delta$, where a and δ are the intercept and slope parameters in the regression. The truncated regression is combined with a bootstrapping procedure in order to perform bias correction in the estimated coefficients that result from serial correlation problem in the eco-efficiency scores among farms (Simar and Wilson, 2007).

Data description

The survey data for this analysis were obtained from the New Zealand Monitor Farm Data (NZMFD) developed by Motu Economic and Public Policy Research Institute (Henry et al., 2017). The NZMFD consists of two datasets. The first one covers financial information of sampled farms, which was collected by the Ministry for Primary Industries (MPI) under the Farm Monitoring Programme. This

MPI financial survey was conducted in five aggregated regions: Waikato/Bay of Plenty, Canterbury, Lower North Island, Northland, Southland, and Taranaki. The second dataset provides information on the farm's physical and environmental aspects. These data were sourced from OVERSEER® version 6.2.1., which is an agricultural decision support tool that is often used to investigate the on-farm impacts of nutrient flows (Wheeler, 2012). Table 1 describes the survey data used in our analysis.

Our sample consists of 108 dairy farms for the year 2011 - 12. In the first stage DEA, milk solid productions were used to estimate the economic value added, while GHG emissions and nutrient leaching were used to estimate the environmental pollutants measure. The economic value added was calculated by multiplying the observed milk solid productions by 2011 prices and then subtracting the intermediate costs (Askin D. & Askin V., 2012; MPI, 2013). In the second stage, other factors such as geophysical characteristics and management practices that could indirectly affect the eco-efficiency of the dairy farms were used in the truncated regression. The geophysical characteristic factors include topography, soil group, temperature, and rain fall. The management practice factors include structure type and irrigation. The structure type represents the on-farm management practices that could reduce environmental pollutants which result from the farm's production activity. The truncated regression was bootstrapped by running across 1000 iterations.

Results

The results show that 7 farms (6.5%) in our survey data were operating at the frontier (eco-efficiency score = 1) while 101 farms (93.5%) were inefficient in some regard. The estimated mean and the median of the eco-efficiency score were 0.73 and 0.71. This means that, on average, a reduction of 27% in environmental externalities is possible while maintaining the same level of output and that GHG emission, N leaching, and P loss is moderately excessive and inefficient (Figure 1 and Table 2). The pollutant-specific eco-efficiency mean values for P Loss, N leaching, and GHG emissions were estimated at 0.39, 0.46, and 0.72. This means that there is a greater opportunity to reduce P loss compared to N leaching and GHG emissions. Results indicate that replicating the practices of the best performing farmers, could reduce P loss by 61%, while N leaching and GHG emissions could be reduced by 54% and 28% respectively.

Results from the bootstrapped truncated regression suggested that adopting irrigation and on-farm management practices (structure type) such as feed-pads, in-shed feeding, or wintering-pads improved efficiency. It also shows that higher temperatures could reduce eco-efficiency. Sand, peat, podzol, and sedimentary soils also had reduced eco-efficiency compared with volcanic, pumice, and recent/YGE/BGE soils. In contrast, higher rainfall had no discernible effect on eco-efficiency. The few

dairy farms located on sloped land were found to be less efficient than those on flat land. The estimated mean effect size of the “structure type” factor (defined as sand, peat, podzol, sedimentary versus volcanic, pumice, and recent/Yellow grey earths (YGE)/ Brown grey earths (BGE)) was negative (-0.252). This means that having farms on sand, peat, podzol, and sedimentary soils could reduce the farmer’s eco-efficiency. Similarly, the estimated mean effect size of the “irrigation” factor (defined as ‘yes’ vs ‘no’) has a positive value (0.532). This means that by adopting irrigation eco-efficiency could be improved.

Discussion

Although a small percentage of the farmers were operating at the eco-efficiency frontier (6.5%), more than half of the farmers (56 out of 108) had the median eco-efficiency score (i.e., 0.71) or more. The largest opportunity to reduce pollutants from dairy production was in P loss (61%), followed by N leaching (54%), and GHG emissions (28%).

Eco-efficiency is positively associated with irrigation. Irrigation has been shown in several studies to support the productivity of dairy cows through maintaining reliable summer pasture production (Grayling W., 2008). However, the effective size of irrigation of eco-efficiency has shown a large range of uncertainty between -0.87 and 1.93. This might be due to the fact that irrigation can also increase livestock run-off and fertiliser leaching if the correct management practices are not in place. Eco-efficiency also decreased for sand, peat, and podzol soils compared to those on volcanic, pumice, and recent/YGE/BGE soils. Sand, peat, and podzol soils are less resilient and have greater risks of drought and nutrient leaching. Volcanic, pumice, and recent/YGE/BGE soils tend to have higher water storage, deep root zones, and greater inherent fertility. We noted, however, that the mean effective size is quite small (-0.027), which might be due to the influence of the YGE soil type that is expected to be on the margin (being vulnerable to anaerobic conditions, stock pugging, and with moderate to low P storage, plus potential for preferential drainage through artificial drainage through to surface waters).

Furthermore, eco-efficiency decreases with farms that are implementing winter-standoff compared to those that are implementing feed-pad, wintering-pad, and in-shed feeding. This result can be explained by the availability of designated paddock/area for animals with no specific collection of effluent or feeding mechanism in the case of the winter-standoff practices, whereas all the other management practices (i.e. feed-pad, wintering-pad, and in-shed feeding) have specific effluent collection, management, and capacity to control feed in this space. As expected, eco-efficiency is lower with higher temperatures. This conclusion has previously been shown in studies such as Pereira

et al. (2012). They have shown that temperature had a significant positive effect on ammonia and GHG emissions.

Contrary to what was expected, rain fall did not affect the eco-efficiency of dairy farms. We note, however, that in 2011-12, the country faced exceptional heat for the first half of February. In addition, the summer period extended into May, which was the warmest on record and June was the 3rd warmest experienced (NIWA, 2012). This could indicate that our sample didn't capture the expected effect of rainfall due to the unusual data of that year. Finally, eco-efficiency decreases with farms that are on rolling and easy-hill compared to those that are on flat land. Flat land is characterized as deep resilient and easily worked soils with climate favourable for the growth of a wide range of crops, pasture and forest. In contrast, rolling and gently sloping hills are seen as land that has slight to moderate physical limitations (i.e. moderately steep slopes and stoniness) and could be exposed to several hazards (i.e., flooding) (Lynn et al., 2009). This indicates that the favourable biophysical conditions of farms on flat land will improve their eco-efficiency. Improving the eco-efficiency of dairy farms in New Zealand has the potential to reduce GHG emission, Nitrogen leaching, and Phosphorous loss by 3.45 million tonnes, 20,610 tonnes, and 366 tonnes, respectively.

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Table 1: Summary statistics for dairy farms survey data. The mean, interquartile range and median are given for continuous variables. The frequency for each level is given for categorical variables.

Variable	Min	1st Quartile	Median	Mean	3rd quartile	Max
Area (ha)	56	109	120	142	157	400
Herd per ha	1.7	2.6	2.9	2.9	3.2	5
Milk Solids per ha (kg)	514	870	1,064	1,052	1,210	2,105
N Loss per ha (kg)	8	36	47	52	63	123
P Loss per ha (kg)	0.4	1	1.6	2.6	3.1	18.3
GHG per ha (kg)	6,124	11,044	12,297	12,210	13,378	23,503
Temperature (C°)	0	0	13	9.6	15	16
Rainfall (mm)	650	1,200	1,500	1,426	1,600	3,000
Variable	Categories					Frequency
Topography	Easy hill; Flat; Rolling; Steep hill					12; 71; 24; 1
Soil Group	Peat; Podzol; Pumice; Recent/YGE/BGE; Sand; Sedimentary; Volcanic					6; 6; 1; 15; 3; 34; 43
Irrigated	Yes; No					9; 99
Structure Type	Feed pad; In-shed feeding; Wintering pad; Winter stand-off					60; 16; 5; 27

Table 2: Radial eco-efficiency and Pollutant-specific eco-efficiency for N leaching, P Loss, and GHG emissions

	Mean	Median	st. dev	Minimum	Maximum
Radial eco-efficiency					
	0.73	0.71	0.11	0.54	1
Pollutant-specific eco-efficiency					
N leaching	0.46	0.42	0.21	0.15	1
P Loss	0.39	0.33	0.27	0.25	1
GHG emissions	0.72	0.7	0.12	0.48	1

Table 3: Effect sizes of the variables related to geophysical characteristics and management practices on the eco-efficiency scores. Effect sizes estimated from 1,000 iterations of the truncated regression. Topography refers to rolling, easy hill, and steep hill versus flat land. Soil refers to sand, peat, podzol, sedimentary versus volcanic, pumice, and recent/Yellow grey earths (YGE)/Brown grey earths (BGE). Structures refers to winter-standoff versus feed-pad, wintering-pad, and In-shed feeding

Variable	Mean effect Size	Lower effect size	Upper effect size	Median value	Std error
Topography	-0.213	-0.840	0.416	-0.216	0.007
Temperature	-0.085	-0.143	-0.033	-0.084	0.001
Rainfall	-0.002	-0.003	-0.001	-0.002	0.000
Soil	-0.027	-0.250	0.201	-0.024	0.003
Irrigated	0.532	-0.875	1.930	0.543	0.016
Structure	-0.252	-0.554	0.031	-0.254	0.003

Figure 1: Density plot shows the distribution of eco-efficiency scores across all Dairy farms.

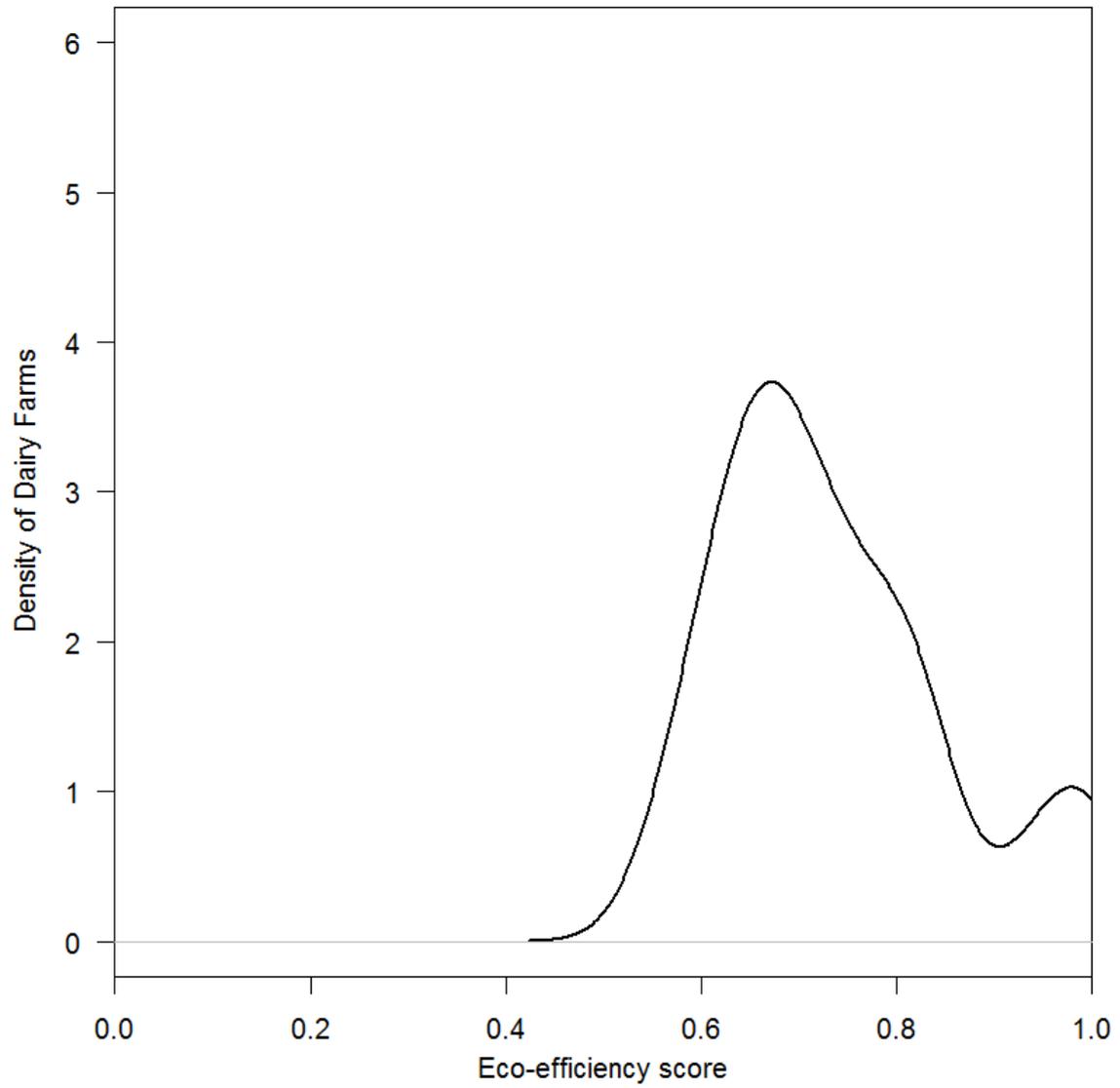


Figure 2. Graph shows effect sizes of each variable from multiple iterations of the truncated regression on the eco-efficiency scores. Black dots show median effect sizes over 1000 iterations. Error bars denote the 95% range of effect sizes across the 1000 iterations. Topography refers to rolling, easy hill, and steep hill versus flat land. Soil refers to sand, peat, podzol, sedimentary versus volcanic, pumice, and recent/Yellow grey earths (YGE)/Brown grey earths (BGE). Structures refers to winter-Standoff versus feed-pad, wintering-pad, and In-shed feeding

