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A parametric analysis of eco-efficiency and its determinants: Evidence from Norwegian dairy farms

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Abstract: This study aims to estimate eco-efficiency scores and identify determinants of Norwegian dairy farms using a parametric approach that accounts for methane emissions. The study incorporates an environmental output measure and draws on 30 years of panel data from 692 specialist dairy farms (1991–2020). The findings indicate that Norwegian dairy farms are inefficient, with room for improvement in the dairy production system and the environment. According to the average eco-efficiency score, conventional dairy farms could cut input use and CH_4 emissions by 5% while maintaining output. Furthermore, the study found that land tenure, experience, and government subsidies all positively impact eco-efficiency. Policymakers should encourage the best-performing dairy farms to share information on increasing productivity while considering environmental concerns to achieve better social and agricultural development. It should be noted that the study only looks at livestock methane emissions; future research may investigate other environmental factors.

Keywords: agricultural system; dairy farming; emission; farm performance; technology

The concept of eco-efficiency aims to measure the success of economic actions concerning their environmental impact. Eco-efficiency measurement has gained increasing importance recently due to the significant environmental effects caused by dairy products, including greenhouse gas emissions, nutrient pollution, and loss of biodiversity (FAO 2020; Alem 2023). In simple terms, eco-efficiency means achieving greater outputs of goods and services while using fewer resources and causing minimal environmental harm (Robaina-Alves et al. 2015; Song and Chen 2019). Eco-efficiency balances ecology and the economy so that economic activity does not harm the environment (Saling et al. 2002). Consequently, increasing resource productivity must be accompanied by reduced greenhouse gas (GHG) emissions. The eco-efficiency of dairy farms can be affected by various factors. One of these is the technology and management practices implemented on the farms. Precision farming, for instance, is a contemporary approach that can enhance resource efficiency and minimise environmental effects. Another important factor is the size and structure of dairy farms. Small

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and medium-sized farms frequently have higher environmental impacts per unit of production than larger farms due to lower economies of scale and less efficient resource use. Furthermore, policies, land tenure, farm experiences, and regulations all impact the performance of dairy farms. The Norwegian government has implemented and supported various policies and regulations to reduce agriculture's environmental impacts, such as the Climate and Agriculture Initiative and the Nitrogen Emission Reduction Program. These policies incentivise farmers to adopt more environmentally friendly practices and technologies. The empirical analysis was based on 30 years of unbalanced panel data from 692 specialist dairy farms (1991–2020) and a parametric procedure that accounts for poor output.

Several frameworks exist in the literature that addresses the issue of eco-efficiency in the dairy sector (e.g. Pelletier et al. 2008; Picazo-Tadeo et al. 2011; Shortall and Barnes 2013; Perez-Urdiales et al. 2015; Wettemann and Latacz-Lohmann 2017; Le et al. 2020; Czyżewski 2021; Baležentis et al. 2022). The studies used different methods to assess eco-efficiency scores, with each approach having its strengths and weaknesses. Generally, eco-efficiency can be calculated using either the ratio or frontier approaches [for details, see Song and Chen (2019)]. Kuosmanen and Kortelainen (2005) have defined eco-efficiency as the ratio of the economic value generated to the environmental impact created. The economic value generated is frequently assessed using life cycle costs in cost-benefit analyses (Huppes and Ishikawa 2005; Shortall and Barnes 2013). The most typical environmental effect is an aggregation of material usage, energy usage, pollutants, and waste (Shortall and Barnes 2013). Ratio approaches have difficulty categorising and combining environmental influences [for details, see Huppes and Ishikawa (2005) and Song and Chen (2019)]. The frontier method seeks to identify the best-practice frontier for a given farm and measures eco-efficiency by calculating the percentage of actual production to frontier output while accounting for both desirable and undesirable outputs (Orea and Wall 2017; Song and Chen 2019; Stetter and Sauer 2022). Two categories of frontier-based methods exist parametric and non-parametric approaches. Both approaches have advantages and disadvantages, and which approach to use will be determined by the specific data and research question (Murty et al. 2012; Førsund 2018). In agricultural research, the parametric approach is often considered the preferred method as it offers the advantage of accommodating measurement errors. This makes it particularly suitable for addressing issues related to agriculture specific to dairy farming (Cabrera et al. 2010).

In several ways, this paper differs from the existing literature. Unlike previous studies, which mainly employed nonparametric methods such as the Data Envelopment Analysis framework, this study takes a parametric approach to assessing eco-efficiency on a farm-by-farm basis, considering both desirable and undesirable outputs. Furthermore, only a few studies have looked at eco-efficiency and its determinants at the farm level (e.g. Perez-Urdiales et al. 2015). As a result, this study adds to the existing literature on eco-performance and agricultural policy. Finally, this study takes advantage of a large panel dataset spanning dairy farms over a 30-year period, which adds significant value to the analysis.

MATERIAL AND METHODS

Theory of environmental production technology and CH_4 estimates. Environmental production technology theory is a framework used in environmental economics to study how firms produce goods and services while using as few natural resources as possible and minimising negative environmental impacts. The theory is founded on the concept of environmental production technology, which describes the processes and inputs that firms use to convert inputs into outputs. Let us define environmental production technologies (T) as Equation (1):

$$T = \{(x,y,b)\text{: } x \text{ can produce } (y, b)\} \tag{1}$$

where: T – environmental production technology, characterised by: x – the inputs, y – desired output; and b – undesirable output or CH_4 emissions vectors.

See Alem (2023) for more information on the modelling and properties of the technology set. We estimated the input distance function and CH_4 emissions vectors using Alem's (2023) and IPCC's (2006) procedures as Equation (2), the CH_4 emissions factors for dairy:

$$EF_D = \frac{GE_D \times Y_m \times 365 \text{ days/year}}{55.65 \text{ / kg } CH_4} \tag{2}$$

where: EF_D – factors influencing dairy CH_4 emissions; Y_m – methane conversion rate, measured in per cent, represents the percentage of methane produced; GE_D – gross energy intake for dairy farms is the total energy consumed. For detailed estimation, see Alem (2023).

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The empirical model. Our empirical analysis opted for a translog (TL) representation of the environmental production technology for Equation (1) due to its flexibility. Therefore, Equation (1) is formulated as a logarithmic translog input distance function as Equation (3):

$$\begin{aligned}-\ln x_1 = \alpha_0 &+ \sum_{n=1}^{N}\beta_n \ln \breve{x}_{n,it} + \sum_{j=1}^{J}\beta_m \ln y_{m,it} + \\ &+ \sum_{j=1}^{J}\beta_j \ln b_{j,it} + \beta_t D_t + \\ &+ \frac{1}{2}\sum_{n=1}^{N}\sum_{n=2}^{N}\beta_{nn} \ln \breve{x}_{n,it} \ln \breve{x}_{n,it} + \\ &+ \frac{1}{2}\sum_{h=1}^{H}\sum_{h=2}^{H}\beta_{hh} \ln b_{h,it} \ln b_{h,it} + \\ &+ \frac{1}{2}\sum_{j=1}^{J}\sum_{j=2}^{J}\beta_{jj} \ln y_{j,it} \ln y_{j,it} + \\ &+ \sum_{n=1}^{N}\sum_{l=1}^{L}\beta_{nl} \ln \breve{x}_{n,it} \ln b_{j,it} + \\ &+ \sum_{n=1}^{N}\sum_{j=1}^{J}\beta_{nj} \ln \breve{x}_{n,it} \ln y_{j,it} + \\ &+ \sum_{l=1}^{L}\sum_{j=1}^{J}\beta_{lj} \ln b_{l,it} \ln y_{j,it} + \\ &+ \sum_{n=1}^{N}\beta_{nt} \ln \breve{x}_{n,it} D_t + \sum_{l=1}^{L}\beta_{lt} \ln b_{l,it} D_t + \\ &+ \sum_{j=1}^{J}\beta_{jt} \ln y_{j,it} D_t + \frac{1}{2}\beta_{tt} D_t^2 + \omega_i + v_{it} - u_{it}\end{aligned} \tag{3}$$

where: the natural logarithm of dairy output (ln$y$) is regressed on the natural logarithm of inputs per unit of land (ln$x$) and methane emissions (ln$b$); D_t – time trend; v_{it} – white noise; ω_i– farm effect or unobserved heterogeneity; u_{it}, [$u_{it} \sim N^{+}(\mu_{it}, \sigma_u^2)$] – eco-inefficiency effects; all Greek letters are variables to be estimated.

The estimation procedure of Equation (3) is based on Greene's (2005) method. To calculate the eco-efficiency and marginal effects of exogenous factors, we employ the methodologies established by Jondrow et al. (1982) for eco-efficiency computation and by Wang (2002) for estimating marginal effects.

Farm level-data. The empirical analysis utilises panel data from 692 specialised dairy farms, comprising 6229 observations from 2091 to 2020. To reduce heterogeneity in the sample, we applied selection criteria focused on farmers primarily engaged in dairy production whose primary revenue source (80%) was derived from dairy-related activities. This criterion ensured that dairy farming constituted these farms' primary area of emphasis. The study employs a two-output four-input model to represent environmental production technology. The total revenue generated by dairy products serves as the desired output in this analysis. Farm-level data regarding CH_4 emission is sourced from Statistics Norway (SSB 2021) and Norwegian Environment Agency (NIR 2020). The input variables include agricultural land (x_1) measured in hectares and labour (x_2) calculated for all labour inputs and materials (x_3). The capital input is denoted by the implicit quantity in-

Table 1. The main variables' descriptive statistics

Variables	Description	Unit	Mean	SD
Output (y)	output	EUR	146 650	116 749
Output (b)	CH_4 emission	tonnes (1 000 kg)/year	0.99	0.61
Undesirable output price	CH_4 emission	EUR/tonnes (1 000 kg)	0.45	0.13
Undesirable output value	CH_4 emission	EUR	4.20	2.90
Inputs (x_i) x_1	land	hectares	33.10	20.20
x_2	labour	hours	3 562	1 074
x_3	material	EUR	48 006	45 345
x_4	capital	EUR	40 463	41 566
Environmental variables (Z)	Description	Unit	Mean	SD
$Z1$	land tenure	hectares	14	16
$Z2$	farm experience	year	28	11
$Z3$	debt asset ratio	ratio	0.40	0.17
$Z4$	government support	100 EUR	2 840	1 500
Year (t)		1 for 1991		
n (observations)		6 229		

Source: own calculation based on farm level data

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dex (x_4) and is calculated by adjusting the value of live livestock, buildings, and machinery at the start of each year to 2015 based on the consumer price index. We include the exogenous variable in Equation (3) based on the literature (Minviel and Sipiläinen 2018) and data availability. These are: *i*) tenure of farmland ($Z1$) is the proportion of total acres rented; *ii*) a year's worth of agricultural experience; *iii*) to assess the financial strength of dairy farms using the debt-to-asset ratio, and *iv*) subsidy. We expect all exogenous variables to positively contribute to improving the eco-efficiency of the dairy farm. STATA® version 17 estimates the empirical model Equation (3). The estimated parameters and standard errors are shown in Table 1.

On average, Norwegian dairy farms are characterised by relatively small size and generate approximately 0.15 million EUR in annual revenue from dairy products. This figure has increased gradually, leading to an average yearly CH_4 emission of 0.99 tonnes.

RESULTS AND DISCUSSION

Eco-efficiency estimates scores. Table 2 presents the calculated parameters and their corresponding standard errors (SE). The table provides information on the variables included in the model and indicates their statistical significance.

The distribution of the sample farms according to how eco-efficient they are is also shown in Table 3. For instance, 25% of the sample farms get a 94% rating, compared to 10% of the farms' 81% rating for eco-efficiency. The average eco-efficiency score of 0.95 implies that many dairy farms may have low environmental performance. That is, if an average dairy farm becomes eco-efficient, it can use 5% less input to produce the same environmentally friendly output (output with low environmental impact). Our results align with previous studies in the literature. For instance, Le et al. (2020) utilised the hyperbolic distance function and obtained a similar eco-efficiency score of 0.93 for dairy farms in Alberta. Although direct comparisons can be challenging, our findings align with other research that employed nonparametric approaches. For instance, Mamardashvili et al. (2016) reported an average eco-efficiency of 0.97 for Swiss dairy farms, while Adenuga et al. (2018) found a similar average score of 0.97 for dairy farms in Ireland.

Entrepreneur management factors of eco-efficiency. The lower section of Table 2 displays the coefficients calculated for the marginal impacts of environmental factors on eco-efficiency. The results indicate a strong correlation between all socioeconomic factors and eco-efficiency in dairy farms. The analysis revealed a positive and significant relationship between land tenure and higher levels of eco-efficiency. While secure land tenure is generally thought to be positively correlated with eco-efficiency, renting land can also be associated with some eco-efficiency benefits. Dairy farmers who rent land may have more flexibility to implement environmentally friendly practices, which can help to reduce the financial risks associated with land ownership, such as the upfront costs of purchasing land or the financial risks related to land value fluctuations. This can free up resources for investment in environmentally friendly practices. Furthermore, farmers renting land are more likely to work with other farmers or landowners to implement eco-friendly practices like sharing equipment or rotating crops. Identifying such patterns can facilitate the advancement of resilient and sustainable farming systems, and our findings align with prior research, exemplified by Byerlee and Deininger (2013).

As anticipated, the effect of farm experience is positive and statistically significant, indicating that experienced farm managers are more likely to be eco-efficient than less experienced ones. Due to various factors, experienced dairy farmers are often positively correlated with eco-efficiency. For starters, experienced farmers have a better understanding of the production process, which allows them to manage resources better and optimise production. This can lead to more efficient resource use, such as lower feed and water consumption per unit of milk produced, and ultimately reduce the environmental impact of dairy farming. Second, experienced farmers have developed practical skills and problem-solving abilities to adapt to changing circumstances and challenges. Third, experienced farmers frequently have established networks and relationships within the dairy industry, which can provide access to information, resources, and support. This can include access to training, research and development programs, and collaborative opportunities with other farmers or industry stakeholders. Finally, experienced farmers may have a stronger motivation and commitment to sustainability, often motivated by a desire to maintain their farm's long-term viability and preserve natural resources for future generations. This can lead to a willingness to adopt new environmental practices and technologies, even if they require some initial investment or learning. Similar results have been published in the literature (e.g. Kumbhakar et al. 2015).

Based on the empirical analysis, the debt-to-asset ratio exhibits a negative correlation with the eco-efficien-

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Table 2. Parameter estimates

Variable	First orders	$\ln x_2$	$\ln x_3$	$\ln x_4$	$\ln y_1$	$\ln b$	t
$\ln x_2$	0.280*** (0.029)	0.177*** (0.008)	–	–	–	–	–
$\ln x_3$	0.278*** (0.029)	–0.079*** (0.012)	0.100*** (0.017)	–	–	–	–
$\ln x_4$	0.142*** (0.022)	0.003 (0.010)	–0.059 (0.011)	0.100*** (0.017)	–	–	–
$\ln y_1$	–0.166*** (0.035)	0.165*** (0.020)	–0.027 (0.022)	0.044* (0.018)	0.033** (0.010)	–	–
$\ln b$	–0.452*** (0.037)	–0.074*** (0.020)	0.044** (0.020)	0.006 (0.015)	–0.093*** (0.024)	–0.051 (0.032)	–
Year	–0.022*** (0.003)	–0.003* (0.001)	0.003** (0.001)	–0.003** (0.001)	–0.016*** (0.002)	0.013** (0.002)	0.001*** (0.000)
Environmental variables[b] n **= 6229**							
Land tenure					–0.006*** (0.001)		
Farm experience					–0.253** (0.008)		
Debt asset ratio					1.241** (0.462)		
Government support					–0.001*** (0.000)		
log likelihood= 7 188***					$\gamma = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_v^2} = 0.88$		

*, **, ***significant at $P < 0.05$, $P < 0.01$, $P < 0.001$, respectively; [a]standard errors (SE) – displayed within parentheses; [b]negative values – positive impact of the variable on eco-efficiency; variables expressed in logarithmic form: x_2 – labour input per unit of land; x_3 – materials input per unit of land; x_4 – capital input per unit of land; y_1 – desirable outputs; b – undesirable outputs; t – time; γ – gamma; σ^2– sigma squared; v – variance; u – inefficiency term

Source: own calculation based on farm level data

cy of dairy farms. More indebted farms are predicted to have better environmental efficiency if they have previously invested extensively in environmentally favourable technologies. The finding might be that dairy farmers who are heavily in debt may be financially constrained and unable to invest in more environmentally friendly technologies or practices that could boost their efficiency. Furthermore, dairy farmers heavily in debt may be forced to prioritise short-term profitability and may lack the time or resources to invest in longer-term eco-efficient practices that may necessitate an initial investment. Farm debt, in general, can hinder the adoption of eco-efficient practices and technologies, leading to a decline in the eco-efficiency of dairy farms. This finding is consistent with prior research, as exemplified by e.g. Sipiläinen et al. (2013) in the literature.

The analysis implies that subsidies have a marginally positive and statistically significant correlation with the eco-efficiency of dairy production. There are several reasons why farm subsidies are positively related to a dairy farm's eco-efficiency. Farm subsidies, for example, can provide dairy farmers with the financial support they need to invest in environmentally friendly

Table 3. Eco-efficiency scores distribution

Percentile	Eco-efficiency score
1%	0.805
5%	0.889
10%	0.919
25%	0.949
Mean	0.954
75%	0.973
90%	0.979
95%	0.982
99%	0.986
SD	0.035
Observations	6 229

Source: author's own elaboration

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technologies and practices. Subsidies can give farmers access to resources and information to help them adopt environmentally friendly practices. Training programs, technical assistance, and research and development initiatives are examples. Furthermore, subsidies can help farmers plan for the long term by providing a consistent source of income that allows them to invest in environmentally friendly practices that may not yield immediate returns. Our results align with prior research indicating that subsidies enhance the performance of dairy farms by facilitating investments in technological innovation (e.g. Alem et al. 2019). However, contrasting views are presented by Minviel and Sipiläinen (2018), who argue that government support might distort the timing of adjustment decisions. Farmers may substitute government subsidies for agricultural income because of higher government payments, and they may also put less effort into enhancing their farms' technical and environmental performance (Skevas and Cabrera 2020). Dairy farmers receive various subsidies based on their output, inputs, and location, making it difficult to determine which subsidies have impacted the most eco-efficiency. We might have been able to produce more meaningful findings about government support if we had used fewer aggregated subsidy variables. However, the data does not allow us to.

CONCLUSION

This study aims to evaluate the eco-efficiency and factors influencing it in Norwegian dairy farming, considering the CH_4 emissions produced by the farms. Eco-efficiency encompasses the concept of maximising agricultural production or minimising input usage while minimising negative environmental impacts. The research analyses unbalanced panel data at the farm level, spanning 1991 to 2020. The findings indicate that an average dairy farm has the potential to reduce input usage and CH_4 emissions by 5% while maintaining the same output level, based on the average eco-efficiency score. Furthermore, the study identifies that land tenure, experience, and government subsidies positively impact eco-efficiency, whereas the debt-asset ratio negatively correlates with dairy farm performance.

The analysis in this paper has important policy implications for promoting sustainable agricultural practices in Norway and elsewhere. To begin, the results highlight the potential for enhancing the eco-efficiency of Norwegian dairy farms, indicating the need for targeted improvements. Policymakers are encouraged to facilitate knowledge sharing among farms to promote eco-efficiency while considering environmental considerations. Second, policymakers should consider socioeconomic factors such as increased public support for agricultural extension and farmer training to improve dairy farms' long-term output. Furthermore, emission-reduction policies and technological advancements, such as using lower-CH_4-emitting dairy feed, can improve dairy farm performance.

It is important to acknowledge that this study focused solely on methane emissions from livestock as a means to support sustainable development. Future analyses should consider additional environmental factors such as biodiversity, waste management, N_2O emissions, and dynamic elements to provide a more comprehensive understanding of the overall environmental impact and further promote sustainable practices.

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