Renewable Agriculture and Food Systems

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Evaluating agricultural sustainability in Newfoundland, Canada: insights from a data envelopment analysis approach

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Research Paper

Cite this article: Islam K., Sabau G., Dawson J., Cheema M., Daraio J., and Galagedara L. 2026. Evaluating agricultural sustainability in Newfoundland, Canada: insights from a data envelopment analysis approach. *Renewable Agriculture and Food Systems*, **41**, e15, 1–14
https://doi.org/10.1017/S1742170526100350

Received: 10 February 2025
Revised: 20 January 2026
Accepted: 26 January 2026

Keywords:
data envelopment analysis; efficiency metrics; environmental stewardship; resource use optimization; stepwise regression model; sustainable farming practices

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Abstract

This study assesses the sustainability of agricultural practices in Western Newfoundland by evaluating the technical, allocative, cost, scale, and environmental efficiencies of 15 local farms using data envelopment analysis. The findings reveal that while most farms demonstrated high technical efficiency (average score: 95%), notable inefficiencies persist in the allocative, cost, and environmental efficiency dimensions. Key issues include labor inefficiency, chemical fertilizer overuse, and suboptimal farm scale, whereas effective land management and quality seed use were identified as major drivers of productivity. A detailed case study highlights a farm achieving full efficiency across all metrics through sustainable practices such as no-dig methods, permaculture, rainwater harvesting, and composting, demonstrating how regenerative strategies can enhance both economic and ecological performance. The study also uses stepwise regression to identify education, farm experience, and farm type as significant factors influencing efficiency outcomes. These results underscore the potential for targeted interventions, technology adoption, and policy support to improve farm performance and advance sustainable agriculture in the province of Newfoundland and Labrador. By integrating multidimensional efficiency metrics, this research provides actionable insights for optimizing resource use, reducing environmental impact, and strengthening the resilience of regional agrifood systems.

Introduction

Agricultural productivity and efficiency are key metrics in farming policy development, serving as the foundation of sustainable agriculture by optimizing resource use to ensure food security, economic viability, and environmental preservation (Picazo-Tadeo, Gómez-Limón and Reig-Martínez, 2011). While often used interchangeably, these concepts, both rooted in classical economics growth theory (Solow, 1956), differ. Productivity measures the ratio of agricultural output to input, assessing the amount produced by a given unit (country, sector, or farm) using resources like land, labor, and capital. Economic efficiency is reached when 'the marginal value of the inputs is equal to their respective unit costs' (Kelly et al., 1995) and evaluates the return generated by using an additional input. Productivity growth stems from technological advancement, such as the introduction of chemical fertilizers during the Green Revolution, and is due to technical efficiency defined as 'the ratio of actual to best-practice production' (De Koeijer et al., 2003).

Historically, agricultural policies prioritized productivity growth through technological change, but recent research emphasizes improving efficiency as essential due to resource constraints and environmental concerns (FAO, 2017). Studies suggest that increasing technical efficiency, particularly through the reduced use of polluting inputs such as pesticides, chemical fertilizers, and fossil fuel–based energy, directly supports farming sustainability by balancing 'economic and environmental objectives' (De Koeijer et al., 2003).

Newfoundland and Labrador (NL) presents a unique case for agricultural sustainability assessment due to its geographic isolation, acidic soils, short growing seasons, and heavy dependence on imported food, with over 90% of the food consumed in the province sourced externally. These factors raise critical food security concerns, particularly for rural and Indigenous communities. Furthermore, the province's rural economy is highly dependent on a small number of agricultural producers producing a limited number of commodities (dairy, chicken, and eggs), making farm-level sustainability essential for community resilience and economic diversification. Provincial policy has increasingly prioritized local food production and environmental stewardship, underscoring the need for evidence-based tools like data envelopment analysis (DEA) to inform decision-making.

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In Western Newfoundland, Canada, agriculture faces unique constraints, including acidic soils, a harsh boreal climate, and short growing seasons. Achieving production efficiency under these conditions is critical for sustainable agricultural practices (Keske, 2021; Reza and Sabau, 2022). Efficient farm management at the individual farm level is essential for the sustainability of an agricultural sector and of the broader agrifood system (Soteriades et al., 2020). Farming efficiency is categorized into technical, allocative, cost, scale, and environmental efficiencies, each addressing specific aspects of resource use and performance (Chankoson, Jermsittiparsert and Wareewanich, 2020). Together, these metrics offer a comprehensive framework for evaluating the agricultural performance of the studied farms and identifying sustainability pathways (Grzelak and Kryszak, 2023).

This study evaluates the economic, environmental, and social performance of local farms in Western Newfoundland using DEA to assess their overall efficiency. The first objective is to measure the technical, allocative, cost, scale, and environmental efficiencies of the farms in the region to determine the overall resource-use effectiveness. The second objective is to identify key factors contributing to inefficiencies, such as in labor use, fertilizer application, and farm size, to pinpoint areas for improvement. The third objective is to analyze the relationship between farm management practices and efficiency scores, highlighting how sustainable approaches impact the overall farm performance. Given the boreal climate and acidic soils of the region, the study also assesses the influence of environmental factors on farm efficiency. Ultimately, the findings provide targeted recommendations for optimizing input use, minimizing environmental impacts, and improving long-term agricultural sustainability.

To achieve this, the study implements a multidimensional DEA framework that analyzes five efficiency types: technical, allocative, cost, scale, and environmental. These measures are interrelated: technical efficiency captures how well inputs are transformed into outputs; allocative and cost efficiencies address economic optimization; scale efficiency examines operational size; and environmental efficiency accounts for sustainability impacts. Together, they provide a comprehensive picture of how farms perform across economic and ecological dimensions. By integrating these efficiency metrics, this research establishes a comprehensive framework for enhancing both economic viability and environmental sustainability in Western Newfoundland's agricultural sector. To the best of our knowledge, this is the first study in NL, Canada, to apply a comprehensive DEA framework incorporating technical, allocative, cost, scale, and environmental efficiencies to evaluate farm-level sustainability. By integrating these dimensions and linking them to both farm-level practices and contextual challenges, this research provides a novel empirical contribution to agricultural sustainability assessment in boreal climates.

This study adopts a holistic approach to agricultural sustainability by integrating economic (technical, allocative, cost, and scale efficiency), environmental (environmental efficiency), and social dimensions into the evaluation framework. By embodying all three pillars of sustainability, the study provides a multidimensional assessment of farm performance and aligns closely with the conceptual definition of sustainability underpinning the study's title.

Literature review

The concept of agricultural sustainability

From a purely anthropocentric perspective, which seeks to meet the food and fiber needs of the current generation without jeopardizing the capacity of future generations to do the same (WCED, 1987), sustainability in agriculture is a multidimensional concept defined by the three pillars of the Brundtland Commission's sustainable development concept: environmental, economic, and social, each of which is essential for ensuring the long-term viability of farming systems. Environmentally, sustainable agriculture focuses on preserving natural resources, enhancing soil health, conserving biodiversity, and mitigating harmful practices such as overexploitation of water and greenhouse gas emissions (Campanhola and Pandey, 2018; Muhie, 2022). Economically, it ensures that agricultural activities remain profitable for farmers, resilient against market volatility and climate variability, and capable of sustaining livelihoods (Pretty, 2008). Socially, it emphasizes equitable access to resources, fair labor practices, and the well-being of rural communities (Timmermann and Félix, 2015).

From a more holistic perspective, which sees sustainability not only as a theoretical concept about humans 'living in harmony with nature and with one another' (Mebratu, 1998) over generations, but also 'as an objective feature of the world, a numinous condition that makes life on planet Earth possible and meaningful for this and future human generations', and 'which implies that life in all forms is precious, it is worth sustaining' (Sabau, 2024), sustainability in agriculture receives essentially a new connotation. By viewing sustainability as an intrinsic value inherent in the interconnected systems of life on Earth, those practicing agriculture will pay attention not only to what humans can extract from the Earth or what they can dispose of as waste in the terrestrial and ocean environments, but also to how they need to participate responsibly in the maintenance of the life-web at the core of sustainability. The farm's sustainability will be measured not only by its economic efficiency but also by its capacity to exist and function as a social-ecological system in the long-term (Ostrom, 2009, 2014). This requires scientific knowledge of how ecosystems work, and how humans can benefit from protecting the structures, functions, and processes specifically embedded in the ecosystems that sustain life, by organizing farming activities to work with nature and not against it, and by observing the laws of nature (Georgescu-Roegen, 1971) and the planetary boundaries (Rockström, Steffen and Noone, 2009; Steffen et al., 2015). It also requires changes in human behavior, enabling farmers to promote environmental stewardship and social cooperation. Some of the ethical principles that farmers need to consider for a life of sustainability are: contentment, which calls for living harmoniously within ecological limits; justice, which broadens the scope of fairness to include ethical obligations not only to their families and communities, but also to all forms of life; and meaningful freedom, advocating for responsible actions within ecological and moral boundaries (Sabau, 2024). Similarly, Ekardt (2024) expands the sustainability discourse by emphasizing transformation, governance, ethics, and legal frameworks as critical dimensions that can be applied in practicing sustainable agriculture. Ekardt (2024) argues that achieving true sustainability requires systemic changes that extend beyond technological advancements. This includes rethinking human beings' essential needs, and considering frugality as consumers, redesigning governance systems by embedding sustainability into legal and policy structures, and addressing ethical imperatives such as intergenerational justice and global equity (Ekardt, 2024). Together, these perspectives deepen the understanding of agricultural sustainability as a comprehensive approach whose aim is not only to enhance productivity but also to ensure the protection of ecosystems, to foster social equity, and to support the ethical stewardship of resources. By integrating environmental, economic, social, ethical,

https://doi.org/10.1017/S1742170526100350 Published online by Cambridge University Press

and governance dimensions, sustainable agriculture becomes a transformative pathway toward securing long-lasting agrifood systems and livelihoods for farmers while safeguarding the planet's ecological balance for future generations.

While sustainability has deep ethical and philosophical roots, as highlighted by Sabau (2024) and Ekardt (2024), this study operationalizes it using empirical farm-level efficiency measures. We define agricultural sustainability through the three pillars: economic, environmental, and social. These are quantified through a DEA-based framework to assess how farms manage resources while aligning with ecological and economic objectives. This pragmatic lens helps translate abstract sustainability concepts into actionable indicators, which are essential for policy decision-making.

The importance of achieving efficiency in agriculture

Technical efficiency refers to the ability of farms to achieve the maximum possible output given the resources available. It measures operational performance and identifies whether farms are fully utilizing their inputs, such as labor, land, and machinery, sunshine, rainfall, and traditional knowledge. Allocative efficiency, on the other hand, evaluates whether the mix of inputs is being utilized in a cost-effective manner, considering their relative prices and marginal productivity (Farrell, 1957). Cost efficiency is an amalgamation of technical and allocative efficiencies, reflecting the overall economic performance of a farm. Scale efficiency examines whether farms are operating at the optimal size to maximize productivity and minimize costs, offering insights into the potential benefits of adjusting operational scale (Charnes, Cooper and Rhodes, 1978). Environmental efficiency considers not only inputs and outputs but also the environmental impacts of farming processes (Fraanje et al., 2019). These efficiency metrics play a crucial role in advancing agricultural sustainability when farmers make deliberate choices to optimize resource use, enhance economic viability, and protect ecological resilience on the farm (De Koeijer et al., 2003).

Achieving these efficiencies is critical for agricultural sustainability, especially in regions like Western Newfoundland, where environmental and socio-economic challenges require innovative farming strategies. Improvements in efficiency can enhance profitability for farmers, reduce resource wastage, and mitigate environmental impacts, thereby supporting the long-term sustainability of farming systems. Understanding these efficiencies is particularly relevant for informing evidence-based policies and promoting resilient agricultural practices in the face of climate change and resource constraints (Färe et al., 1994). Table 1 provides an overview of the efficiency types used in the study.

Recent studies have increasingly employed the DEA tool to assess sustainability from a multidimensional perspective. For example, Ait (2023) proposed a DEA-based framework to jointly evaluate economic, environmental, and social performance at the farm level, offering a comprehensive sustainability efficiency metric. Kyrgiakos et al. (2023) conducted a systematic review of DEA applications in agriculture and highlighted emerging trends and methodological innovations under the lens of sustainability. Similarly, Dong, Mitchell and Colquhoun (2016) combined principal component analysis with DEA to assess improvements in soybean production systems in the U.S. Midwest, emphasizing resource optimization and environmental stewardship. These studies underscore the versatility of the DEA method in sustainability analysis and validate its growing role in agri-environmental assessments.

The agricultural context of Western Newfoundland

The study area, Western Newfoundland, lies in the NL province of Canada. It is an island, part of the boreal ecozone, characterized by acidic soils, rugged terrain, and a harsh climate. The region's boreal climate features cool summers, cold winters, and a short growing season of approximately 3–4 months, as well as high annual precipitation, including significant snowfall in winter, which affects soil moisture recharge and drainage (AAFC, 2021). These climatic conditions, combined with frequent freeze–thaw cycles, create challenges for soil health, crop growth, and farm management. As a result, the province experiences the challenges of the highest food insecurity among all Canadian provinces, with 23% of the province's families being food insecure in 2022 (Statistics Canada, 2023). The province has about 300 different farms, and most of the farms in the province are small-scale, with an average farm size of 144 acres, which produce a limited number of commodities, including dairy products, chicken, eggs, greenhouse and nursery produce, vegetables, and berries (NL, 2019). In 2019, food self-sufficiency in the province was assessed to be 10–12%, and at that time the provincial government set the target of doubling food self-sufficiency in the province by 2022 (NL, 2018).

The sustainability challenges faced by Newfoundland share similarities with other global agricultural systems facing climatic and resource-based constraints. For example, Gong et al. (2025) demonstrated that optimizing soil phosphorus status can significantly reduce fertilizer use, which aligns with the findings of this study that highlight chemical fertilizer overuse as a major inefficiency. Similarly, Wu et al. (2025) showed how improved evapotranspiration modeling can inform better irrigation practices, which is relevant to boreal regions where water management is

Table 1. Summary of efficiency types used in the study

Efficiency type	Definition	Measurement approach	DEA model used
Technical efficiency (TE)	Ability to maximize output with given inputs or minimize inputs for a given output	DEA with land, labor, seed, fertilizer, fuel, and so forth, as inputs and revenue as output	Input-oriented DEA (VRS and CRS)
Allocative efficiency (AE)	Using inputs in optimal proportions based on their prices	Incorporates input prices to assess cost-minimizing input mix	DEA with cost minimization
Cost efficiency (CE)	Overall economic efficiency = TE × AE	Compares observed versus minimum total input costs	Derived from AE and TE
Scale efficiency (SE)	Efficiency due to optimal farm size or scale of operation	Compares VRS and CRS DEA scores	DEA with scale decomposition
Environmental efficiency (EE)	Minimizing environmental impacts per unit of output	DEA using environmental impact metrics (e.g., emissions, chemical input equivalents) as inputs	Modified DEA (input-oriented)

https://doi.org/10.1017/S1742170526100350 Published online by Cambridge University Press

seasonally critical. Moreover, international efforts to enhance agro-ecosystem resilience in saline and degraded landscapes (Hu et al., 2022; Du et al., 2024) parallel local needs for soil restoration and climate-adapted farming in Western Newfoundland. These global advances underscore the importance of localized efficiency strategies informed by broader scientific progress in agro-environmental sustainability.

Beyond agro-climatic constraints, Newfoundland presents unique challenges related to food security, rural economic development, and geographic isolation. With one of the lowest food self-sufficiency rates in Canada (10–12%) and 23% of households experiencing food insecurity in 2022 (Statistics Canada, 2023), there is a growing need to enhance local agricultural productivity and resilience. This context makes Western Newfoundland an important case study for exploring regionally tailored strategies to support sustainable agriculture through efficiency improvements.

Research methodology

Study area

The study area is Western Newfoundland (Figure 1), the island portion of the NL province in Atlantic Canada. The region is characterized by podzolic soils (low fertility) and a cool summer boreal climate that significantly influences its agricultural production. The predominant soils are acidic podzols, often low in nutrients and prone to leaching, requiring amendments for optimal crop growth. Poorly drained gleysols are also common in the area's valleys and wetlands, affecting soil water retention. The region's boreal climate is characterized by arctic summers, freezing winters, and high annual precipitation ranging from 1100 to 1400 mm, with significant snowfall in winter. A short growing season of 90–120 days makes timing critical for planting and harvesting. Vegetables and root crops thrive in the region due to their adaptability to acidic soils and cooler temperatures, though careful management of soil pH, drainage, and nutrient levels is essential. There are 37 farms in the research area, each producing a combination of field and greenhouse vegetables, herbs, berries, fruit, flowers, hay, and nursery sod.

Farm efficiency as a measure of sustainability

Assessing sustainability in agriculture is inherently complex, given the many ways in which crops and livestock sustain human populations and the diverse pathways by which farming can be managed to balance profitability with environmental stewardship (Färe et al., 1994; Harris and Fuller, 2014). In this study, we adopt the premise that farm-level productive efficiency is a useful proxy for sustainability, since efficiency gains often result from reducing the use of inputs such as chemical fertilizers and pesticides that typically generate negative environmental impacts.

The methodological foundation of this research builds on the seminal work of Farrell (1957), later advanced by Afriat (1972) and Charnes, Cooper and Rhodes (1978), and subsequently refined by Färe et al. (1994). These developments established DEA as a robust non-parametric approach for measuring efficiency. While the technical underpinnings of DEA are well established (Coelli, Rao and Battese, 1998), the novelty of this study lies in applying a multidimensional DEA framework that integrates both economic and environmental dimensions of sustainability in a boreal agricultural context.

This research evaluates five efficiency measures, each representing a distinct sustainability dimension:

- **Technical efficiency (TE):** defines the ability of farms to convert inputs (land, labor, seed, fertilizer, fuel) into outputs (revenue, yield). A score of 1 indicates full efficiency, while values below 1 reflect inefficiencies (Farrell, 1957).
- **Allocative efficiency (AE):** assesses whether farms select the most cost-effective mix of inputs given their relative prices (Farrell, 1957; Coelli et al., 2005).
- **Cost efficiency (CE):** combines TE and AE to capture farms' overall economic performance, reflecting whether they minimize costs while maintaining outputs.

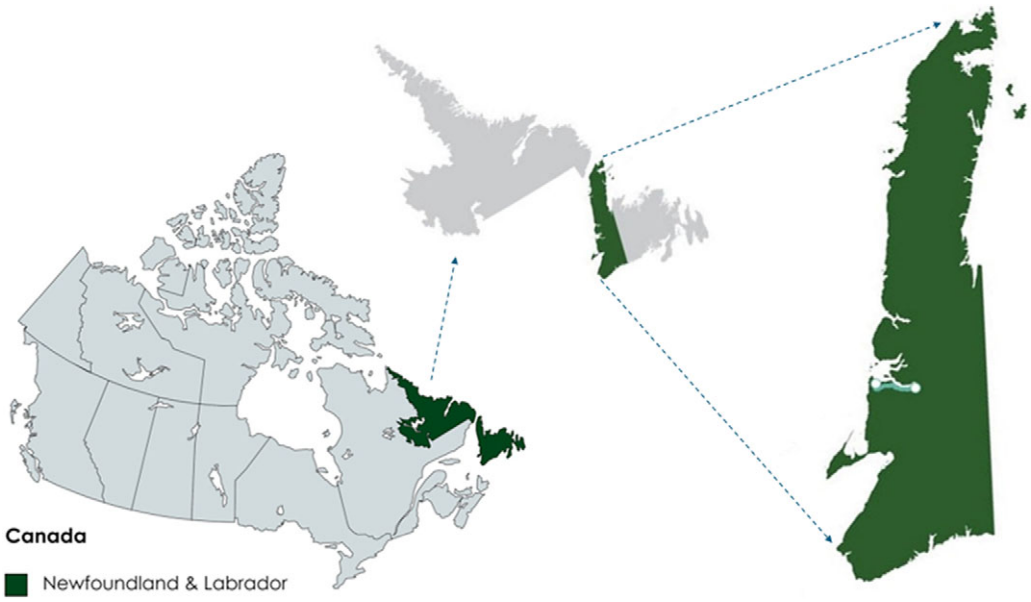


Figure 1. This study area illustrates the geographical location of Western Newfoundland, NL, Canada, highlighting key agricultural areas and the distribution of farms within the region.

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- **Scale Efficiency (SE):** examines whether farms operate at an optimal size, distinguishing between inefficiencies due to under-scaling (IRS) or over-scaling (DRS) (Charnes, Cooper and Rhodes, 1978).
- **Environmental efficiency (EE):** extends DEA to include ecological impacts of inputs (e.g., CO_2 emissions from fertilizer and fuel use), assessing whether farms minimize environmental burdens per unit of output (De Koeijer et al., 2003; Ait, 2023). To calculate EE, we derived the environmental burden of each input from standardized impact coefficients found in peer-reviewed life-cycle assessment (LCA) studies and public databases. For example, carbon footprint values for nitrogen fertilizer were estimated at 5.88 kg CO_2e per kg of active ingredient (Gallardo, 2024), while pesticide toxicity was weighted using a composite toxicity index (De Koeijer et al., 2003). Diesel fuel consumption was converted to CO_2e using 2.68 kg CO_2e per liter. Where data were reported per unit area (e.g., water use per hectare), values were normalized based on reported farm sizes. These environmental impact equivalents were used as input proxies in the DEA model, replacing raw input quantities to estimate EE scores that reflect ecological performance. This approach aligns with the environmental DEA methods used in recent sustainability studies (Ait, 2023; Kyrgiakos et al., 2023).

Detailed mathematical formulations, linear programming models, and illustrative figures supporting these efficiency measures are provided in Supplementary Material. By relocating technical details outside the main text, this study is more easily readable. Besides, it highlights its novel contribution: demonstrating how a multidimensional DEA framework can integrate environmental sustainability with farm-level efficiency analysis, providing context-specific insights for agricultural policy and practice in Newfoundland.

Data collection

The agricultural study conducted in Western Newfoundland involved contacting all 37 crop farms in the region during September–November 2024. Fifteen farms agreed to participate, yielding a response rate of approximately 40%. Data collection was achieved through structured questionnaire surveys, focusing on both input and output metrics. Input data encompassed resource usage, including land area, labor, water, fertilizer and pesticide usage, and energy consumption. On the output side, data were gathered on farm productivity and sustainability indicators such as crop yield, economic returns, and environmental indicators, like soil health and carbon emissions, and social indicators, including labor conditions and community impact. The survey instrument included 32 closed-ended questions, divided into five thematic sections: general farm characteristics, production inputs, environmental practices, economic performance, and labor dynamics. The questionnaire was pilot tested with two local farmers and one agricultural extension officer to ensure clarity, relevance, and data quality. Based on their feedback, minor revisions were made to improve survey usability. This structured approach ensured the collected data were both consistent and representative of the farms' operational practices, providing an overview of agricultural sustainability in the region.

Participation was voluntary, though participants were promised access to a summary of results and personalized efficiency profiles. Missing data were minimal and were addressed using pairwise deletion in non-critical fields; however, farms with missing data in key input or output variables required for DEA modeling were excluded from specific model runs. Consistency screening and normalization of the final dataset were conducted using the R programming language.

Decision-making units

The decision-making units (DMUs) in this study are the 15 individual farms surveyed in Western Newfoundland. Each farm as one DMU operates independently, employing various agricultural practices and resource management strategies. The analysis evaluates the efficiency of these farms by comparing their input usage against output production, providing insights into the effectiveness and sustainability of their operations. Although the 15 participating farms produced a diverse mix of crops, they shared key characteristics that ensured the methodological homogeneity required for DEA. All farms grow a combination of field and greenhouse vegetables (e.g., potatoes, carrots, lettuce), berries, and herbs, and follow similar production goals focused on yield and revenue optimization. Thus, despite crop variety, the output structure (measured in revenue and residue) and resource use patterns were sufficiently similar to justify their inclusion as comparable DMUs under the DEA method.

Implementation of DEA

An input-oriented DEA model was selected for this study because the primary goal was to evaluate how farms could minimize input use while maintaining their current output levels. In the context of Western Newfoundland, where resources such as labor, fertilizer, and energy are often limited, expensive, or environmentally sensitive, optimizing input usage is critical for improving sustainability. Moreover, output levels (e.g., crop yields or revenue) are often constrained by environmental factors like climate and soil conditions, which farmers have limited control over. Therefore, an input minimization approach aligns more realistically with farmers' operational decision-making and offers practical guidance for enhancing efficiency without requiring significant changes in output targets.

The selection of input and output variables was guided by their relevance to evaluating agricultural sustainability from an economic and environmental perspective. Inputs such as land, labor, machinery, fertilizer, pesticide, seed, fuel, and electricity represent major resource expenditures that impact both cost-efficiency and environmental performance. These inputs are commonly used in DEA studies of farm efficiency (Ait, 2023; Grzelak and Kryszak, 2023) and align with sustainability goals by reflecting areas where resource optimization can reduce economic costs and ecological impacts.

Outputs included revenue (economic output), yield (agronomic productivity), and crop residue (a proxy for biomass and soil health contribution). These indicators were chosen to capture the dual goals of productivity and ecological stewardship. The residue, in particular, provides insight into soil carbon input and organic matter recycling, which are both critical to long-term environmental sustainability. This variable mix supports a holistic assessment of the farms' ability to balance output maximization with responsible input use.

To evaluate agricultural efficiency and sustainability in Western Newfoundland, a structured DEA was implemented. Both constant returns to scale (CRS) and variable returns to scale (VRS) DEA models were applied to assess scale efficiency and better capture the

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diversity in farm sizes. While no formal statistical test (e.g., likelihood-ratio test or bootstrapping) was performed due to sample size constraints, the model outputs were compared across CRS, VRS, and non-increasing returns to scale (NIRS) specifications to evaluate consistency and identify the nature of scale inefficiencies. The use of both CRS and VRS models is consistent with recommendations for small farm sample analysis in agricultural DEA studies (Coelli et al., 2005).

Input and output data were normalized to maintain consistency across datasets, and efficiency scores for each DMU were calculated using the 'Benchmark' and 'deaR' packages in the RStudio Integrated Development Environment (IDE) (Coll-Serrano, Vicente and Benito, 2023; Bogetoft and Otto, 2024). This package streamlined the process by enabling seamless data integration, efficient computation of DEA scores, and application of both VRS and CRS models. It also provided visualization tools to depict efficient frontiers and highlight best-performing farms, allowing for an intuitive understanding of the results. The analysis identified areas of inefficiency and generated actionable insights to enhance farm productivity and sustainability. By incorporating both CRS and VRS approaches, the study offered a holistic understanding of technical and scale efficiencies. This dual approach emphasized resource use optimization and supported the development of sustainable agricultural practices tailored to the specific needs of the region. Additionally, a stepwise regression model was employed to identify key factors influencing farm efficiency (Żogała-Siudem and Jaroszewicz, 2021). Stepwise regression is a systematic statistical method that iteratively selects or removes predictor variables based on predefined criteria, such as the Akaike information criterion (AIC) or p values, to improve model performance and reduce multicollinearity (Smith, 2018). In this study, stepwise regression was used to determine the most significant socioeconomic and environmental variables affecting technical, allocative, cost, and environmental efficiencies.

Regarding sample size, while DEA does not require large samples, using only 15 DMUs can increase sensitivity to outliers and reduce discriminatory power. This limitation was mitigated by (i) selecting a parsimonious set of inputs and outputs; (ii) ensuring homogeneity among DMUs; and (iii) complementing DEA scores with regression analysis to strengthen interpretability. Nevertheless, the relatively small sample size is acknowledged as a constraint and an area for future study expansion.

This approach enabled a more targeted analysis of efficiency determinants, allowing for the identification of critical factors such as farmer experience, farm size, education level, and environmental practices that impact overall farm performance. The combination of DEA and stepwise regression provided a robust framework for evaluating agricultural efficiency while offering actionable insights to optimize resource use and enhance sustainability.

Results

Figure 2 presents the correlation heatmap, which is employed to examine the relationships between key agricultural inputs used by

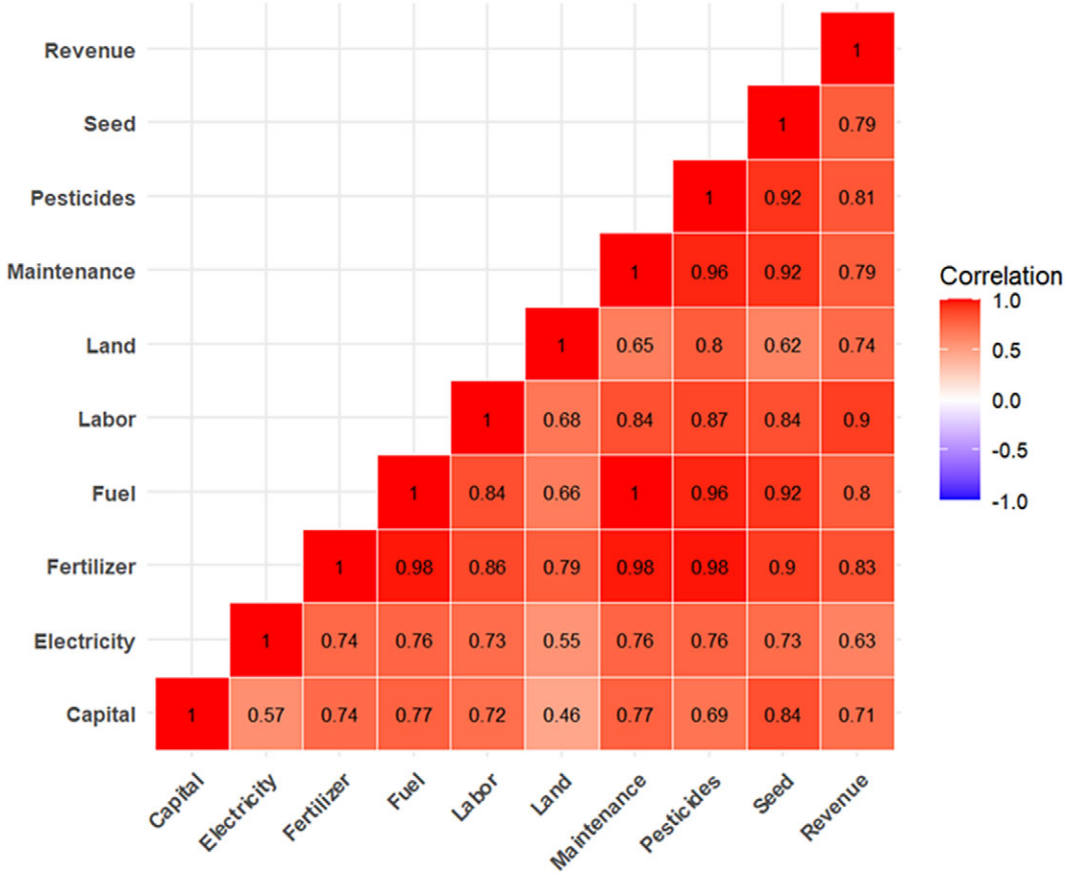


Figure 2. Heatmap of Pearson correlation coefficients between key agricultural inputs (capital, electricity, fertilizer, fuel, labor, land, maintenance, pesticides, seed, revenue) and the output (revenue). Correlation coefficients are displayed within each cell. Color and its contrast indicate the direction (red: positive, blue: negative) and strength of relationships, respectively.

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the farms (Capital, Land, Labor, Fertilizer, Pesticides, Fuel, Maintenance, Electricity, Seed) and the output (Revenue). By visualizing the Pearson correlation matrix, the heatmap offers an intuitive means to identify the strength and direction of these relationships. The inputs *Fertilizer, Pesticides*, *Labor*, and *Fuel* exhibit strong positive correlations with *Revenue*, underscoring their substantial impact on productivity. Moreover, the heatmap highlights interdependencies between inputs, such as the high correlation between *Fertilizer* and *Pesticides*, indicating their combined influence on the outcomes. This visualization simplifies the interpretation of complex numerical relationships, allowing for the identification of key variables driving farms' *Revenue* and a deeper understanding of how the inputs interact. It also aids in making informed decisions regarding resource allocation and optimizing farms' agricultural performance. As a result, the selected input and output indicators for this study align with the assumption of the same direction, enabling the use of the DEA model for analysis.

Efficiencies

The TE of the 15 decision-making units (DMUs) under the input-oriented DEA model with VRS demonstrates a high level of operational efficiency among most farms. With a mean efficiency score of 0.952 (95.2%), most DMUs are performing near the production frontier. Notably, 12 out of the 15 DMUs (80%) achieved full efficiency (TE = 1), indicating optimal input utilization (Figure 3). The remaining farms showed varying levels of inefficiency, with one DMU operating at a TE of 0.6473 (64.7%) and two others within the range of $0.8 \leq TE < 0.9$ (13.3%). The median and quartile statistics further reinforce the strong performance, as 50% of the DMUs achieved full efficiency, and the first and third quartiles both equaled 1. These results highlight a dominant group of efficiency leaders, while a small subset of farms requires targeted improvements to better align with the efficiency frontier. The summary statistics for the efficiency metrics are provided in Table 2.

Table 2. Summary statistics of DEA efficiency metrics

Metric	Mean	Median	SD	Q1	Q3	IQR
TE	0.93	1.00	0.14	0.91	1	0.095
AE	0.74	0.83	0.25	0.49	1	0.510
CE	0.69	0.62	0.27	0.46	1	0.540
SE	0.96	1.00	0.12	0.99	1	0.005

Figure 3, illustrating the efficiency analysis of the 15 DMUs, reveals significant variations in their performance across TE, CE, AE, and SE. While most DMUs exhibit full technical efficiency (TE = 1), indicating optimal resource utilization, cost and allocative inefficiencies are evident in several cases. DMUs 2, 3, 6, 7, and 10 stand out as fully efficient across all metrics, serving as benchmarks. Conversely, DMU 4 demonstrates the lowest performance, with a CE of 0.31 and AE of 0.38, highlighting significant cost and resource allocation issues. Other DMUs, such as 13 and 5, also exhibit low CE and AE scores, indicating room for improvement in managing costs and resource allocation. Scale inefficiency is most pronounced in DMU 11 (SE = 0.55), suggesting the need for resizing operations. These results emphasize the importance of targeted strategies to address specific inefficiencies in farming operations, such as improving cost management, optimizing input use, and adjusting scale for underperforming DMUs.

Environmental efficiency

The EE scores provide critical insights into the sustainability of the operations of the 15 DMUs by evaluating their efficiency (Figure 4) in minimizing environmental impact relative to their outputs. The environmental efficiency scores range from a low of 0.2597 (DMU 13) to a perfect score of 1 (achieved by several DMUs, including 3, 5, 6, and 7), indicating significant variability in the environmental

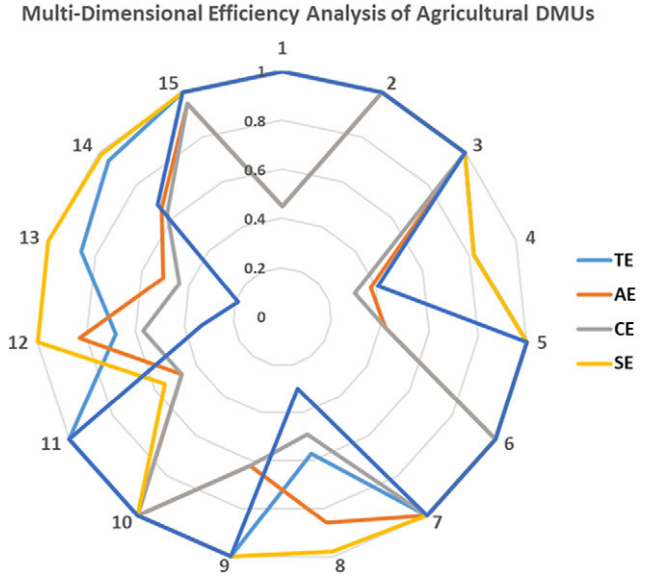


Figure 3. Radar chart depicting the multi-dimensional efficiency performance of 15 agricultural decision-making units (DMUs). The chart compares four key efficiency indicators: technical efficiency (TE); allocative efficiency (AE); cost efficiency (CE); and scale efficiency (SE). Each spoke represents a distinct DMU, while the radial scale ranges from 0 (lowest efficiency) to 1 (highest efficiency). Lines for each metric illustrate how individual DMUs perform across different efficiency dimensions.

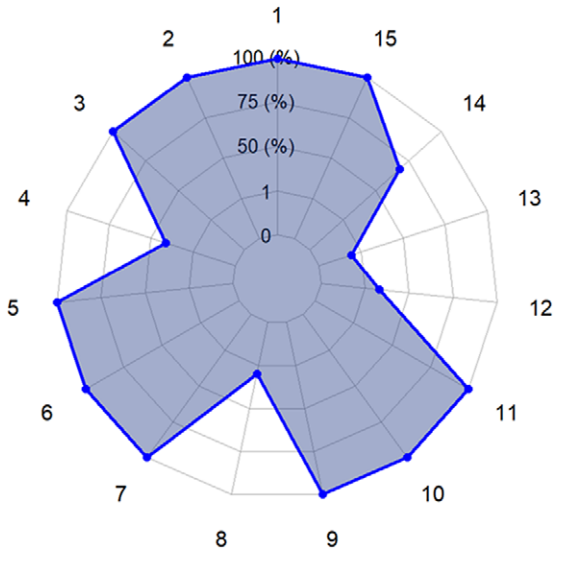


Figure 4. Radar chart displaying the environmental efficiency (EE) scores of 15 farm decision-making units (DMUs). Each spoke represents an individual DMU, numbered from 1 to 15. The concentric circles correspond to efficiency score benchmarks: 0 (center), 50%, 75%, and 100% (outermost ring), with an additional reference marker at score = 1, indicating the maximum possible efficiency. The shaded region visualizes the relative EE of each DMU, where values closer to the outer edge denote higher efficiency and proximity to the environmental performance frontier.

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performance of the units. High environmental efficiency scores, such as those of DMU 3, 5, 6, 7, and DMU 10, suggest that these units are managing their resources and production processes sustainably, with minimal environmental degradation. In contrast, DMUs with lower scores, such as DMU 4 (0.2630) and DMU 12 (0.3179), highlight potential areas for improvement, such as optimizing input usage or adopting greener practices. These variations underscore the importance of integrating environmental efficiency considerations into agricultural management practices. The results align with existing literature that emphasizes the role of sustainable resource management in achieving both economic and ecological goals in farming operations (Mehmood and Munawar, 2023). Future interventions should focus on promoting eco-friendly technologies, efficient resource utilization, and environmental education to enhance the sustainability of operations across all DMUs in the study area.

In DEA, the *frontier* (or *efficiency frontier*) represents the boundary defined by the best-performing farms in the sample. Farms on this frontier, with an efficiency score of 1, are considered fully efficient because they either maximize output with their available inputs or minimize inputs for a given output. In contrast, farms with scores below 1 lie beneath the frontier, indicating inefficiency and potential for improvement. These farms can enhance their performance by adopting practices closer to those of the frontier farms, which serve as benchmarks for the best possible performance.

The summary of the input use ratios farms-wise across the 15 DMUs in Figure 5 reveals a pattern of inefficient resource utilization. With a mean input use ratio of 2.10, on average, farms are using more inputs than necessary for cost efficiency. While some DMUs (DMU 2, 3, 6, 7, and 10) operate at an optimal level with a ratio of 1.00, indicating cost-efficient use of inputs, other DMUs exhibit significant resource overuse. For instance, DMU 13 has an input use ratio of 4.31, signaling extreme inefficiency. The median ratio of 1.79 suggests that overuse of inputs is more common than optimal usage, but the overuse is generally moderate. Addressing these inefficiencies could lead to better resource allocation and enhanced farm productivity.

Factors explaining efficiency

The stepwise regression model reveals that several factors influence the TE of the farms, with significant predictors including *Farmer's Experience* and *Age* and the *Number of years of farm's operation.* Marginal significance was observed for *Female Labor*, while *Drainage* was not a significant predictor in this model. These findings highlight the importance of farmers' *Age and Experience*, as well as the *Number of years of farm's operation* in determining technical efficiency, but they also suggest that additional factors or model adjustments may be necessary for a more comprehensive understanding of the drivers of farm efficiency.

The stepwise regression model examining the factors influencing environmental efficiency suggests that both *Education* and *Farm Type* significantly affect environmental efficiency, with Education emerging as the stronger predictor. Specifically, *Education* has a positive impact on environmental efficiency (p-value = 0.02), while *Farm Type* has a marginally significant effect (p-value = 0.05), indicating that farms with different types of operations may exhibit varying levels of environmental efficiency. However, when controlling for the other factors, the baseline value for environmental efficiency is not significantly different from zero. This model highlights the importance of education and farm type in determining environmental efficiency, but further research may be needed to

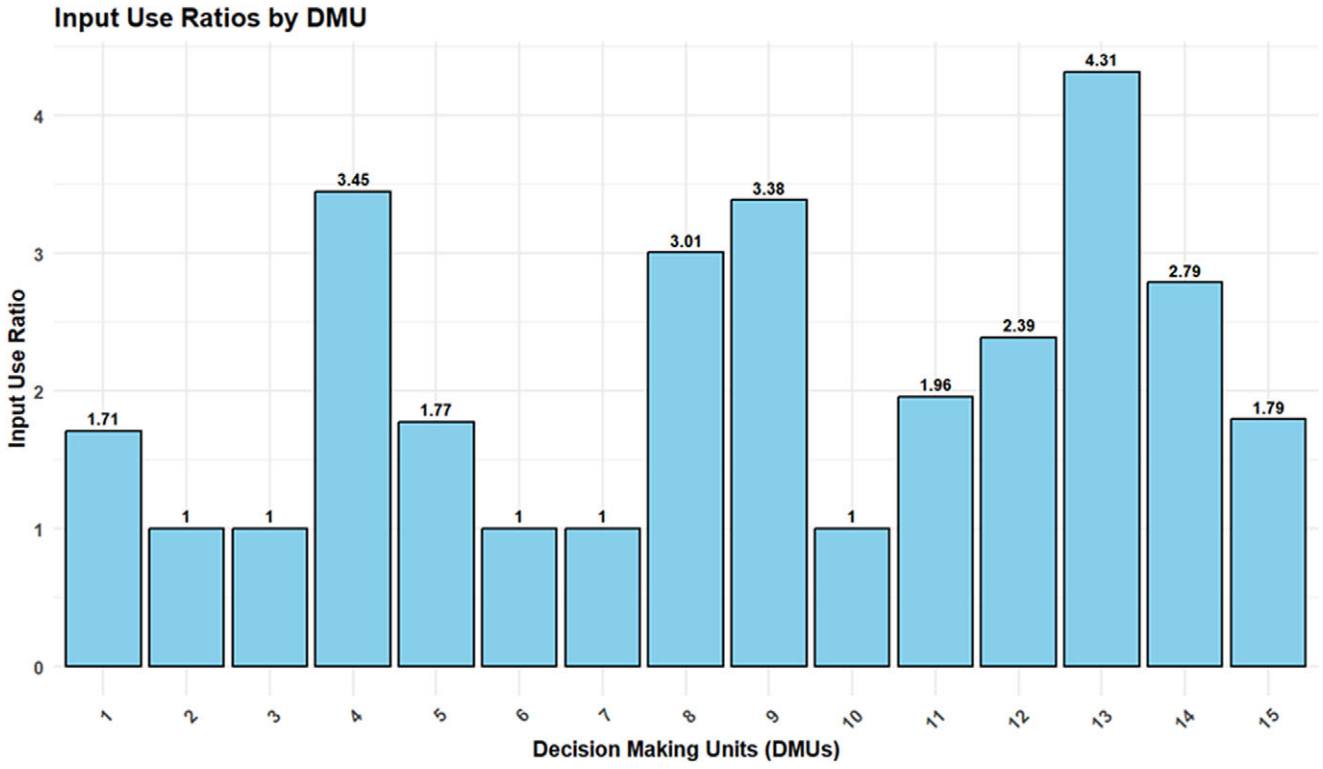


Figure 5. Bar graph presents the input use ratios of 15 agricultural Decision-Making Units (DMUs) in Western Newfoundland, NL, Canada, calculated as the ratio of observed input usage to the optimal input level estimated through input-oriented Data Envelopment Analysis (DEA). A value of 1.0 indicates technically efficient input utilization, while values exceeding 1.0 denote overuse of inputs relative to the DEA benchmark.

https://doi.org/10.1017/S1742170526100350 Published online by Cambridge University Press

explore other factors that could contribute to environmental efficiency.

Case study

One farm (DMU 3) has embraced sustainable farming practices by implementing no-dig farming methods, permaculture techniques, introducing rainwater harvesting systems, and integrating poultry farming with crop growing operations. Composting and reusing as many natural resources as possible have formed the backbone of the farm's sustainable operation design, promoting efficient resource use and minimizing waste (Owsianiak et al., 2021). The farm raises ducks, turkeys, egg-laying chickens, and is home to an energetic Labrador Retriever, Benelli, contributing to the farm's dynamic ecosystem (Oldfield et al., 2018). The farm grows a wide variety of crops, providing nourishment for the farmer's family and promoting self-sufficiency. This farm stands out as a model of efficiency, excelling in all efficiency metrics of this study, and serves as a prime example of a truly sustainable farm (Campanhola and Pandey, 2018).

This farm contributes significantly to environmental sustainability through its holistic and regenerative practices (Todirică et al., 2024). By adopting no-dig farming methods and permaculture techniques, the farm reduces soil disturbance, enhancing soil health, carbon sequestration, and biodiversity. The integration of rainwater harvesting systems ensures efficient water use, conserving this vital resource and mitigating the effects of droughts (Lankford and Orr, 2022). Composting and resource reuse minimize waste, reducing the farm's ecological footprint and fostering a circular economy. The integration of diverse commodities, livestock, poultry, and crops contributes to a balanced ecosystem, enhancing resilience against pests and diseases without relying on chemical inputs (Stojanovic, 2019). Additionally, the farm's self-sufficiency approach reduces dependence on external resources, lowering greenhouse gas emissions associated with transportation and industrial farming. Altogether, this farm exemplifies sustainable agriculture by restoring environmental health, conserving resources, and contributing effectively to building a resilient agri-food system (Boschiero et al., 2023).

DMU 3 was selected as an illustrative case study because it achieved full efficiency scores across all evaluated dimensions, technical, allocative, cost, scale, and environmental efficiency, placing it consistently on the DEA efficiency frontier. As such, this farm represents a benchmark unit within the sample and provides a concrete example of how high multidimensional efficiency can be achieved under the biophysical and economic constraints characteristic of Western Newfoundland. The purpose of this case study is illustrative rather than representative, aiming to translate the quantitative DEA results into a practical management context and to highlight farming practices associated with frontier performance.

The study's findings provide actionable guidance for NL policymakers seeking to reduce inefficiencies and enhance sustainability in small-scale, climate-constrained agricultural systems. Strengthening localized training, providing support for farms' investment in green infrastructure, and adapting existing agri-environmental policies will be essential for scaling up sustainable practices province-wide.

Discussion

The analysis in this study offers valuable insights into the agricultural farms' operational performance and sustainability of agricultural practices in Western Newfoundland, NL, Canada, by examining the farms' technical, allocative, cost, scale, and environmental efficiency. This multifaceted approach highlights areas where resource management can be improved and provides benchmarks for high-performing units aiming to be sustainable in the long run and building blocks of sustainable agri-food systems.

Efficiency

The study explored the factors influencing agricultural efficiency, noting positive correlations between land, seed, and maintenance costs and efficiency, and negative correlations between efficiency and labor, chemical fertilizer use, and fuel costs. These findings align with existing research, which consistently shows that larger land areas and investments in high-quality seeds contribute to efficiency by facilitating economies of scale and improving crop yields (Bournaris, Vlontzos and Moulogianni, 2019). On the other hand, excessive labor usage and inefficient chemical fertilizer and non-renewable fuel consumption are linked to lower efficiency, as they often result in lower use efficiency in resource allocation and environmental damage, as demonstrated by Dube and Guveya (2014) and Galluzzo (2017). The positive effect of maintenance costs on efficiency further supports the importance of proper asset management and equipment upkeep, which are crucial for minimizing downtime and enhancing operational efficiency (Batzios et al., 2022). Additionally, the study observed low variability in efficiency scores, with many farms achieving maximum efficiency. This observation aligns with previous findings by Taoumi and Lahrech (2023), which similarly highlighted that a small proportion of farms operate at peak efficiency, emphasizing the opportunity for broader resource optimization across the agricultural sector.

A closer examination of underperforming farms suggests that several socio-economic and managerial factors may be contributing to observed inefficiencies. For example, farms with lower technical and environmental efficiency scores (DMUs 4, 12, and 13) were often characterized by limited access to trained labor, lower levels of formal education among operators, and reduced experience with sustainable farming techniques. Additionally, smaller farm size and the absence of capital-intensive tools (rainwater harvesting, composting infrastructure, etc.) likely constrained scalability and efficiency. Limited access to agricultural extension services and credit support may also hinder the adoption of efficiency-enhancing innovations. These findings align with previous research indicating that farm-level managerial capacity and socio-economic status are key determinants of performance in small-scale agriculture (Ait, 2023; Grzelak and Kryszak, 2023). Future interventions should consider these structural barriers and incorporate targeted training, financial support, and technical assistance to help underperforming farms improve their efficiency outcomes.

An additional constraint that emerged from interviews and field observations is the aging profile of farm operators and the limited evidence of succession planning. This poses a medium- to long-term risk to the sustainability of the agricultural labor force in NL. At the same time, farms are being asked to navigate three overlapping transitions: (i) a sustainability transition toward practices that protect biodiversity and ecosystem functions; (ii) an energy transition to decarbonize operations and adopt renewables; and (iii) a digital/IT transition that requires new skills in data, sensors, and decision-support tools. Expecting small, resource-constrained farms to implement these transitions efficiently without targeted support is unrealistic. Workforce renewal (attracting and training younger farmers, upskilling existing operators, and facilitating orderly succession) is, therefore, a critical enabling condition for realizing the efficiency and environmental gains identified by the DEA results.

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High environmental efficiency scores reflect the successful integration of sustainable farming practices that maximize output while minimizing environmental impacts. On the other hand, DMUs with lower environmental efficiency scores indicate inefficiencies in resource utilization, leading to higher environmental burdens relative to their output. These findings align with studies like De Koeijer et al. (2003) and Leite-Moraes et al. (2023), which emphasize the importance of environmental efficiency in promoting sustainable agricultural systems. The variability in environmental efficiency suggests that while some DMUs are operating sustainably by design, others face challenges related to overuse of inputs, limited access to efficient technologies, or poor resource management. For example, the high environmental efficiency scores of DMUs 3 and 5 demonstrate that achieving both economic and environmental goals is possible, offering sustainability benchmarks for other farming units. Improving the environmental efficiency of underperforming DMUs could involve strategies such as enhancing farmer education on sustainable agro-ecological practices, promoting access to eco-friendly inputs, and implementing policies to incentivize resource conservation. The adoption of precision farming practices could also reduce input wastage and minimize environmental harm, as suggested by (Gallardo, 2024).

Soil and water conservation

Healthy soil and water conservation directly affect the technical efficiency of farming operations by influencing nutrient uptake, crop growth, and overall biomass production (Shahbaz, Haq and Boz, 2022). Insufficient water limits plant metabolism and reduces yield potential, while excessive water can lead to nutrient leaching, root diseases, and soil structure degradation (Fontes, 2020). Efficient water management practices, such as precision irrigation and rainwater harvesting, ensure that crops receive the right amount of water at the right time, maximizing productivity and resource use efficiency (Gyimah et al., 2020; Forster et al., 2022). Case studies from this research demonstrate that farms employing rainwater harvesting systems and no-dig farming methods achieved significantly higher efficiency scores. By minimizing water wastage and enhancing soil moisture retention, these farms exemplify the benefits of integrating sustainable water management into agricultural practices.

From an environmental perspective, soil and water conservation contribute to sustainability by mitigating the adverse effects of water scarcity and runoff (Ingrao et al., 2023). Practices such as no-dig farming, agroecology, and permaculture improve soil health by enhancing organic matter content and water-holding capacity (Reza et al., 2025). This not only reduces reliance on external irrigation sources but also fosters resilience against droughts and erratic rainfall patterns (Ingrao et al., 2023). Environmental efficiency metrics from the study highlight the critical role of water management in achieving sustainability. Farms with efficient water use practices exhibited lower environmental footprints, demonstrating that balancing productivity with ecological conservation is achievable (Hashemi et al., 2024). Moreover, these practices align with global sustainability goals by conserving water resources, protecting soil ecosystems, and reducing greenhouse gas emissions associated with water-intensive farming operations (Saleem et al., 2024).

Seasonal soil water availability

Seasonal variations in soil water availability significantly impact agricultural efficiency and sustainability (Mukherjee, 2021). During the short growing season in regions like Western Newfoundland, efficient use of available soil water is crucial for maximizing crop yields. Periods of high soil water content following snowmelt or heavy rainfall support rapid growth, but excessive moisture can lead to waterlogging and reduced soil aeration, negatively affecting plant roots and microbial activity (Hannah et al., 2020). Conversely, drier periods during late summer or insufficient moisture retention pose challenges to maintaining productivity. Addressing these seasonal fluctuations requires adaptive practices such as timely crop planting, use of cover crops to enhance water retention, and efficient drainage systems to prevent waterlogging (Habib-ur-Rahman et al., 2022; Grigorieva, Livenets and Stelmakh, 2023). By aligning farming practices with seasonal soil water dynamics, farms can optimize resource use, reduce waste, and enhance sustainability in agricultural systems.

Climate change impact on agricultural efficiency

Climate change significantly impacts the efficiency metrics assessed in this study—technical, allocative, cost, scale, and environmental efficiency by altering the foundational conditions of agricultural production. In regions like Western Newfoundland, farmers face challenges from freeze–thaw cycles, fluctuations in growing degree days, and an increase in very hot and wet days, all of which disproportionately affect field crops, particularly potato farming. These climatic shifts disrupt crop growth cycles, reduce soil health, and exacerbate water stress, making it more difficult for farms to optimize input use and achieve technical efficiency. Allocative efficiency is hindered as resource allocation becomes more unpredictable due to the rising costs and variability of critical inputs like water and fertilizers. Cost efficiency is similarly affected by increased expenditures on irrigation systems, climate-resilient crops, and pest control measures required to adapt to these changing conditions. Scale efficiency suffers as smaller farms may struggle to remain viable amidst these pressures, while larger farms face challenges in maintaining consistent outputs. Environmental efficiency is directly impacted as intensified input use and carbon emissions from mechanized and energy-intensive adaptations become necessary. Additionally, King et al. (2018) found evidence of a northern shift in agriculture driven by rising temperatures, further altering regional farming practices and efficiency dynamics. These changes highlight the urgent need for adaptive strategies that enhance efficiency while mitigating the impacts of climate change, ensuring the resilience and sustainability of agricultural systems in the face of these ongoing challenges.

Integration of economic, environmental, and social dimensions in the DEA model

The DEA framework explicitly incorporates all three sustainability pillars through its choice of inputs, outputs, and contextual variables. Economically, the model includes key farm inputs like land, labor, seeds, fuel, and other capital inputs—these represent major cost factors and productivity drivers—and uses outputs such as farm revenue and crop yield to capture profitability and production performance. Technical, allocative, cost, and scale efficiency scores are computed to reflect each farm's economic efficiency, ensuring that the DEA results speak to economic viability in terms of resource use and cost optimization. Environmentally, the analysis adds an environmental efficiency metric that accounts for the ecological impacts of farming inputs (e.g., fertilizer, pesticides, energy use) relative to outputs. In practice, this means that inputs with high environmental footprints are considered in how

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efficiently farms minimize negative impacts per unit of output, and an output like *crop residue* is included as a proxy for soil health and nutrient recycling, linking productive output with long-term ecological stewardship. Socially, the model represents human and community factors through labor-related inputs and farm-characteristic variables: labor use (in quantity and quality) is directly included, reflecting the contribution of human capital, and the study considers workforce attributes (such as gender participation in farm labor) and farmer characteristics like experience, age, and education as part of the broader analysis. These socio-economic factors, incorporated via the DEA inputs or in a supplementary regression analysis, ensure that the framework acknowledges labor availability, know-how, and equitable participation when evaluating sustainability. By aligning specific inputs and outputs with each sustainability pillar in this way, the DEA model provides a balanced evaluation of economic viability, environmental responsibility, and social well-being for the farms under study. However, broader social dimensions of sustainability, such as equity, well-being, community cohesion, and governance, are not directly quantified within the DEA framework due to data limitations. Accordingly, the social dimension in our empirical analysis should be interpreted cautiously and in alignment with the scope of the available dataset.

Government support

Government support is pivotal for transitioning the agricultural sector in NL toward sustainable and efficient practices. This study highlights several targeted and region-specific policy implications that can strengthen the environmental, economic, and social performance among small-scale farms in the province.

Expand targeted financial incentives and input subsidies

To address the high-cost barriers for adopting sustainable inputs and technologies in NL's smallholder farms, financial support must be localized and specific (CA, 2025). The provincial government can:

- Provide cost-sharing programs for precision agriculture tools like soil sensors and moisture-efficient irrigation systems (e.g., drip kits).
- Subsidize environmentally friendly inputs, including organic fertilizers, cover crops, and low-emission fuels, through adaptations of existing programs like the Agri-Environmental Program or the Canadian Agricultural Partnership (CAP).

Leverage and scale up existing programs (e.g., living labs)

Newfoundland is uniquely suited to benefit from existing innovation-driven models. One key example is the Living Lab initiative, piloted in NL since 2021, which can be scaled up to include more farm clusters, especially in Cormack, Codroy Valley, and so forth This would foster co-development of best practices and farm-level experimentation in soil health, biodiversity, and climate resilience.

Strengthen and modernize extension services

Due to the province's dispersed rural geography and limited human capital, conventional extension models are insufficient. Government efforts should include:

- Mobile advisory units to serve isolated farming communities.
- Free access for farmers to digital knowledge platforms, courses, printed textbooks, and helplines to deliver real-time agronomic advice.
- Embedding sustainability officers in regional offices to guide eco-efficiency practices and interpret performance results like those from DEA evaluations.

Align policy with DEA findings on efficiency

This study's DEA results provide actionable evidence for identifying performance gaps across provincial farms. Government support should:

- Prioritize technical assistance for farms with sub-optimal DEA scores, especially in eco-efficiency and cost-efficiency.
- Support benchmarking networks that encourage knowledge exchange between high-efficiency and low-efficiency farms.
- Use DEA diagnostics to design precision policy interventions tailored to farm types, input-use patterns, and ecological zones.

Support resilience, food security, and social sustainability

Beyond environmental goals, NL's agriculture also plays a vital role in:

- Enhancing rural development and maintaining livelihoods in remote regions.
- Strengthening food security, especially given the island's high level of dependency on imported food.
- Promoting social sustainability by supporting aging farmer populations and encouraging youth participation through education and innovation grants.

Broader challenges and transitions

Beyond the immediate inefficiencies identified in this study, the agricultural sector in NL faces broader, interconnected transitions that threaten its long-term sustainability. First, the advanced age of farmers and the widespread lack of succession planning are a concern, reflected in the significance of the 'Age' and 'Experience' variables in our models, which pose a direct threat to the stability of the provincial labor force and the continuity of farm operations. Without a new generation of farmers, knowledge transfer and operational sustainability are at risk.

Second, contemporary farmers are simultaneously navigating a triple transition:

i. The agro-ecological transition to sustainable practices that protect biodiversity and ecosystem functions;
ii. The energy transition to decarbonize operations through renewable energy and reduced fossil fuel dependence; and
iii. The digital transition to adopt precision agriculture and IT solutions for improved efficiency.

The findings of this study, particularly the gaps in allocative, cost, and environmental efficiency, demonstrate that most small-scale farms lack the capital, capacity, and risk tolerance to manage these complex transitions alone. Therefore, government support is not merely beneficial but essential. Policy interventions must be holistic, addressing not only input optimization but also actively supporting youth attraction and training programs to secure a future labor force, while facilitating investments in green infrastructure, renewable energy, and digital technologies. This integrated support is critical for building a resilient and sustainable agri-food system in the province.

Limitations and future research

One limitation of this study is the reliance on a small sample of available data, which may not fully capture the complexity of

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agricultural input usage and efficiency across different contexts or geographic regions. The study focuses on a specific set of inputs and outputs, which may not encompass all factors influencing agricultural productivity, such as weather conditions, soil quality, technological advancements, and local market conditions. Additionally, the study assumes that the cost-efficient and technically efficient input levels can be directly compared, which may not always be the case in real-world scenarios where market fluctuations, policy changes, and other external factors can influence input prices and usage. Another limitation is the use of average input use ratios, which may overlook variability and outliers that could provide more nuanced insights. Furthermore, although there are 37 farms in the western region of Newfoundland, the data were only collected from 15 farms, which may not be a representative sample of the entire farming community. The data were collected through a questionnaire survey, and the limited sample size could introduce biases or affect the generalizability of the findings.

To overcome these limitations, future research could employ longitudinal designs to monitor efficiency dynamics over multiple seasons, capturing year-to-year variability in input use, climate, and management practices. Additionally, expanding the sample size to include a broader range of farm types and geographic subregions across NL would enhance the generalizability of findings. A mixed-methods approach combining DEA with qualitative interviews or focus groups could also provide richer insights into farmer decision-making, adoption barriers, and sociocultural factors influencing sustainability. Facilitating the involvement of farmers in collaborations with provincial agriculture departments, co-ops, academic research initiatives, and local NGOs could facilitate broader participation, improve data accuracy, and support the co-development of context-relevant solutions.

Future research could explore several avenues to further enhance the sustainability and efficiency of agricultural practices in NL and beyond. One key area of investigation could be the integration of advanced technologies such as precision farming tools, which use data and automation to optimize input use and reduce environmental impacts. Additionally, studying the role of climate change in altering farming practices and the adaptability of different farm systems could provide critical insights into the long-term sustainability of the NL agriculture industry. Research could also examine the economic and social factors influencing farm efficiency, including access to capital, knowledge, renewable energy sources, and markets. Investigating the adoption of alternative farming methods, such as agroecology, agroforestry, integrated farming, or regenerative agriculture, could also provide valuable comparisons with traditional farming practices. Furthermore, future studies could focus on improving the scalability of sustainable practices by analyzing farm operations of various sizes and their feasibility in different regions. Finally, cross-disciplinary research that combines agronomy, economics, and environmental sciences, or transdisciplinary approaches that co-create knowledge by integrating insights from various academic disciplines and social partners, could offer a more comprehensive understanding of the factors that contribute to agricultural sustainability and resilience in the face of evolving environmental and market conditions.

Conclusion

This study provides an assessment of agricultural sustainability in the Canadian province of NL by focusing on the technical, allocative, cost, and environmental efficiency of a sample of farms located in Western Newfoundland. The findings demonstrate that most farms operate with high technical efficiency, highlighting their effective use of available resources. However, disparities in the cost, allocative, scale, and environmental efficiency reveal significant room for improvement, particularly in optimizing input utilization and minimizing environmental impacts. Factors such as excessive chemical fertilizer overuse and suboptimal scaling were identified as key contributors to inefficiency, while land optimization, quality seed use, and regular maintenance emerged as drivers of enhanced productivity and efficiency. Similarly, the integration of environmental efficiency metrics into the analysis underscores the importance of balancing economic performance with environmental sustainability in agriculture, a social-ecological system that thrives on the life-sustaining ecological services available in nature. High-performing farms can serve as benchmarks for implementing sustainable farming practices, such as precision farming, targeted input application, and resource conservation, while underperforming farms can highlight areas for targeted interventions. The study emphasizes the potential of advanced technologies, government support, and farmer education in promoting sustainable practices and reducing the environmental footprint of farming operations.

Localized insights from NL's unique agricultural context provide actionable strategies for addressing region-specific challenges, such as small-scale operations and resource constraints. By identifying inefficient farms, agricultural extension specialists can implement targeted interventions to enhance efficiency and promote sustainability. Policymakers can leverage these findings to tailor policies that encourage sustainable farming practices and improve farm efficiency. Furthermore, the study identifies opportunities for further research, including the role of climate change, the adoption of alternative farming methods, and the integration of advanced technologies to enhance farming resilience. This study makes several key contributions to the literature on agricultural sustainability. First, it integrates environmental efficiency into a multi-dimensional DEA framework applied in a cold-climate, boreal agricultural context, an area that remains underexplored in existing research. Second, it identifies high-performing sustainable farms within Western Newfoundland that can serve as practical benchmarks for environmental and economic best practices. Third, it provides localized policy insights tailored to small-scale farming systems in climate-constrained regions, emphasizing the importance of adaptive infrastructure, extension services, and regional innovation programs. These contributions advance the empirical application of DEA and offer strategic guidance for improving agricultural sustainability in similar peripheral and northern regions. By bridging the gap between efficiency and sustainability, this study lays the groundwork for developing a resilient agrifood system in the NL province. It highlights the critical need for collaboration among farmers, researchers, and policymakers to foster innovative thinking in the efficient use of resources and ensure long-term agricultural sustainability in the face of evolving environmental and economic challenges.

Supplementary material. To view supplementary material for this article, please visit http://doi.org/10.1017/S1742170526100350.

Data availability statement. All data that support the findings of this study are included within the article.

Author contribution. Conceptualization: K.I., G.S.; Data curation: K.I.; Formal Analysis: K.I.; Funding acquisition: L.G.; Methodology: K.I., G.S., Ja.D., L.G.; Project administration: L.G.; Supervision: G.S., J.D., M.C., L.G.; Validation: G.S., Ja.D., M.C., Jo.D., L.G.; Visualization: K.I.; Writing—original draft: K.I.; Writing—review, and editing: G.S., Ja.D., M.C., Jo.D., L.G.

Funding statement. This research was supported by multiple funding sources, including the Government of Newfoundland and Labrador's Department of Industry, Energy, and Technology (IET; Grant No. 5404-1962-102), and an SBM grant from Memorial University of Newfoundland.

https://doi.org/10.1017/S1742170526100350 Published online by Cambridge University Press

Competing interests. The authors declare that they have no affiliations with or involvement in any organization or entity with a financial interest in the subject matter or materials discussed in this manuscript.

Ethics statement. This research received ethical approval from the Grenfell Campus Research Ethics Board (GC-REB) due to the involvement of human participants.

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