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Exploring the adoption of beneficial management practices on leased first nations agricultural lands: a modelling approach for integrated nitrogen management

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In Canada, beneficial management practices (BMP) are being used to reduce agricultural greenhouse gas emissions, manage environmental risks, and contribute to national climate goals. A key component of BMP is effective nitrogen (N) fertilizer management, which is essential for improving both soil health and economic profitability and reducing environmental risk. This research employed a modelling approach to evaluate the potential adoption of BMPs related to nitrogen fertilizer management in canola production on agricultural lands on the Mistawasis Nêhiyawak First Nation (MNFN) reserve in central Saskatchewan. The MNFN lands have a unique historical and cultural perspective, where systemic barriers to modern agricultural adoption have limited participation of local farmers and shifted agricultural decision making to non-Indigenous farmers who rent Indigenous governed lands—a common arrangement across most First Nations in the region. The modelling exercise serves as a starting point for engaging with tenant farmers on future nitrogen management strategies that more closely reflect community values and desired outcomes for their lands, including the balance of economic viability with environmental stewardship. Two distinct fertilizer application scenarios were simulated: inorganic nitrogen fertilizer and the integrated use of organic and inorganic fertilizers as BMP for canola yield. Results indicate that the combined approach within the context of the integrated nitrogen management regime could increase crop yields. The economic evaluation highlighted the financial viability of nitrogen management BMPs, leading to higher net present values (NPV). Sensitivity analysis revealed the impact of market fluctuations on economic indicators, particularly prices and costs, indicating that BMPs offered greater resilience against price volatility and rising input costs. This study contributes to ongoing efforts to improve nitrogen fertilizer practices in the region and to facilitate adoption of BMPs, particularly on First Nation reserves in Canada, with spillover benefits for the Canadian agricultural sector.

KEYWORDS

beneficial management practices, climate, fertilizer management, canola, first nations

1 Introduction

In 2021, the Government of Canada launched the Agricultural Climate Solutions (ACS) – Living Labs Program. The aim of the ACS program is to develop and test innovative agricultural solutions for reducing greenhouse gas emissions and sequestering carbon in real-world conditions. A fundamental component of the ACS program is the testing and deployment of Beneficial Management Practices (BMPs), which are defined as agricultural practices that promote sustainable land stewardship and maintain or increase farm profitability. Examples of BMPs include the integration of organic and inorganic fertilizers, integrated pest management systems, crop rotation, zero tillage, irrigation, and cover cropping (Kadykalo et al., 2020). The adoption of BMPs is considered essential for enhancing agricultural productivity, reducing environmental impacts, and improving farm resilience in the face of climate change (Liu et al., 2018; Therond et al., 2017). These practices promote sustainable agriculture by supporting soil health, maintaining organic matter, and encouraging nutrient cycling (Rahman et al., 2020), while minimizing waste and environmental damage, that together can foster long-term sustainability. The adoption of these practices is therefore considered pivotal for advancing climate-smart agricultural systems in Canada (Stavi and Lal, 2013; Efroymson et al., 2021).

To hasten the adoption of BMPs, the federal government has incentivized their uptake (Liu and Brouwer, 2022), promising both profitability and environmental sustainability. However, there remains limited understanding of the constraints at the farm level that might hinder widespread BMP adoption (Anantha et al., 2021). These constraints may be further compounded on First Nations reserves, where agricultural land is often leased to non-Indigenous farmers. In Saskatchewan alone, where 80% of Canada's agricultural land base is situated (St Pierre and Mhlanga, 2022), First Nations steward over 350,000 ha of cropland (Yu et al., 2025), with most of this land rented to non-Indigenous farmers (Natcher and Allen, 2017). In such arrangements, decisions about land management are shaped not only by agronomic and economic considerations, but also by the dynamics of land governance, cultural values, and relationship with the lessee farmer. Compared to farmers operating on their own land or non-Indigenous rented land, lessee farmers on reserve lands may face different incentives, expectations, and limitations. The research presented in this paper addresses these complexities by using a modelling approach to simulate nitrogen fertilizer BMPs in canola production—the cash crop grown on the largest number of acres in Saskatchewan—on leased reserve lands. The modelling approach allows for the evaluation of both agronomic performance and economic viability under different fertilizer scenarios, providing a low-risk, data-informed basis for dialogue between Indigenous land managers and lessee farmers. This approach supports more collaborative decision-making that reflects community priorities for profitability and environmental sustainability.

This study was made possible by the Bridge to Land, Water, Sky (BTLWS) Living Lab, which is one of fourteen Living Lab projects across Canada funded by the ACS Program. The goal of BTLWS is to reimagine farming systems on First Nations reserves, advancing improved livelihoods through climate-smart management.¹ This

specific study was conducted in collaboration with the Mistawasis Nêhiywak First Nation (MNFN), whose reserve lands are located in the Treaty 6 region of central Saskatchewan. Although the research focuses on a specific location, insights from this study are also transferable to other Indigenous communities across the Prairie region who face similar land leasing arrangements and are seeking to align land use with community values. For the MNFN, BMPs are being considered as pathways toward more sustainable land management practices for reserve lands, and insights from this study offer spillover benefits for the broader Canadian agricultural sector.

2 Beneficial management practices—nitrogen management

In Canada, BMPs are being used to reduce agricultural greenhouse gas emissions, manage environmental risks, and contribute to national climate goals (France et al., 2019; Ezui et al., 2022). This has included farm-level strategies to mitigate soil nitrogen losses (Rasouli et al., 2014) via nutrient runoff and chemical leaching (Warrington et al., 2017). A key component of BMPs is effective nitrogen (N) fertilizer management, which is essential for improving both soil health and economic profitability and reducing environmental risk. While nitrogen promotes plant growth and increases yields, it also contributes to nitrous oxide (N₂O) emissions, a potent greenhouse gas (Xu et al., 2012; Lew et al., 2018; Canola Council of Canada, 2022). To mitigate environmental impacts and maximize productivity, the 4Rs of Nutrient Stewardship—Right Source, Right Rate, Right Time, and Right Place—provide a framework for optimizing nitrogen use efficiency (NUE).

This science-based strategy improves nutrient use efficiency, enhances crop yields, and reduces environmental impacts such as nutrient runoff and greenhouse gas emissions (Fixen, 2020; Fertilizer Canada, 2024). The 4R framework is widely adopted across Canada, tailored using local soil and climate data, and supported by extension services to optimize fertilizer application provincially (Canola Council of Canada, 2025). Globally, fertilizer BMP adoption varies as Sub-Saharan African farmers often rely on organic inputs due to access and affordability constraints (Policy Center for the New South, 2019), over-application in South Asia leads to soil degradation (Kumar et al., 2020), and Latin American producers increasingly implement climate-smart practices such as precision agriculture and conservation tillage (Food and Agriculture Organization, 2021). These instances show diverse BMP strategies worldwide and highlight how the 4R framework provides a robust, adaptable model for sustainable fertilizer management globally.

The 'Right Source' principle recommends selecting fertilizers based on crop needs and soil fertility, with nitrogen-intensive crops benefiting from synthetic fertilizers and organic sources like manure or compost improving soil structure and microbial health. The 'Right Rate' involves applying nitrogen at levels that meet crop demands without excess, minimizing nitrogen leaching and reducing N₂O emissions. Precision agriculture tools, including soil fertility mapping and variable-rate fertilizer application, are critical for optimizing nitrogen use (Canola Council of Canada, 2022). The 'Right Time' ensures that nitrogen is applied at key growth stages, such as early in the season or through split applications, to align nutrient availability

¹ <https://www.bridgetolandwatersky.ca>

with crop uptake patterns, reducing nitrogen losses. Lastly, the 'Right Place' focuses on efficient fertilizer placement, such as banding or side-dressing, to reduce nutrient losses and enhance uptake. This includes proper seed and fertilizer separation to avoid seedling damage and ensuring nutrient availability (Canola Council of Canada, 2022).

To mitigate the environmental impact of nitrogen fertilizer use, integrating organic and inorganic nitrogen sources can sustain crop productivity while improving soil health. Studies have found yields can increase between 12.5 and 44.6% when replacing a portion of inorganic fertilizers with organic alternatives, such as manure and compost, in crop production (Zhou et al., 2022). While these practices show yield potential, their adoption is limited by factors like the availability of organic fertilizers and additional costs (Tyagi et al., 2022). Indeed, in the context of Canadian Prairie agricultural systems, the adoption of organic nitrogen inputs remains limited due to several key challenges. Livestock operations that produce manure are located far from grain farms, making access uneven across the region. Most grain farms are equipped for synthetic fertilizer application and lack the infrastructure to handle and apply organic materials efficiently. Agronomically, canola has a high nitrogen demand and is sensitive to timing of nutrient supply; organic sources release nitrogen slowly and unpredictably, which may not align well with the crop's peak nitrogen demands, potentially limiting yield. These factors, combined with limited incentives and lack of region-specific extension support, contribute to the low adoption of organic nitrogen sources in prairie grain and canola systems. The widespread use of inorganic nitrogen fertilizers continues to pose significant environmental risks, affecting soil, water, and air quality (Tyagi et al., 2022). Excessive nitrogen poses a risk to biodiversity in soil and water (United States Environmental Protection Agency, 2021), can negatively impact human and livestock health (Tyagi et al., 2022), and is a source of N₂O emissions. In response, Canada's ACS Living Labs program aims to reduce these emissions by promoting climate-smart nutrient management practices. Mitigating strategies include organic amendments, slow- and controlled-release fertilizers, and nano-enabled fertilizers (Tyagi et al., 2022). Economic optimum nitrogen rates (EONR) vary with soil and environmental conditions, with estimates ranging from 84 to 101 kg N/ha in the Brown soil zone to 146–166 kg N/ha in the Black soil zone (Barker, 2024). These application estimates are typically based on factors such as yield response, nitrogen prices, and canola seed prices. However, environmental conditions such as heat stress and thermal accumulation can significantly influence EONR, indicating the importance of site-specific evaluations before application (Barker, 2024). Given canola's status as Canada's most economically important crop, and its dominance in Saskatchewan where this study is conducted, optimizing nitrogen management is essential for promoting both economic efficiency and environmental sustainability.

Despite the currently low adoption of organic nitrogen sources in Prairie canola systems, particularly at the large scale typical of most farms, First Nations may have a unique opportunity to facilitate their adoption. While there are limited number of community grain farmers, there are community members who raise small herds of cattle, which could provide more localized access to manure inputs. This proximity to organic nutrient sources presents an opportunity to integrate manure into cropping systems, particularly through partnerships with tenant farmers operating on First Nations lands.

Such collaborations could support more sustainable nutrient management practices while enhancing soil health and reducing reliance on synthetic fertilizers.

3 Materials and methods

3.1 Study area

This research was conducted in collaboration with the Mistawasis Nêhiyawak First Nation (MNFN) who leads the BTLWS Living Lab. The MNFN has a registered population of 3,045 citizens, 1,277 of whom live on a 15,486 ha reserve in central Saskatchewan, Canada. As of 2025, roughly 6,194 ha (40 percent) of the reserve lands are farmed; all of the grain production is performed by settler farmers under lease arrangements with MNFN, while there are a few MNFN members who raise cattle on a small scale. The involvement of MNFN in agriculture, as well as other First Nations in western Canada, has been shaped by a complex history of cultural, political and environmental change. Following the near extermination of the plains bison (*Bison bison bison*) in the late 19th century, the MNFN was forced to adapt to its changing economic and cultural conditions, by adopting agriculture as an alternative means of subsistence. The inclusion of agricultural provisions in Treaty 6 were made only after the insistence of Chief Mistawasis who recognized that agriculture afforded one of the few remaining opportunities for survival. The calls for agricultural provisions by Chief Mistawasis and other First Nations leaders were generally welcomed by treaty commissioners who saw agriculture as the most expedient route to acculturation and ending what they characterized as the 'Indian problem' in Western Canada. For these reasons it was agreed that agricultural provisions would be included in Treaty No. 6 (1876), including 640 acres allocation of land for a family of 5, 4 hoes, 2 spades, 2 scythes, 1 whetstone, 2 hay forks, 2 reaping hooks, per family, and 1 plough for every 3 families (Stoneberg Holt, 2018; Lux, 2001).

Notwithstanding this material support, federal policies, such as the Indian Act, the peasant farm policy, and the pass-and-permit systems, imposed severe restrictions on First Nations agriculture by limiting access to essential resources, including credit and land ownership rights, and enabling the loss of prime agricultural lands through forced surrenders and leasing arrangements (Arcand et al., 2020). This legacy has left over 80% of First Nations agricultural land leased to non-Indigenous producers, limiting Indigenous control over farming decisions, including the implementation of BMPs that could enhance productivity and sustainability of First Nations lands (Natcher and Allen, 2017; O'Faircheallaigh and Corbett, 2005). Decision-making on leased lands is largely guided by settler lessees, with minimal input from the First Nation community. Understanding this socio-economic and governance context is critical for interpreting agricultural practices and assessing the potential adoption and effectiveness of BMPs within the MNFN community.

The MNFN reserve is situated in Saskatchewan's Black soil zone, one of the province's most productive agricultural regions due to its high organic matter content and favourable microclimate. This soil type supports high-yield cropping systems, with canola-wheat rotations being the most practiced due to their adaptability and economic value in the region. While pulses such as peas are also grown, they are generally less prevalent. To capture these conditions,

two adjacent fields—Field A (53 ha in the northeast) and Field B (43 ha in the northwest)—were selected as representative MNFN-governed agricultural lands. These two fields are light in soil texture, which poses challenges to crop production as moisture retention is limited. Both fields are rated as Class 3 lands under Canada’s agricultural capability classification system, developed by Agriculture and Agri-Food Canada through the Canada Land Inventory (CLI) using detailed soil survey data. Class 3 soils have moderately severe limitations that restrict the range of crops or require special conservation practices to maintain productivity (Agriculture and Agri-Food Canada, 2013). The marginal soils of these two fields are not unlike many First Nations where there is a higher proportion of marginal cropland on reserves (Yu et al., 2025). These sites reflect prevailing characteristics and production practices and were made available by the MNFN leadership to investigate the influence of soil characteristics, particularly organic matter content, on crop productivity. The fields were chosen based on farmer-reported nitrogen fertilizer practices, with a typical rate of 135 kg/ha, providing a realistic basis for modeling crop responses.

The study employed the Decision Support System for Agrotechnology Transfer (DSSAT) model to simulate two fertilizer application scenarios: a business-as-usual scenario based on actual production data provided by the tenant farmer, and a hypothetical BMP scenario involving the integrated use of organic and inorganic nitrogen sources. This approach enables an assessment of BMP adoption potential under the actual constraints and behaviors of farmers renting MNFN land, offering insights that are both locally relevant and transferable to similar Indigenous communities and regions with comparable environmental characteristics.

3.2 Data sources

This study utilized a comprehensive dataset to model the impact of management practices on canola yield. Soil properties, including soil depth, texture, pH, organic carbon, and nitrogen content, were measured through in-field sampling of surface (0–15 cm) and subsurface (15–60 cm) soils, which occurred in April 2021, and laboratory analysis, with additional area-specific data sourced from the Saskatchewan Soil Information System (n.d.) (see Table 1). Sampling procedures were designed to capture representative soil variability across each field, with measurements taken at multiple points for each soil type. The rationale for including soil texture, pH, and depth is that these parameters directly influence nutrient availability and crop response to fertilizer, which in turn determines the effectiveness of BMPs. These distinct soil characteristics of Fields A and B were essential for accurately simulating realistic crop growth and yield responses under varying management scenarios.

Business-as-usual agronomic management data for Fields A and B, including planting and emergence dates, planting density, row spacing, and fertilizer application, were provided by the farmer through the annual farm records. The data were sourced from crop reports spanning the 2017–2023 growing seasons, ensuring that field conditions and management practices reflect multi-year trends.

Weather data for 2017–2023 were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database using

TABLE 1 Sampled soil data from Fields A and B of the study area.

Fields	Field A	Field B
Top Soil Depth (cm)	12	19
% Clay	11	3
% Silt	11	9
% Sand	78	88
Soil organic carbon (%) (Mg ha ⁻¹)	(1.07) (21.47)	(1.55) (33.87)
pH in water	4.76	4.49
Total Nitrogen (%)	0.18	0.15
Soil Texture	Sandy Loam	Sand
P ₂ O ₅ (mg kg ⁻¹)	83.64	28.05
Bulk density (g cm ⁻³)	1.34	1.46

the study area coordinates (latitude 53.147° N, longitude −106.797° W) to ensure site-specific accuracy for the Mistawasis Nêhiyawak community. Elevation (533 m) from Statistics Canada was incorporated to refine the dataset. The POWER Docs tool provided daily observations of key parameters influencing canola growth, including maximum and minimum temperature (TMAX, TMIN), solar radiation (SRAD), precipitation, wind speed, and relative humidity (RHUM). Future weather for 2023–2040 was simulated using normal distribution methods based on historical daily means and standard deviations. Daily values were generated by randomly sampling from these distributions while preserving seasonal patterns, ensuring that simulated weather reflects representative intra-annual variability. While the 5-year historical dataset may not capture long-term climate cycles, regional and global climate projections for Saskatchewan indicate that temperature and precipitation trends over this period are broadly consistent with projected patterns (Environment and Climate Change Canada, 2022). By integrating site-specific NASA POWER data with these statistically generated projections, the simulations provide a robust representation of local climate conditions suitable for DSSAT crop modeling and scenario analysis.

3.3 Crop modeling simulation

The Decision Support System for Agrotechnology Transfer (DSSAT) is a process-based crop simulation software developed by an international research consortium (Jones et al., 2003). It integrates multiple cropping system models (CSMs) to evaluate crop growth, development, and productivity under defined environmental and management conditions. DSSAT allows detailed monitoring of soil and crop parameters, including water, carbon, and nitrogen levels, while accounting for dynamic interactions between soil, plants, weather, and management practices. Unlike other process-based models such as APSIM (Agricultural Production Systems iMulator) model, DSSAT can incorporate genotype-specific crop parameters and real CO₂ levels from the Mauna Loa Observatory, providing robust and reliable yield predictions. DSSAT has been widely used in agricultural research to simulate yield responses, soil carbon retention, nitrogen cycling, and climate change impacts (Li et al., 2015; Adeyemi, 2019;

He et al., 2018, 2021), demonstrating its suitability for evaluating complex crop-soil interactions. In this study, DSSAT model specifically the CRGRO048 model was employed to assess canola growth and yield under two nitrogen fertilizer scenarios on Mistawasis Nêhiyawak First Nation (MNFN) reserve lands. Real-world crop management data, including fertilizer application rates, and harvest practices, were incorporated to reflect actual farmer behavior. Simulations included Baseline (business-as-usual) and the integrated nitrogen management BMP scenario, allowing assessment of potential BMP adoption under local socio-economic and historical constraints. Prior studies (Basak and Alam, 2013; Ngwira et al., 2014; Huffman et al., 2015) further support DSSAT's effectiveness in similar applications.

With the exception of nitrogen management, other management practices were consistent for both fields to isolate the effects of soil properties and simulated BMP adoption on canola yield, allowing a precise assessment of environmental and management interactions. The simulated BMP fertilizer management scenario followed a combined organic-inorganic approach. Approximately 4.67 tons (4,666.67 kg) of composted manure were incorporated to supply 70 kg ha⁻¹ of nitrogen, based on a 1.5% nitrogen content (Clemson University Agricultural Service Laboratory, 2025). This organic amendment provided 50% of the nitrogen requirement, while the remaining 50% was supplied through usual inorganic fertilizer, maintaining the total nitrogen applied in the baseline scenario (135 kg ha⁻¹). Other nutrients applied included phosphorus (80 kg ha⁻¹), potassium (20 kg ha⁻¹), and sulfur (40 kg ha⁻¹). The planting density, row spacing, and planting depth were also standardized across both fields (90 plants m⁻² at seeding, 85 plants m⁻² at emergence, 20 cm row spacing, 1.2 cm depth). These detailed farm management practices from the farmers report were incorporated into the DSSAT simulations to evaluate crop responses under accurate local conditions and farmer practices.

A paired *t*-test was performed using Stata statistical software to evaluate the accuracy of the crop model in simulating crop growth stages and yield by comparing observed and simulated data from the 2017 growing season. This test is appropriate since it compares paired observations between observed and simulated values for the same location, thereby detecting systematic biases while validating variability in the simulation (Yang et al., 2014; Balkovič et al., 2013). The 2017 season was selected as the baseline year due to the availability of complete agronomic and weather data, providing a robust reference for model validation. Similar

studies have effectively used paired *t*-tests to confirm that simulation outputs do not differ significantly from observed values, supporting model reliability and accuracy (Suleiman et al., 2017). The test results in this study ($t(5) = -0.97$, $p = 0.38$) (see Table 2) indicate no statistically significant difference ($p > 0.05$) between observed and simulated values, reinforcing the conclusion that the model reliably represents real-world crop development and yield under varying management scenarios.

3.4 Evaluate the profitability and long-term economic viability of canola crop production

3.4.1 Estimation of benefit, NPV and BCR

A profitability analysis was conducted to compare a baseline scenario which involved applying 135 kg/ha of nitrogen exclusively through conventional inorganic fertilizer, and a BMP scenario that maintained the same total nitrogen rate but used a 50:50 blend of organic (compost) and inorganic sources. The analysis examined critical financial indicators such as net present value (NPV) and benefit-cost ratio (BCR), and the sensitivity or stability was justified by estimating the percentage variation (PV). These metrics help evaluate the long-term viability of strategies like applying the economic optimum nitrogen rate (EONR), enabling farmers to achieve high yield returns while minimizing input costs (Penot et al., 2021).

The NPV was computed using Equation 1, which discounts future benefits (B_t) to their present value based on the discount rate (d_r):

$$NPV = \sum_{t=1}^n \frac{B_t}{(1+d_r)^t} \quad \# \quad (1)$$

The BCR, presented in Equation 2, measures the ratio of discounted total benefits to discounted total costs:

$$BCR = \sum_{t=0}^n \frac{B_t}{(1+d_r)^t} / \sum_{t=0}^n \frac{C_t}{(1+d_r)^t} \quad \# \quad (2)$$

The Percentage Variation (PV), used to assess the sensitivity or stability of the estimated results, was calculated using Equation 3:

TABLE 2 A paired *t*-test comparing actual and DSSAT simulated data based on growing conditions.

Paired <i>t</i> test						
Variable	Observation	Mean	Standard error	Standard deviation	95% confidence interval	
Actual	6	620.938	570.664	1397.835	−845.9996	2087.876
Simulated	6	639.083	589.391	1443.707	−875.9945	2154.161
difference	6	−18.145	18.753	45.936	−66.352	30.062
mean (diff) = mean (Actual−Simulated)					<i>t</i> = −0.9676	
H0: mean (diff) = 0		Degrees of freedom = 5				
Ha: mean (diff) < 0		Ha: mean (diff)! = 0		Ha: mean (diff) > 0		
Pr (T < t) = 0.1888		Pr (T > t) = 0.3777		Pr (T > t) = 0.8112		

$$\text{Percentage Variation (PV)} = \frac{\text{Value under change} - \text{Actual Value}}{\text{Actual Value}} \times 100\% \quad (3)$$

Where B_t indicates the profit generated by the study farm annually over a 23-year timeframe, using Excel, this benefit is computed by subtracting the total costs incurred (C_t) from the farm revenue (R_t). Additionally, d_r denotes the discount rate of 8.68% utilized in the analysis (Islam, 2022; Marmanillo Mendoza, 2020), while t represents the number of years within the 23 years under consideration.

The discount rate was derived using the weighted average cost of capital (WACC) approach, as shown in Equation 4:

$$d_r = K_e W_e + K_d (1 - t_r) W_d \quad (4)$$

Where; d_r = Discount rate; K_e = Return on Equity (ROE) = 10.2% [obtained from Farm Credit Canada (FCC) (2018)]; W_e = Equity asset ratio = 80.5% [obtained from Marmanillo Mendoza (2020)]; K_d = Interest rate on debt = 3.64%; t_r = Income tax rate = 12.50% in Saskatchewan for taxable income between \$45,225 up to \$129,214 (based on Government of Saskatchewan (2018)) and W_d = Debt asset ratio = 14.9% [obtained from Statistics Canada (2017)].

The methodology enabled an estimation of benefits and cost, which quantified the financial viability from various fertilizer strategies. The benefit was calculated by multiplying canola yield, predicted using the DSSAT model under diverse management and weather conditions, and by the constant market price of CAD 0.73/kg. Costs were derived from fixed and variable inputs, detailed through an assessment of expenses associated with canola cultivation based on the Saskatchewan Crop Guide in 2024 (Saskatchewan Ministry of Agriculture, 2024), particularly concerning the application of inorganic fertilizer.

A partial budget analysis was also used to isolate the impact of fertilizer costs on overall financial outcomes, focusing on the primary cost differences between Baseline and BMP scenarios. Through these evaluations, MNFN producers will gain insights into the economic trade-offs involved, allowing them to make informed decisions that balance profitability with environmental impact (Economic Evaluation Working Group, 2017–2019).

Also, in evaluating the cost of applying nitrogen-based organic fertilizer, the current market prices for bulk compost ranged from \$30 to \$70 per ton, leading to direct material costs between \$140.10 and \$326.90 (HomeGuide, 2023). However, an estimated average cost of \$233.50 based on the material cost was used for the study. The analysis also considered the slow-release nature of compost, with only 33% of nitrogen typically available in the first year (Ohio State University Extension, 2016), indicating potential long-term benefits by reducing fertilizer needs in subsequent seasons.

The cost estimation did not include additional factors such as delivery fees, application costs, or broader impacts on soil health such as improved soil structure, water retention, and microbial activity. Although financing costs were excluded, scenarios involving larger initial investments or the need for financing could negatively affect profitability and reduce net present values, thereby influencing adoption decisions. While the initial investment for manure may exceed that of inorganic fertilizers, the study suggests that long-term

benefits such as enhanced soil fertility, improved crop quality, and greater environmental sustainability could justify the higher costs. If paired with local sources of manure from MNFN, the costs could potentially be mitigated. The Economic Evaluation Working Group emphasizes the importance of identifying appropriate cost–benefit information to support agrifood strategies and nutrition policies, enabling interventions that strengthen food systems and improve nutrition outcomes (Economic Evaluation Working Group, 2017–2019; Shanmugavel et al., 2023).

3.5 Sensitivity analysis

A sensitivity analysis was conducted to determine the estimate the potential financial impacts of applying BMPs. One of the primary components of the sensitivity analysis is the price sensitivity, which aims to assess how variations in canola prices influence the NPV and BCR for both the Baseline and BMP scenarios. Understanding the relationship between crop prices and economic performance is vital for producers who seek to optimize their returns. To achieve this, we examined a range of canola prices, specifically evaluating fluctuations of ± 10 and $\pm 20\%$ from the baseline price of \$0.73 per kilogram, as outlined in the Saskatchewan Crop Guide 2024 (Saskatchewan Ministry of Agriculture, 2024). By analyzing the NPV and BCR across this range of prices, we identified critical thresholds that significantly impact profitability. This analysis reveals the sensitivity of economic outcomes to market conditions. It equips producers with the knowledge to make informed decisions regarding adopting BMP technology in a dynamic pricing environment.

In addition to price sensitivity, a cost sensitivity analysis was conducted. This aspect focuses on assessing the impact of changes in input costs—such as fertilizers, compost, labour, and other relevant expenses—on the overall economic performance of canola production. Given the variability in input costs that farmers may encounter, understanding these dynamics is essential for long-term planning and investment decisions. To conduct this analysis, we adjusted the costs associated with nitrogen fertilizers and organic amendments, particularly compost, within realistic ranges of ± 10 and $\pm 20\%$. By observing the changes in NPV and BCR that result from these variations, we gained insight into how sensitive the project's economic outcomes are to fluctuations in input costs. This information is invaluable for producers, as it highlights the financial implications of adopting BMP practices, especially during rising agricultural input costs.

4 Results and discussion

4.1 Impact of fertilizer management practices on canola crop yield

The results as illustrated in Figures 1, 2 shows significant impacts from fertilizer management practices on canola yield, with apparent differences observed between the two fields in the MNFN reserve. Field A, with its sandy loam texture and higher clay content, shows more favourable conditions for nutrient retention, which supported crop resilience and improved yield performance under BMP scenario. These results are consistent with research that has focused on BMPs improving soil health, nutrient cycling and resource efficiency and

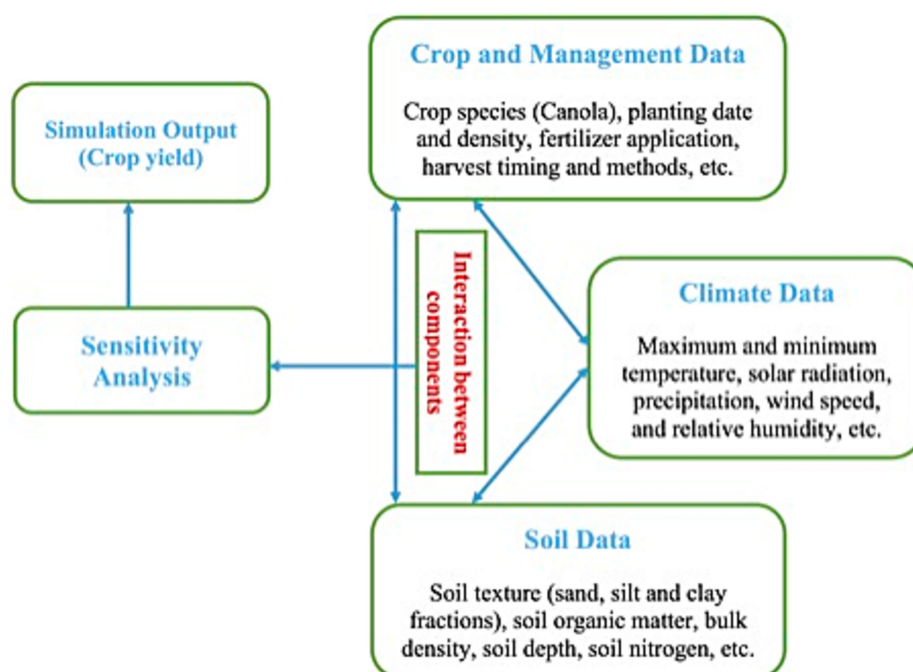


FIGURE 1
Overview of the DSSAT modular structure and simulation components source. Adapted from Jones et al. (2003).

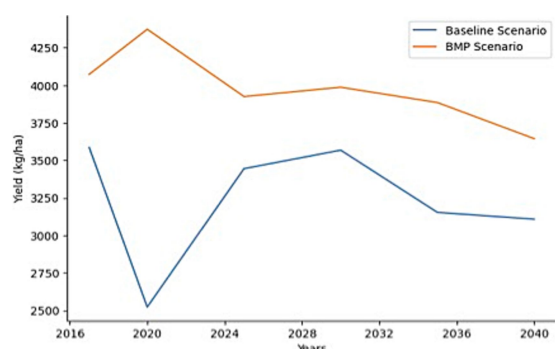


FIGURE 2
Canola yield under baseline and BMP fertilization scenario at Field A.

eventually increasing long-term agricultural sustainability (Liu et al., 2018; Rahman et al., 2020). However, despite the integration of organic and inorganic fertilizers, a decline in yield over the study period was still evident, indicating that increasing temperatures and climate change may continue to impact crop production, even under optimal management conditions negatively (Qiao et al., 2022; Wang et al., 2022).

In contrast, Field B, with its sand texture and low nitrogen content, faced significant challenges in nutrient retention and crop response to fertilizer applications. Despite applying BMPs, the field's high sand content and acidic pH restricted nutrient availability, resulting in a more pronounced yield decline. This emphasizes the critical role of soil properties in determining the effectiveness of BMPs, as shown in the literature (Adane et al., 2020; Rasouli et al., 2014). The fact that Field B could maintain a different amount of nutrients than Field A demonstrates

the need for better soil-specific nutrient management plans to maximize crop yields, especially in areas with low nutrient concentrations.

Nitrogen fertilizer management was crucial in both fields for optimizing yield while minimizing environmental impacts. The integration of organic and inorganic nitrogen sources, a strategy recommended by the 4R Nutrient Stewardship principles, also aligns with the findings of Zhou et al. (2022), who reported yield increment of 12.5 to 44.6% when organic fertilizers like manure and compost are incorporated. However, the challenges in obtaining organic fertilizers and their additional costs, as noted by Tyagi et al. (2022), limit the widespread adoption of this practice. The observed improvements in yield under the BMP scenario can be attributed to adherence to Right Source component of the 4R Nutrient Stewardship framework; field-specific fertilizer management considered the 'Right Source' by combining inorganic and organic nitrogen sources to enhance soil fertility and microbial activity. Combined organic and inorganic fertilizers can decrease the need for synthetic fertilizers, increase biodiversity and promote sustainable agriculture by reducing the environmental impact of nitrogen fertilizers, as noted by the United States Environmental Protection Agency (2021). These results illustrate the need to tailor fertilizer management to soil type and more comprehensive environmental variables at each location for optimal productivity and sustainability in canola farming (see Figure 3).

4.2 Economic impact of fertilizer management on canola crop production

The results presented in Table 3 show the financial performance of canola crop production under both the Baseline and BMP scenarios for Fields A and B, providing valuable insights into the economic benefits

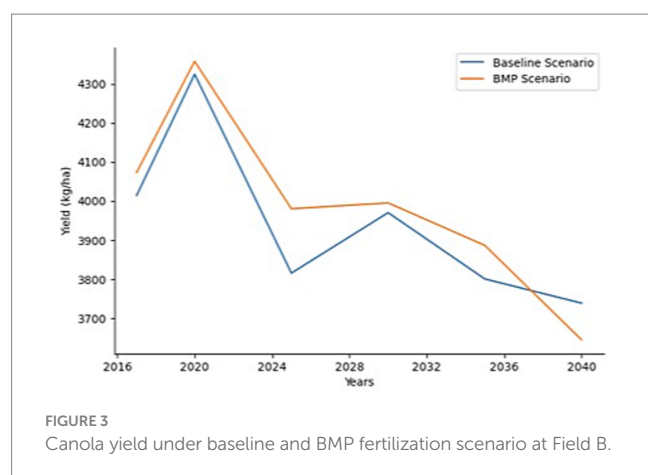


TABLE 3 Financial evaluation under the baseline and BMP scenarios for Fields A and B.

Field	Financial indicator	Baseline scenario	BMP scenario
Field A	NPV (CAD)	2925.10	3891.28
	BCR	1.51	1.69
Field B	NPV (CAD)	4765.55	4021.66
	BCR	2.47	1.75

of adopting sustainable farming practices. In Field A, the Baseline Scenario, which uses nitrogen fertilizer at 135 kg/ha, yields an NPV of CAD 2,925.10. However, when integrated organic and inorganic fertilizers, are adopted, the NPV increases significantly to CAD 3,891.28. This increase stresses the economic viability of BMPs, aligning with findings from Penot et al. (2021) and the Food and Agriculture Organization (1997), which suggest that sustainable practices like those incorporating the economic optimum nitrogen rate (EONR) can enhance long-term profitability by maximizing yield returns while minimizing input costs. The positive NPV under the BMP scenario indicates that farmers can generate surplus revenue, demonstrating the economic sustainability of BMPs despite the higher upfront costs associated with organic fertilizers. This is consistent with research by the Economic Evaluation Working Group (2017–2019), which emphasizes that economic evaluations, such as NPV, are crucial for assessing the long-term viability of agricultural practices, helping producers make informed decisions that balance profitability and environmental impact.

The economic benefits of BMP adoption, reflected in higher NPVs and BCRs, are closely linked to the implementation of the 4R Nutrient Stewardship principles. By optimizing nitrogen source, rate, timing, and placement, farmers can achieve better yield outcomes with controlled input costs, enhancing financial sustainability. While upfront investments in organic amendments increases initial expenses, the 4R-aligned management reduces inefficiencies and long-term losses, supporting profitable and environmentally responsible canola production.

In Field B, the Baseline Scenario yields a higher NPV of CAD 4,765.55, while the BMP Scenario shows about CAD 743.89 lower NPV compared to the baseline scenario. The reduction in NPV is primarily attributed to the higher costs associated with organic fertilizers, particularly compost in the early stage of investment.

Despite this, the BMP approach still proves financially viable, aligning with the financial sustainability principles outlined by Penot et al. (2021). The Benefit–Cost Ratios (BCRs) for both scenarios in Field B are 2.47 for the Baseline and 1.75 for the BMP scenario, suggesting that although BMPs result in lower returns per dollar invested, they offer significant long-term benefits. This finding resonates with the work of Khakbazan et al. (2021) and the Organic Council of Ontario (2024), who advocate for adopting BMPs, even in the face of higher initial costs, to achieve greater long-term returns while promoting ecological health. Additionally, the resilience of the BMP scenario to price fluctuations and its ability to maintain profitability in varying cost conditions are consistent with findings from the Food and Agriculture Organization (1997) and Penot et al. (2021), who highlight the importance of robust economic evaluation methods in ensuring the stability and sustainability of farm management practices. Overall, these results reinforce the idea that integrating sustainability into farming practices contributes to environmental stewardship and supports long-term financial viability.

4.3 Sensitivity analysis

4.3.1 Price sensitivity and its effects on net present value and benefit–cost ratios in canola production

The price sensitivity analysis demonstrates the critical role that market price fluctuations play in the financial viability of canola production (Table 4). The results for the Baseline Scenario in Field A are highly sensitive to price changes. With a 10% decline in price, the NPV reduces to CAD 2,238.43 (BCR of 1.16) and a 20% drop further lowers it to CAD 1,551.77 (BCR of 0.80), indicating an unprofitable investment. These declines correspond to percentage variation of 23 to 47%, demonstrating significant vulnerability under the use of inorganic fertilizer application practices. These findings align with the literature, highlighting that conventional farming practices, particularly those reliant on high external input costs such as fertilizers, are more vulnerable to price volatility (Penot et al., 2021). The NPV's significant decrease in response to price reductions supports the assertion that price fluctuations can lead to financial instability under traditional practices, making it difficult for producers to maintain profitability during adverse market conditions (Food and Agriculture Organization, 1997).

In contrast, the BMP Scenario increases absolute NPVs and BCRs, particularly in Field A, due to higher yields from integrated fertilizer management. For instance, in Field A, a 10% price decrease still produces a positive NPV of CAD 3,032.19 (BCR of 1.32), and a 10% price increase raises the NPV to CAD 4,750.37 (BCR of 2.06). However, Field B under BMP exhibits greater sensitivity to price changes compared to the Base scenario, with larger percentage variation in NPV and BCR, indicating that economic resilience varies by field. These results suggest that while BMP adoption enhances profitability and supports long-term financial and environmental sustainability, its relative stability under price fluctuations depends on field-specific conditions. These findings align with recent Canadian research on sustainable and diversified management, which demonstrates that such practices improve risk management, increase profitability, and build resilience to market variability (Khakbazan et al., 2021; see

TABLE 4 Sensitivity analysis of NPV and BCR under varying canola market prices.

Field	Scenario	Price change ($\pm$ CAD)	NPV (CAD)	BCR	PV (%) for NPV	PV (%) for BCR
Field A	Base Scenario	10%	3611.77	1.87	23.48	23.84
		20%	4298.44	2.22	46.95	47.02
		−10%	2238.43	1.16	−23.48	−23.18
		−20%	1551.77	0.80	−46.95	−47.02
	BMP Scenario	10%	4750.37	2.06	22.08	21.89
		20%	5609.46	2.44	44.15	44.38
		−10%	3032.19	1.32	−22.08	−21.89
		−20%	2173.11	0.94	−44.15	−44.38
Field B	Base Scenario	10%	5636.27	2.92	18.27	18.22
		20%	6506.98	3.37	36.54	36.44
		−10%	3894.84	2.02	−18.27	−18.22
		−20%	3024.13	1.57	−36.54	−36.44
	BMP Scenario	10%	4893.79	2.12	21.69	21.14
		20%	5765.92	2.50	43.37	42.86
		−10%	3149.54	1.37	−21.69	−21.71
		−20%	2277.41	0.99	−43.37	−43.43

TABLE 5 Sensitivity analysis of NPV and BCR under varying market varying fertilizer cost.

Field	Scenario	Price change ($\pm$ CAD)	NPV (CAD)	BCR	PV (%) for NPV	PV (%) for BCR
Field A	Base Scenario	10%	2881.69	1.49	−1.48	−1.32
		20%	2838.27	1.47	−2.97	−2.65
		−10%	2968.54	1.54	1.49	1.99
		−20%	3011.96	1.56	2.97	3.31
	BMP Scenario	10%	3772.04	1.64	−3.06	−2.96
		20%	3652.81	1.59	−6.13	−5.92
		−10%	4010.49	1.74	3.06	2.96
		−20%	4129.72	1.79	6.13	5.92
Field B	Base Scenario	10%	4772.14	2.44	0.14	−1.21
		20%	4678.72	2.42	−1.82	−2.02
		−10%	4808.99	2.49	0.91	0.81
		−20%	4852.41	2.51	1.82	1.62
	BMP Scenario	10%	3902.42	1.64	−2.96	−6.29
		20%	3783.19	1.59	−5.93	−9.14
		−10%	4140.88	1.8	2.96	2.86
		−20%	4260.11	1.85	5.93	5.71

also [Organic Council of Ontario, 2024](#)). Reports from the Organic Council of Ontario confirm that adopting sustainable and organic practices supports stable income and cash flow by reducing input dependency and providing economic resilience through improved soil health and diversified production. While both conventional and sustainable practices can result in positive financial returns, these studies collectively show that BMPs and sustainable choices offer farmers a favorable risk–return profile and enhance long-term viability in dynamic agricultural markets.

4.3.2 Cost sensitivity and its effects on net present value and benefit–cost ratios in canola

The cost sensitivity analysis of fertilizer expenses highlights the influence of input price fluctuations on canola production profitability ([Table 5](#)). In Field A, the Baseline scenario shows slight declines in NPV and BCR with increased fertilizer costs, with a 10% rise reducing NPV by 1.48% (BCR by 1.32%) and a 20% rise decreasing NPV by 2.97% (BCR by 2.65%). While these reductions are modest, they indicate that the Baseline scenario depends on stable input costs

to maintain optimal returns, consistent with [Food and Agriculture Organization \(1997\)](#), which emphasizes the importance of stable input costs for profitability. The BMP scenario demonstrates higher absolute NPVs and BCRs and remains profitable even under rising fertilizer costs, suggesting that integrated management practices provide greater financial resilience and buffer the effects of cost variability.

Equally in Field A, the BMP scenario demonstrates improved financial performance, maintaining positive NPVs and BCRs even under modest fertilizer cost increases, reflecting the long-term efficiency of integrating organic and inorganic fertilizers. This aligns with [Khakbazan et al. \(2021\)](#), who report that BMPs enhance nutrient-use efficiency and reduce reliance on costly synthetic fertilizers. In Field B, the Baseline scenario shows higher absolute NPVs and BCRs due to economies of scale, remaining relatively stable even with rising fertilizer costs, consistent with [Penot et al. \(2021\)](#). While the BMP scenario in Field B yields slightly lower returns, reductions are modest, and profitability is maintained, especially when fertilizer costs decrease.

Despite these insights, the study has some limitations. Firstly, weather projections based on normal distribution sampling remain subject to uncertainty and may not fully capture long-term climate variability or extreme events. The cost estimates for the Baseline (business-as-usual) and BMP scenarios also relied on farmer reports and the 2024 Saskatchewan Crop Guide, excluding potential financing, which could influence NPV and BCR. The modelling was limited to two fields that were relatively similar in size and soil characteristics, particularly sandy soil texture, which may constrain crop productivity and limit the generalizability of results to other soil types, particularly of lesser agricultural capability limitations. Additionally, while the DSSAT model provided a robust framework for simulating crop responses, it could not account for other 4R Nutrient Stewardship strategies such as variations in nitrogen placement, the use of slow-release fertilizers, or the inclusion of urease and nitrification inhibitors. Variability in BMP adoption among farmers and fields, together with site-specific soil characteristics, management practices, and operational scale, may limit the generalizability of the exact results beyond the reserve. Although BMP adoption in this study aligns with the 4R Nutrient Stewardship framework, variations in local practices, farmer knowledge, and adoption levels may affect the consistency of these benefits. Further research is needed to explore how adherence to 4R principles interacts with local governance and socio-economic constraints to influence BMP outcomes across different Indigenous and regionally specific contexts. Nonetheless, the study offers useful guidance for policymakers, farmers, and researchers aiming to promote sustainable and resilient canola production on First Nations reserves under leases, with insights that may be transferable to other Indigenous and regionally specific contexts.

5 Conclusion

This study investigated the impact of fertilizer management practices on canola crop yield and economic performance on the MNFN reserve. Firstly, the implementation of BMPs, which combine organic and inorganic fertilizers, resulted in an improved

economic outcome for Field A, with a higher net present value (NPV) compared to the Baseline business-as-usual scenario (CAD 3,891.28 vs. CAD 2,925.10), demonstrating the potential long-term economic benefits of integrated nitrogen management. In contrast, Field B showed a reduction in NPV under the BMP scenario (CAD 4,021.66 vs. CAD 4,765.55 in the Baseline), largely due to the higher initial costs of organic fertilizers. Despite this, the modelled BMP approach remained economically viable and offered resilience against price fluctuations and rising fertilizer costs.

Sensitivity analyses further revealed that adopting BMPs in Field A provided a buffer against fluctuating prices and fertilizer costs, while Field B maintained more stable profitability under the Baseline scenario due to economies of scale. These findings highlight the importance of tailoring BMP adoption to site-specific conditions, particularly soil characteristics and operational scale. Importantly, the use of the DSSAT model provided a low-risk, exploratory tool for evaluating BMPs that are not yet widely adopted in the region. Due to agricultural land leasing conditions and presence of local sources of manure on First Nations, this may increase the viability of this modelled scenario in real world conditions at the smaller scales on reserve. This modelling approach allowed for scenario testing without requiring immediate changes to on-the-ground practices, making it a valuable method for informing future decision-making and farmer engagement.

To facilitate adoption, policymakers should also consider providing financial support and incentives to ease the transition toward sustainable farming practices on First Nations reserves, ensuring that both environmental and economic goals are met. This should include financial incentives, subsidies, and educational support to facilitate the adoption of BMPs. This approach aligns with the broader goals of the ACS program of sustainable agriculture and climate adaptation, contributing to farming systems' long-term stability and profitability in the face of ongoing environmental changes in Canada's agricultural sector.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

SA: Formal analysis, Writing – original draft. MA: Writing – review & editing, Funding acquisition, Project administration. DN: Project administration, Writing – review & editing, Supervision, Funding acquisition.

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Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1620590/full#supplementary-material>

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