frontiers | Frontiers in Agronomy

TYPE Original Research
PUBLISHED 11 August 2025
DOI 10.3389/fagro.2025.1617873

Check for updates

OPEN ACCESS

EDITED BY
Naser A. Anjum,
Aligarh Muslim University, India

REVIEWED BY
Laura M Shannon,
University of Minnesota Twin Cities,
United States
Juan De Dios Franco-Navarro,
Spanish National Research Council (CSIC),
Spain

*CORRESPONDENCE
Kate A. Congreves
kate.congreves@usask.ca

RECEIVED 25 April 2025
ACCEPTED 25 June 2025
PUBLISHED 11 August 2025

CITATION
Carruthers LC and Congreves KA (2025) High yield and efficiency: cultivar selection to improve potato nitrogen use efficiency.
Front. Agron. 7:1617873.
doi: 10.3389/fagro.2025.1617873

High yield and efficiency: cultivar selection to improve potato nitrogen use efficiency

Laura C. Carruthers and Kate A. Congreves*

Department of Plant Sciences, University of Saskatchewan, Saskatoon, SK, Canada

Optimizing nitrogen use efficiency (NUE) of crops is critical to maintain yields and profits while minimizing environmental damage from excessive fertilization and nitrogen (N) losses. Potato (*Solanum tuberosum* L.) typically requires high N rates to support yield, but low NUE risks N losses with cascading environmental and financial consequences. Identifying potato cultivars with improved NUE may reduce fertilizer needs and lower the risk of N loss. However, little research has focused on identifying such cultivars, especially on the Canadian Prairies. We conducted a field study encompassing five site-years in Saskatchewan to compare six seed potato cultivars (Clearwater Russet, Dark Red Norland, Milva, Poppy, Russet Burbank, and Sangre) for NUE traits, under N fertilizer rates ranging from 0 to 200 kg N ha^{-1}. Total yield, tuber N content, N balance intensity (NBI) and tuber N uptake efficiency (NUpE) were quantified as measures of NUE. Cultivar significantly influenced all metrics ($p < 0.05$), whereas fertilizer or the two-way interaction did not. Cultivar yield varied by more than 45%, highlighting substantial productivity differences among cultivars. Dark Red Norland, Sangre and Poppy also showed 22.5-33.2% higher NUE than other cultivars. Our findings support the need for improved predictions of soil mineralizable N supply, as reducing or forgoing N fertilization improves potato NUE when indigenous soil N meets crop demand. Our results suggest that when yield is not limited by soil N, NUE is largely driven by the ability of the plant to produce greater yield. This research demonstrates specific cultivars deliver high yields and improved NUE, allowing for improved N balance in potato production systems.

KEYWORDS

nitrogen balance, agronomic efficiency, prairie agriculture, soil fertility, potato

1 Introduction

Global agricultural production must increase by 50% to meet the demands of the expected population of nearly 10 billion people by 2050 (FAO, 2017). An important strategy for increasing food production is the use of synthetic nitrogen (N) fertilizers, which have significantly increased crop yields in past decades (Milroy et al., 2019). However, the production of fertilizer is energy-intensive, requires non-renewable resources, and excessive use can cause environmental damage through N leaching, runoff, nitrous oxide (N_2O)

emissions, and ammonia volatilization (Janzen et al., 2003). Leaching of N into groundwater and the accumulation of high nitrates in plant tissues can have a negative effect on human health (Rosales et al., 2020). When nitrate is consumed, it is converted to N compounds that may cause methemoglobinemia (blue baby syndrome), gastric cancer, and increased risks of non-Hodgkin's lymphoma and Parkinson's disease (Rosales et al., 2020; Stark and Richards, 2008). Nitrate contamination in waterbodies can cause eutrophication; decreasing oxygen levels and creating dead zones that cannot support marine life, in addition to being toxic to livestock (Stark and Richards, 2008). For these reasons, reactive N has been identified as one of the top five emerging threats facing the planet (UNEP, 2019). With increasing input costs for farmers, risk of environmental pollution, and targets to reduce greenhouse gas emissions from agriculture, ensuring crops use N efficiently is critical for producing high yields in a sustainable way.

Potatoes are the third most important food crop in the world in terms of human consumption (International Potato Center). They act as a fundamental element of food security by yielding two to four times the food quantity of grain crops and serving as a source of important nutrients (International Potato Center; Koch et al., 2020). Potatoes are currently grown on 19 million hectares around the world in many different climates, with key producers including China, India, and the Ukraine (Agriculture and Agri-Food Canada, 2023; International Potato Center). While Canada only accounts for 2% of global production, potatoes are the largest vegetable crop in the country, accounting for 28% of all vegetable receipts (Agriculture and Agri-Food Canada, 2023).

Nitrogen is the most critical nutrient for plant growth and potatoes require high N fertilizer rates to achieve high yields and top-quality tubers (Zebarth and Rosen, 2007). Typical fertilizer rates for Canadian potato producers range from 125–225 kg N ha^{-1} (Gao et al., 2018; Government of Saskatchewan; Zebarth et al., 2007). Plants can take up N from the soil in the forms of ammonium (NH_4) and nitrate (NO_3), the latter of which is prone to leaching (Koch et al., 2020). Plant-available N can be supplied by synthetic fertilizers or through mineralization, a soil microbial process that converts organic matter into inorganic N forms (Ros et al., 2011). Nutrient use efficiency encompasses the ability of a plant to obtain nutrients from the soil and utilize those nutrients to produce yield (Chahal et al., 2021; Ospina et al., 2014). It is influenced by a multitude of factors including the soil's capacity to supply macro and micronutrients, fertilizer, ecology, and production practices (Congreves et al., 2021). Agricultural crops struggle to use N efficiently, with only one-third of total N applied to cereals being removed in the grain (Raun and Johnson, 1999). Potatoes also have relatively low NUE (ranging from 40-60%), and producers often overapply fertilizer as a strategy to safeguard yields for this high-value crop (Zebarth and Rosen, 2007). Significant amounts of unutilized fertilizer can remain in the soil where it is susceptible to surface runoff, leaching into groundwater, and/or undergoing the process of nitrification/denitrification to produce N_2O gas (Koch et al., 2020). High rates of fertilizer paired with low NUE means that potato has high emission potential relative to other crops.

Studies have found cultivar differences in traits that might influence NUE of potato, including tuber number per plant, days to maturity, tuber dry matter, canopy cover, root mass, and root surface area (Getahun et al., 2020; Ospina et al., 2014; Sattelmacher et al., 1990; Zebarth et al., 2004). This suggests potential to utilize breeding methods to create cultivars with greater N efficiency. Crop growth patterns also influence NUE, whether driven by cultivar maturation or fertilizer-induced changes, and extending the period of vegetative growth is recommended to improve potato NUE (Getahun et al., 2020; Ospina et al., 2014; Zebarth et al., 2004). However, this strategy may not be suitable for enhancing yield and NUE in regions with short growing seasons, like the Canadian Prairies (Ospina et al., 2014). Furthermore, background soil N dynamics can alter cultivar expressions of NUE, such that NUE differences between cultivars were less pronounced on lower N soils (Zebarth et al., 2004). Therefore, in the quest to find potato cultivars with improved NUE, cultivars must be tested on soils with various levels of background soil N. Studying potato NUE dynamics on soils with relatively high levels of background N is a research gap that must be addressed. Repeatedly high N fertilizer rates combined with drier than normal conditions and poor crop N removal, year after year, can lead to soils with high residual N. This makes improving NUE even more challenging.

Plant and tuber N uptake can be highly variable, with studies reporting tuber N uptake from 59–151 kg N ha^{-1} (Haase et al., 2007; Rens et al., 2016; Waddell et al., 1999). Even in unfertilized control plots, potato plant N uptake ranged from 26–162 kg N ha^{-1} (Zebarth et al., 2012). By harvest, the majority of N in the plant has been translocated to the tuber; for example, Rens et al. (2016) found 80% of total plant N in the tuber at harvest. Accordingly, tuber N content is a good metric for assessing cultivar differences and NUE traits. Variability in tuber N content results from differences in cultivar growth patterns, agronomic traits, soil N pool dynamics, and mineralization during the growing season (Zebarth et al., 2012). Cultivars that accumulate higher tuber N would remove greater levels of N from the field, attenuating residual soil N levels after harvest, thus reducing potential for N loss. Selecting the right cultivar for improved NUE in addition to understanding of fertilizer requirements and soil N pools is important for sustainable production.

In recent decades, potato NUE has largely been improved via fertilizer management, irrigation strategies, and genomics (Tiwari et al., 2020; Wu et al., 2022; Zebarth et al., 2012). Fertilizer management includes strategies to apply at the right rate, at the right place, in the right formulation, and at the right timing. Pre-plant soil testing is an important tool that is widely used to determine rate, however most soil tests account for inorganic N but do not consider mineralization potential - a critical consideration although a costly and time-consuming one (Zebarth and Rosen, 2007). Advances in predicting soil N mineralization capacity could provide producers with a more complete understanding of a soil's ability to supply N to the potato crop. While agronomic management is a major strategy for improving potato NUE, cultivar selection may also contribute to variations in NUE. Identifying cultivars with superior NUE could guide further research into underlying mechanisms that govern NUE. Such cultivars could be grown more widely by producers, and management practices tailored to the mechanism of improved

NUE. Given the potential of cultivar selection as a method for improving NUE, this study sought to identify potato cultivars with high yield and improved NUE for production on the Canadian Prairies, a major agricultural region. We hypothesize that while environmental factors and soil characteristics like indigenous soil N supply will influence N uptake, cultivar differences will be significant drivers of variation in NUE.

2 Materials and methods

2.1 Sites and experimental design

This research was conducted at the University of Saskatchewan's Horticultural Field Research Station and North Management Area in Saskatoon on a Dark Brown Chernozem (Sutherland Association), encompassing five site-years. For three years (2021-2023) the experiment was established on a clay loam soil (characterized by pH of 7.4, 4.9% organic matter, bulk density of 1.18 g cm^{-3} in the 0–15 cm depth). A sandy loam site was included in 2022 (0–15 cm soil pH of 7.3, 3.7% organic matter, bulk density of 1.24 g cm^{-3}) and also in 2023 (0–15 cm soil pH of 7.7, 3.8% organic matter, bulk density of 1.31 g cm^{-3}). Prior to planting, soil total extractable N (in the 0–60 cm depth) was 77.5, 92.5, and 110.9 kg N ha^{-1} at the clay loam site in 2021, 2022, and 2023, respectively; and 84.4 and 100.6 kg N ha^{-1} at sandy loam site in 2022 and 2023 (Supplementary Table 1). In each year, the experiment was established on an area, that in the year prior, grew barley or was otherwise fallow and had not previously grown potatoes in the past decade. Each year, the soil was prepared for production by discing the top 10 cm of the entire field area in early spring, and a pre-season herbicide [Eptam® (PCT) and Sencor® (metribuzin)] was applied.

To compare six different potato cultivars under a range of N fertilizer applications, 3 by 3 m plots were established and arranged in a split-plot design with cultivar as the main effect and fertilizer rate as the sub-effect. Potato cultivars selected were fresh market or processing types that are commonly grown for seed potato production on the Prairies, selected in consultation with the Saskatchewan Seed Potato Growers Association (SSPGA). All seed was certified and sourced from growers in the SSPGA. Cultivars included Clearwater Russet (russet skin, mid-season maturity), Dark Red Norland (red skin, early-season maturity), Milva (yellow skin, mid-season maturity), Poppy (red skin, mid-season maturity), Russet Burbank (russet skin, late-season maturity) and Sangre (red skin, mid-season maturity). All six potato cultivars are suitable for the fresh market, although some are dually suitable for the processing market (the Russets). Additionally, all six cultivars are regionally representative of the seed potato market. For the purposes of this research, we are considering potato production for the fresh market. For a target yield of 44 Mg ha^{-1} (Government of Manitoba, 2022), soil tests conducted through AgVise Laboratories recommended average applications of 22 kg N ha^{-1} at the clay loam sites and 152 kg N ha^{-1} at the sandy loam sites. For our experiment, fertilizer treatments were established for 0, 10, 20, 30 and 40 kg N ha^{-1} at the clay loam site (2021-2023), and 0, 50, 100, 150, and 200 kg N ha^{-1} at the sandy loam sites (2022-2023). This represented a range of N application starting at zero and including rates below, similar to, and above the recommended rate for each site. Granular urea (46-0-0) was the source of N and was broadcast incorporated into the top 10 cm of each plot prior to planting. Other nutrients such as phosphorus (triple super phosphate 0-45-0) and/or potassium (soluble potash 0-0-60) fertilizer were broadcast incorporated alongside N fertilizer as needed based on soil-test recommendations. At the 2022 sandy loam site, 20 kg P ha^{-1} and 48 kg K ha^{-1} was applied. No additional fertilizer was applied in other site-years.

The plots were seeded May 13, 2021, May 12, 2022, and May 9, 2023, at the clay loam site, and May 17, 2022, and May 15, 2023, at the sandy loam site. Potato seed pieces were placed 10 cm deep with 75cm between-row spacing and 38 cm in-row spacing; each plot encompassed four rows. Potato plots were mechanically hilled after emergence in mid-June each year. Irrigation was applied using a travelling gun system (Micro Rain 58, Southern Irrigation, Saskatoon, SK) as needed based on soil moisture observations and the weather forecast.

2.2 Weather information

Weather data was collected from the Saskatchewan Research Council Saskatoon station located at the sandy loam site (52.09227° N 106.36288°W). This weather data is representative for all sites as the station is within 3 km of all sites. The average temperature and total precipitation were monitored during the growing season of each study year (May-August). All three years of the trial were drier and warmer than the historical average (Table 1). Growing degree days were calculated using a T_{min} of 7°C and a T_{max} of 30°C. The sites accumulated a total degree days of 724.3, 907.6, 961.8 at the clay loam sites (2021-2023) and 907.6 and 916.8 at the sandy loam sites in 2022 and 2023, respectively. The clay loam sites received total precipitation (rainfall + irrigation) of 198.9 mm (2021), 219.7 mm (2022), and 273.7 mm (2023). The sandy loam sites received total precipitation of 236.4 mm (2022) and 278.9 mm (2023) (Table 1).

2.3 Plant sampling and analysis

In-season N was monitored with Soil Plant Analysis Development (SPAD) readings collected every week starting after hilling (SPAD-502+ chlorophyll meter, Konic Minolta, Japan). Two readings were recorded from each plot, on the apical leaflet of the 4th youngest leaf (Li et al., 2012). Potatoes were monitored for insects, especially the Colorado potato beetle, and insecticides [deltramethrin (applied as Decis®) or chlorantraniliprole (Coragen®)] were applied when needed. Plots were hand-weeded in-season to control weeds. Two weeks prior to harvest, plants were top-killed via herbicide [diquat (Reglone®)] application.

Plots were harvested mid-September each year (Sept 14, 2021, Sept 12, 2022, and Sept 11, 2023, at the clay loam site, and Sept 13,

TABLE 1 Monthly mean temperature (°C), precipitation and irrigation (mm) for May-August of 2021–2023 and the 30-year mean (1991-2020) in Saskatoon, SK.

Mean Temperature (°C)					Precipitation + Irrigation (mm)					
Month	2021	2022	2023	30-year Average	Clay loam 2021	Clay loam 2022	Clay loam 2023	Sandy loam 2022	Sandy loam 2023	30-year Average Precipitation
May	12.3	12.2	16.8	12.4	27.8 + 0	34.4 + 0	33.7 + 0	34.4 + 0	33.7 + 0	37.6
June	19.6	16.7	20.2	16.3	18.2 + 22.8	59.3 + 0	54.6 + 29.9	59.3 + 12.7	54.6 + 29.9	73.9
July	22.6	20.2	18.7	19.0	4.2 + 58.4	35.7 + 52.7	22.5 + 48.3	35.7 + 56.7	22.5 + 67.9	60.1
August	18.9	20.9	19.3	18.4	28 + 22.8	33.7 + 0	36.9 + 38.1	33.7 + 0	36.9 + 34.0	46.4

*data obtained from the Saskatchewan Research Council Climate Reference Station located at the sandy loam experimental site.

2022 and Sept 12, 2023 at the sandy loam site). From each plot, tubers from one 3 m center row were harvested, collected into mesh bags and immediately weighed to record fresh weight. Tubers from each bag were sorted into Grade 1, Grade 2, Undersize or Cull categories based on size, shape, and firmness (Canadian Food Inspection Agency, 2021). Total yield was calculated as the sum of the weight of tubers in each category, and yield is reported as tuber fresh weight in megagrams/metric ton (Mg ha^{-1}). A sub-sample of ten tubers were checked for internal defects and a sub-set of five tubers were collected, cut using a fry cutter and dried at 60°C for three weeks until no weight change was recorded to determine dry matter. Dry tubers were ground using a Thomas Wiley Laboratory Mill with a 1mm mesh screen. To determine %N, the dried and ground tuber samples were analysed by LECO (CN 628 series combustion analyser, LECO Corporation, MI, USA).

2.4 Soil sampling and analysis

Soil samples were collected prior to planting as a composite sample of 6–8 cores (3.5 to 5 cm diameter) randomly spaced throughout the entire field at 0-15, 15-30, and 30–60 cm depths. Samples were shipped to AgVise or A&L Laboratories for soil characterization. Bulk density measurements were collected from each site using the core method (Hao et al., 2008). After potato harvest, soil samples (in 15 cm increments from 0–60 cm depth) were collected to determine soil nutrient levels separately for each potato cultivar. Soil samples were kept in a cooler while working in the field, sieved to 2 mm, and kept frozen until analysis. All samples were analyzed for extractable N (NO_3-N and NH_4-N) at the University of Saskatchewan following a KCl extraction procedure (Keeney and Nelson, 1982). Inorganic N was determined with the extract analyzed colorimetrically using a Technicon AutoAnalyzer III.

2.5 Nitrogen use efficiency

Two NUE metrics were investigated, N Balance Intensity (NBI) and tuber N uptake efficiency (NUpE). The NBI conceptualizes the difference between N removed as yield relative to the N added as fertilizer, indicating whether N outputs are balanced by N inputs, or not. Based on this balance, NBI indicates if an accumulation or a decline in soil N may be expected over a growing season. Calculation of NBI was determined as the difference between fertilizer N applied and N removed as yield (Equation 1)

$$NBI = Yn - Fn \tag{1}$$

where Yn denotes N contained in the yield (tuber N) (kg N ha^{-1}); Fn denotes the amount of fertilizer N applied (kg N ha^{-1}). Positive NBI values indicate that tubers removed a quantity of N equivalent to the N fertilizer applied in addition to removing more N from the indigenous soil N pool. Negative values indicate the tubers did not remove the equivalent quantity of the N fertilizer applied, rather they left a portion of fertilizer N in the soil as excess. Values closer to zero indicate a balance between N fertilizer input and tuber N removal from the system (Congreves et al., 2021).

Tuber NUpE was calculated as an index relating tuber N at harvest to the relative availability of soil N at planting (Equation 2)

$$NUpE = \frac{Yn}{Fn + Sn} x \ \ 100 \tag{2}$$

where Yn denotes N contained in the yield (tuber N) (kg N ha^{-1}); Fn denotes the amount of fertilizer N applied (kg N ha^{-1}) and Sn represents the inorganic N levels (kg N ha^{-1}) in the spring prior to seeding. Tuber NUpE was calculated using the extractable soil N levels at pre-plant from 0–60 cm.

2.6 Statistical analysis

Statistical analyses were done using R Statistical Software (v4.2.2; R Core Team, 2022) within RStudio (version 2023.12.0; RStudio Team, 2023). R is an open-source language and environment for statistical computing, while RStudio provides an interface to facilitate visualization and analysis. The site-years were analysed separately because of the unique growing-season conditions and soil characteristics in each case; our main objective was to determine cultivar differences in each case. To test the null hypothesis that treatment groups have identical mean values, analyses of variance (ANOVA) tests were performed. Models were fit using the "agricolae" package in RStudio that considered the split plot design (de Mendiburu and Yaseen, 2020) and relies on least squares estimation. Replicate was used as the blocking term (random factor), cultivar was the main effect, and fertilizer rate was the sub-effect (both fixed factors). The model was run for various response variables including yield, tuber N, and NUE indices. Shapiro-Wilks test (p>0.05) and visual tests (qq plots) were used to assess the residuals for normality. Levene's test and residual plots were used to assess homogeneity of variance. Residuals were normally distributed and the data met the assumption of homogeneity of variance in most cases, with the exception of the 2022 sandy loam site. Data for that site-year was either log or square-root transformed with a shift and was back transformed for tables and figures. Probability values were evaluated at a 95% confidence interval (p<0.05). Two-way interactions between the fixed effects (cultivar and fertilizer) were only significant in one case, discussed in more detail in the results and discussion. To investigate significant differences between levels of the same factor (i.e. different cultivars or fertilizer rates), post-tests (multiple means comparison) were performed using the least significant difference (LSD) test via the "agricolae" package with a 95% confidence interval (de Mendiburu and Yaseen, 2020). Linear regressions (model II regressions) were done for each site-year separately to analyze the relationship between total yield and NUE using base R (R Core Team, 2022).

3 Results and discussion

3.1 Cultivar impacts potato yield and tuber N content

Cultivar significantly influenced total yield in all site-years, whereas the two-way interaction of cultivar and fertilizer rate did not (Table 2). The highest yielding cultivars varied by site and year, with Sangre and Milva having the greatest yield at the clay loam site in 2021, Poppy in 2022, and Dark Red Norland, Poppy and Sangre in 2023. At the sandy loam site, Sangre, Poppy and Dark Red Norland had top yields in 2022, and Dark Red Norland and Milva in 2023. Sangre and Dark Red Norland averaged 15.8% and 15.2% higher yields than Russet Burbank across the years. Clearwater Russet had consistently lower yields in all site-years. Similar yield differences among cultivars were also observed at another (adjacent) experiment, but one that focused on P fertilizer and P use efficiency instead of NUE (Carruthers and Congreves, 2025). Given Saskatchewan's short growing season, potatoes were harvested in September regardless of cultivar. While staggering cultivar harvest (as would normally be done by a grower) might have reduced the gap between cultivar yields or tuber N, the cool fall climate would likely have limited any substantial benefits from extended growth

TABLE 2 Analysis of variance results (p-values) and multiple means comparisons (mean ± standard error) for potato production response variable of total yield (Mg ha^{-1}) for five site-years.

Fixed effect	2021 Clay loam	2022 Clay loam	2023 Clay loam	Fixed effect	2022 Sandy loam	2023 Sandy loam
ANOVA p-value						
Cultivar	**<0.001**	**<0.001**	**0.0044**	Cultivar	**<0.001**	**<0.001**
Fertilizer	0.6420	0.2542	0.0704	Fertilizer	0.4095	0.2017
Cultivar x Fertilizer	0.6759	0.1034	0.3582	Cultivar x Fertilizer	0.2200	0.5958
Potato Total Yield (Mg ha^{-1}) by Cultivar (mean ± standard error)						
Clearwater Russet	25.7 ± 1.1 c	26.7 ± 1.1 c	45.1 ± 1.6 b	Clearwater Russet	9.8 ± 0.8 b	29.6 ± 1.1 d
Dark Red Norland	32.5 ± 0.7 bc	34.7 ± 0.7 b	58.7 ± 1.9 a	Dark Red Norland	20.8 ± 0.7 a	55.0 ± 1.7 a
Milva	41.2 ± 1.1 a	33.7 ± 0.7 b	52.7 ± 1.8 a	Milva	12.6 ± 1.2 b	51.4 ± 1.1 a
Poppy	33.4 ± 1.0 b	42.4 ± 1.1 a	56.1 ± 2.4 a	Poppy	21.2 ± 1.7 a	37.8 ± 1.1 c
Russet Burbank	39.2 ± 1.5 ab	29.6 ± 0.9 c	44.4 ± 1.8 b	Russet Burbank	19.3 ± 1.1 a	40.5 ± 1.1 bc
Sangre	43.9 ± 1.5 a	34.3 ± 0.9 b	54.0 ± 2.2 a	Sangre	23.3 ± 2.0 a	44.1 ± 1.2 b
Potato Total Yield (Mg ha^{-1}) by Fertilizer (mean ± standard error)						
0 kg N ha^{-1}	36.4 ± 1.8	33.9 ± 1.5	49.5 ± 1.7	0 kg N ha^{-1}	18.4 ± 1.5	44.1 ± 1.7
10 kg N ha^{-1}	35.4 ± 1.6	34.1 ± 1.3	53.9 ± 2.4	50 kg N ha^{-1}	18.7 ± 1.5	44.7 ± 2.1
20 kg N ha^{-1}	35.5 ± 1.8	33.5 ± 1.3	49.0 ± 2.3	100 kg N ha^{-1}	17.7 ± 1.5	42.1 ± 2.2
30 kg N ha^{-1}	36.9 ± 1.6	32.1 ± 1.2	54.4 ± 2.2	150 kg N ha^{-1}	18.0 ± 1.7	42.6 ± 2.2
40 kg N ha^{-1}	35.7 ± 1.6	34.3 ± 1.3	52.3 ± 1.6	200 kg N ha^{-1}	16.4 ± 1.5	41.4 ± 2.1

Degrees of freedom: cultivar = 5, fertilizer = 4, cultivar x fertilizer interaction = 20. Significant p-values (<0.05) are bolded. For cultivar and fertilizer comparisons, means with different letters indicate significantly different values (LSD test, a= 0.05).

periods. Regardless, yield differences between cultivars of similar market class and maturity emerged, demonstrating variation in yield. To place our yield results in context of expected potato yield in Canada, the average total tuber yields across all cultivars were 36 Mg ha^{-1}, 33.6 Mg ha^{-1}, and 51.8 Mg ha^{-1} (clay loam 2021, 2022, and 2023, respectively), and 17.8 Mg ha^{-1} and 43.3 Mg ha^{-1} (sandy loam 2022 and 2023) (Table 2). The yields produced in our study are comparable to the national average of 36.9 Mg ha^{-1} (Agriculture and Agri-Food Canada, 2021), with the exception of the 2022 sandy loam site-year which had significantly lower yield likely due to moisture stress and a compounding effect of drought in previous years (Table 1).

Cultivar influenced tuber N in four of five site-years, while the two-way interaction of cultivar and fertilizer rate was negligible (Table 3). Only at the clay loam site in 2021 was there no significant differences between cultivars in terms of tuber N content. In other years at the clay loam site, the cultivars with the highest tuber N were Dark Red Norland and Poppy (2022), and Dark Red Norland and Sangre (2023) (Table 3). At the sandy loam site in 2022, Clearwater Russet and Milva had significantly lower tuber N relative to other cultivars which yielded similarly, possibly suggesting the ability of these cultivars to take up N was impacted more by water availability relative to other cultivars. Overall, Dark Red Norland, Sangre, and Poppy had consistently high tuber N content throughout this study, with tuber N content 8.18-44.45 kg N ha^{-1} greater than other cultivars. As long as nitrate accumulation in tubers is not excessive (to the point of potential health impacts), then these cultivars may provide an agronomic and environmental benefit by removing more N from the field as harvested tubers, thereby leaving less residual soil N in the field, vulnerable to losses over the subsequent winter and spring. In the current study, average tuber N content was 115 kg N ha^{-1}, 134 kg N ha^{-1}, and 140 kg N ha^{-1} for clay loam sites in 2021, 2022, and 2023, respectively. At the sandy loam site, average tuber N was 78.1 kg N ha^{-1} in 2022 and 135 kg N ha^{-1} in 2023 (Table 3). These tuber N values are in line with other reported findings (Haase et al., 2007; Rens et al., 2016; Waddell et al., 1999; Zebarth et al., 2012).

3.2 Cultivar influences potato NUE

Cultivar influenced NBI at four of the five site-years (Table 4). NBI was not influenced by the two-way interaction of cultivar and fertilizer rate, except for the 2022 sandy loam site-year (Table 4). In this case, the interaction was caused by minor differences in cultivar performance across fertilizer rate, but the overall trend was decreasing NBI with increasing fertilizer rate, thus the interaction was not explored further. All cultivars had positive NBI values in all

TABLE 3 Analysis of variance results (*p*-values) and multiple means comparisons (mean ± standard error) for potato production response variable of tuber N (kg N ha^{-1}) for five site-years.

Fixed effect	2021 Clay loam	2022 Clay loam	2023 Clay loam	Fixed effect	2022 Sandy loam	2023 Sandy loam
ANOVA *p*-value						
Cultivar	0.1282	**<0.001**	**<0.001**	Cultivar	**<0.001**	**<0.001**
Fertilizer	0.0952	0.3748	0.5536	Fertilizer	0.5930	0.2432
Cultivar x Fertilizer	0.9299	0.6813	0.7664	Cultivar x Fertilizer	0.1002	0.0742
Potato Tuber N (kg N ha^{-1}) by Cultivar (mean ± standard error)						
Clearwater Russet	92.6 ± 3.4	115.3 ± 4.6 c	124.7 ± 5.1 bc	Clearwater Russet	49.9 ± 3.7 b	116.0 ± 4.2 c
Dark Red Norland	125.7 ± 5.5	156.5 ± 3.7 a	170.1 ± 6.9 a	Dark Red Norland	101.2 ± 6.6 a	167.4 ± 6.8 a
Milva	123.4 ± 3.9	114.5 ± 3.4 c	112.3 ± 3.7 c	Milva	55.0 ± 4.8 b	144.1 ± 4.0 b
Poppy	105.5 ± 3.7	159.4 ± 3.1 a	140.4 ± 6.2 b	Poppy	92.0 ± 5.8 a	114.1 ± 3.7 c
Russet Burbank	123.8 ± 6.7	121.3 ± 3.6 c	128.8 ± 5.1 bc	Russet Burbank	79.4 ± 4.0 a	119.2 ± 4.2 c
Sangre	116.2 ± 5.1	139.6 ± 3.7 b	163.6 ± 5.7 a	Sangre	91.1 ± 7.1 a	143.6 ± 4.1 b
Potato Tuber N (kg N ha^{-1}) by Fertilizer (mean ± standard error)						
0 kg N ha^{-1}	112.1 ± 5.9	137.2 ± 5.3	136.6 ± 5.7	0 kg N ha^{-1}	76.0 ± 6.8	126.9 ± 4.5
10 kg N ha^{-1}	113.3 ± 4.5	136.1 ± 5.2	144.2 ± 6.9	50 kg N ha^{-1}	79.6 ± 5.5	135.3 ± 5.1
20 kg N ha^{-1}	110.8 ± 5.6	133.0 ± 4.4	133.9 ± 6.9	100 kg N ha^{-1}	78.7 ± 5.9	136.4 ± 6.4
30 kg N ha^{-1}	123.6 ± 4.6	129.1 ± 5.0	143.7 ± 6.7	150 kg N ha^{-1}	81.7 ± 7.5	138.8 ± 7.0
40 kg N ha^{-1}	112.9 ± 4.0	136.6 ± 5.6	141.3 ± 6.7	200 kg N ha^{-1}	74.6 ± 6.1	132.7 ± 5.6

Degrees of freedom: cultivar= 5, fertilizer = 4, cultivar x fertilizer interaction =20. Significant *p*-values (<0.05) are bolded. Means with different lowercase letters indicate significantly different values (LSD test, *a*= 0.05).

TABLE 4 Analysis of variance results (p-values) and multiple means comparisons (mean ± standard error) for potato production response variable of nitrogen balance intensity (NBI) for five site-years.

Fixed effect	2021 Clay loam	2022 Clay loam	2023 Clay loam	Fixed effect	2022 Sandy loam	2023 Sandy loam
ANOVA p-value						
Cultivar	0.1282	**<0.001**	**<0.001**	Cultivar	**<0.001**	**<0.001**
Fertilizer	**<0.001**	**<0.001**	**<0.001**	Fertilizer	**<0.001**	**<0.001**
Cultivar x Fertilizer	0.9300	0.6813	0.7664	Cultivar x Fertilizer	**0.0310**	0.0742
Potato NBI (kg N ha^{-1}) by Cultivar (mean ± standard error)						
Clearwater Russet	72.6 ± 4.8	95.3 ± 6.3 c	104.7 ± 6.5 bc	Clearwater Russet	-50.0 ± 16.6 b	16.0 ± 17.6 c
Dark Red Norland	105.7 ± 6.2	136.5 ± 4.2 a	150.1 ± 7.0 a	Dark Red Norland	1.2 ± 17.5 a	67.4 ± 13.1 a
Milva	103.4 ± 4.6	94.4 ± 4.5 c	92.3 ± 5.3 c	Milva	-44.9 ± 18.1 b	44.1 ± 18.0 b
Poppy	85.5 ± 4.1	139.4 ± 5.1 a	120.4 ± 6.2 b	Poppy	-8.0 ± 16.2 a	14.1 ± 16.0 c
Russet Burbank	103.8 ± 7.5	101.3 ± 5.4 c	108.8 ± 6.0 bc	Russet Burbank	-20.5 ± 15.9 a	19.3 ± 16.6 c
Sangre	96.2 ± 5.6	119.6 ± 5.0 b	143.5 ± 6.6 a	Sangre	-8.8 ± 18.4 a	43.6 ± 17.4 b
Potato NBI (kg N ha^{-1}) by Fertilizer (mean ± standard error)						
0 kg N ha^{-1}	112.1 ± 5.9 a	137.2 ± 5.3 a	136.7 ± 5.7 a	0 kg N ha^{-1}	76.0 ± 6.8 a	126.9 ± 4.5 a
10 kg N ha^{-1}	103.3 ± 4.5 ab	126.1 ± 5.2 b	134.2 ± 6.9 a	50 kg N ha^{-1}	29.6 ± 5.5 b	85.3 ± 5.1 b
20 kg N ha^{-1}	90.8 ± 5.6 c	113.0 ± 4.4 c	113.9 ± 6.9 b	100 kg N ha^{-1}	-21.3 ± 5.9 c	36.4 ± 6.4 c
30 kg N ha^{-1}	93.6 ± 4.6 bc	99.1 ± 5.0 d	113.7 ± 6.7 b	150 kg N ha^{-1}	-68.2 ± 7.5 d	-11.2 ± 7.0 d
40 kg N ha^{-1}	72.9 ± 4.0 d	96.6 ± 5.6 d	101.3 ± 6.7 b	200 kg N ha^{-1}	-125.4 ± 6.1 e	-67.3 ± 5.7 e

Degrees of freedom: cultivar= 5, fertilizer = 4, cultivar x fertilizer interaction =20. Significant p-values (<0.05) are bolded. Means with different lowercase letters indicate significantly different values (LSD test, a= 0.05).

site-years, except for the 2022 sandy loam site (the site-year with the driest conditions). Positive NBI values from most years indicates that tubers removed a quantity of N equivalent to the amount of N fertilizer applied in addition to acquiring more N from the soil. However, the negative NBI values at the 2022 sandy loam site indicates that cultivars left more fertilizer N behind in the soil than put towards yield - all except Dark Red Norland. Overall, Dark Red Norland resulted in the greatest NBI values, up to 1.5–5 times greater than the other cultivars, depending on the site-year (Table 4), demonstrating potential for better NUE across different years and different environmental conditions. There was sufficient variation in NUE between cultivars of the same market class and therefore further exploration of these differences could allow for cultivar selection as a sustainable management tool.

Tuber NUpE was influenced by cultivar at four of the five site-years (Table 5). Tuber NUpE ranged from 61-240% in the clay loam site-years, and from 7.82-227% in the sandy loam site-years. Such high values indicate a significant amount of N was mineralized from the soil over the course of the growing season, enabling the tubers to take up more than 100% of the quantity of N that was present at planting. Lower tuber NUpE values at the sandy loam site were caused by low tuber N in 2022 due to drought that limited plant N uptake paired with the higher N fertilizer rates at this site. There was no cultivar difference in NUpE at the clay loam site in 2021, but Sangre numerically recovered the most N. Dark Red Norland, Poppy and Sangre had the highest NUpE in this study, outperforming the other cultivars by 22.5-33.2%.

Significant variation in NUE driven by cultivar has been widely reported (Cohan et al., 2018; Getahun et al., 2022, 2020; Jones et al., 2021; Ospina et al., 2014). In the current study, the improved NUE observed in Dark Red Norland, Sangre and Poppy was primarily driven by yield differences among cultivars - specifically the ability of those cultivars to produce high yields, which in turn increased N contents of tubers. The relationship between NUE and total yield was assessed using linear regression (Figure 1). Despite yield differences across site-years (driven by environmental factors), there was a significant (p<0.001) positive linear trend between average total yield and NUE metrics. Given that soil N was not limiting, NUE was primarily driven by yield differences among cultivars and site-year yield production. When investigating the relationship between yield and NBI at clay loam site-years, R^2 was found to be 0.862, 0.865, and 0.812 in 2021, 2022, and 2023, respectively. Similarly, the relationship between yield and NUpE showed R^2 of 0.866, 0.865, and 0.811 for those same years, indicating a consistent and strong relationship between yield and NUE on clay loam soils. At the sandy loam site, a strong relationship was observed between yield and NBI in 2023 (R^2 = 0.865), which was comparable to the clay loam site-years, while the

TABLE 5 Analysis of variance results (*p*-values) and multiple means comparisons (mean ± standard error) for potato production response variable of tuber nitrogen uptake efficiency (NUpE) for five site-years.

Fixed effect	2021 Clay loam	2022 Clay loam	2023 Clay loam	Fixed effect	2022 Sandy loam	2023 Sandy loam
ANOVA *p*-value						
Cultivar	0.2799	**<0.001**	**<0.001**	Cultivar	**<0.001**	**<0.001**
Fertilizer	**<0.001**	**<0.001**	**<0.001**	Fertilizer	**<0.001**	**<0.001**
Cultivar x Fertilizer	0.9486	0.6163	0.8124	Cultivar x Fertilizer	0.1003	0.4172
Potato NUpE (%) by Cultivar (mean ± standard error)						
Clearwater Russet	103.6 ± 5.9	104.7 ± 5.9 c	96.7 ± 5.0 bc	Clearwater Russet	32.5 ± 4.3 b	68.4 ± 7.7 c
Dark Red Norland	110.9 ± 5.6	140.9 ± 4.6 a	130.8 ± 5.4 a	Dark Red Norland	66.2 ± 9.7 a	92.0 ± 6.5 a
Milva	122.3 ± 5.1	103.2 ± 3.9 c	86.9 ± 3.9 c	Milva	37.3 ± 5.8 b	85.3 ± 8.2 ab
Poppy	121.5 ± 4.9	144.5 ± 5.9 a	107.8 ± 4.8 b	Poppy	58.5 ± 6.3 a	65.0 ± 5.8 c
Russet Burbank	125.7 ± 8.7	110.0 ± 5.2 c	99.6 ± 4.8 bc	Russet Burbank	50.2 ± 5.2 a	68.5 ± 6.7 c
Sangre	136.6 ± 7.5	126.2 ± 5.2 b	126.4 ± 5.6 a	Sangre	59.9 ± 7.3 a	83.1 ± 8.0 b
Potato NUpE (%) by Fertilizer (mean ± standard error)						
0 kg N ha^{-1}	145.4 ± 7.4 a	148.4 ± 5.7 a	123.2 ± 5.1 a	0 kg N ha^{-1}	90.1 ± 8.0 a	126.1 ± 4.5 a
10 kg N ha^{-1}	129.6 ± 4.5 b	132.8 ± 5.0 b	119.2 ± 5.7 a	50 kg N ha^{-1}	59.2 ± 4.0 b	89.8 ± 3.4 b
20 kg N ha^{-1}	114.2 ± 5.9 c	118.3 ± 3.9 c	102.3 ± 5.2 b	100 kg N ha^{-1}	42.7 ± 3.2 c	69.7 ± 3.5 c
30 kg N ha^{-1}	115.1 ± 4.0 c	105.4 ± 4.1 d	101.9 ± 4.7 b	150 kg N ha^{-1}	34.8 ± 3.2 d	55.4 ± 2.8 d
40 kg N ha^{-1}	96.3 ± 3.2 d	103.1 ± 4.2 d	93.6 ± 4.4 b	200 kg N ha^{-1}	26.2 ± 2.2 e	44.1 ± 1.8 e

Degrees of freedom: cultivar= 5, fertilizer = 4, cultivar x fertilizer interaction =20. Significant *p*-values (<0.05) are bolded. Means with different lowercase letters indicate significantly different values (LSD test, *a*= 0.05).

NUpE relationship was slightly weaker (R^2 = 0.794). However, the 2022 sandy loam site displayed the weakest relationship for both metrics (R^2 = 0.681 for NBI and R^2 = 0.753 for NUpE). This suggests that at the 2022 sandy loam site, environmental factors other than N availability (like water limitation or heat stress) may have had a stronger influence on yield. This could have resulted in a weaker relationship between yield and NUE relative to other site-years. The low yields at the sandy loam site in 2022 translated into lower tuber N removal, which may also explain why the regression for that site-year is distinct from other years. Despite differences in site-years, a few consistent trends emerged: Clearwater Russet produced consistently low yield and NUE, while Dark Red Norland, Sangre, and Poppy had high yields and NUE (Figure 1). These findings highlight a win-win situation for producers: selecting high yielding cultivars also leads to greater NUE. This creates both economic and environmental benefits with increased yields generating greater profits, and lower fertilizer requirements reducing N lost to the environment.

Looking to the N translocation patterns of the cultivars, it appears that in addition to yield potential, cultivars may have different mechanisms driving increased NUE. Dark Red Norland had a different pattern of N translocation over the growing season relative to other cultivars, shown by SPAD values over time (Figure 2). Due to its early-season maturity, Dark Red Norland relocated N from aboveground biomass to tubers earlier in the season relative to other cultivars, which could explain the higher NUE, especially under the driest conditions at the sandy loam site in 2022. Thus, earlier-maturing cultivars may have stronger performance under short growing seasons or harsh environmental conditions due to their more advanced stage when drought stress occurs. Some advantages of earlier cultivars were uncovered in a greenhouse study that found higher photosynthetic capacity, starch accumulation, and final yield (Mokrani et al., 2018). However, other research has found late-maturing cultivars to have higher NUE than early cultivars (Getahun et al., 2020). Climate plays a substantial role in these findings, as later-maturing cultivars may achieve greater yield and NUE, but only if the length of the growing season allows for it.

Poppy and Sangre (both mid-season maturity) generally maintained the highest SPAD values across the growing season. The N content in leaves did not plummet as sharply as Dark Red Norland, suggesting a different mechanism for increased NUE compared to Dark Red Norland. One explanation for this could be the dark leaf color of Poppy and Sangre observed in the field, suggesting these cultivars might have an increased capacity for N in vegetative tissues during the growing season, compared to other cultivars. In theory, higher N content in leaves could increase total

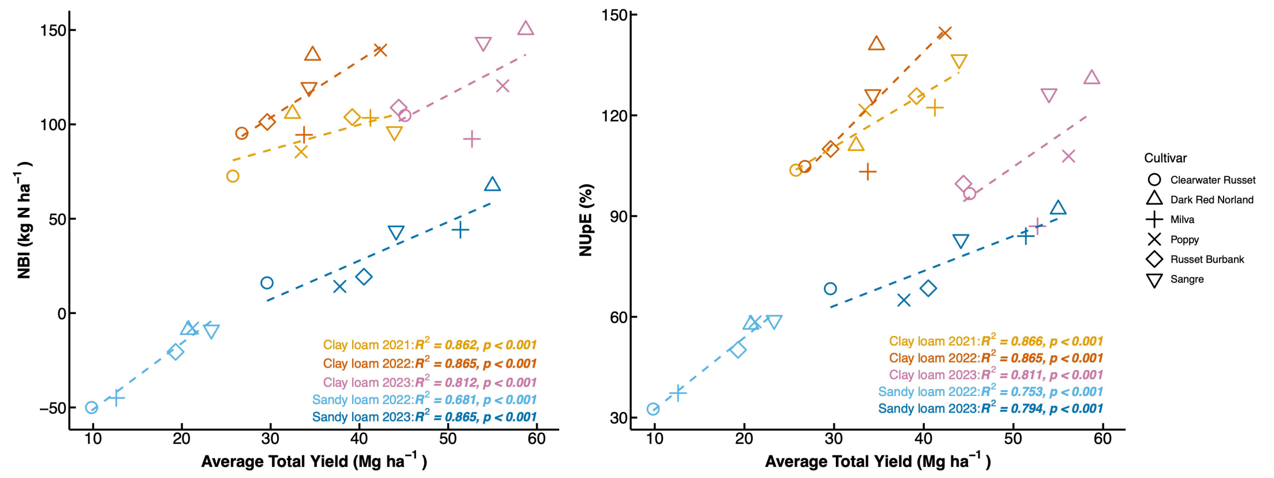

FIGURE 1
Linear regression (model II) between nitrogen balance intensity (kg N ha^{-1}) and average total yield (Mg ha^{-1}) (left panel). *F*-statistics and *p*-values: clay loam 2021 (F=95.3, p<0.001), clay loam 2022 (F=96.2, p<0.001), clay loam 2023 (F=65.1, p<0.001), sandy loam 2022 (F=32.44, p<0.001), sandy loam 2023 (F=95.8, p<0.001). Linear regression (model II) between nitrogen uptake efficiency (%) and average total yield (Mg ha^{-1}) (right panel). *F*-statistics and *p*-values: clay loam 2021 (F=97.1, p<0.001), clay loam 2022 (F=96.4, p<0.001), clay loam 2023 (F=64.6, p<0.001), sandy loam 2022 (F=46.0, p<0.001), sandy loam 2023 (F=57.8, p<0.001). Difference site-years denoted by colour, and cultivar by shape (n=20).

N translocated to tuber later in the growing season. However, more research would need to be done to link improvements in NUE to N translocation during the growing season. Quantitative trait loci (QTL) studies have found multi-trait genomic regions with associations with potato NUE on chromosomes III, V, and VI (Getahun et al., 2022), but this research also highlighted the importance of growing season conditions on NUE. Further research to determine specific phenotypic traits linked to NUE and their interaction with environment is critical.

The cultivar differences observed in our experiment may not necessarily indicate a superiority in specifically acquiring or utilizing N but instead may reflect superiority in other aspects (photosynthetic efficiency, water use efficiency, early-season vigor, early maturity, etc.) which then translate into using more N, when soil N is readily available for uptake. It is possible that earlier-maturing cultivars are better able to move more N to tubers before harvest than later-maturing cultivars. Fertilizer considerations are also important, as high applications or split applications can promote extended vegetative growth which can delay N translocation to tubers. Overall, Dark Red Norland and Sangre consistently performed equal to or better than other cultivars across yield and NUE metrics. Hence, the ability of a plant to produce high yielding tubers also corresponds with greater NUE. In other research, the development of “Alturas” - a late-maturing russet that requires 40% less fertilizer than Russet Burbank, showed potential for improvements in NUE through cultivar (Novy et al., 2003). Our findings demonstrate sufficient variation to prompt further investigation into NUE mechanisms in potato, and that cultivar selection could allow producers to reduce fertilizer rates and improve the N balance of potato production systems. Healthy and vigorous plants that produce high biomass tubers not only represent agronomic yield benefits, but also present environment benefits in the form of NUE.

3.3 Diverging effects of fertilizer on yield and NUE highlight the role of soil N supply

Fertilizer rate did not significantly impact total yield or tuber N content in any site-year (Tables 2, 3). This highlights the potential to reduce or omit N application without yield penalties, and our findings align with prior studies. Research in Manitoba investigated potato yields at 80% of the recommended N rate (ranged from 119–168 kg N ha^{-1}) and found that fertilizer recommendations over-estimated crop N needs and could be reduced (Gao et al., 2018). In evaluating 15 site-years across Canada, there was no yield response at N rates above 60 kg N ha^{-1} for four of those site-years, and no yield response above 120 kg N ha^{-1} for another five site-years (Nyiraneza et al., 2021). Research shows that typical N fertilizer recommendations for potato are excessively high, and could be reduced without yield reductions in many cases (Gao et al., 2018; Nyiraneza et al., 2021).

Excessive fertilizer rates are known to reduce the NUE of cropping systems (Ruža et al., 2013). Our findings confirm this, with both indicators of NUE: NBI and NUpE, being influenced by fertilizer rate alone, rather than by interactions of cultivar and fertilizer rate (Tables 4, 5). Consistently, the 0 kg N ha^{-1} treatment led to the highest NBI values, while increases in fertilizer generally led to incrementally lower values (Table 3). Likewise, tuber NUpE generally decreased with greater N applications (Table 5). These results suggest lower fertilizer rates (0–10 kg N ha^{-1} at the clay loam site, or 0–50 kg N ha^{-1} at the sandy loam sites) would be sufficient for potato production, while minimizing residual N buildup that could increase risk of N loss and input costs for producers.

The lack of yield response to fertilizer points to the importance of soil N mineralization during the growing season. Prior to planting, total extractable N (0–60 cm) at the clay loam site was 77.5, 92.5, 110.9 kg N ha^{-1} for 2021, 2022, and 2023, respectively. At

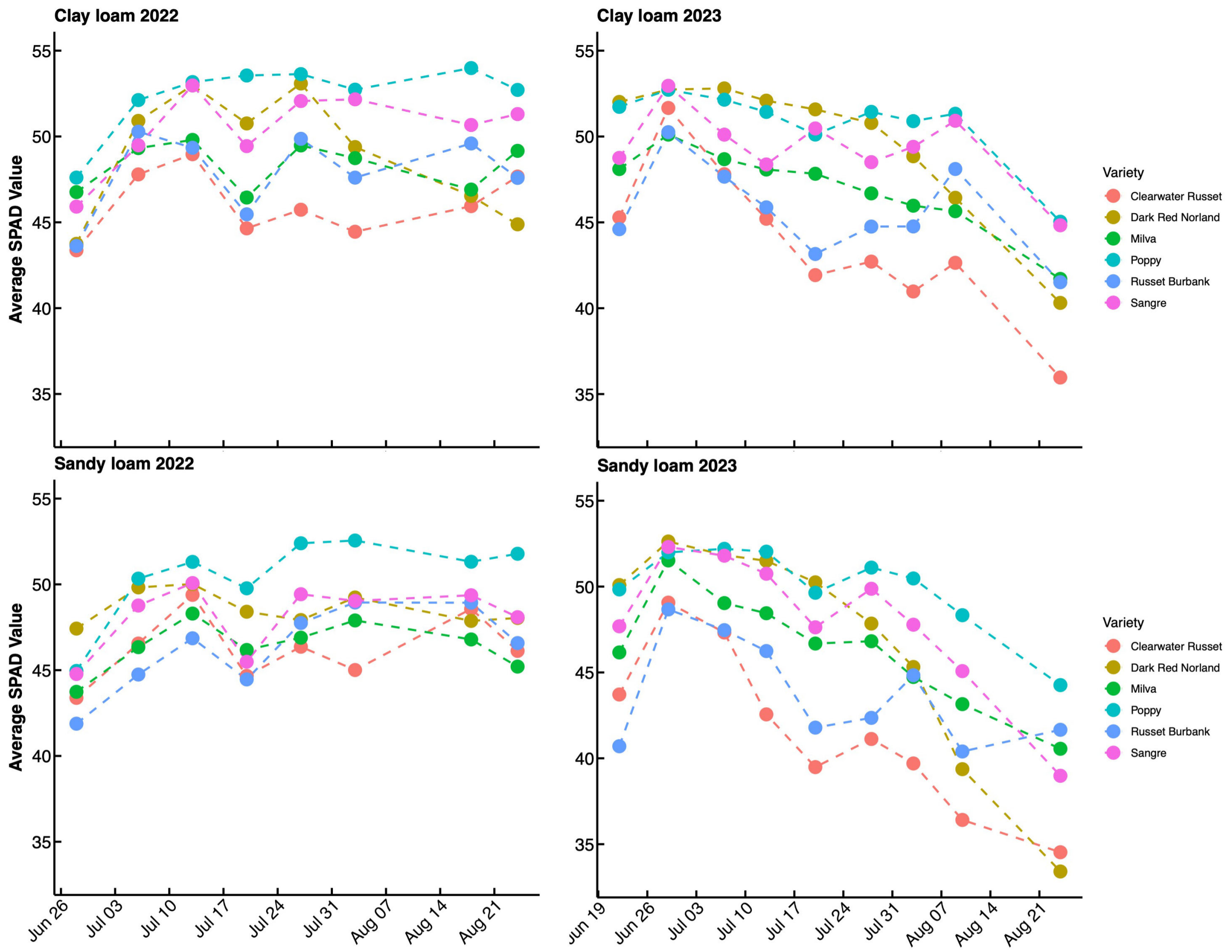

FIGURE 2
Average soil plant analysis development (SPAD) leaf N measurements over the growing season for each site year. Cultivar is denoted by colour.

the sandy loam site, pre-plant total extractable N (0–60 cm) was 84.4 and 100.6 kg N ha^{-1} for 2022 and 2023. These levels are below the typical crop N demand for potato production, which ranges between 125-225 kg N ha^{-1} on the Canadian Prairies (Gao et al., 2018; Government of Saskatchewan). However, the lack of yield response to fertilizer is likely explained by significant amounts of soil N mineralized during the growing season.

Growing season N mineralization was estimated by subtracting the pre-plant soil N levels (0–60 cm) from the amount of N in the soil (0–60 cm) plus the plant N contained in the unfertilized controls after harvest. At the clay loam site, estimated soil N mineralization was 55, 89, and 304 kg N ha^{-1} for 2021, 2022, and 2023, respectively. At the sandy loam site, soil N mineralization varied, with only 17 kg N ha^{-1} in 2022 compared to 154 kg N ha^{-1} in 2023. This demonstrates a moderate to substantial contribution to crop N needs depending on the site-year. Moisture was likely a driving factor behind mineralization, with dry conditions at the 2022 sandy loam site-year resulting in the lowest mineralization, yields and tuber N uptake. In comparison, improved moisture conditions in other years (especially 2023) resulted in significantly higher mineralization, yields and tuber N uptake. Thus, environmental factors have a critical role in facilitating soil N mineralization and subsequent crop N uptake. It is important to note that total rainfall plus irrigation during the growing season at the sites was still generally low (182–280 mm) in comparison to typical potato production systems that target 25 mm per week (Government of Saskatchewan). Therefore, the moisture provided in other potato fields could be sufficient to promote significant growing season N mineralization.

This points to the importance of determining mineralization potential of soils, to avoid over-application of fertilizers on sites that may be able to support high yields without additional N. Therefore, accounting for mineralizable soil N is a critical link that many producers may be missing. However, research still needs to determine a standardized protocol to estimate soil potentially mineralizable N (Clark et al., 2020; Ros et al., 2011), let alone to determine an accurate projection. Large differences in results are found between various methodologies and the length of incubations can vary significantly (7–210 days) (Ros et al., 2011). Advancement in this area could reduce the trade-offs which include processing time, cost, and accuracy (Clark et al., 2020). Fast and effective mineralizable N testing would further enhance the toolbox producers can utilize to determine appropriate fertilizer rates to optimize input costs and NUE.

This research confirms that there is sufficient cultivar variation in potato to create differences in yield and NUE. Cultivar selection can therefore be a sustainable management tool, assuming future research will work to identify top performing cultivars in different market or maturity classes. While we identified cultivar-based differences, there was a strong relationship between yield and NUE, and the implications from this are positive for producers: selecting a high yielding cultivar also confers improved NUE. The impact of environment and climate is one limitation, as growing season can restrict later-maturing cultivars from reaching their full potential; however cultivars should be selected with the climate in mind. Additionally, there is more risk than reward to high fertilizer rates, especially if growing an improved NUE cultivar or on soils with repeated historical application of N and high mineralization potential that could satisfy potato N requirements. It is clear improvements in soil testing are needed to give producers a quick decision tool that allows for reductions in fertilizer rates. Using these strategies together will improve sustainability of potato production.

4 Conclusions

This five site-year trial explored NUE across multiple potato cultivars and fertilizer rates on the Canadian Prairies. The results show that cultivar strongly influences yield and NUE metrics. Dark Red Norland and Sangre were top performing cultivars, as both demonstrated improved N uptake and recovery in tubers compared to other cultivars. A significant relationship between yield and NUE demonstrates that effective use of N is typically characterized by improved yields, and therefore producers can optimize both yield and NUE by way of cultivar selection. Fertilizer did not influence yield or tuber N, likely due to soil N mineralization over the growing season which provided sufficient N. Therefore, we highlight the urgent need to better estimate the soil N supplied throughout a growing season to help inform fertilizer needs. Selecting potato cultivars with high yields also confers greater NUE, thus, cultivar selection offers a path towards more sustainable potato production- improving crop performance while reducing fertilizer costs and environmental N loss.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. KC: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported by the Saskatchewan Ministry of Agriculture through an Agriculture Development Fund grant. Funding was also provided by the Natural Sciences and Engineering Research Council of Canada through a Discovery Grant and a Canada Graduate Scholarship.

Acknowledgments

This work was carried out on Treaty 6 Territory, homeland of the Métis. We pay our respect to the First Nations and Métis ancestors of this place and reaffirm our relationships with one another. Thanks to Olivia Otchere, Jamie Taylor, Jackie Bantle, Neil LaBar, Jenna St. Jacques, Autumn Collins, Dane Harder, Daphnee Ferland, and Rachelle McCannell for technical support and contributions to field work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1617873/full#supplementary-material

SUPPLEMENTARY TABLE 1

Soil characteristics at each site taken in the spring prior to planting. pH, organic matter (%) and bulk density (g cm^{-3}) from 0–15 cm soil depth. Spring soil total extractable N (kg N ha^{-1}) from 0–60 cm soil depth.

References

Agriculture and Agri-Food Canada (2021). *Potato Market Information Review 2020-2021*. (Ottawa, Ontario: Government of Canada) Available online at: https://publications.gc.ca/collections/collection_2022/aac-aafc/A71-32-2021-eng.pdf (Accessed July 2, 2025).

Agriculture and Agri-Food Canada (2023). *Potato Market Information Review 2022-2023*. (Ottawa, Ontario: Government of Canada) Available online at: https://publications.gc.ca/collections/collection_2024/aac-aafc/A71-32-2023-eng.pdf (Accessed July 2, 2025).

Canadian Food Inspection Agency (2021). *Part 2- Grade Requirements for Fresh Vegetables. Canadian Grade Compendium Volume 2.* (Ottawa, Ontario: Government of Canada) Available online at: https://inspection.canada.ca/en/about-cfia/acts-and-regulations/list-acts-and-regulations/documents-incorporated-reference/canadian-grade-compendium-volume-2#s31c3 (Accessed July 2, 2025).

Carruthers, L. C., and Congreves, K. A. (2025). Exploring phosphorus use efficiency of different potato cultivars on the Canadian Prairies. *Can. J. Plant Sci.* 105, 1–11. doi: 10.1139/cjps-2024-0121

Chahal, I., Baral, K. R., Congreves, K. A., Van Eerd, L. L., and Wagner-Riddle, C. (2021). Opportunities to reduce nitrous oxide emissions from horticultural production systems in Canada. *Can. J. Plant Sci.* 101, 999–1013. doi: 10.1139/cjps-2021-0107

Clark, J. D., Veum, K. S., Fernández, F. G., Kitchen, N. R., Camberato, J. J., Carter, P. R., et al. (2020). Soil sample timing, nitrogen fertilization, and incubation length influence anaerobic potentially mineralizable nitrogen. *Soil Sci. Soc. Amer J.* 84, 627–637. doi: 10.1002/saj2.20050

Cohan, J. P., Hannon, C., Houilliez, B., Gravoueille, J. M., Geille, A., Lampaert, E., et al. (2018). Effects of potato cultivar on the components of nitrogen use efficiency. *Potato Res.* 61, 231–246. doi: 10.1007/s11540-018-9371-6

Congreves, K. A., Otchere, O., Ferland, D., Farzadfar, S., Williams, S., and Arcand, M. M. (2021). Nitrogen use efficiency definitions of today and tomorrow. *Front. Plant Sci.* 12. doi: 10.3389/fpls.2021.637108

de Mendiburu, F., and Yaseen, M. (2020). *agricolae: Statistical Procedures for Agricultural Research*. (Vienna: R foundation for statistical computing) Available online at: https://CRAN.R-project.org/package=agricolae

FAO (2017). *The future of food and agriculture and challenges*. (Rome: Food and Agriculture Organization of the United Nations).

Gao, X., Shaw, W. S., Tenuta, M., and Gibson, D. (2018). Yield and nitrogen use of irrigated processing potato in response to placement, timing and source of nitrogen fertilizer in manitoba. *Am. J. Potato Res.* 95, 513–525. doi: 10.1007/s12230-018-9656-y

Getahun, B. B., Kassie, M. M., Visser, R. G. F., and van der Linden, C. G. (2020). Genetic diversity of potato cultivars for nitrogen use efficiency under contrasting nitrogen regimes. *Potato Res.* 63, 267–290. doi: 10.1007/s11540-019-09439-8

Getahun, B. B., Tiruneh, M. A., Aliche, E., Malossetti, M., Visser, R. G., and van der Linden, C. G. (2022). Genotype-by-environment interaction for quantitative trait loci affecting nitrogen use efficiency and associated traits in potato. *Potato Res.* 65, 777–807. doi: 10.1007/s11540-022-09548-x

Government of Manitoba (2022). *2022/2023 Cost of Production Irrigated Potato*. Available online at: https://www.gov.mb.ca/agriculture/farm-management/cost-production/pubs/cop-crop-irrigated-potato.pdf (Accessed July 2, 2025)

Government of Saskatchewan. *Potatoes | Horticultural Crops* (Government of Saskatchewan). Available online at: https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/horticultural-crops/potatoes (Accessed July 2, 2025).

Haase, T., Schüler, C., and Heß, J. (2007). The effect of different N and K sources on tuber nutrient uptake, total and graded yield of potatoes (Solanum tuberosum L.) for processing. *Eur. J. Agron.* 26, 187–197. doi: 10.1016/j.eja.2006.09.008

Hao, X., Ball, B. C., Culley, J. L. B., Carter, M. R., and Parkin, G. W. (2008). "Soil Density and Porosity," in *Soil Sampling and Methods of Analysis*. Eds. M. Carter and E. Gregorich (Boca Raton: Canadian Society of Soil Science), 743–759.

International Potato Center. (2017). *Potato Facts and Figures - International Potato Center*. Available online at: https://cipotato.org/potato/potato-facts-and-figures/ (Accessed July 2, 2025).

Janzen, H. H., Beauchemin, K. A., Bruinsma, Y., Campbell, C. A., Desjardins, R. L., Ellert, B. H., et al. (2003). The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. *Nutrient Cycling Agroecosystems* 67, 85–102. doi: 10.1023/A:1025195826663

Jones, C. R., Michaels, T. E., Schmitz Carley, C., Rosen, C. J., and Shannon, L. M. (2021). Nitrogen uptake and utilization in advanced fresh-market red potato breeding lines. *Crop Sci.* 61, 878–895. doi: 10.1002/csc2.20297

Keeney, D. R., and Nelson, D. W. (1982). "Nitrogen- Inorganic Forms," in *Methods of Soil Analysis*. Eds. R. H. Miller and D. R. Keeney (Madison, WI: American Society of Agronomy), 643–693.

Koch, M., Naumann, M., Pawelzik, E., Gransee, A., and Thiel, H. (2020). The importance of nutrient management for potato production part I: plant nutrition and yield. *Potato Res.* 63, 97–119. doi: 10.1007/s11540-019-09431-2

Li, L., Qin, Y., Liu, Y., Hu, Y., and Fan, M. (2012). Leaf positions of potato suitable for determination of nitrogen content with a SPAD meter. *Plant Production Sci.* 15, 317–322. doi: 10.1626/pps.15.317

Milroy, S. P., Wang, P., and Sadras, V. O. (2019). Defining upper limits of nitrogen uptake and nitrogen use efficiency of potato in response to crop N supply. *Field Crops Res.* 239, 38–46. doi: 10.1016/j.fcr.2019.05.011

Mokrani, K., Hamdi, K., and Tarchoun, N. (2018). Potato (Solanum tuberosum L.) response to nitrogen, phosphorus and potassium fertilization rates. *Commun. Soil Sci. Plant Anal.* 49, 1314–1330. doi: 10.1080/00103624.2018.1457159

Novy, R. G., Corsini, D. L., Love, S. L., Pavek, J. J., Mosley, A. R., James, S. R., et al. (2003). Alturas: A multi-purpose, Russet potato cultivar with high yield and tuber specific gravity. *Am. J. Pot Res.* 80, 295–301. doi: 10.1007/BF02854312

Nyiraneza, J., Cambouris, A. N., Nelson, A., Khakbazan, M., Mesbah, M., Perron, I., et al. (2021). Potato yield, net revenue and specific gravity responses to nitrogen fertilizer under different canadian agroecozones. *Agronomy* 11, 1392. doi: 10.3390/agronomy11071392

Ospina, C. A., Lammerts van Bueren, E. T., Allefs, J. J. H. M., Engel, B., van der Putten, P. E. L., van der Linden, C. G., et al. (2014). Diversity of crop development traits and nitrogen use efficiency among potato cultivars grown under contrasting nitrogen regimes. *Euphytica* 199, 13–29. doi: 10.1007/s10681-014-1203-4

Raun, R. W., and Johnson, G. V. (1999). Improving nitrogen use efficiency for cereal production. *Agron. J.* 91, 357–363. doi: 10.2134/agronj1999.00021962009100030001x

R Core Team (2022). *R: A Language and Environment for Statistical Computing*. (Vienna: R foundation for statistical computing).

Rens, L., Zotarelli, L., Alva, A., Rowland, D., Liu, G., and Morgan, K. (2016). Fertilizer nitrogen uptake efficiencies for potato as influenced by application timing. *Nutrient Cycling Agroecosystems* 104, 175–185. doi: 10.1007/s10705-016-9765-2

Ros, G. H., Temminghoff, E. J. M., and Hoffland, E. (2011). Nitrogen mineralization: a review and meta-analysis of the predictive value of soil tests. *Eur. J. Soil Sci.* 62, 162–173. doi: 10.1111/j.1365-2389.2010.01318.x

Rosales, M. A., Franco-Navarro, J. D., Peinado-Torrubia, P., Díaz-Rueda, P., Álvarez, R., and Colmenero-Flores, J. M. (2020). Chloride improves nitrate utilization and NUE in plants. *Front. Plant Sci.* 11. doi: 10.3389/fpls.2020.00442

RStudio Team (2023). *RStudio: Integrated Development Environment for R*. (Boston MA: Posit Software).

Ruža, A., Skrabule, I., and Vaivode, A. (2013). Influence of nitrogen on potato productivity and nutrient use efficiency. *Proc. Latvian Acad. Sciences Section B: Natural Exact Appl. Sci.* 67, 247–253. doi: 10.2478/prolas-2013-0043

Sattelmacher, B., Klotz, F., and Marschner, H. (1990). Influence of the nitrogen level on root growth and morphology of two potato varieties differing in nitrogen acquisition. *Plant and Soil* 123, 131–137. doi: 10.1007/BF00011258 (Accessed Jul 2, 2025).

Stark, C. H., and Richards, K. G. (2008). The continuing challenge of nitrogen loss to the environment: Environmental consequences and mitigation strategies. *Dynamic Soil Dynamic Plant* 2, 41–55.

Tiwari, J. K., Buckseth, T., Singh, R. K., Kumar, M., and Kant, S. (2020). Prospects of improving nitrogen use efficiency in potato: lessons from transgenics to genome editing strategies in plants. *Front. Plant Sci.* 11. doi: 10.3389/fpls.2020.597481

UNEP (2019). *Frontiers 2018/19: Emerging Issues of Environmental Concern*. (Nairobi: United Nations Environment Programme) Available online at: https://www.unep.org/resources/frontiers-201819-emerging-issues-environmental-concern.

Waddell, J. T., Gupta, S. C., Moncrief, J. F., Rosen, C. J., and Steele, D. D. (1999). Irrigation and nitrogen management effects on potato yield, tuber quality, and nitrogen uptake. *Agron. J.* 91, 991–997. doi: 10.2134/agronj1999.916991x

Wu, L., Li, L., Ma, Z., and Fan, M. (2022). Improving potato yield, water productivity and nitrogen use efficiency by managing irrigation based on potato root distribution. *Int. J. Plant Production* 16, 547–555. doi: 10.1007/s42106-022-00205-4

Zebarth, B., Belanger, G., Cambouris, A., and Ziadi, N. (2012). "Nitrogen Fertilization Strategies in Relation to Potato Tuber Yield, Quality, and Crop N Recovery," in *Sustainable Potato Production: Global Case Studies* (Dordrecht, Heidelberg, New York, London: Springer), 165–186.

Zebarth, B., Karemangingo, C., Savoie, D., Scott, P., and Moreau, G. (2007). *Nitrogen Management for Potatoes: General Fertilizer Recommendations*. (New York: Springer, American Journal of Potato Research)

Zebarth, B. J., and Rosen, C. J. (2007). Research perspective on nitrogen BMP development for potato. *Am. J. Potato Res.* 84, 3–18. doi: 10.1007/BF02986294

Zebarth, B. J., Tai, G., Tarn, R., De Jong, H., and Milburn, P. H. (2004). Nitrogen use efficiency characteristics of commercial potato cultivars. *Can. J. Plant Sci.* 84, 589–598. doi: 10.4141/P03-050