



Potato (*Solanum tuberosum* L.) Responses to Nitrogen Fertilisation in Different Groundwater Nitrate Environments

Ophelia Tsai¹ · Andrew Stammer² · Matthew D. Ruark³ · Yi Wang¹ 



Received: 3 March 2025 / Accepted: 20 June 2025 / Published online: 11 August 2025
© The Author(s) 2025

Abstract

Reducing the over-use of nitrogen (N) fertiliser and mitigating leaching in highly cultivated agricultural areas have become the top priorities for potato researchers and the industry in the USA. In response, field trials were conducted in 2022 and 2023 at the University of Wisconsin Hancock Agricultural Research Station to explore the effects of different N fertilisation treatments on the in-season N status and at-harvest yield and size distribution of three potato (*Solanum tuberosum* L.) cultivars (Colomba, Snowden, Goldrush) grown in irrigated sandy soil. The study was performed in two field sites with varied background irrigation groundwater nitrate–N concentrations. The findings revealed that (1) N treatment effects were season- and cultivar-dependent; (2) the high N rate at 350 kg N ha⁻¹ significantly increased petiole nitrate–N during the latter part of tuber bulking, yet this increase was not always associated with higher total and marketable tuber yields at harvest; (3) in a year when high N inputs came from the background nitrate in irrigation water, high yields were observed even in the control treatment with no supplemental N added; (4) nitrate–N concentrations in irrigation could be confounding variables when assessing potato responses to N fertilisation. This study provides new insights into sustainable N management for potato production in irrigated sandy soil, emphasising that different nitrogen sources—including fertiliser N and nitrate in irrigation groundwater—should be accounted for when making N application recommendations.

Keywords Irrigation · Nitrogen · Potato · Sandy soil · Size · Yield

✉ Yi Wang
wang52@wisc.edu

¹ Department of Plant and Agroecosystem Sciences, University of Wisconsin—Madison, 1575 Linden Drive, Madison, WI 53706, USA

² University of Wisconsin Soil and Forage Lab, Madison, WI, USA

³ Department of Soil and Environmental Sciences, University of Wisconsin—Madison, Madison, WI, USA

Abbreviations

N	Nitrogen
kg	Kilogram
ha	Hectare
mt	Metric ton
mg	Milligram
cm	Centimetre
mm	Millimetre
ET	Evapotranspiration
L	Litre
NO ₃ -N	Nitrate-N
NH ₄ -N	Ammonium-N
g	Gram
mL	Millilitre
SG	Specific gravity
°C	Celsius
RCBD	Randomised complete block design
CRD	Complete randomised design
NUE	Nitrogen-use efficiency
PNB	Partial nutrient balance
ANOVA	Analysis of variance
Tukey's HSD	Tukey's honestly significant difference
DAE	Days after emergence
UAN	Urea ammonium nitrate
OM%	Organic matter percentage

Introduction

Being the third-largest producer in the USA, Wisconsin dedicates roughly 25,500 hectares of land to potato farming, and the industry contributes over half a billion dollars to the state's economy annually (Kashian et al. 2014). Wisconsin's agricultural industry is deeply rooted in the Central Sands region, where the unique sandy soils, frequent summer precipitations, and readily available irrigation groundwater not only promote higher yields but also accommodate an earlier start to the planting season, further enhancing potato crop's productivity (Kashian et al. 2014; USDA 2022; Waddell et al. 2000).

However, the high-value nature of this crop is accompanied by a high input demand, and intensive nitrogen (N) fertilisation is pivotal to ensure high yield and premium tuber quality. The combination of sandy soils, frequent heavy precipitation, and high crop N demands has created environmental challenges, particularly the potential for nitrate leaching into the groundwater that poses risks to both public health and agricultural sustainability in the Central Sands (Kucharik and Campbell 2020; Shrestha et al. 2010). Although groundwater serves as the main source of drinking water, nitrate–N concentrations in private wells in the Central Sands have exceeded the USA Environmental Protection Agency's safe drinking water standards at 10 mg L⁻¹ (Liang n.d.;

DHS 2020). High nitrate intake is associated with adverse human health outcomes, such as an increased risk of blue baby syndrome, further highlighting the urgency of addressing this environmental concern (DHS 2020); Ward et al. 2018; Yang et al. 1998).

To address such pressing environmental and public health issues, the sustainable management of N in potato production systems becomes paramount. Efficient fertilisation practices, such as split-N application, have been shown to significantly reduce the risks of N loss and environmental contamination while optimising crop performance (Rosen and Bierman 2008; Shrestha et al. 2010, 2023; Zebarth and Rosen 2007). Farmers use petiole nitrate–N analysis to guide their split application timing and amount, as petiole nitrate–N indicates the immediate plant N status on the day of sampling (Wang et al. 2021).

Additionally, N management is further complicated by unaccounted N contributions from irrigation groundwater, particularly when the irrigation source contains high nitrate–N concentrations. The high water demand for potato crops over the growing season often necessitates frequent irrigation in the absence of sufficient precipitation. Potato yields are highly sensitive to soil moisture fluctuations, with yield losses occurring when soil moisture levels vary by as little as 10% (King and Stark 1997). In the Central Sands region, potato crops typically receive 380–480 mm of irrigation water per growing season (Crosby and Wang 2021). This highlights the critical role of irrigation as an interactive factor in N management because previous studies have suggested that 60–80% of the nitrate–N from irrigation water may contribute to the crop's N requirements during the growing season (Karim 1995; Keeney and Follett 1991). Furthermore, other studies have reported high yields in control treatments that received no N fertiliser during the growing season (Maltas et al. 2018; Joern and Vitosh 1995; Wilson et al. 2009). These findings prompted the need to investigate unaccounted N sources, such as nitrate from irrigation water, that might explain the lack of yield response to N fertilisation.

Recognising these needs, field trials were conducted with treatments including varied N fertiliser application rates and timings on three potato cultivars in fields with differing nitrate–N concentrations in irrigation groundwater. The objective of this study is to determine the effects of different N treatments on in-season plant tissue N status and the tuber yield and size distribution at harvest. The overall goal is to offer a novel understanding of the complex response of potatoes to N fertilisation, influenced by interactions between cultivar, N application, and N from irrigation water.

Materials and Methods

Agronomic Practices and Field Design

This field research was conducted at the University of Wisconsin Hancock Agricultural Research Station in Hancock, WI (latitude: 44.12°N; longitude: 89.53°W; elevation: 328 m) in 2022 and 2023. The soil at this location is characterised as

loamy fine sand from 0 to 45 cm depth and fine sand (organic matter < 0.5%) from 45 to 75 cm depth (National Cooperative Soil Survey [n.d.](#)). Previous research has shown that water applications greater than 33 mm led to deep drainage and potential nitrate leaching in potato ridges at this location (Starr et al. [2005](#)). Three cultivars were selected for this study due to their popularity in the region and variances in N use efficiency: Snowden (a white chipping cultivar) and Colomba (a yellow fresh market cultivar) were grown in 2022, while Snowden and Goldrush (a russet cultivar) were grown in 2023. Snowden and Goldrush were found responsive to high N rates in previous studies (Reiter et al. [2012](#); Wang et al. [2022](#)). Colomba, a recently released variety from the Netherlands, was bred from the Dutch potato germplasm and shown to have a small canopy size but high tuber yield potential (D. Maum, Personal Communication, January 13, 2021). The present study was the first time that Colomba was trialled in Wisconsin.

Two experimental fields at the station were used: field C and field K, which are 500 m apart, and use two separate irrigation wells that have different nitrate–N concentrations. In this study, an individual experiment was performed within each cultivar and site-year, because there was no practical need to compare the three cultivars belonging to different market sectors. In each site-year for each cultivar, each plot measured 6 by 0.9 m and was comprised of eight rows. Guard rows were established on the outermost rows (1 and 8), and rows 2 and 3 were designated for in-season petiole collections. Rows 5 and 6 were used to evaluate tuber yield and size distribution at harvest. The study used a randomised complete block design (RCBD) with four replications in all site-years.

Pre-planting and post-harvest soil samples (0–30 and 30–60 cm depth), each being a composite of six cores, were collected in each site-year. Soil samples were analysed for $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, pH, organic matter (OM%), phosphorus (P), and potassium (K) by the University of Wisconsin Soil and Forage Analysis Laboratory (Laboski et al. [2006](#)). Across all site-years, OM% ranged between 0.5 and 0.8, and pH levels remained between 5.6 and 6.5. Soil $\text{NO}_3\text{-N}$ content remained below 6 mg kg^{-1} , and $\text{NH}_4\text{-N}$ content did not exceed 10 mg kg^{-1} both pre-planting and post-harvest (Table 1). 185 kg ha^{-1} of phosphorus was applied at planting (in the form of 0–46–0). 438 kg ha^{-1} of potassium (in the form of 0–0–60) was applied two weeks prior to planting. Both P and K, and all micronutrients needed for potatoes, were maintained at optimal levels throughout each season.

A weather station 400 m away from the plots provided daily maximum and minimum temperatures as well as precipitation records. Irrigation was administered bi-daily (in the absence of precipitation) at approximately $13 \pm 4 \text{ mm}$ to fulfil 100% evapotranspiration (ET) to maintain soil moisture within the plant rooting zone (the upper 30 cm of soil) above 80% of field capacity. Total irrigation amounts in field C were 338 and 564 mm in 2022 and 2023, and total irrigation records in field K were 356 and 620 mm in 2022 and 2023, respectively. In each site-year, planting occurred between April 25 and 30 with 30 cm seed spacing and 90 cm row spacing, plant emergence was observed around May 15, vine desiccant was applied around September 10 to promote tuber skin set, and final harvest took place between September 21 and September 25. Besides N treatments, all other agronomic practices, including herbicide, pesticide, and vine desiccant,

Table 1 Pre-planting and post-harvest soil test results for C and K fields in 2022 and 2023

Year	Field	Time	Depth (cm)	pH	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Organic matter%	NO ₃ -N (mg kg ⁻¹)	NH ₄ -N (mg kg ⁻¹)
2022	C	Pre-planting	0–30	6.2	22	221	0.8	5.8	9.7
			30–60	6.4	275	549	0.6	0.9	6.8
		Post-harvest	0–30	NA				3.4	4.0
			30–60					2.7	3.4
	K	Pre-planting	0–30	5.6	117	147	0.7	1.5	8.3
			30–60	5.9	22	67	0.5	1.4	5.5
		Post-harvest	0–30	NA				5.3	4.6
			30–60					4.1	3.0
2023	C	Pre-planting	0–30	6.4	82	119	0.8	1.6	1.2
			30–60	6.5	72	119	0.6	0.8	0.9
		Post-harvest	0–30	NA				1.2	5.3
			30–60					1.2	6.8
	K	Pre-planting	0–30	5.9	120	109	0.8	1.3	3.9
			30–60	5.8	82	78	0.5	0.6	1.5
		Post-harvest	0–30	NA				2.7	8.3
			30–60					2.4	7.3

NA, not available

were based on best management practices recommended by the University of Wisconsin—Madison Extension (Bradford et al. 2024).

N Treatments and Groundwater Nitrate–N Concentrations

There were three N treatments: (1) control at 0 kg ha⁻¹ with no fertiliser applied, (2) a treatment with 250 kg ha⁻¹ applied in split doses ('low N'), and (4) a treatment with a high N rate of 350 kg ha⁻¹ also applied in split doses ('high N'). 'Low N' and 'high N' treatments included four split-N applications approximately every 10 days from early tuber bulking to late tuber bulking. Details regarding N rates and timings at C and K fields in each year are presented in Table 2. In field C, split-N applications during tuber bulking were administered using fertigation with 32% urea ammonium nitrate fertiliser (UAN), a process combining irrigation and fertilisation. In field K, due to the limitations of the irrigation system, plots were side-dressed with dry ammonium nitrate fertiliser and irrigated immediately. No canopy damage using this application approach was observed on any of the plots in field K.

Furthermore, an additional N source was calculated from irrigation groundwater, which was attributed to the elevated nitrate–N concentration in the wells that watered C and K fields, respectively. In each growing season, groundwater samples were collected from each well and sent to the University of Wisconsin—Stevens Point Water and Environmental Analysis Laboratory to measure nitrate–N concentrations. Testing results and estimated total N input from irrigation groundwater can be found

Table 2 Timeline of nitrogen applications at different potato growth stages for both C and K fields in each year

Treatment*	Emergence ammo- nium sulphate	Tuber initiation of ammonium nitrate	Split-N applications			Seasonal total N
			Early bulking	Mid-bulking	Late bulking	
Date/year	05/17/22	06/07/22	06/30/22	07/10/22	07/20/22	07/29/22
	05/18/23	06/08/23	06/29/23	07/11/23	07/20/23	07/31/23
	kg N ha ⁻¹					
Control	0	0	0	0	0	0
Low N	80	36	33.5	33.5	33.5	250
High N	80	136	33.5	33.5	33.5	350

*Starter fertiliser applied to all plots did not include any nitrogen

in Table 3. Notably, irrigation water at the K field contained substantially higher nitrate–N compared to field C in both years, offering this study a unique opportunity to observe potato N responses under low and high background N environments.

Data Collection

Plant Tissue Collection

During the tuber bulking period when split-N was applied, weekly plant tissue samplings were performed from the final week of June to the first week of August to assess the N status of the plants. To avoid sampling variation, sample collections were performed between 8 AM and 12 PM. The fourth fully expanded leaf from the apex of 20 randomly selected healthy plants was collected within the designated rows, and petioles were then separated from the rest of the compound leaves to analyse nitrate–N. On the day of tissue sampling, when split-N application was scheduled, samples were collected before N fertiliser was applied. The petioles were immediately placed into paper bags and transported to a dryer at 70 °C for a minimum duration of 48 h until no more weight was lost. Post-drying, the tissues were ground using a Wiley mini mill (Thomas Scientific, Swedesboro, NJ) to facilitate passage through a 2-mm sieve.

For nitrate–N analysis, nitrate was extracted using 2% acetic acid (MacKown and Weik 2004). Firstly, 0.1 g of ground dry tissue samples was weighed into a 50-mL centrifuge tube before the addition of 25 mL of 2% acetic acid. Capped tubes were then shaken for fifteen minutes before filtration of samples through Whatman No. 2 filter papers. The filtered samples were analysed by flow injection analysis on a FIA-lyzer 1000 Series instrument (FIALab, Seattle, WA) using a nitrate/nitrite analysis by the Griess method with cadmium reduction of nitrate to nitrite (Gal et al. 2004). The unit of petiole nitrate–N was mg kg⁻¹ of dry weight.

Yield and Quality Assessment

This study evaluated two designated rows in each plot for total yield, size distribution, tuber specific gravity (SG), and N removal from the tubers. After harvest, tubers were washed and graded by either weight or diameter, depending on the cultivar, using an AgRay Vision x-ray grading machine (AgRay Vision, Acampo, CA). The specific grading criteria for each cultivar that belongs to different market sectors are listed in Table 4. The total yield for each plot was calculated as the sum of the weights of all

Table 3 Irrigation amount, irrigation nitrate–N concentration, and total N input from groundwater that irrigated the field plots in 2022 and 2023

Year	Field	Total irrigation applied (mm)	Irrigation Nitrate–N (mg L ⁻¹)	Irrigation N input (kg N ha ⁻¹)
2022	C	338	9.9	34
	K	356	25.3	91
2023	C	564	19.9	114
	K	629	33.3	212

harvested tubers. Tubers that were misshapen, rotten, or green from sunlight exposure were recorded as culls and included in the total yield.

For specific gravity (SG) determination, twelve marketable-sized tubers weighing 2000–3000 g in total from each plot were randomly selected and measured using a Weltech PW-2050 Dry Matter Assessment System. The system calculated the SG using the following formula published by Kleinkopf et al. (1987):

$$SG = \text{weight in air} \div (\text{weight in air} - \text{weight in water})$$

Subsequently, a subsample ranging from 200 to 350 g was randomly selected from the same batch, chopped, and placed in paper bags for drying at 70 °C until no more weight was lost. Post-drying, these samples were ground using a Thomas-Wiley laboratory mill (Model 4) to pass through a 2-mm mesh screen. Ground dry tissue samples were then weighed (2–5 mg) into tin foil capsules and analysed using an elemental combustion analyser (Costech Analytical Technologies, INC., Valencia, CA) to evaluate the total N content (% dry weight) of the plants in each plot. N removal was calculated using the following formula:

$$N \text{ Removal} = \text{Total N content}(\% \text{ dry weight}) \times \text{total yield}(\text{kg ha}^{-1}) \\ \times (\text{dry weight of sample} \div \text{fresh weight of sample})$$

Partial nutrient balance (PNB), a calculation that compares N removal to N input, was calculated using the formula listed as follows (Bero et al. 2014). There were two types of PNB calculated in this study, the first one only included fertiliser N as the N input in the denominator, and the second one included both fertiliser N and nitrate–N from irrigation water as the total N input in the denominator:

$$PNB^a = \text{Total N removal}(\text{kg ha}^{-1}) \div \text{N fertilizer input}(\text{kg ha}^{-1})$$

Table 4 Regional industry grading criteria of specific potato cultivars used for different market sectors

Cultivar	Size distribution	Diameter (mm)	Weight (g)
Colomba (fresh yellow)	Size A	> 63.5	< 340
	Size B	38.1–63.5	
Snowden (white chipping)	Small	< 47.6	
	Large	> 88.9	
	Marketable	47.6–88.9	
Goldrush (fresh russet)	Grade 1		0–113
	Grade 2		113–170
	Grade 3		170–283
	Grade 4		283–454
	Grade 5		> 454
	Marketable		Grades 2–4; 113–454

$$PNB^b = \text{Total N removal}(\text{kg ha}^{-1}) \\ \div [\text{Total N input}(\text{N fertilizer} + \text{irrigation nitrate} - \text{N})(\text{kg ha}^{-1})]$$

Statistical Analysis

Responses of each cultivar's in-season and at-harvest traits to N treatments were evaluated following an RCBD. In-season petiole nitrate–N was assessed using linear mixed-effect models, with N rate as the main factor and sampling date as the repeated measure. Data from each year-site were separately analysed due to significant year-site-N interactions. At-harvest traits, including yield, size distribution, N removal, and PNB of each cultivar, were also examined using linear mixed-effect models, with N rate as the main effect. ANOVA was employed for determining statistical significance in R, with subsequent post-hoc comparisons performed using Tukey's honestly significant difference (HSD) test to identify mean differences, applying an alpha level of 0.05 for statistical significance (R Core Team 2022).

Results

Environmental Conditions

Weather conditions during the growing seasons exhibited high year-to-year variations. For instance, the field season in 2022 experienced notably higher amounts of precipitation, accumulating a total precipitation of 530 mm, in contrast to the 214 mm of precipitation recorded in 2023. In 2022, two large precipitation events (> 33 mm) were documented (Fig. 1A). Comparatively, no rainfall event higher than 33 mm was recorded in 2023 (Fig. 1B). Despite the differences in rainfall, temperatures were relatively similar in both years, with an average temperature of 18.0 °C in 2022 and 18.7 °C in 2023 (Fig. 1).

Due to the drought stress in 2023, high irrigation amounts were recorded (564 mm in field C and 629 mm in field K) (Table 3). Considering that the well water nitrate–N concentrations in those two fields were 19.9 and 33.3 mg L⁻¹ separately, there were 114 and 212 kg ha⁻¹ of extra N inputs from the irrigation groundwater in fields C and K, respectively (Table 3; Fig. 1). Those amounts more than doubled the extra N inputs from irrigation water in 2022 (Table 3), a wetter year when 34 kg ha⁻¹ (nitrate–N concentration 9.9 mg L⁻¹ in C well) and 91 kg ha⁻¹ (nitrate–N concentration 25.3 mg L⁻¹ in K well) of extra N was noted from the irrigation water in the two fields, separately (Table 3; Fig. 1).

In-Season Plant N Status

In both years, distinct patterns of petiole nitrate–N concentrations as influenced by different N treatments were observed. There were consistently significant two-way

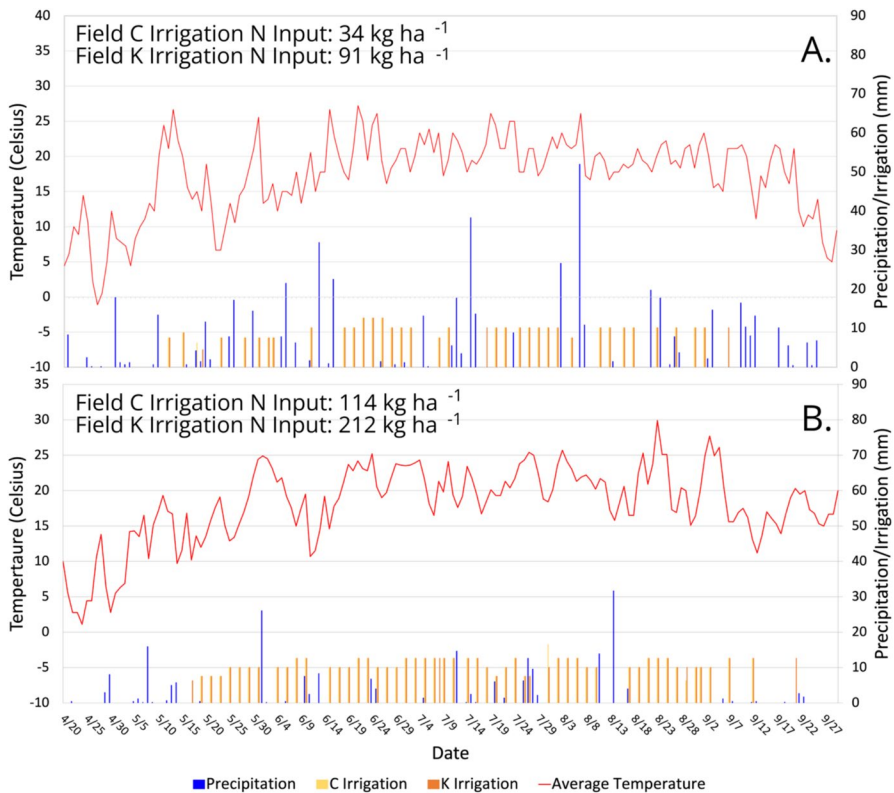


Fig. 1 Daily average temperature, precipitation, and irrigation data between planting and harvesting in 2022 (A) and 2023 (B). In each year, irrigation records in the C and K fields were highlighted using two different colours. Extra N inputs from the irrigation groundwater were shown in the upper left corner of each graph

interactions between N treatments and time of sampling (indicated by days after emergence, DAE) in all cultivars in both years (Table 5). Typically, petiole nitrate–N significantly increased under the two N treatments compared to the control for all cultivars in both fields. However, the effects of the low and high N treatments on petiole nitrate–N exhibited large variations across site-year combinations and cultivars.

For Colomba, N treatments (low N and high N) resulted in higher petiole nitrate–N concentrations than the control, particularly as the season progressed to the later four sampling dates (Fig. 2a, 2b). For Snowden, plants at the C field in both years showed higher petiole nitrate–N concentrations under the high N treatment in contrast to those under the control and the low N treatment (Fig. 2c, 2e). Whereas at the K field, petiole nitrate–N concentrations of the two N treatments were always higher than those under the control, but they were mostly not significantly different during the sampling period (Fig. 2d, 2f). In 2023, the Goldrush cultivar grown under control generally displayed lower petiole nitrate–N concentrations than the two N treatments, with high N exhibiting the highest values of late-season petiole

Table 5 ANOVA table that shows *P*-values for effects of N treatment (trt), sample collection date (indicated by days after emergence (DAE)), and their two-way interaction on petiole nitrate–N of Colomba in 2022, Snowden in both years, and Goldrush in 2023

Cultivar	Variables	Colomba	Snowden	Goldrush
Year/field		Petiole NO ₃ -N		
2022				
C	N trt	< 0.0001	< 0.0001	NA
	DAE	0.002	< 0.0001	
	N trt × DAE	0.140	< 0.0001	
K	N trt	< 0.0001	< 0.0001	
	DAE	0.007	< 0.0001	
	N trt × DAE	< 0.0001	< 0.0001	
2023				
C	N trt	NA	< 0.0001	< 0.0001
	DAE		< 0.0001	< 0.0001
	N trt × DAE		< 0.0001	< 0.0001
K	N trt		< 0.0001	< 0.0001
	DAE		< 0.0001	< 0.0001
	N trt × DAE		< 0.0001	< 0.0001

The *P*-values that were lower than 0.0001 were all marked as < 0.0001, and those that were higher than 0.0001 were presented with their true numbers. All *P*-values that were lower than 0.05 were bold. NA, not available

nitrate–N concentration, as shown in Fig. 2g and 2h. Plants under low N displayed lower early-season petiole nitrate–N concentrations at field C, yet these differences were not noted later in the season. It is also noteworthy that petiole nitrate–N concentrations varied greatly between different site-year combinations in all three cultivars, but numbers were overall higher in the K field than in the C field, especially under the two N treatments.

At-Harvest Yield and Size Distribution

ANOVA results are shown in Tables 6, 7, and 8, and yield and size distribution results are shown in Figs. 3 and 4. No significant N effects were found on Colomba in 2022 (Table 6). Total yields from fields C and K, respectively, were as high as 55 and 64 Mg ha^{−1} even under the control treatment, and they were not significantly different from total yields under the two N treatments.

For Snowden, plants under the low N treatment exhibited significantly higher marketable and total yields compared to the control at field K in 2022 (Fig. 3a). In 2023 at field C, both low N and high N treatments resulted in higher marketable and total yields as well as lower small tuber yield than the control (Fig. 3c). At field K, even the control treatment produced 82 Mg ha^{−1} of total yield, a very high yield that was not significantly different from the other yields (Fig. 3d). In both years, only one of the two fields that grew Snowden showed significant effects of N treatments on tuber yield and size distribution (Table 7).

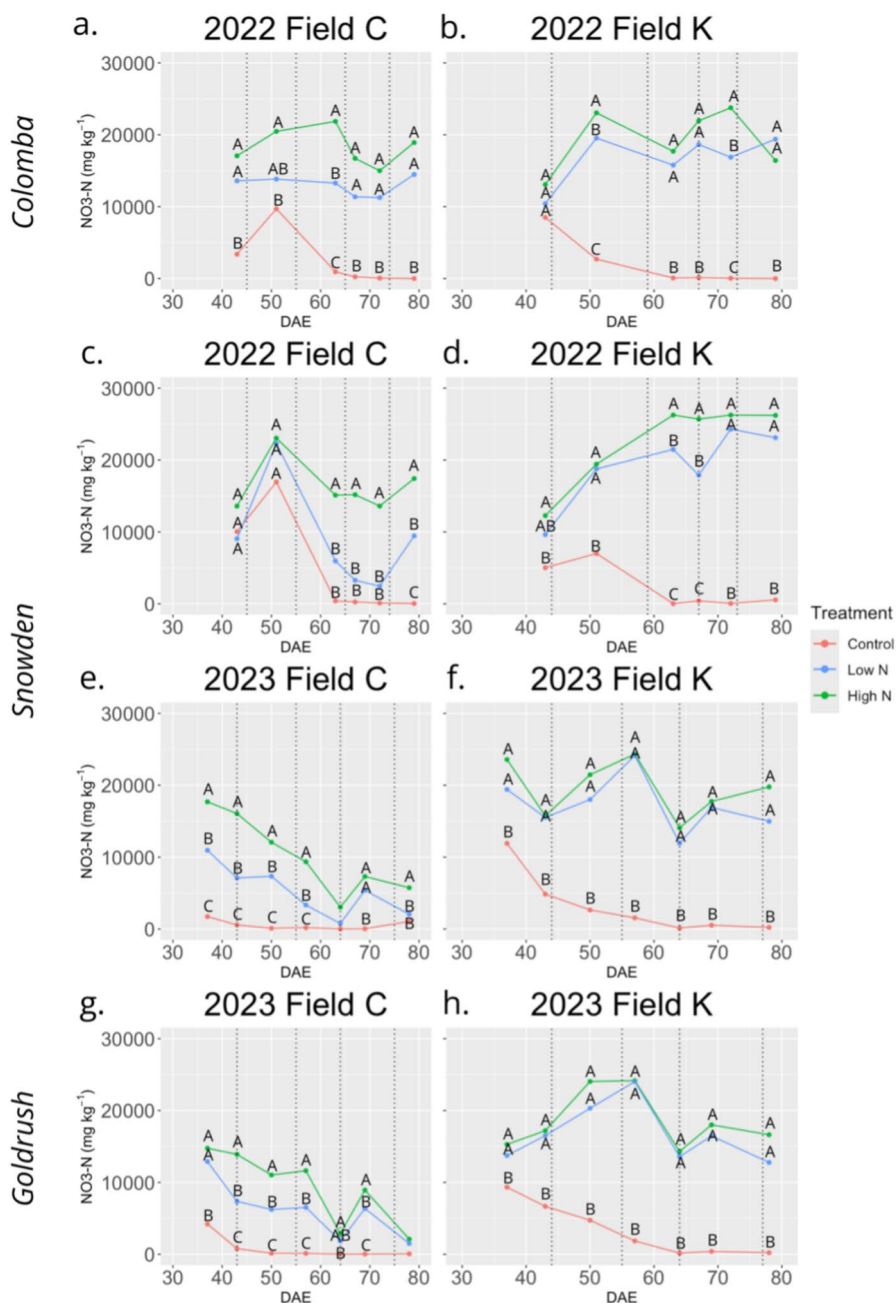


Fig. 2 In-season petiole nitrate-N of Colomba in 2022 (a, b), Snowden in 2022 and 2023 (c–f), and Goldrush in 2023 (g, h) at different sample collection points (indicated by days after emergence (DAE)) under different nitrogen treatments at field C and K. On each sampling day, values followed by different letters are significantly different at $\alpha=0.05$ using Tukey's HSD

Table 6 ANOVA table of N treatment effects on Colomba yield and size distribution at both fields in 2022

Field	Size A tuber yield	Size B tuber yield	Total yield	Specific gravity
C	0.449	0.992	0.701	0.473
K	0.068	0.759	0.205	0.057

Table 7 ANOVA table of N treatment effects on Snowden yield and size distribution at both fields in 2022 and 2023

Field/year	Large tuber yield	Marketable yield	Small tuber yield	Total yield	Specific gravity
2022					
C	0.264	0.079	0.139	0.136	0.472
K	0.465	0.004	0.573	0.002	0.158
2023					
C	0.005	< 0.0001	< 0.0001	< 0.0001	0.056
K	0.140	0.125	0.405	0.018	0.056

The *P*-values that were lower than 0.0001 were all marked as < 0.0001, and those that were higher than 0.0001 were presented with their true numbers. All *P*-values that were lower than 0.05 were bold

Results from 2023 indicated that Goldrush responded significantly to N treatments only at the C field (Table 8), where marketable and total yields under both low and high N treatments were higher than the control (Fig. 4a). At the K field, the total yield under the control was as high as 80 Mg ha⁻¹, and not significantly different from the others (Fig. 4b). At both fields, Goldrush plants under the high N treatment yielded more grades 4 and 5 tubers (weighing more than 283 g) and produced lower yields of grades 1 and 2 tubers (weighing lower than 170 g) than under the control treatment. Across all site-year environments, N treatments had no significant impact on the specific gravity of any cultivars.

N Removal and NUE Indicators at Harvest

Table 9 presents the results of N removal and partial nutrient balance (PNB) considering fertiliser N as the N input compared to both fertiliser N and irrigation nitrate–N as the N input. Two consistent trends in N removal were observed: (1) while the control treatment exhibited lower N removal by tubers in some instances, the differences among the three treatments were generally not significant; and (2) compared to field C, which had lower nitrate–N concentrations in irrigation groundwater, tuber N removal values were consistently higher in field K, where irrigation N contributed to higher N backgrounds across all treatments and cultivars. Regarding PNB, the control treatment consistently displayed the highest value, no matter which equation was used for the calculation. For the other two N treatments,

Table 8 ANOVA table of N treatment effects on Goldrush yield and size distribution at field C and K in 2023

Field/year	Grade 1 (0–113 g)	Grade 2 (113–170 g)	Grade 3 (170–283 g)	Grade 4 (283–454 g)	Grade 5 (>454 g)	Marketable yield	Total yield	Specific gravity
C	<0.0001	0.010	<0.0001	<0.0001	0.010	<0.0001	<0.0001	0.774
K	0.035	0.008	0.699	0.008	0.041	0.366	0.147	0.054

The *P*-values that were lower than 0.0001 were all marked as <0.0001, and those that were higher than 0.0001 were presented with their true numbers. All *P*-values that were lower than 0.05 were bold

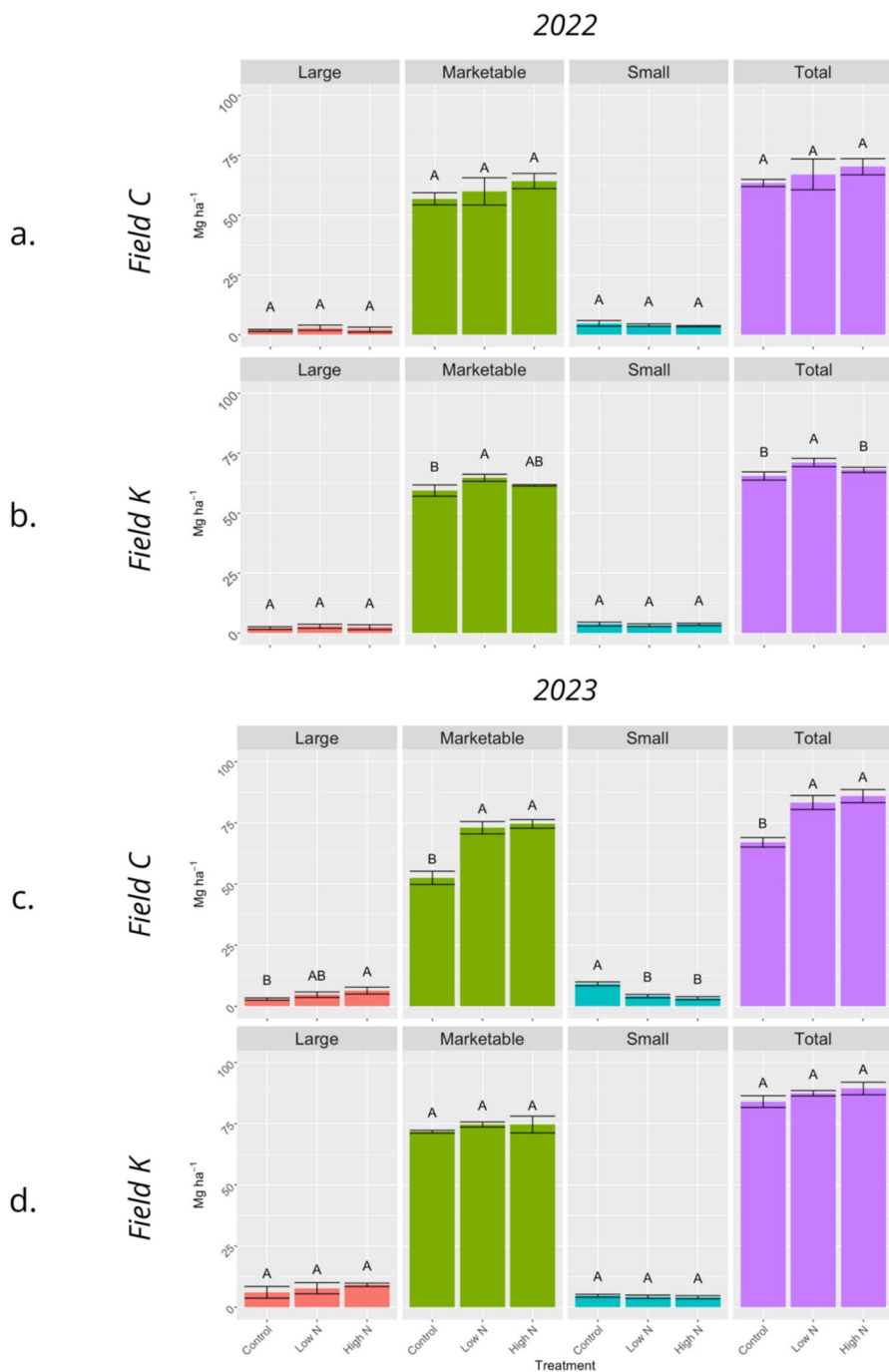


Fig. 3 Yield and size distribution of Snowden under three nitrogen treatments at field C and K in 2022 (a, b), and field C and K in 2023 (c, d). In each graph, bars with different letters are significantly different at $\alpha=0.05$ using Tukey's HSD

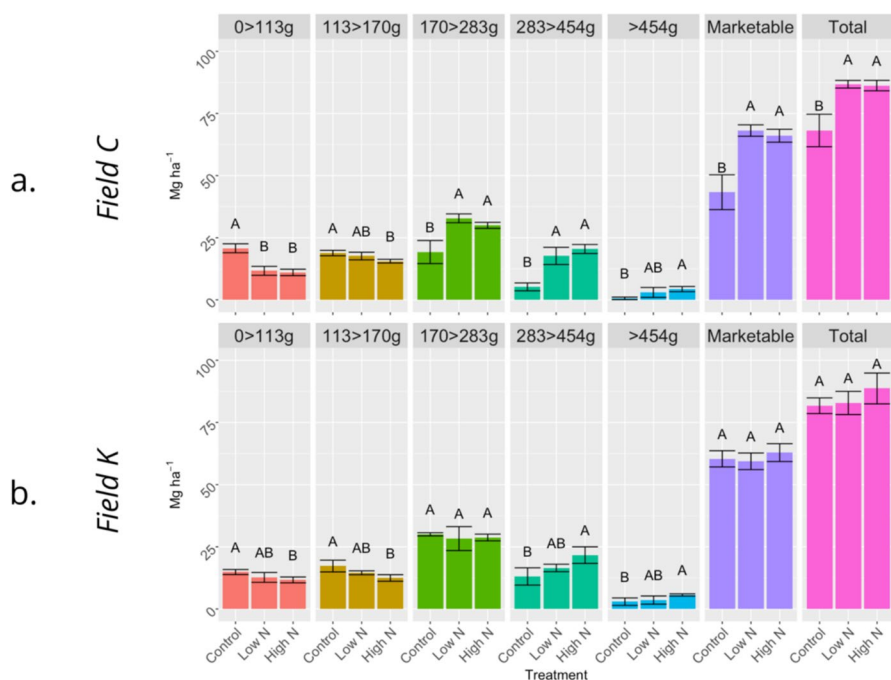


Fig. 4 Yield and size distribution of Goldrush under three nitrogen treatments in field C (**a**) and K (**b**) in 2023. In each graph, bars with different letters are significantly different at $\alpha=0.05$ using Tukey's HSD

differences were mostly insignificant, although the high N treatment consistently resulted in the lowest PNB values, which potentially suggests a surplus of N.

Discussion

Yield Response to N Treatments by each Cultivar

In the 2022 trials, Colomba, a fresh yellow potato cultivar bred in the Netherlands, showed no yield response to N at either field. Remarkably, despite no additional N application, the control treatment achieved average total yields of 55 Mg ha^{-1} in field C and 64 Mg ha^{-1} in field K, respectively. Similar findings of high yields from control treatments of N trials have been reported in previous studies (Maltas et al. 2018; Joern and Vitosh 1995; Wilson et al. 2009). The low or high N treatments provided no benefits to Colomba's total yield or tuber size, showcasing its high nitrogen use efficiency and the sufficiency of irrigation-derived N to meet its yield goal.

In comparison, the four-site-year data of Snowden, an American chipping potato cultivar, showed that it responded to N fertilisation at field K in 2022 and at field C in 2023. In 2022, the low N treatment achieved the highest marketable and total yields, and in 2023, both N treatments produced higher marketable and total tuber yields compared

Table 9 Nitrogen removal (kg N ha^{-1}), partial nutrient balance (PNB) considering only fertiliser N (PNB^a) vs. both fertiliser N and irrigation nitrate-N as the N input (PNB^b), of the three cultivars under the three N treatments at fields C and K in 2022 and 2023

Treatment	Cultivar	Field/ year	N fertiliser rate	N input from irriga- tion	N Removal	PNB ^a	PNB ^b	Cultivar	Field/ year	N fertiliser rate	N input from irriga- tion	N removal	PNB ^a	PNB ^b
			(kg N ha^{-1})			$\text{kg N removed (kg N from fertiliser)}^{-1}$	$\text{kg N removed (kg N from fertiliser + irrigation nitrate-N)}^{-1}$							
Year	Colomba	2022												
Control		C	0	34	95	2.12 A	0.84 a	Snowden	C	0	114	107 b	2.36 A	0.96 a
Low N			250		107	0.37 B	0.29 b			250		144 ab	0.49 B	0.50 b
High N			350		112	0.29 B	0.24 b			350		179 a	0.46 B	0.37 c
Control		K	0	91	112 b	2.49 A	0.68 a		K	0	212	162	3.61 A	0.63 a
Low N			250		148 a	0.51 B	0.36 b			250		199	0.68 B	0.39 ab
High N			350		152 a	0.39 B	0.30 b			350		205	0.52 B	0.34 b
Control	Snowden	C	0	34	136	3.03 A	1.2 a	Goldrush	C	0	114	106	2.35 A	0.66 a
Low N			250		164	0.56 B	0.46 b			250		143	0.49 B	0.35 b
High N			350		179	0.46 B	0.39 b			350		158	0.4 B	0.31 b
Control		K	0	91	159	3.54 A	0.96 a		K	0	212	189	4.2 A	0.73 a
Low N			250		210	0.72 B	0.51 b			250		207	0.71 B	0.41 b
High N			350		194	0.49 B	0.37 c			350		204	0.52 B	0.34 b

Within each site-year-cultivar, numbers that are followed by different letters are significantly different at $\alpha = 0.05$ using Tukey's HSD

to the control, and there was no significant difference between the low and high N treatments. These findings indicated that although Snowden's yield response to supplemental N is site- and season-dependent. Overall, the low N treatment at 250 kg ha⁻¹ produced the best crop yield and tuber size in this study, and additional N fertiliser supplied in the high N treatment at 350 kg ha⁻¹ did not add any new yield benefits.

The 2023 trial revealed that Goldrush, an American fresh market russet cultivar, produced higher marketable and total yields under the two N treatments only at field C, although the high N treatment resulted in more production of large-sized tubers (grades 4 and 5) and less production of small-sized tubers (grades 1 and 2) on both fields. These findings align with previous studies (Ghosh et al. 2019; Kelling et al. 2011; Zebarth et al. 2004) demonstrating that N application increases the proportion of larger tubers in russet potatoes. N treatments significantly increased the marketable yield of Goldrush at field C, suggesting supplemental N benefits (Reiter 2012). However, there were no significant yield differences between the low N and high N treatments.

Variability in potato yield responses to N across cultivars and site-year environments, especially the high marketable and total yields of Snowden and Goldrush under the control treatment with no N fertiliser added at field K in 2023, emphasises the potential influence of other factors such as weather conditions and irrigation-derived N inputs on potato growth in the Upper Midwest of the USA (Li et al. 1999; Wang et al. 2021). In more detail, total irrigation amounts were substantially higher in 2023 due to distinct rainfall patterns, and field K had higher nitrate–N concentrations in the irrigation groundwater, both of which subsequently led to as high as 212 kg ha⁻¹ of extra N contributions from irrigation. Further research is needed to investigate if plants take up all of the extra foliage-applied N for growth and producing yield, and how N partitioning between vines and tubers changes in different irrigation N environments.

Linking Plant N Need with In-Season Petiole Nitrate–N

Significant two-way interactions between N treatments and sampling time on petiole nitrate–N concentrations, measured as days after emergence (DAE), were consistently detected across almost all cultivars and years. The high N treatment could maintain higher petiole nitrate–N numbers, especially towards the later part of the sampling period, compared to the control (always significant) and low N treatment (sometimes significant), with the control exhibiting the lowest petiole nitrate–N for all cultivars and site-year environments.

Farmers often rely on petiole nitrate–N tests to guide split-N fertilisation decisions when growing potatoes on sandy soils. According to the University of Wisconsin recommendations (Bradford et al. 2024), if petiole nitrate–N numbers fall below the sufficiency range, a split-N application of 11–28 kg N ha⁻¹ is typically applied. However, results from this study did not show any notable relationship between in-season petiole nitrate–N concentrations and yields at harvest for the Colomba cultivar in 2022, as indicated by the higher petiole nitrate–N under the high N treatment, but non-significant yield differences between the control and the two N treatments at both fields. For Goldrush at both fields in 2023, higher in-season petiole nitrate–N concentrations appeared to be related to more yields of larger-sized tubers at harvest rather than total

yield. The results for Snowden varied by years and sites. These findings suggest that, while petiole nitrate–N concentrations are useful for assessing the immediate N uptake status of some potato cultivars, they may not reliably and precisely indicate the N need to achieve a certain yield potential of other cultivars (Zotarelli et al. 2014). Indeed, our results indicate that lower petiole nitrate–N concentrations for cultivars like Colomba may be sufficient to achieve higher yield potential.

Observed Effects of N in Irrigation Groundwater on Yield and Plant N Removal

In 2022 and 2023, petiole nitrate–N during the growing season, total N removal, and final tuber yield at harvest were consistently higher in field K compared to field C across all cultivars. This trend can likely be attributed to three main factors: (1) variability in the inherent physical and chemical properties of the soil affecting N mineralisation between the two fields; (2) differences in split-N application methods, with field K utilising side-dressed dry fertiliser before irrigation, whereas field C employed foliar fertigation; and (3) higher nitrate–N concentrations in the irrigation groundwater at field K. While pre-planting and post-harvest soil tests showed marginal differences of N sources (nitrate and ammonium) between the two fields (Table 1), and environmental factors such as soil temperature and moisture were largely uniform, the split-N application methods themselves likely had minimal effects on plant N utilisation and yield, as supported by previous findings (Kumar et al. 2014). Thus, the increased N removal and tuber yield observed in field K are primarily attributed to the additional N supplied through irrigation groundwater. This is particularly evident in petiole nitrate–N, where plants in field K had petiole nitrate–N values approximately 5000 mg kg⁻¹ higher than those in field C.

These findings indicate that an over-supply of N may have occurred in plants grown under the high N treatment (350 kg ha⁻¹) at field K due to additional N inputs from irrigation groundwater. In the control treatment, the existing soil N and irrigation-derived N were sufficient to achieve yield potentials comparable to those of the N treatments with supplemental fertiliser for all three cultivars tested in this study. Furthermore, PNB values exhibited great differences between N treatments in both fields during 2022 and 2023, with the high N treatment at 350 kg ha⁻¹ consistently showing the lowest PNB, regardless of whether N input (only from fertiliser N vs. from both fertiliser N and irrigation nitrate–N) was used for the calculation. This finding was consistent with previous studies, and could again indicate a highly N-surplus environment under that high N rate, suggesting that N additions beyond what can be utilised by the plants do not enhance efficiency and may result in N losses to the environment (Bélanger, et al., 2002; Moll, et al., 1982; Wang et al. 2020).

Campbell (2023) reported average nitrate–N concentrations in irrigation water across Wisconsin Central Sands to be 19.0 mg L⁻¹, emphasising the critical importance of accounting for irrigation-derived N inputs when making future potato N management decisions on sandy soils. This N input is mostly not included in N-related agricultural policies and practices, which could result in underestimating the magnitude of N pollution hotspots and overestimating the N use efficiency. Serra et al. (2023) suggested that irrigation water containing nitrate–N should be

considered in fertilisation plans and in the calculation of agri-environmental indicators related to water and nutrient efficiency in agriculture. Previously, it was suggested that N in irrigation water applied during the growth stages with rapid N uptake by the plants (i.e., the tuber initiation to early tuber bulking stages for potatoes) is just as useful as the same amount of N fertiliser, and N in water applied late in the growing season after the crop has already taken up most of its N needs (i.e., late tuber bulking and tuber maturation stages), is of limited value. Therefore, irrigation scheduling is critical, and 80% of the 5-year average irrigation amount could be used to estimate N contribution by irrigation water (Kranz 2023). In another study, it was recommended that well water samples should be collected at the beginning of the irrigation season and tested for nitrate–N concentrations (Sharma 2023). Most of the time, the nitrate–N concentration in irrigation water is consistent throughout the growing season (Sharma 2023), but it could vary between different seasons (Table 2). Therefore, testing the irrigation water nitrate–N concentration each year will be a good practice. However, with the ongoing global warming and high year-to-year weather variations, predicting irrigation water needs for crops will be difficult, making it even more difficult to take credit for irrigation nitrate in N management plans. Future research should: 1) collaborate with local and regional potato farmers who have fields with varied irrigation nitrate–N concentrations; 2) collect multiple years of yield and size distribution data under different N fertilisation regimes; 3) investigate how much of the extra N from irrigation can be taken up and utilised by the plants; 4) further investigate the best approach to potentially replace N fertiliser use with N inputs from irrigation water.

Conclusion

This study was conducted in two sites over two years on three potato cultivars under three different N treatments. We found that although the high N treatment at 350 kg N ha⁻¹ resulted in the greatest petiole nitrate–N (a plant N status indicator commonly used by growers to guide N fertilisation), especially during the late part of tuber bulking, its influence on final yield and tuber size distribution is highly variable. For Colomba, even the control treatment with no supplemental N added could produce high marketable and total yields. For Snowden and Goldrush, yields and tuber sizes under different N treatments showed site-year variations, possibly caused by varied N inputs from irrigation groundwater. Additionally, a higher N fertiliser rate and a high amount of extra N input from irrigation could result in an N-surplus environment where cultivars would not respond to supplemental N. In summary, this study demonstrated the highly intricate interaction between the effects of cultivar, environment (site and year), and management (N application and irrigation water nitrate), resulting in a lack of potato responses to N in irrigated sandy soils. Future research is needed to explore how to replace N fertiliser with N sources in irrigation water to reduce overall fertiliser use for specific potato cultivars.

Acknowledgements The authors thank Paul Sytsma and the field crew at the University of Wisconsin Hancock Agricultural Research Station for providing field management assistance, particularly for applying nitrogen at different rates and timings for this study.

Funding This research was funded by the Wisconsin Fertilizer Research Council, the Wisconsin Potato and Vegetable Growers Association, and the Wisconsin Department of Agriculture, Trade and Consumer Protection.

Data Availability All data that support the findings of this study are included within this paper and its Supplementary Materials.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2002) Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am J Potato Res* 79(4):269–279
- Bero NJ, Ruark MD, Lowery B (2014) Controlled-release fertilizer effect on potato and groundwater nitrogen in sandy soil. *Agron J* 106(2):359–368
- Bradford BZ, Colquhoun JB, Chapman SA, Gevens AJ, Groves RL, et al (2024) Commercial vegetable production in Wisconsin—2024. University of Wisconsin—Madison Extension Publication #A3422. Retrieved from <https://learningstore.extension.wisc.edu/products/commercial-vegetable-production-in-wisconsin>
- Campbell TJ (2023) Improving water and nitrogen use efficiency under changing weather variability in the central sand [Doctoral dissertation, University of Wisconsin—Madison]. University of Wisconsin—Madison library catalog: ProQuest LLC.
- Crosby TW, Wang Y (2021) Effects of different irrigation management practices on potato (*Solanum tuberosum* L.). *Sustainability* 13(18):10187
- Department of Health Services (DHS) (2020) Nitrate in private wells. Retrieved from <https://www.dhs.wisconsin.gov/water/nitrate.htm>
- Gal C, Frenzel W, Möller J (2004) Re-examination of the cadmium reduction method and optimisation of conditions for the determination of nitrate by flow injection analysis. *Microchim Acta* 146(2):155–164
- Ghosh U, Hatterman-Valenti H, Chatterjee A (2019) Russet potato yield, quality, and nitrogen uptake with enhanced efficiency fertilizers. *Agron J* 111(1):200–209
- Joern BC, Vitosh ML (1995) Influence of applied nitrogen on potato part I: yield, quality, and nitrogen uptake. *Am Potato J* 72(1):51–63
- Karim A (1995) A study evaluating the feasibility of crediting nitrogen from irrigation water in the Stevens Point, Whiting, Plover wellhead protection project area and in the Central Sands of Wisconsin.
- Kashian R, Depas J, Fogarty P, Peterson J (2014) Potato production in Wisconsin: analyzing the economic impact. University of Wisconsin-Whitewater.
- Kelling KA, Wolkowski RP, Ruark MD (2011) Potato response to nitrogen form and nitrification inhibitors. *Am J Potato Res* 88(6):459–469

- King BA, Stark JC (1997) Potato irrigation management. University of Idaho, Cooperative Extension System, College of Agriculture. Bulletin No. 789. Moscow, Idaho, USA.
- Kleinkopf GE, Westermann DT, Wille MJ, Kleinschmidt GD (1987) Specific gravity of Russet Burbank potatoes. *Am Potato J* 64(11):579–587
- Kranz WL (2023) Section F: giving credit for non-fertilizer nitrogen sources. In *Irrigation and nitrogen management*. University of Nebraska – Lincoln Extension Publication #EC2008. Retrieved from <https://extensionpubs.unl.edu/publication/ec2008/2023/pdf/view/ec2008-2023.pdf>
- Kucharik CJ, Campbell T (2020) Improving water and nitrogen use efficiency under changing weather variability in the central sands. University of Wisconsin Water Resources Institute.
- Kumar P et al (2014) Time and method of nitrogen application for chipping potato cultivar Kufri Chipsona-3 for higher productivity, profitability and processing quality during long-term storage. Retrieved from <https://krishi.icar.gov.in/jspui/handle/123456789/23448>
- Laboski CA, Peters JB, Bundy LG (2006) Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. Division of Cooperative Extension of the University of Wisconsin-Madison Publication #A2809. Madison, WI, USA.
- Li H, Parent LÉ, Tremblay C, Karam A (1999) Potato response to crop sequence and nitrogen fertilization following sod breakup in a Gleyed Humo-Ferric Podzol. *Can J Plant Sci* 79(3):439–446
- Liang G (n.d.) Strategies to grow potatoes and reduce nitrate leaching in Wisconsin. University of Wisconsin-Madison. Retrieved from <https://agwater.extension.wisc.edu/articles/strategies-to-grow-potatoes-and-reduce-nitrate-leaching-in-wisconsin/>
- MacKown CT, Weik JP (2004) Comparison of laboratory and quick-test methods for forage nitrate. *Crop Sci* 44(1):218–226
- Maltas A, Dupuis B, Sinaj S (2018) Yield and quality response of two potato cultivars to nitrogen fertilization. *Potato Res* 61(2):97–114
- Moll RH, Kamprath EJ, Jackson WA (1982) Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agron J* 74(3):562–564
- National Cooperative Soil Survey (n.d.) NCSS Soil Characterization Database (Lab Data Mart). Available online. Accessed [07/17/2024]
- Reiter MS, Rideout SL, Freeman JH (2012) Nitrogen fertilizer and growth regulator impacts on tuber deformity, rot, and yield for russet potatoes. *Int J Agronomy* 2012:1–7
- Rosen CJ, Bierman PM (2008) Best management practices for nitrogen use: irrigated potatoes. University of Minnesota Extension Publication #08559. Retrieved from <https://wrl.mnpals.net/islandora/object/WRLRepository%3A3031>.
- Serra J, Paredes P, Cordovil CMdS, Cruz S, Hutchings NJ, Cameira MR (2023) Is irrigation water an overlooked source of nitrogen in agriculture? *Agric Water Manag* 278:108147
- Sharma V (2023) How to calculate a nitrogen credit from irrigation water. University of Minnesota Extension. Retrieved from <https://blog-crop-news.extension.umn.edu/2021/07/how-to-calculate-nitrogen-credit-from.html>.
- Shrestha RK, Cooperband LR, MacGuidwin AE (2010) Strategies to reduce nitrate leaching into groundwater in potato grown in sandy soils: case study from north central USA. *Am J Potato Res* 87(3):229–244
- Shrestha D, Masarik K, Kucharik CJ (2023) Nitrate losses from Midwest US agroecosystems: impacts of varied management and precipitation. *J Soil Water Conserv* 78(2):141–153
- Starr GC, Cooley ET, Lowery B, Kelling K (2005) Soil water fluctuations in a loamy sand under irrigated potato. *Soil Sci* 170(2):77–89
- USDA. Wisconsin Ag News – Potatoes (2022) United States Department of Agriculture National Agricultural Statistics Service.
- Waddell JT, Gupta SC, Moncrief JF, Rosen CJ, Steele DD (2000) Irrigation- and nitrogen-management impacts on nitrate leaching under potato. *J Environ Qual* 29(1):251–261
- Wang C, Zang H, Liu J, Shi X, Li S et al (2020) Optimum nitrogen rate to maintain sustainable potato production and improve nitrogen use efficiency at a regional scale in China. A meta-analysis. *Agronomy Sustain Dev* 40(5):37
- Wang Y, Naber M, Crosby TW, Liang G (2021) Evaluating multiple diagnostic tools for monitoring in-season nitrogen status of chipping potatoes in the Upper Midwest of the USA. *Potato Res* 65:31–50
- Ward MH, Jones RR, Brender JD, De Kok TM, Weyer PJ et al (2018) Drinking water nitrate and human health: an updated review. *Int J Environ Res Public Health* 15(7):1557
- Wilson ML, Rosen CJ, Moncrief JF (2009) Potato response to a polymer-coated urea on an irrigated, coarse-textured soil. *Agron J* 101(4):897–905

- Yang CY, Cheng MF, Tsai SS, Hsieh YL (1998) Calcium, magnesium, and nitrate in drinking water and gastric cancer mortality. *Jpn J Cancer Res* 89(2):124–130
- Zebarth BJ, Rosen CJ (2007) Research perspective on nitrogen BMP development for potato. *Am J Potato Res* 84(1):3–18
- Zebarth BJ, Leclerc Y, Moreau G, Botha E (2004) Rate and timing of nitrogen fertilization of Russet Burbank potato: yield and processing quality. *Can J Plant Sci* 84(3):855–863
- Zotarelli L, Rens LR, Cantliffe DJ, Stoffella PJ, Gergela D, Fourman D (2014) Nitrogen fertilizer rate and application timing for chipping potato cultivar Atlantic. *Agron J* 106(6):2215–2222

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.