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Impact of Bannock seed age on yield components.

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Executive Summary

Poor emergence, stand development, and yields have been observed from ND produced Bannock seed lots in recent years. These field observations may be attributed to delayed seed physiological age resulting from the shortened growing season typical in ND production. Yield parameters such as stems/plant, tuber size profiles, and overall yield can be manipulated with seed aging storage treatments. Several seed aging treatments were imposed on three Bannock seed lots produced in ND (2021). In 2022, a replicated field trial was conducted at the Hoverson Farm's research pivot in Larimore, ND. No differences in emergence rates were detected in 2022. In general, seed with longer storage degree days (older seed pieces) resulted in increased stems per plant and tubers per plant. Significant difference in total yield were attributed to specific seed lot, but not aging treatment. A second year of seed aging treatments is being conducted and a replicated field trial will be repeated in 2023.

Procedures:

Three 2021 ND Bannock seed lots (coded A, B, C) grown in Oakes, ND, 2021 were harvested on October 1st, 2021. These three seed lots were selected for study as they possessed significant differences in total yield. Seed Lot A, B, and C yielded 381, 562, and 432 cwt/A, respectively. Immediately following harvest, 1000# tote bags for each lot were transported to the USDA-ARS laboratory in East Grand Forks, MN. Samples were suberized for three weeks at 95% RH, 12°C. After suberization, the samples were separated into duplicate 50 lb storage crates and storage degree day aging treatments (SDD) were implemented through adjustment of storage temperature and duration (Table 1). Storage degree day is defined as the days >4°C in storage prior to a storage holding period. These SDD treatments were based and adapted from research conducted by Knowles in the Columbia Basin.

Knowles NR and Knowles LO. 2006. Manipulating stem number, tuber set, and yield relationships for Northern- and Southern-Grown Potato Seed Lots. Crop Sci. 46: 284-296.

As highlighted in Table 1, to obtain seed tubers with varying age, tubers were stored at varying temperature/duration. Treatment 1 serves as an 'un-aged' control. Treatments 2, 3, and 4 were defined as the moderate aged 500 SDD treatments, and tubers from treatment 5, 6, and 7 were referred as the 900 SDD age and were the oldest tubers. After a 4°C holding period, all treatments were uniformly warmed, and tuber pieces of similar size were cut for planting. The field study was arranged as a randomized complete block with four field replicates. Emergence, stand counts, tuber size profiles and total yields were calculated. Samples were harvested on

October 3, 2022, and brought to USDA-ARS potato worksite, East Grand Forks. Samples were stored at 12°C,95% until grading. Tuber size profiles and yields (total and marketable) were assessed using an AgRay sorting system, with two-point calibration

Table 1, 2021-22 Storage treatments to create contrasting physiological age.

		Storage Phase					
	Tuber age[1]	Curing		Aging		Holding	
Trt #	(SDD >4°C)	°C	Day	°C	Day	°C	Date[2]
1	168	12	21	-	-	4	Oct-26
2	536	12	21	12	46	4	Dec-10
3	546	12	21	22	21	4	Nov-21
4	532	12	21	32	13	4	Nov-08
5	984	12	21	12	102	4	Feb-05
6	996	12	21	22	46	4	Dec-10
7	952	12	21	32	28	4	Nov-28

[1] storage degree day (SDD) is the days >4°C prior to storage holding period.

[2] date transferred to 4°C storage holding period.

Results:

Plant Emergence: Cool, wet weather in the Spring 2022, delayed planting until June 6, 2022. Emergence notes were recorded through 36 days after planting (DAP) at 2-day intervals (Table 2). After 36 DAP, total stand counts and stems/plant were recorded (Table 3).
No significant differences in total emergence were detected among the seed lots and storage aging treatments in 2022 (Table 2). We were expecting to observe more rapid emergence from aged seed treatments. However, the delayed June planting date may have masked our ability to detect difference in emergence rate among the seed age treatments. The date of 50% emergence was slightly greater from seed lot 'B', but differences in 50% emergence date between seed lots and seed age treatments were not statistically significant (data not shown).

Tuber Yield Parameters:

No significant differences in yield components (stems/plants, tubers/plant, and tuber yields) were detected in 2022. Although not statistically significant, there was a close association between older seed and both increased stems/plant and tubers/plant (Table 3, Table 4). When averaged across seed lot, stem number per plant increased from 2.8 (control), 3.0 (500 SDD), and oldest seed tubers (900 SDD) produced the highest (3.3) stems per plant (Table 3). In general, older seed pieces resulted in higher stem number across the individual seed lots (Table 4). However, the higher storage (32°C, 90°F), temperatures used to achieve Treatment 4 and 7 may have negatively impacted tuber health, especially in Lot C. In the ongoing 2022-23 storage evaluation, the high temperature treatments (Table 1, treatments 4, 7) were eliminated and the 2023 field evaluation will only contain 5 seed age treatments.
Similar to stem number, tubers per plant increased with increased seed age treatment (Table 3,

4). The control, 500 SDD, and 900 SDD treatments had 4.0, 4.2 and 5.0 tubers per plant, respectively. Examination of tubers size profiles revealed older seed tuber treatments (900 SDD) provided a slight increase in percentage of small tubers, but these differences were not statistically significant.

The delayed June 2022 planting date resulted in poor overall yields. Significant differences in yield (total and marketable) were associated with seed lot, but not seed age treatment (Table 4). Seed Lot B had significantly higher total and marketable yields (286 and 254 cwt/A) than from both Seed Lot A (221, 188) and Seed Lot C (211, 183). Interestingly, trends in 2021 parent tuber yield were similar with 2021 yield of Lot B (562 cwt) being highest, with lower yields (381, 432 cwt/A) from seed lot A, and C. A physiological explanation for the yield differences among these three lots in 2021 and 2022 is not clear. This research is being repeated in 2023 with two ND Bannock seed lots.

Table 2, % Emergence 23 and 36 days after planting (DAP) among three Bannock Seed Lots (2022).

	Seed Lot A		Seed Lot B		Seed Lot C	
DAP	23	36	23	36	23	36
Age Trt#						
1	63	89	67	87	58	80
2	64	82	53	88	48	84
3	56	81	68	85	45	85
4	56	82	68	82	49	86
5	48	77	57	82	45	87
6	64	87	63	89	58	85
7	60	79	60	80	34	71

[1] seed pieces were cut on May 16, 2022 and stored at a similar holding temp (10°C) prior to planting on June 6, 2022 at Larimore, ND. Emergence notes were recorded in 2-day intervals.

Table 3. Impact of seed age on yield parameters average across Bannock seed lots (2022).

				% Tuber Size Profile			CWT/A	
Age Trt[4]	% stand	S/P[1]	T/P[2]	<4 oz	4-10 oz	>10 oz	Total	MRKT[3]
Control	81.3	2.8	4.0	17.0	72.4	10.7	236.5	209.0
500 SDD	79.6	3.0	4.2	16.5	74.9	8.6	232.4	203.9
900 SDD	75.5	3.3	5.0	18.9	73.1	8.0	249.4	214.8

[1] S/P = stems per plant

[2] T/P = tubers per plant

[3] marketable yield is reported as the total yield minus the undersized (<4 ounce) tubers

[4] the 500 SDD aging treatment data is the reported average across storage degree day aging treatments 2, 3, and 4 where 900 SDD means were averaged across aging treatment 5, 6, and

7
and control (un-aged) is aging treatment 1.

Table 4. Impact of seed age on yield parameters among three Bannock seed lots (2022).

	Age Trt	% stand	S/P[1]	T/P[2]	% Tuber Size Profile <4 oz	4-10 oz	>10 oz	CWT/A Total	MRKT[3]
Lot A	1	84.4	3.1	4.0	22.5	70.6	6.9	208.0	170.4
	2	77.1	2.6	4.3	16.1	72.8	11.2	243.0	217.0
	3	81.3	3.0	4.0	13.3	80.6	6.0	212.3	187.0
	4	81.3	2.9	4.4	24.2	70.2	5.6	202.6	160.8
	5	68.8	3.0	4.7	18.3	71.2	10.4	231.8	204.1
	6	82.3	3.4	5.0	20.1	76.0	3.9	227.6	184.4
	7	77.1	3.4	4.5	15.6	77.4	7.0	224.7	195.1
Mean[4]	500 SDD	81.0	2.9	4.2	19.0	73.6	7.3	216.5	183.8
	900 SDD	76.0	3.3	4.7	18.1	75.1	6.8	228.0	194.6
Lot B	1	80.2	2.7	4.4	14.1	75.0	10.9	265.9	241.4
	2	79.2	3.1	4.8	14.0	78.3	7.6	268.1	236.7
	3	81.3	3.5	4.5	16.5	74.8	8.8	256.4	225.4
	4	76.0	3.3	4.7	12.6	78.1	9.3	274.6	248.6
	5	70.8	3.6	5.2	13.0	71.4	15.6	303.8	282.2
	6	77.1	3.4	5.5	14.9	76.5	8.6	308.1	274.0
	7	72.9	4.0	6.6	22.0	68.8	9.2	325.4	273.4
Mean	500 SDD	79.2	3.1	4.6	14.3	76.6	9.1	266.2	238.1
	900 SDD	73.6	3.6	5.8	17.0	72.2	10.8	312.4	276.5
Lot C	1	79.2	2.6	3.8	14.3	71.5	14.2	235.5	215.0
	2	78.1	3.1	3.9	12.9	77.9	9.2	217.4	198.2
	3	75.0	3.2	4.0	17.2	75.4	7.4	200.5	173.6
	4	81.9	2.7	3.9	19.4	72.8	7.8	204.5	173.2
	5	80.2	2.8	3.9	17.4	76.7	6.0	197.2	170.2
	6	78.1	3.5	5.2	21.8	71.6	6.7	247.4	206.6
	7	71.9	2.9	4.2	26.0	66.7	7.2	178.8	143.0
Mean	500 SDD	78.6	2.9	3.9	16.0	74.5	9.5	214.5	190.0
	900 SDD	76.7	3.1	4.4	21.5	71.9	6.6	207.8	173.3

[1] S/P = stems per plant

[2] T/P = tubers per plant

[3] marketable yield is reported as the total yield minus the undersized (<4 ounce) tubers

[4] for each seed lot the 500 SDD data is the reported average across storage degree day aging treatments 2, 3, and 4 where 900 SDD means were average across aging treatment 5, 6, and 7.

Identification of Effective Cover Crops for Managing the Root-lesion Nematode, *Pratylenchus penetrans*

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Summary

Root-lesion nematode is one of important nematode pests, causing significant economic loss to potato production. Other secondary pathogens could aid in causing more damage to potato due to their interaction. Use of nematicides can be detrimental to other beneficial organisms and the environment. The demand for alternative management strategies has increased because of the deregistration of some synthetic chemical pesticides and their negative effects on the environment. Cover crops that are nonhosts, poor hosts, and/or have nematicidal activities can be used for managing *P. penetrans* in infested potato fields. A greenhouse trial was conducted to screen 12 entries of cover crops, seed meals and controls for the hosting and population reduction abilities to *P. penetrans* under controlled greenhouse conditions. Experiments were arranged in a completely randomized design with five replications for each treatment and control. Alfalfa (Vernema) and potato (Castle Russet) showed a poor hosting ability to *P. penetrans*. This is the first time that we identified a potato cultivar with resistance to *P. penetrans*. However, Alfalfa (High Five) increased the nematode population showing a good hosting ability. Pacific Gold seed meal alone reduced the nematode population and Idagold seed meal alone maintained the nematode population. Mustard seeds of Pacific Gold and Idagold as well as litchi tomato and winter rye (Dacold) increased the nematode population showing good or excellent hosting abilities. There was no much difference in final nematode populations in potato (Red Norland) planted with Pacific Gold seed meal as compared to the potato without seed meal. These entries still need to be validated by conducting more trials to confirm their abilities. Additionally, two greenhouse trials were conducted to investigate the penetration and pathogenicity of *P. penetrans* on selected cover crops at different time points. Alfalfa (FSG 527) was consistently identified as a poor host and no penetration was found in the roots at all three time points (20, 40 and 80 days after planting) through root staining, indicating it is an effective cover crop. Annual ryegrass (Tetilia) reduced the initial population in both trials, however, there was root penetration of *P. penetrans* 80 days after planting. Faba bean (Petite) continued to increase the nematode population in the soil at different time points. The susceptible potato (Red Norland) showed a good hosting ability for the nematode in all the trials and penetrated the roots at all the time points. The cover crops with poor hosting ability and the potato with resistance to *P. penetrans* have a great potential to be utilized in infested potato fields for managing *P. penetrans* to minimize yield loss.

Background

The root-lesion nematode, *Pratylenchus penetrans* was reported to have caused significant damage in potato production, with yield loss ranging from 30-70% (Florini and Loria, 1990; Olthof, 1986, 1987, 1989; Olthof and Potter, 1973; Holgado, et al., 2009). *Pratylenchus penetrans* is an important plant-parasitic nematode that penetrates and feeds on plant roots, resulting in reduced nutrient uptake and leading to economic loss. The feeding habit of *P. penetrans* could make the roots more susceptible to secondary microbial infections from fungi like *Verticillium dahliae*, and this synergistic effect causes Potato Early Dying disease complex (Adrienne, 2021). The wide host range and their parasitic mode of action to many commercially grown crops have made the management of this nematode difficult (Davis and Ann, 2000). Over the years, cultural, biological, and chemical methods have been used to reduce the nematode population density in infested soil in attempts to control this soil-borne pathogen. However, the use of nematicides is expensive and can have negative impacts on long-term soil viability and detrimental to other organisms (Dyrdahl-Young et al., 2020; Yeates and Barker, 1986).

Alternative management strategies to control root-lesion nematodes is crucial for the potato industry. Cover cropping has potential to control plant parasitic nematodes, and are generally not toxic to beneficial organisms and subsequent crops (McKeown and Potter, 2001). Potential advantages of cover crops include improved soil health, reduced weed growth, reduced soil erosion, greater water distribution, increased soil organic matter structure, enhanced nutrient control and cycling, pest control, and promotion of beneficial soil microorganisms, as well as pathogen control (Freyman, 1989; Mazzola and Gu, 2002; Forge et al. 2000; Sarrantonio, 2007; Magdoff and Van, 2009). However, some cover crops can be an excellent host to root-lesion nematodes, while others can reduce nematode reproduction.

With last funding support from NPPGA and Minnesota Area II Potato Growers Association, we tested 18 cover crop species and cultivars for their ability to act as a host of *P. penetrans* in 2021. All four alfalfa cultivars (Vernal, Signature, Bullseye, FSG 527) and three annual ryegrass cultivars (CNS, Gulf, Tetilia) reduced the nematode population, meaning they are poor hosts. Alfalfa (FSG 527) showed the greatest nematode population reduction (average 74%), followed by annual ryegrass (Tetilia) with population reduction of 64%. All five winter rye cultivars (Rymin, Aroostook, Hazlet, Dylan, Wheeler) increased the nematode population and were classified as maintenance hosts. However, Miller (1978) observed the highest number of this nematode per total root mass of alfalfa cultivar Saranac, and Mbiro and Wesemael (2016) reported alfalfa cultivar Alpha was a good host. More alfalfa cultivars and cover crops need to be tested to ascertain their hosting and population reduction abilities to *P. penetrans*.

Therefore, the objectives of this project were to 1) evaluate more cover crops and seed meals to determine their hosting and population reduction abilities to *P. penetrans* and 2) investigate penetration and pathogenicity of *P. penetrans* on selected cover crops to identify effective cover crops for managing *P. penetrans* in potato fields.

Materials and Methods

Selection of cover crop species/cultivars and seed meals:

Cover crops and seed meals were screened for their hosting and population reduction abilities to *P. penetrans* in the greenhouse under controlled conditions. These entries include alfalfa (cultivars Vernema and High Five), winter rye (Dacold and Spooner), litchi tomato, mustard seeds and meals of *Sinapis alba* (IdaGold) and *Brassica juncea* (Pacific Gold), and potatoes (Castle Russet and Red Norland) (Table 1). Potato (Red Norland) planted with Pacific Gold seed meal was included in the treatments. Potato (Red Norland), a known susceptible cultivar, planted without seed meal was included as a positive control. An unplanted infested soil treatment was also included as a negative control. However, winter rye (Spooner) seeds did not germinate in any of the pots and they were later removed from the analysis in the final results. The crops and seed meals were tested to determine their reactions to *P. penetrans*.

Alfalfa (FSG 527) and annual ryegrass (Tetilia), showing the lowest population reproduction from our previous trials, were selected for penetration and pathogenicity study of *P. penetrans*. Potato (Red Norland) identified as a good host and Faba bean (Petite) identified as an excellent host were included for comparison. The cover crop seeds were acquired from Allied Seed (Nampa, ID), National Small Grains Collection (Aberdeen, ID), Gilleshammer-Thiele Farms Inc. (St. Thomas, ND), Great Northern AG (Plaza, ND), and Pulse USA (Bismarck, ND). The mustard seeds and seed meals were acquired from Farm Fuel Inc. (Freedom, CA).

Inoculum preparation and greenhouse experiments:

Root-lesion nematode, *Pratylenchus penetrans* collected from a Potato field in Central Minnesota was increased in the greenhouse for three months using a susceptible potato cultivar Red Norland. The potato tubers were initially sprouted on moist paper towels placed in a plastic tray for ten days before planting. The sprouted tubers were cut into 2-3 pieces and a single piece of sprouted potato tuber was planted in a plastic pot with naturally infested soil and grown in greenhouse conditions (16 hours of daylight and an average temperature of 22ºC). After increasing the nematode population for three months, the potato plants were harvested and nematodes were extracted from soil and roots for quantification. Soil from all pots was mixed thoroughly and three soil subsamples were taken to extract nematodes using the sugar centrifugal floatation method (Jenkins, 1964). Nematodes were then identified and quantified under an inverted light microscope (Zeiss Axiovert 25, Carl Zeiss Microscopy, NY, USA).

Infested and pasteurized soil was thoroughly mixed for even nematode distribution. Three subsamples from the newly mixed soil were then taken to determine the initial nematode population for the experiment. Ten treatments and two controls (Table 2) each in five replicates were included for comparison. The trial was set up in October 2022 with a nematode population of 1,741 *P. penetrans* per kg of soil. The emerging seedlings were thinned to the appropriate number of plants per pot (Table 1). The seed meals were incorporated by evenly mixing them into 1 kg of infested soil per pot at the rate of 1% (weight/weight) which is equivalent to 10 g of seed meal per 1 kg of infested soil.

For the penetration and pathogenicity study, two greenhouse experiments were conducted using selected cover crops to identify effective cover crops in managing *P. penetrans*. Infested soil was planted with the selected cover crop seeds in three replicates, including alfalfa (FSG 527), Faba bean (Petite), annual ryegrass (Tetilia), and potato (Red Norland). An unplanted infested soil was included as a negative control. The first and second trial was set up in February and June of 2022, respectively. The initial nematode population for the first and second trials was 2,615 and 1,530 per kg of soil, respectively. A slow-release fertilizer (14-14-16 NPK) was mixed with soil before planting at the rate of 5 g per kg of soil. Each pot was filled with 1 kg of soil before planting and pots were arranged in a completely randomized design (CRD).

Each cover crop seed was planted by directly placing them into the soil at 1-3 cm depending on the size of the seed. The potato tuber was pre-sprouted before planting as described above. The emerging seedlings were thinned to the appropriate number of plants per pot (Table 3) after their establishment and the healthiest or best plants were kept in the pots. Both trials were conducted in the Agriculture Experiment Station, NDSU greenhouse in controlled conditions (16 hours of daylight and an average of 22ºC) for 12 weeks. The trials were terminated and harvested at three time points, 20 days, 40 days, and 80 days after planting (DAP) except for annual ryegrass (Tetilia) which was terminated at 60 DAP because of their early maturity date in the second trial. During harvesting of the trials, the plant height was taken, plant tops were removed, roots were gently separated from the soil, and they were stored in a cold room at 4ºC in separate individual plastic bags until they were processed.

Processing of harvested soil samples and identification and quantification of nematodes from soil

Nematodes were extracted from the soil samples after harvest using the sugar centrifugal floatation method (Jenkin, 1964). A subsample of 200 g of the soil was taken from the soil sample of each pot for the sugar centrifugal floatation extraction method. After extraction, nematodes were identified and counted using an inverted light microscope (Zeiss Axiovert 25). The nematode population extracted from 200 g of soil was converted to the total number of *P. penetrans* in 1 kg of soil.

Processing of harvested root samples, nematode extraction and counting, and roots staining

The harvested roots of the crops from the hosting and population reduction experiment were rinsed with running tap water and cut into 1 to 2 cm, they were then placed on tissue paper on a mesh in a tray for 48 hours. The whole roots per pot were extracted using the whitehead tray method (Whitehead and Hemming, 1965). After extraction, they were identified and counted using an inverted light microscope (Zeiss Axiovert 25). Nematode numbers obtained from both roots and soil were used for calculating the final nematode population in each pot.

For the penetration and pathogenicity study, the harvested roots kept in the plastic bags were gently rinsed with running tap water. The brown lesion in the roots of each of the crop cultivars was observed after washing and cleaning them thoroughly to assess the lesion of *P. penetrans*. After that, the root staining was performed with red food color dye according to the method described by Thies et al. (2002) to examine the penetration of the *P. penetrans* in the roots. For the root staining, the roots were chopped into 1 to 2cm pieces and agitated in 100 ml 1.5% NaOCl solution for 4 min. They were then rinsed with tap water for 30 s and placed in a beaker containing about 150 ml tap water for 15 min. They were then placed in 12.5% (v/v) food coloring dye solution

(McCormick & Co., Inc., Hunt Valley, MD, U.S.), brought to boil for about 30 s, and left for cooling to room temperature. The dyed roots were rinsed with tap water, and 40 ml glycerol (VWR Chemicals, Solon, Ohio, U.S.) and a few drops of 5N HCl were added. This glycerol mix was then heated to about 40ºC and allowed to cool to room temperature and subsequently kept at 4ºC until roots were observed under a stereo microscope (ZEISS Stemi 508, Carl Zeiss Microscopy, White Plains, NY, U.S.).

The same staining method was used for the roots harvested at three time points. However, the roots of potato (Red Norland) were divided into two parts with one part used for root staining and the other part for white head tray extraction to examine and quantify the *P. penetrans* penetration in the roots in the first trial.

Reproductive factor and host ability ratings

The reproductive factor (Rf) for each treatment (crop cultivar/seed meal) was calculated by dividing the final nematode population density on the tested crop (nematodes from soil and roots) by the initial population density after the trial was completely harvested. The average Rf of nematodes for each treatment was calculated as a mean of Rf from all replications of the treatment. Five host groups including N = non-host (Rf < 0.15), P = poor host (Rf = 0.15 to 1.0), M = maintenance host (Rf = 1.0 to 2.0), G = good host (Rf = 2.0 to 4.0), and E = excellent host (Rf > 4.0) were designated based on the average Rf to determine the hosting ability of cover crops and controls (Mbiro and Wesemael 2016).

Data analysis

The average final population densities and population reduction percentage (PRP) of nematodes in cover crops and controls were analyzed using the SAS software (SAS 9.4, SAS Institute Inc. Cary, NC). The average final population density was determined by adding the nematode population from the soil and roots from each pot. PRP was calculated using the formula [(initial nematode population density on a tested crop - mean final nematode population density on the tested crop)/initial nematode population density on the tested crop x 100]. The general linear model (GLM) with Tukey's honestly significant difference (HSD) mean separation at a significance level of 5% was used to determine the significant difference in the values of final nematode population densities for the tested cover crops and controls.

Results and Discussion

The two cultivars of alfalfa (cv. Vernema and High Five) tested for *P. penetrans* showed poor and good hosting abilities, respectively. Alfalfa (Vernema) reduced the population of the nematode by about 31% (Rf = 0.69) while alfalfa (high five) showed a good hosting ability (Rf = 2.59) (Table 2). The alfalfa (High Five) showed a contrasting result to our previous trials on the tested alfalfa cultivars to *P. penetrans* which was previously thought to be a poor host. This indicated that more alfalfa cultivars need to be tested for their host status to this nematode species. Winter rye (Dacold) increased the nematode population two times more than the initial population showing a good hosting ability (Rf = 2.47). Litchi tomato shows a good hosting ability to *P. penetrans* (Rf = 2.2). For the mustard seeds, Pacific Gold and Idagold both increased the nematode population in two and four folds indicating a good and excellent hosting ability, respectively. The Pacific Gold seed meal incorporated into the soil reduced the nematode population as compared to the initial population, but did not significantly reduce the population compared to the unplanted control. The Idagold seed meal, however, slightly increased the initial population (Rf = 1.2).

Potato (Castle Russet) (Figure 1A) showed a poor hosting ability to the nematode (Rf = 0.17) with a great population reduction (PRP = 82%) (Table 2). As expected, potato (Red Norland) increased the nematode population (Rf = 7.25). The potato (Red Norland) planted with the incorporated Pacific Gold seed meal at 1% (w/w) into the soil did not show much difference to the potato planted without seed meal as they both increased the nematode population showing that the seed meal did not have any significant effect on reducing the nematode population in the presence of a susceptible potato cultivar. The nematode was reduced by 59% in the non-planted infested soil. Recent studies by Quick et al. (2020) reported that both alfalfa cultivar Vernema and potato Castle Russet were resistant to the *Tobacco rattle virus* vectored by stubby root nematode and may be used to eliminate the virus from fields affected by corky ringspot, a widespread potato tuber necrotic disease. Dandurand et al. (2017) reported the effectiveness of mustard seeds and meals of *Brassica juncea* (Pacific Gold) for the control of potato cyst nematode.

For the penetration and pathogenicity study, the results in both trials from the nematode reproduction in the soil were similar to our previous trials, which supported that Faba bean (Petite) and Potato (Red Norland) are good/excellent hosts of *P. penetrans* (Tables 4 and 5). They also supported the results from our previous trials of alfalfa (FSG 527) and annual ryegrass (Tetilia) being a poor host of *P. penetrans*; this was evident in the trials conducted and harvested at the final harvest time with average reproductive factor values ranging from 0.21 to 0.80 for alfalfa and annual ryegrass as they both reduced the nematode population in the soil over time. Alfalfa (FSG 527) (Figure 1B) was found to reduce the nematode population consistently at all the three time points observed in both trial 1 and trial 2 (Tables 4 and 5).

In both trials of penetration and pathogenicity study, at 20 days and 40 days after planting, only a few nematodes were found in the potato roots planted with infested soil while there was no penetration observed in faba bean plant roots (Table 6). Alfalfa (FSG 527) and annual ryegrass (Tetilia) did not show any penetration of *P. penetrans* from the root staining (Figure 1C) from both trials since both crops are not good hosts of *P. penetrans*. The brown lesion in the roots of all the crops was assessed; the roots of alfalfa (FSG 527) and annual ryegrass (Tetilia) did not show any significant lesion. It was difficult to observe the brown lesion on the faba bean (Petite) roots because they were dark in color after being cleaned and washed while the potato roots planted in the infested soil had lesions but they were not significantly different from those in pasteurized soil. White sand instead of soil substrate might be more suitable for observing lesion formation on the plant roots.

For 80 days after planting, in both trials, there was a significant increase in the penetration of *P. penetrans* in the potato (Red Norland) roots as compared to 20 and 40 days after planting (Figure

2). Faba bean (Petite) roots showed nematode penetration at 80 DAP as compared to 20 and 40 days after planting when no penetration was found in the roots. Alfalfa did not show any nematode penetration from the root staining in both trials, indicating it is effective against root penetration of *P. penetrans*. Surprisingly, in the first trial, there was *P. penetrans* penetration in the annual ryegrass (Tetilia) roots at 80 DAP but none was found at 60 DAP in the second trial when it was harvested earlier due to their maturity date. The brown lesion was difficult to observe on the roots of the potato (Red Norland) because of the effect of dark soil color on them. The faba bean (Petite) roots were difficult to observe for lesions because of the dark color of the roots. The roots of the poor hosts alfalfa and annual ryegrass did not show any lesion.

Conclusions

Different cover crop species/cultivars have been found to effectively manage root-lesion nematodes from infested soil along with improvement of soil health and soil erosion. The management of root-lesion nematodes depends upon the hosting abilities of cover crops to nematode species and their population reduction abilities.

Twelve entries of cover crops, seed meals and controls were tested to evaluate their hosting abilities and/or population reduction abilities to the root-lesion nematode species *P. penetrans.* Alfalfa (Vernema) and potato (Castle Russet) that were previously reported to be resistant to the *Tobacco rattle virus* vectored by stubby root nematode reduced the initial nematode population showing poor hosting abilities to *P. penetrans*. Potato (Castle Russet) greatly reduced the nematode population by 82% compared to the initial population density. This is the first time that we identified a potato cultivar that was able to suppress the population of *P. penetrans*. More trials will be conducted to confirm *P. penetrans* reproduction in Castle Russet. More potato cultivars will be tested to identify potatoes with resistance to *P. penetrans*. The cover crops with poor hosting ability can be potentially utilized in infested fields for managing this nematode.

In both trials of penetration study, *P. penetrans* nematodes were consistently found in the potato (Red Norland) roots at all three time points (20, 40 and 80 days after planting) through root staining. However, no penetration of *P. penetrans* was observed inside the roots of alfalfa (FSG 527) at any of the three time points. This supports our previous results that alfalfa (FSG 527) is a poor host and has a great population reduction ability. This research further demonstrates that alfalfa (FSG 527) is an effective cover crop and has the great potential to be integrated into management of *P. penetrans* for control of this nematode pest in infested potato fields.

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Table 1. List of crops tested for their host status to the root-lesion nematode, *Pratylenchus penetrans* under controlled greenhouse conditions

Crop (Cultivar)/Seed meal	**Scientific name**	**Family**	**No. of plants per pot**
Alfalfa (Vernema)	*Medicago sativa* L.	Fabaceae	4
Alfalfa (High Five)	*Medicago sativa* L.	Fabaceae	4
Litchi tomato	*Solanum sisymbriifolium*	Solanaceae	2
Mustard seed (Pacific Gold)	*Brassica juncea*	Brassicaceae	2
Mustard seed (Idagold)	*Sinapis alba*	Brassicaceae	2
Potato (Castle Russet)	*Solanum tuberosum*	Solanaceae	1
Potato (Red Norland)	*Solanum tuberosum*	Solanaceae	1
Winter rye (Spooner)	*Secale cereale* L.	Poaceae	2
Winter rye (Dacold)	*Secale cereale* L.	Poaceae	2

Table 2. Mean final population densities, reproductive factor (Rf), population reduction percentage (PRP), and host ranking of cover crops and controls tested in this study for hosting ability of the root lesion nematode, *P. penetrans,* in a greenhouse trial*

Cover crop (cultivars)/seed meal	Final population [w]	Rf [x]	Host ranking [y]	PRP [z]
Pacific Gold seed meal without plant	203 e	0.15	-	88.34
Potato (Castle Russet)	313 e	0.17	P	82.02
Non-planted infested soil	721 de	0.41	-	58.58
Alfalfa (Vernema)	1,204 de	0.69	P	30.84
Idagold seed meal without plant	2,115 d	1.21	-	-21.48
Litchi tomato	3,845 c	2.20	G	-120.85
Mustard seed (Pacific Gold)	4,235 c	2.43	G	-143.65
Winter rye (Dacold)	4,312 c	2.47	G	-147.67
Alfalfa (High Five)	4,516 c	2.59	G	-159.39
Mustard seed (Idagold)	7,393 b	4.32	E	-324.64
Potato (Red Norland) with Pacific Gold seed meal	11,906 a	6.83	-	-583.86
Potato (Red Norland)	12,625 a	7.25	E	-625.15
Pr > F	0.0001			

*The trial was initiated in October 2022 with the initial nematode population density of 1,741 *P. penetrans*/kg of soil.

[w] Mean final population density is the mean of final population densities of nematodes from five replications of each treatment and was obtained by adding total nematode population from roots and total nematode population from 1 kg soil in a single experimental unit (pot). Mean final population densities with same letters are not significantly different ($P < 0.05$).

[x] Rf (Reproductive factor) is the mean reproductive factor of five replications for each treatment and was calculated by dividing the final population density of *P. penetrans* in the tested crop by the initial population density of *P. penetrans*.

[y] Host ranking was based on the categorization of reproductive factor values into five classes: N = non-host (Rf < 0.15), P = poor host (Rf = 0.15 to 1.0), M = maintenance host (Rf = 1.0 to 2.0), G = good host (Rf = 2.0 to 4.0), and E = excellent host (Rf > 4) (Mbiro and Wesemael 2016).

[z] Population reduction percentage (PRP) is the average of % reduction in nematode populations from five replications for each treatment. Nematode population reduction (%) = (initial population density on the tested crop - final population density on the tested crop)/initial population density x 100. Negative (-) PRP indicates nematode population increase in treatments.

- = Host ranking not available

Table 3. List of cover crops with controls tested in the penetration and pathogenicity study for the root-lesion nematode, *Pratylenchus penetrans*

Crop (Cultivar)	**Scientific name**	**Family**	**No. of plants per pot**	**Plant maturity***	**Root type***	**Plant status at final harvest**	**Growth stage at final harvest**
Alfalfa (FSG 527)	*Medicago sativa* L	Fabaceae	4	80-90	Tap	Green	Flowering
Annual ryegrass (Tetilia)	*Lolium lultiflorum* L	Poaceae	2	60-70	Fibrous, adventitious	Green	Flowering
Faba bean (Petite)	*Vicia faba*	Fabaceae	2	75-95	Lateral	Yellow	Seed formation
Potato (Red Norland)	*Solanum tuberosum*	Solanaceae	1	80-100	Fibrous	Green	Tuber maturity

*These data were obtained from greecoverseed.com, harvest management extension, penn state extension (2013), annual ryegrass cover crop fact sheet, Kb seed solution, and Ddegroot-inc.com.

Table 4. Mean final population, population change, and population reduction at different time points in trial 1of penetration and pathogenicity study*

Crops/cultivars /treatments	20 DAP Fina. Pop [v]	Pop. Δ [w]	PRP (%)[x]	40 DAP Fina. Pop.	Pop. Δ	PRP (%)	80 DAP Fina. Pop.	Pop. Δ	PRP (%)	Rf[Z]
Alfalfa (FSG 527)	1,788 bc	-827	31	303 c	-2,311	88	553 b	-2,061	78	0.21
Annual ryegrass (Tetilia)	2,770 b	-155	-5	1,287 c	-1,327	50	661 b	-1,954	74	0.25
Faba bean (Petite)	3,163 b	548	-20	2,788 b	173	-6	6,324 a	3,709	-141	2.41
Potato (Red Norland)	7,165 a	4,551	-174	7,075 a	4,460	-170	5,483 a	2,868	-109	2.09
Unplanted soil	2,000 bc	-615	23	1,311 bc	-1,304	49	1,030 b	-1,585	60	0.39
Pr > F	< 0.001			< 0.001			< 0.001			

* The initial nematode population density of 2,615 *P. penetrans*/kg of soil. DAP = Days after planting.

[v] Mean final population density is the mean of final population densities of nematodes from three replications of each treatment and was obtained by adding total nematode population from roots and total nematode population from 1 kg soil in a single experimental unit (pot). Mean final population densities with same letters are not significantly different ($P < 0.05$).

[w] Population change (Δ) = Final nematode population at different time points minus the initial nematode population; (-) indicates nematode population decrease.

[x] Population reduction percentage (PRP) is the average of % reduction in nematode populations from three replications for each treatment. Nematode population reduction (%) = (initial population density on the tested crop - final population density on the tested crop)/initial population density on the tested crop x 100. Negative (-) PRP indicates nematode population increase in treatments.

[z] Rf (Reproductive factor) is the mean reproductive factor of three replications for each treatment and was calculated by dividing the final population density of *P. penetrans* by the initial population density of the nematode 80 days after planting.

Table 5. Mean final population, population change, and population reduction at different time points in trial 2 of penetration and pathogenicity study*

	20 DAP			40 DAP			80/60DAP			
Crops(cultivar)/ treatments	**Fina. Pop.** [v]	**Pop** Δ[w]	**PRP (%)**[x]	**Fina. Pop.**	**Pop.** Δ	**PRP (%)**	**Fina. Pop.**	**Pop.** Δ	**PRP (%)**	**Rf**[z]
Alfalfa (FSG 527)	1,058 b	-472	30	831 b	-697	45	375 c	-1,155	75	0.24
Annual ryegrass (Tetilia)	1,655 b	125	-8	1,036 b	-493	32	1,225 c	-305	19	0.80
Faba bean (Petite)	5,243 a	3,713	-242	5,600 a	4,070	-266	4,939 b	3,409	-222	2.22
Potato (Red Norland)	7,148 a	5,618	-367	6,187 a	4,657	-304	13,383 b	11,853	-774	8.74
Unplanted soil	1,380 b	-130	9	846 b	-683	44	666 c	-86,375	56	0.43
Pr > F	< 0.001			<0.001			< 0.001			

*The initial nematode population density of 1,530 *P. penetrans*/kg of soil. DAP = Days after planting.

[v] Mean final population density is the mean of final population densities of nematodes from three replications of each treatment and was obtained by adding total nematode population from roots and total nematode population from 1 kg soil in a single experimental unit (pot). Mean final population densities with same letters are not significantly different ($P < 0.05$).

[w] Population change (Δ) = Final population minus initial population at different time points; (-) indicates nematode population decrease

[x] Population reduction percentage (PRP) is the average of % reduction in nematode populations from three replications for each treatment. Nematode population reduction (%) = (initial population density on the tested crop - final population density on the tested crop)/initial population density on the tested crop x 100. Negative (-) PRP indicates nematode population increase in treatments.

[z] Rf (Reproductive factor) is the mean reproductive factor of three replications for each treatment and was calculated by dividing the final population density of *P. penetrans* in the tested crop cultivar by the initial population density at the 60 DAP for annual ryegrass and at 80 DAP for other three crops.

Table 6. The mean number of *Pratylenchus penetrans* penetrated in roots of cover crops and controls from both trials of penetration and pathogenicity study*

Crops (cultivar)	**20 DAP**	**40 DAP**	**80/60**DAP**
Alfalfa (FSG 527)	0	0	0
Annual ryegrass (Tetilia)	0	0	6
Faba bean (Petite)	0	0	20
Potato (Red Norland)	9	11	91

* Number of *P. penetrans* inside roots per pot at different time points.

** All crops were terminated and harvested at 80 DAP except that annual ryegrass (Tetilia) was terminated and harvested at 60 DAP for the second trial.

A)

B)

C)

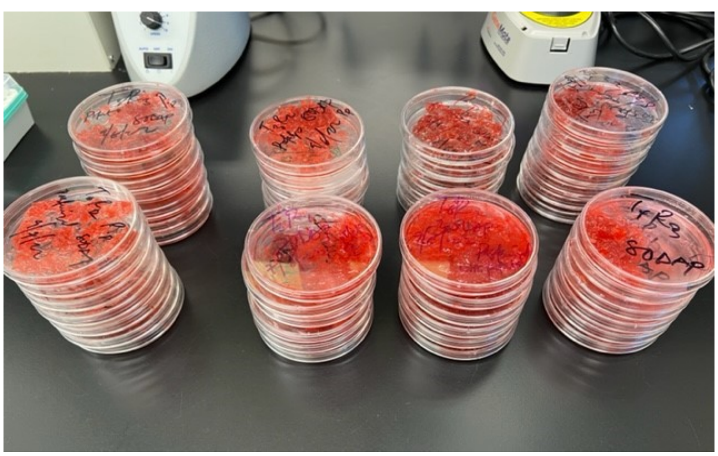
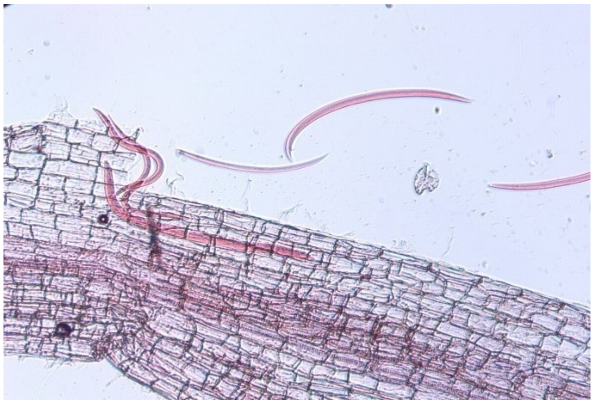
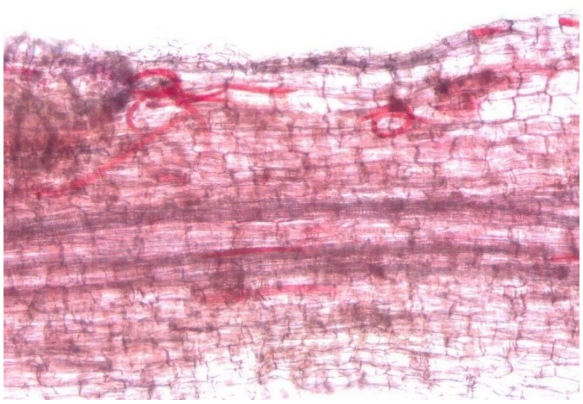


Figure 1. Greenhouse experiment showing **A)** Potato (Castle Russet) plants and **B)** Alfalfa (FSG 527), and laboratory experiment showing **C)** root staining from plant roots.

A)



B)



C)

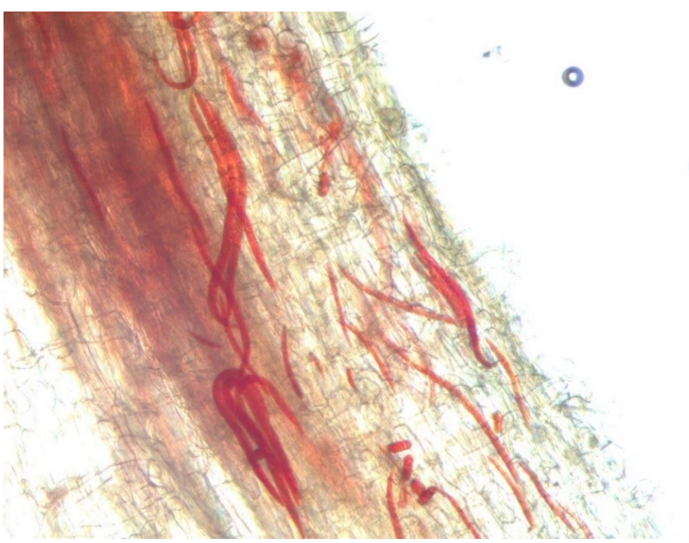


Figure 2. *Pratylenchus penetrans* penetrated inside potato roots at different time points; **A)** 20 days after planting (DAP), **B)** 40 DAP, and **C)** 80 DAP.

Late Blight Spore Trapping Network for Minnesota and North Dakota

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Executive Summary

Late blight is a community disease that can cause dramatic losses in potato production. As a community disease, early detection of late blight spores is important to enable potato growers to quickly apply premium protectant fungicides. This project was initiated to confirm DNA of late blight spores near potato fields in Minnesota and North Dakota. In 2022, 23-spore traps were setup in North Dakota and Minnesota potato fields region starting the first week in July to early September. There no positives found for late blight between July 4 and September 5, 2020. One of the challenges in 2022 was getting filters send in because of lack of workers. Although this monitoring system is costly to operate, it is good insurance for early detection of late blight spores can save millions of dollars in potato losses by allowing growers to adjust fungicide management plans. Weekly reports were emailed out in the Spud Scoop.

Rationale for conducting the research

The threat of late blight is always a concern for potato growers as it has potential to cause severe financial and yield losses. Early detection and protection can help save a potato crop, as it is unknown when late blight spores are present near fields. Currently we do not know if or when late blight spores are present in Minnesota or North Dakota. The focus of this project is to provide real-time data on late blight spores and not just rely on a predictive weather model.

This spore trapping network will enable potato growers to be alerted when late blight spores are found to enable them to know when to apply premium fungicides. Collection traps were placed in cooperating growers' fields and sent to Dr. Pasche's laboratory in a prepaid package. Spores were identified in Dr. Pache's laboratory.

Procedures

Spore traps were distributed to cooperating growers in Minnesota, North Dakota, and Nebraska. On a weekly basis, starting between July 4 cassettes were placed in the spore traps. After one week they were shipping in a prepaid envelope to Dr. Pache's laboratory and the DNA was extracted and evaluated for late blight. Sampling continued until September 5, 2022. After data was collected, growers were sent the

Spud Scoop by email to let them know all reporting traps and findings. It also included some observations from Andy Robinson, the Blightline from Gary Secor, the Potato Late Blight Spore Trapping Network data and Andy Robinson and Julie Pasche, and the AphidAlert from Ian MacRae. One of the challenges the spore trapping network faced this year were lower rates of return of spore filters. This is because of a shortage of workers.

Because of this project with cooperating growers, we were able to ensure that late blight spore DNA was not present allowing improved management by reducing fungicide usage. Thank you to all the grower who participated in this project and for the funding and support to make this happen.

Thank you to the cooperating growers who allow traps on their farms and changed them weekly, Northern Plains Potato Growers Association, Minnesota Area II Potato Council, J.R. Simplot Company, Cavendish, R.D. Offutt Farms for supporting this effort.

Potato Insect Management 2022

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Executive Summary – This is a project to develop and refine management tactics for 2 of the major insect pests of potato, Colorado Potato Beetles, and Aphid Vectors of virus disease in Minnesota and North Dakota. This proposal will include: 1) assessing insecticide resistance of adult Colorado potato beetle in Minnesota and North Dakota to insecticides currently available in management, 2) Continuing to assess the efficacy and economics of foliar applied insecticides, including biocides, and their best-fit in management plans for both insects, and 3) continuing research and outreach that expands and maintains an aphid trapping and monitoring network for aphid vectors of virus disease in potatoes (focusing on PVY) and provides near real-time maps of aphid population distribution in MN and ND. This information will assist in assessing the need for and developing appropriate foliar management programs in anticipation of decreasing availability and/or efficacy of soil applied insecticides.

Rationale – Colorado Potato Beetle (CPB), *Leptinotarsa decemlineata* Say is the most damaging defoliating insect pest of potatoes in North America (Alyokhin 2009). In the past 25 years, at-plant applications of neonicotinoid insecticides have effectively controlled CPB populations. Unfortunately, this tactic is becoming less effective. This insect has a pronounced ability to develop insecticide resistance (Weisz et al. 1994, Alyokhin et al. 2007, Huseth et al. 2014) which has been documented in Central MN for several years (Fig 1), and is increasing in the Red River Valley (MacRae, 2019) leading to decreased efficacy and the increasing use of foliar insecticides.

Figure 1. Abamectin tolerant Colorado Potato Beetle adults feeding in a field that had been treated with an abamectin insecticide ~3 days earlier. Control was later achieved using an abamectin insecticide with Piberonyl Butoxide

There are multiple mechanisms whereby insects can be insensitive to insecticides. Populations of CPB have demonstrated all of these mechanisms; behavioral resistance, reduced penetration of its cuticle by insecticides, increased excretion rate of insecticides, enhanced enzymatic metabolism of toxins, and insensitivity of the active ingredient's target site. Probably the most recognized mechanism is enhanced enzymatic metabolism by the insect of the toxin in the insecticide (e.g. it breaks down the insecticide). This has recently been recognized as occurring in some MN populations of CPB. In recent years, central MN populations of CPB have been shown to be less susceptible to Abamectin based insecticides (e.g. AgriMek, Reaper, etc). We know this to be an enzymatic breakdown by the insect because the lack of susceptibility has been overcome by adding Piperonyl Butoxide (PBO) to the insecticide and expected mortality was restored. The synergist PBO, when added to an insecticide application, impairs the insects' ability to produce the enzymes responsible for the metabolism, allowing more active ingredient to reach the insecticide's target site and restoring efficacy.

The continued use of neonicotinoids is also threatened because of their adverse effect on pollinators and propensity to leach into ground-water systems (Goulson 2013, Huseth & Groves 2014, Hladik et al. 2014). The Environmental Protection Agency has already announced interim regulatory decisions on their use (US EPA 2020). In addition, the extended summer emergence of overwintered adult CPB (Huseth & Groves 2010, Szendrei et al. 2012) means the presence of adults later in the summer erodes the typical two seasonal population peaks. The seasonal presence of CPB is now more evenly dispersed across the season and presents a more persistent defoliation problem, requiring additional within season foliar applications of insecticides.

Data from 2018-19 indicates in some locations, not only is the efficacy of neonicotinoid insecticides decreasing, but efficacy of other modes of action is occurring as well (MacRae 2019). This decreasing sensitivity to other insecticides is especially concerning. Populations of CPB collected from some sites in central MN showed tolerance to Abamectin (e.g. AgriMek) insecticides. Colorado Potato Beetle from a site in ND showed increased tolerance of Coragen (Chlorantraniliprole, a diamide), and populations from two organic production sites in MN showed significant levels of resistance to Blackhawk (Spinosad).

If foliar management programs are to remain effective against Minnesota and North Dakota CPB populations, we must manage potential resistance. It is desirable to know prior to application if products are effective. Consequently, information on the relative efficacy of the available insecticides is necessary to develop working insecticide resistance management programs.

An increased reliance on foliar applications to control CPB is going to require research to ensure both product efficacy and their sustainability, from the viewpoint of both resistance and economics. Continued review of insecticide efficacy vs cost and rotation is required to address newer and existing modes of action. In addition, formulations containing new mixes of chemistries should be assessed for fit and function in the mode of action rotations that are vital to keeping as many of them available for the longest period possible.

North America seed potato production is suffering an epidemic of aphid vectored, virus causing diseases such as Potato Leaf Roll (PLRV) and Potato Virus Y (PVY). PLRV is a non-persistent (circulative) virus; that means after the insect acquires the virus from an infected plant, the virus undergoes a reproductive period inside the insect vector before it can be transmitted to another plant. This is called a *latency period*, and in PLRV it is approximately 72 hours. Consequently, PLRV is often transmitted by aphids that colonize potato; a winged female lands on the plant, decides it's a suitable food species and deposits a daughter aphid, which feeds and reproduces, resulting in a new colony of aphids. The 3-day latency means PLRV transmission can be controlled by well-timed applications of traditional insecticides (there's enough time for the insecticide to kill the aphids before it can transmit the virus).

Conversely, PVY is a non-persistent virus; there is no latency period. The virus can be acquired by an insect vector from an infected plant and transmitted to an uninfected plant in minutes (Bradley 1954). Consequently, PVY is often vectored by aphid species which do not colonize potato. In fact, with regards to PVY transmission, the vector you don't see on the plant is often more important than the ones you find. A non-colonizing aphid species will fly into a potato field, probing plants (puncturing the plant and 'taking a sip') to determine if they're appropriate host plants. If they are not appropriate hosts, the aphid will fly to neighboring plants to try again. Consequently, non-colonizing aphid species will move across a potato field, continuing to probe plants and transferring any inoculum present. This process results in non-colonizing vector species spending short periods in each plant, decreasing the chance of finding them during normal scouting. Not only does this mean that any PVY inoculum will be readily moved from infected to non-infected plants, but non-colonizing aphids aren't in the field long enough for traditional insecticides to have sufficient time to kill the vector. Traditional insecticides, therefore, will not control the spread of PVY. Rather, the most effective insecticides have been those that quickly cause the insect's feeding behavior to stop.

There are a number of aphid species that vector virus diseases to seed potatoes, the most efficient is green peach aphid, *Myzus persicae* (Sulzer) but several others are also capable of efficiently vectoring the virus. For example, soybean aphids are only 10% as effective in vectoring PVY as are green peach aphids (Davis and Radcliffe 2008) but disperses in such high numbers (Ragsdale et al 2004) they can be an important part of PVY's seasonal epidemiology. However, potato is not a suitable host for soybean aphid so it will not colonize the crop. The importance of non-colonizing species means that scouting for aphids in potatoes, while still an excellent management practice, may not provide a complete picture of the amount of vectors present at a given time.

Application of Aphoil and anti-feeding insecticides can limit the transmission of PVY in colonizing in both aphids that colonize potato and those that don't (DiFonzo et al. 1997, Suranyi et al. 2004, Carroll et al. 2004, 2009, Olson et al. 2004, Hodgson et al 2005). But application timing is critical and treatments must be applied prior to aphid populations dispersing into the field from the margin (this takes about 2 weeks from initial presence of winged aphids). Consequently, accurate methods of monitoring aphid presence are essential. The regional aphid monitoring network, *Aphid Alert*, provides Minnesota and North Dakota seed potato growers near real-time information on virus vector flight activity.

Over the past several years, *Aphid Alert* has provided timely information on aphid vector presence and the seasonal patterns of vector population dynamics. This is an estimate of risk; risk is exposure to hazard. The species of aphids that we monitor have a biological ability to transmit PVY, that's hazard. The traps measure their presence, the exposure to the hazard, that's risk.

Our data has identified that the majority of vector flight occurs starting in late July and through August (Fig 2), reflecting many of the non-colonizing species moving from senescing hosts (e.g. small grains) to seek alternate food sources. This late season flight of aphid vectors confirms that the majority of PVY infection must occur late in the growing season. Appropriately timed vine-kill could provide an excellent additional tactic to manage PVY spread.

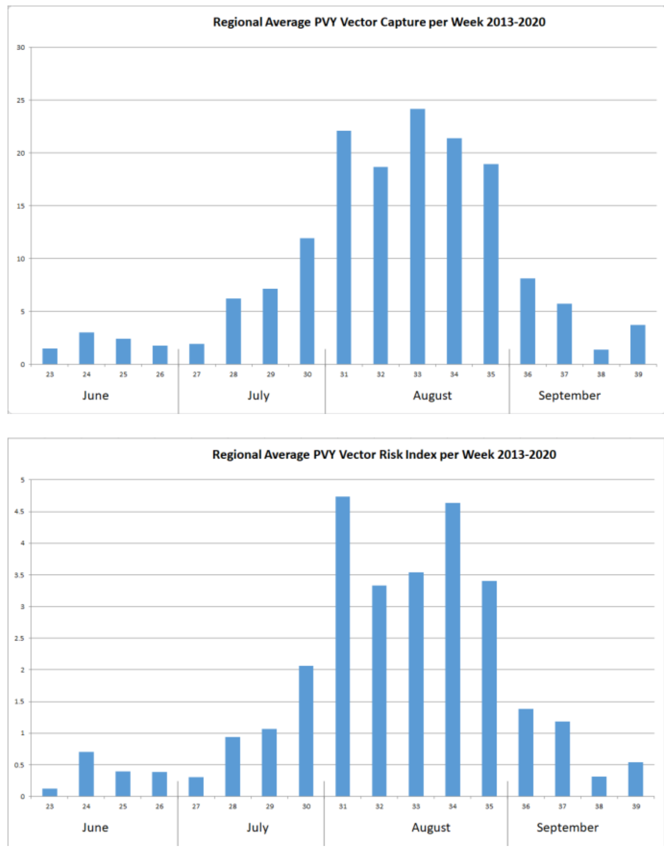

Figure 2. The capture of PVY vectoring aphids in all Aphid Alert traps by week, averaged over 2012-2020 (top graph). And the Regional PVY Risk Index/Week (lower graph) averaged over 2012-2020. The dates were standardized to ISO-8610 week numbers so the data could be compared across years. Note that Vector Risk Index does not precisely mirror the number of

The total number of vectors, however, does not tell the complete story. Not all species of aphids are equal in their ability to transmit PVY virus; some species are much more efficient vectors than others. As mentioned, the Green Peach Aphid (GPA) is the most efficient species when it comes to transmitting PVY. We've developed an index, The PVY Vector Risk Index (Fig 2), which uses the number of vector species captured in a trap and their relative efficiency at transmitting PVY to estimate the relative risk of PVY transmission at any given date.

Regional data also might not reflect what is happening at a specific location. For example, while on average, Vector numbers across Minnesota and North Dakota begin to rise in Mid-July, aphid peaks within that period may vary by site. Some sites, such as Perham, have an average pattern of steady growth of populations starting in mid-July and peaking in August, while other, such as Lake of the Woods, show sudden Index peaks rather than a gradual increase in population (Fig 3).

All of our cooperators have received the historical averaged data for their site. Some sites have fewer years trapping data than others but those data still provide insights into their vector

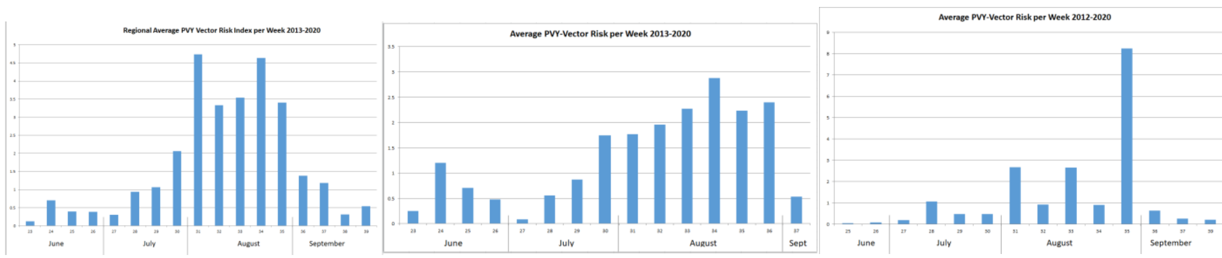

Figure 3. The seasonal PVY Vector Risk Index by week, averaged from 2012-2020 data, for MN & ND (left), Perham (middle) and Lake of the Woods (right). Note the steady ramping of the Index values at

activity. All report the data is, nevertheless, valuable in making management decisions.

Over the past several years, the Aphid Alert Network has grown to provide region-wide coverage, estimating the aphid vector populations. The network relies on grower cooperators to maintain and change traps throughout the growing season and send weekly trap catches to the entomology lab at the University of Minnesota's Northwest Research & Outreach Center (NWROC). There the trap contents are sorted, aphid vector species identified and PVY Vector Risk Index values calculated. Since 2012, the *Aphid Alert* network has provided excellent regional coverage of the Minnesota and North Dakota seed producing areas.

The UMN-NWROC Entomology lab will have a number of additional projects involving Colorado Potato Beetle, alternate potential vectors of PVY, and the epidemiology of PVY. These are funded by Specialty Crop Block Grants from both the MN and ND Depts. of Agriculture.

In 2022, we propose to:

1. Continue monitoring for CPB resistance to different insecticide modes of actions, especially foliar applied classes of insecticide.
2. Assess efficacy and economics of rotational foliar applied CPB management tactics.
3. Continue the Aphid Alert Network, providing potato producers with information on the regional distribution and densities of aphid vectors of virus disease and weekly assessments of PVY risk transmission at each trap location.

Procedures

Monitoring for insecticide resistance in Colorado Potato beetle – Insecticide resistance is the result of an insect's genotype. The only way to determine if a population of insects is truly resistant is to calculate the LD_{50} of a suspected resistant population (i.e. a 'wild' population from the field) and compare it to that of population known to be susceptible to the insecticide. We have obtained and are maintaining a 'naïve' (never exposed to insecticides) CPB colony in the NWROC lab, which should facilitate this research. The LD_{50} values of sampled and susceptible populations will be compared using PROBIT analyses. These analyses will provide a measurement of how much more insecticide it takes to kill the sampled population than it does to kill the susceptible population.

Resistance/tolerance of CPB from each area was assessed using direct exposure tests. A gradient of concentrations of active ingredient (ai), the actual toxin in the insecticide, were used in trials to create a dose curve that indicates the amount of ai necessary to kill 50% of the population (i.e. the Lethal Dose 50% or 'LD_{50}'). Trials were conducted by applying 10µl (microliter) drops of insecticide directly to the insect; in 2022, we changed from a microapplicator to a single channel adjustable pipette with disposable tips. It made conducting the trials faster and more efficient (Fig 4). After the insecticide has dried, beetles were placed onto a potato leaf in Petri plates and left to feed for 5-7 days (120h). Beetles were initially assessed for mortality at 24h to determine any handling mortality. As CPB often appear intoxicated immediately after exposure but recover after several days, mortality was again assessed 5-7 days post application (min. of 120h). Mortality was assessed by placing beetles on their backs and evaluating movement. Any insect not righting itself is assessed as dead or moribund.

Figure 4. Adjustable micropipette, with

No reports of insecticide failure were reported during the 2022 growing season. Contact as made with several consultants but there didn't seem to be unexpected failures (there was a report of a Synthetic Pyrethroid not controlling CPB populations, but Pyrethroid resistance is well documented and their use is not recommended for control. Many locations had shortened presence of overwintering adults which decreased overall seasonal populations. Some sites however, did experience heavy populations. Insects were tested from the UMN Northwest Research and Outreach Center (UMN-NWROC) in Crookston and the UMN Sand Plains Research Farm (UMN-SPRF) in Becker, MN. While there were sufficient populations to test from the NWROC, it was difficult to collect sufficient adults from the UMN-SPRF.

Beetles from the UMN-SPRF were tested against AgriMek (with the synergist PBO) and were found to be susceptible. Comparing mortality to high label rates used against the susceptible lab colony, the UMN-SPRF populations were found to require ~1.3X the rate to achieve similar mortality (~30% more ai was required to achieve the same levels of control). While this does sound like a lack of susceptibility, response rates that are between 1x – 3x the rate required to attain the same LD_{50} response as the naïve population are still considered to be susceptible. This is because the susceptibility of the naïve population would have to be considered artificially low compared to *any* wild population.

Populations tested at the UMN-NWROC were very susceptible to abamectin, indeed, during 2022 insecticide trials in Crookston, AgriMek remained a top performer without requiring the use of PBO. There were no differences in performance when comparing the sampled field population and the naïve lab colony. These populations do, however, seem to be developing some tolerance of Spinosyns. Trials in Crookston using Blackhawk did not have the control we have come to expect. Populations with Spinosad based insecticides required 1.9X the rate to achieve the same LD50 as seen in the naïve colony. Crookston populations are still susceptible but have been exposed to Blackhawk, used in rotational spray trials, for 15 years. An eventual decrease is susceptibility to the insecticide has been expected.

2) Assess efficacy and economics of rotational foliar applied CPB management tactics – replicated plots were established at both the NWROC in Crookston and the UMN-SPRF in Becker. Treatments included 2 new and 1 established but improved modes of action being developed for Colorado Potato Beetle (an RNAi inhibitor, a new broad spectrum insecticide and several new formulations of *Bacillus thuringiensis* (*Bt*)).

Population at Crookston were high in 2022 and the chemistries tested had challenges. Populations at the SPRF were relatively low, but it provided an opportunity to test alternate products that might have better efficacy at different life stages of the beetle or provide an alternative in light populations allowing more effective products to be given a break in the rotation, lengthening their effective utility.

Several biorational products were tested at both Crookston and Becker in 2022. *Bacillus thuringiensis* (*Bt*)is a bacteria commonly found in soil that has insecticidal properties. Certain strains of *Bt* produce crystal proteins (*cry* proteins) that are toxic to insects. Once ingested the cry protein attaches to and lyses (breaks open and destroys) gut epithelial cells, eventually killing the insect. *Bacillus thuringiensis* has been used on the past on CPB, however new strains and formulations are being developed. One strain, not yet labeled, was tested at various rates against Blackhawk as a standard insecticide. The product was targeted against newly hatched, 1st instar larvae and involved two rates (1lb/ac & 1.5lb/ac) and three different application timings (3apps@5d and 2 apps@7d). Blackhawk was applied @3.125oz/ac for 2apps @ 7d intervals. At 1.5lbs/ac rates applied 3apps @ 5d, *Bt* was as effective as Blackhawk at suppressing defoliation. And all treatments had significantly less defoliation than did untreated plots (UTC) (Fig 5).

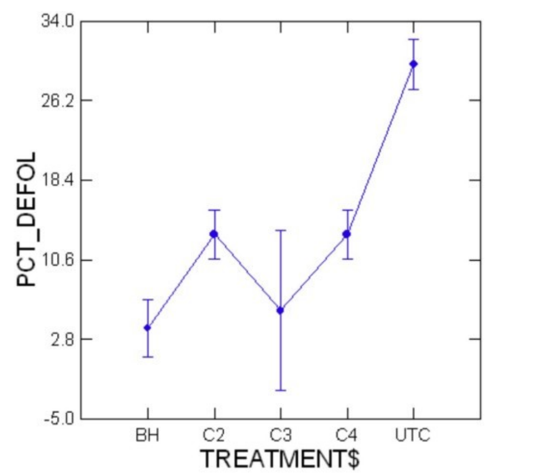

Figure 5. Mean Percent Defoliation of plants in treatment plots.

While biologically based pesticides tend to carry a higher cost /ac and take slightly longer to suppress a population of insects, they can be targeted at early instars, whose feeding pressure is far less than older larvae or adults. In addition, high mortality of young larvae can often lower a population to the point where later management with foliar insecticides is less challenging. Targeting younger larvae is often recommended when using products with slower onsets of action.

Such is the case with the technique of *RNA interference* (RNAi). A relatively new technology, the introduction of double-stranded RNA (dsRNA) disrupts, or 'silences', specific genetic coding, often for a protein. Specific genetic events necessary for the insect to live are targeted. Consequently, as an insecticide, dsRNA interferes with the ongoing genetic control of specific processes. Sometimes, there may be a lag time between the cessation of those processes (e.g. digestion) and insect death. Consequently, it is best to target the stage that will do the least damage during that period.

In 2021 and 2022, a double-stranded RNA (dsRNA) based product, called Calantha (active ingredient is Ledprona) produced by Greenlight Bioscience, was tested at both the Crookston and Becker locations. In both years, Calantha and an industry standard insecticides were product was applied against 1st instar larvae at 30% egg hatch. In both locations in both years Calantha suppressed defoliation (and numbers) as well as the industry standard and both products had significantly less defoliation than did UTC plots (Fig 6, 2022 results as example). Calantha is currently awaiting registration.

Both of these products have a fit in our current insecticide rotations for control of CPB. Both are probably best targeted against 1st instar larvae and can result in a similar benefit as seen in other insecticides targeted against early populations. Prior to the development of resistance, one of the reasons that at-plant applications of neo-nicotinoids were so successful was because they not only caused mortality to overwintering adults that fed on emerging plants, but they imposed significant mortality to hatching larvae, thereby decimating the seasonal population.

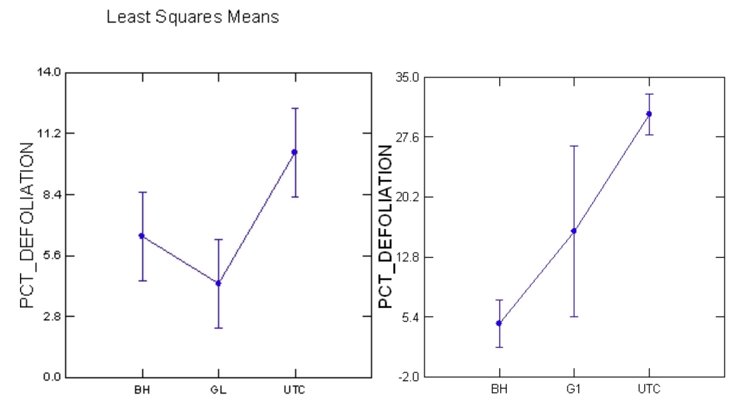

Figure 6. Comparison of %defoliation in Calantha dsRNA trials at Becker (left, light CPB populations) and Crookston (right – heavy CPB populations) sites in 2022. BH = Blackhawk (industry standard), GL = Greenlight's Calantha,

Table 1. Preliminary, non-statistical comparisons of insecticide mode of action activity against CPB stage as tested in foliar application trials at the UMN-NWROC and UMN-SPRF. Numbers represent the proportional comparison to the average control of all insecticides (mean number of CPB in treated plots across all dates of the individual trial). Insecticides with single trials or non-traditional applications were redacted from this table. No statistics were conducted on these data, they are simply averages across trials, consequently no recommendations can be inferred from these data*. Numbers below 1.0 indicate the insecticide was perming better than the average control within that stage.

Insecticide	Small Larvae	Large Larvae	Adults
Abamectin (avermectin)	1.09664	0.66532	0.89915
abamectin & cyantraniliprole (diamide)	0.65713	0.80096	1.09125
Clothianidin (neonicotinoid)	1.00555	1.91312	1.71414
chlorantraniliprole (diamide) & lambda Cyhalothrin (Synthetic Pyrethroid)	1.06036	1.31739	1.57050
cyantraniliprole (diamide)	0.54268	0.40486	0.71715
chlorantraniliprole (diamide)	0.75946	0.78062	1.34550
cyclaniliprole (diamide)	0.92473	0.45057	0.38215
indoxacarb (indoxacarb)		1.88220	0.31347
lambda-lyhlothrin & thiomethoxam (neonicotinoid)	1.29341	1.10578	0.79615
novaluron (benzoylurea))	0.43337	N/A	N/A
spinetoram (spinosyn)	0.74755	0.68440	0.72128
Spinosad (spinosyn)	0.82469	1.25649	1.06527
Thiomethoxam (neonicotinoid)	0.81364	2.98390	8.30426
tolfenpyrad (with PBO)	0.72361	1.39501	0.48560

*Because of confounding effects between trials, this is not a valid comparison between the different insecticide treatments, but can provide insight into comparisons within each treatment regarding the stage of CPB it might best perform against.

In an attempt to provide insight into what CPB life stage registered insecticides might be most effective, historical data from 8 years of insecticide trials were combined to examine efficacy of different modes of action against different life stages of the beetle. In our insecticide trials, a common metric is counting the mean number of CPB/plant in 4 replicated plots per treatment. The different life stages counted are small larvae (1st & 2nd stage), large larvae (3rd & 4th stage), and adults. These numbers were averaged across all treatments (excluding UTC plots) to provide an average control of each stage for each treatment in a trial. The proportion of that average control was then calculated for each insecticide treatment. These average performances within trials were then averaged across all 8 years of trials (Table 1). It is important to remember that there has been no statistical analyses of these data, simply averages. In addition, different locations, variety used in the trials, varying seasonal conditions, etc means this is not a valid comparison between the treatments, but can provide insight into comparisons within each treatment regarding the stage of CPB it might best perform against.

The use of Novaluron based insecticides (e.g. Rimon) are very effective against young larvae (1st & 2nd stage). In fact, they insect growth regulators that targets the construction of new exoskeletons in insects (if an insect fails to molt it dies). As such, they are only effective against 1st and 2nd instar larvae. It is one of the few insecticides that have activity against eggs, 2-3 applications at weekly intervals starting at egg laying can provide a significant decrease in early season populations. A maximum of 24oz/ac per season is indicated on the label. Tolfenpyrad and Anthranilic Diamide based insecticides also have demonstrated good activity against small larvae.

Large larvae (3rd and 4th stage) are more difficult to manage than are younger larvae. Abamectin appears to perform better against large larvae than it does against small larvae. Diamide based insecticides perform well against both larval stages. Some spinosyns also have similar efficacy.

Adult CPB are the most difficult to control. Most modes of action seem to suffer in their comparative performance against adults compared to larvae. In our trials, certain diamide and indoxacarb insecticides are two modes of action that appear to perform better against adults than either does against larvae.

Certainly these data cannot function as a comparison of efficacies between products. At best, they can provide some points of focus for considering experience seen in a producer’s own operation.

3) Aphid Alert Trapping Network. The network of ~20 3m-tall suction traps was again established and maintained in the seed potato production areas of Minnesota and North Dakota in 2022. These traps consist of a fan, powered by solar panel and deep cell battery, drawing air down in through the trap and trapping the incoming aphids in a sample jar. Traps have a photocell, preventing the fan from running through the night and capturing night flying insects (aphids are day-fliers) reducing the amount of bug stew to be sorted and saving power. The sample jars were changed weekly by grower cooperators and sent to the UMN-NWROC entomology lab. Insects in the jars were sorted, aphids identified to species and aphid population dynamics at sample locations were determined. Maps were prepared weekly showing these dynamics. This information was made available to growers on the website (aphidalert.blogspot.com) (Fig 7), via NPPGA weekly email, linked to on the NDSU Potato Extension webpage (http://www.ag.ndsu.edu/potatoextension), and posted on the AgDakota ListServe. Recommendations for beginning oil treatments or targeted edge applications were made based on the information obtained from the regional monitoring system. Traps were established in early June and maintained until the seed field hosting the trap was vine-killed/harvested. At that point the field is no longer attractive to aphids.

Figure 7. Weekly report of the Aphid Alert rapping Network. Available at: aphidalert.blogspot.com.

We continued to operate the Aphid Alert suction trap network incorporating the PVY Vector Risk Index maps into weekly reporting. Aphid species have differing levels of efficiency in their ability to transmit PVY. The PVY Vector Risk Index uses relative transmission efficacies of different aphid vector species to present the relative risk of disease transmission at each location. In 2019, patterns of average seasonal aphid flight was provided to each cooperator to demonstrate how aphids are moving into their particular fields. These will be updated with all current data for all regions and posted on the website as well.

The averaged data for sites can be used to tailor potential management plans for those areas. The seasonal patterns of vector flights can be used to make decisions on when to focus specific management tactics. For example, the technique of adding insecticide to Aphoil applications, first researched by Singh (2019), were recommended by the developers to be applied more frequently early in the season, tailing applications off later in the year. That technique was, however, developed in New Brunswick, which has much earlier flights of aphids than does Minnesota or North Dakota. Data from trapping locations can be used to more accurately decide when to apply insecticide with Aphoil to gain the greatest impact on PVY transmission.

The 2022 season started out slowly with low populations of vectors being recovered for the first several weeks(Fig 8). In the month of June, only 1 or 2 sites were recording catches and those were in the low single digits. July capture numbers remained relatively low and it initially appeared MN & ND seed producers were in for a low vector year. By early August, vector numbers took a jump. This was not surprising, typically our greatest flight activity for PVY vector species is mid-July to mid/late-August. Many of the small grain aphids are vectors of PVY and their flight increases during early August as grain matures and dries off and the aphids populations crash, with winged forms developing to disperse and find seek alternate sources of food. However, on the July 31-Aug 07 trapping period, the Green Peach Aphid (GPA) was recovered. Unfortunately, it was the first of many with almost half of the sites reporting GPA by the end of the season. Green Peach Aphid is the most efficient vector of PVY. In fact, the values attributed aphis species for their importance and contribution to the cumulative PVY Vector Risk Index is based on how they compare as a vector to GPA. High numbers of GPA can skew the PVY Vector Risk Index even if the numbers of other vector species are low. But

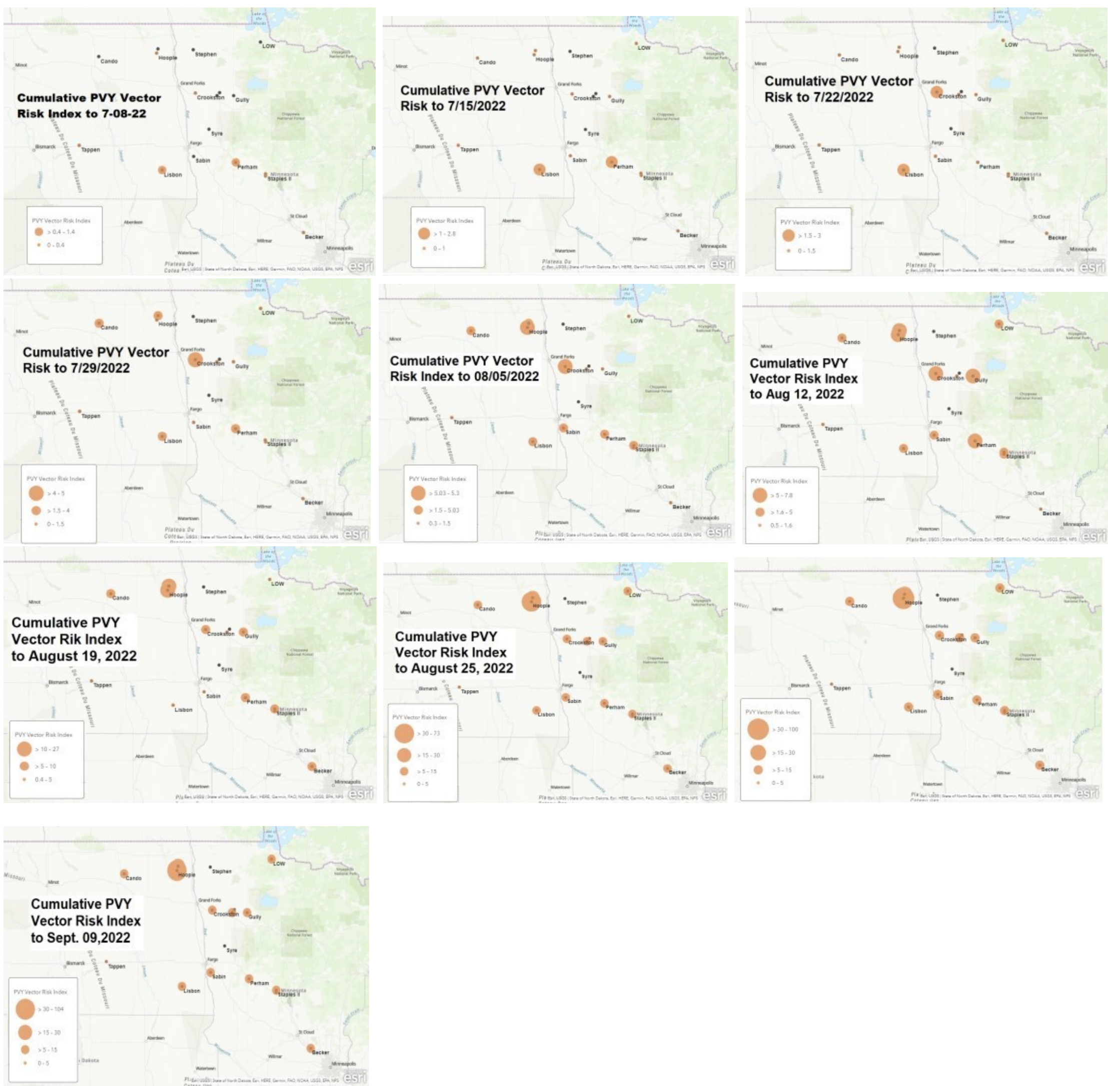

Figure .The cumulative PVY Vector Risk Index across the trapping area as a funciton of time. Each map refelects the weekly PVY Vector Risk Index added to previous dates. The larger the dot, the larger tha sample that's not what happened in 2022. We recovered over 1500 aphids from traps and approximately 85% of them were PVY vectors species. The vast majority caught in mid-late August (Fig 9). Despite the high number of vectors caught, the late appearance of GPA is a bit puzzling.

Green Peach Aphid don't overwinter in MN or ND, they overwinter from southern Kansas south to the Gulf, west of the Mississippi. Aphids are not strong fliers, moderate to long distance travel is only accomplished when they are passengers on relatively fast moving winds. For long distances, they would require winds at altitudes high enough to prevent being run into the ground (which pretty much terminates long distance travel). However, if they are at altitude and the wind is moving faster than they can fly (any wind in excess of 6mph turn aphids from pilots to passengers) they cannot fly out of the wind event. They must be 'rained out' by a precipitation event (Zhu et al 2006). Given their absence in previous trap samples GPA could not have arrived in the area much more than 3 weeks prior to the July 31. The first record of GPA in 2022 was Hoople, ND. According ot the NDAWN station in Grafton, the only rain event in that period was on July19 (Table 2). The NOAA Air Resources Lab has an excellent wind model, called HYSPLIT, that is designed to track airborne particles which can be used to track potential air movement that facilitates aphid movement. It uses NOAA and US Weather Service data to calculate likely end points to wind events and is capable of calculating backtracks ofwind events from a given location on a given date. On July 19, there was a rain event in the Grafton area, there was also 24h wind events at 1500m and 2000m originating in NE Colorado, which would have been hosting GPA at that time (Fig 10).

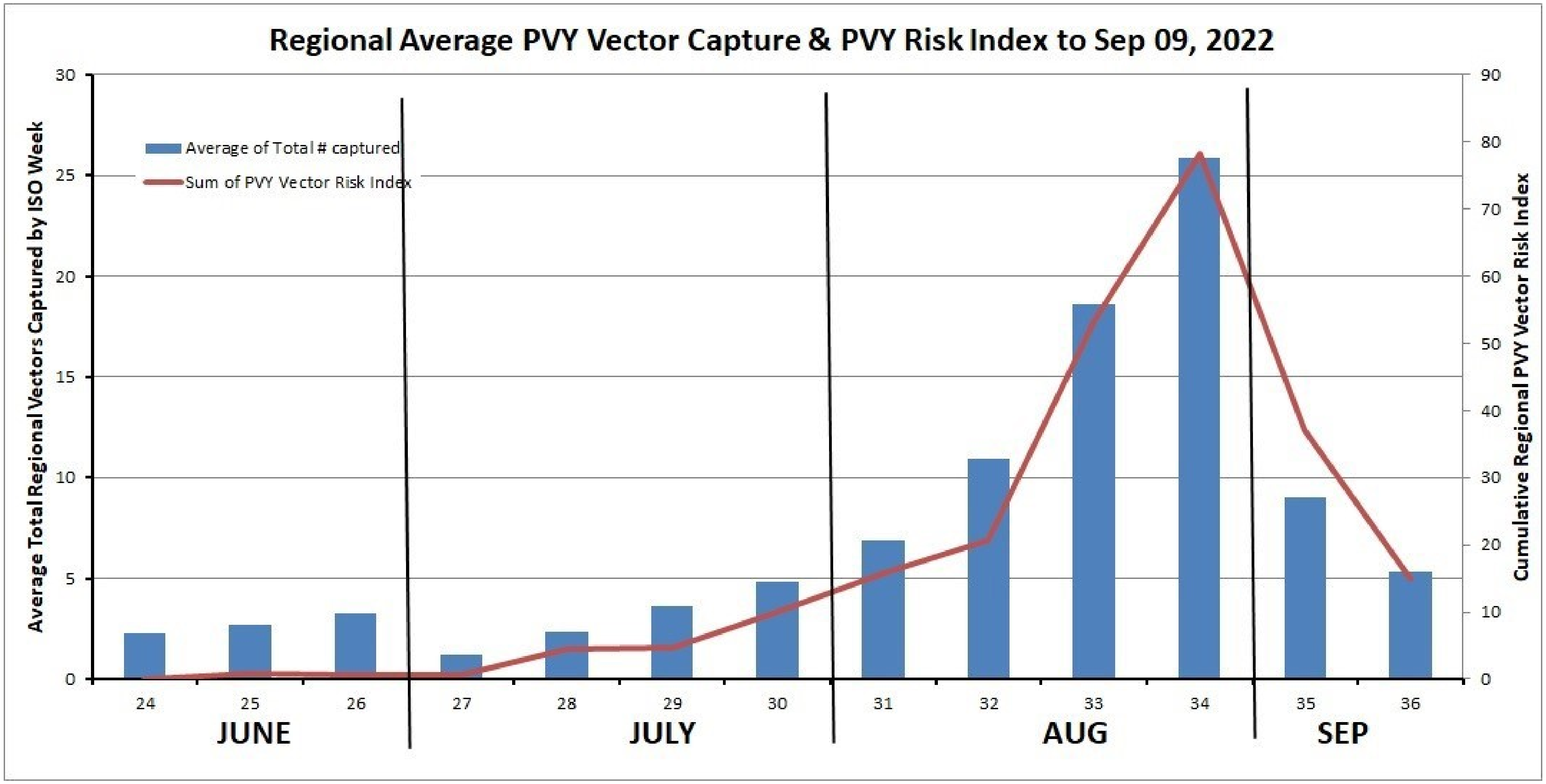

Figure 9. The average regional trap capture and PVY Vector Risk Index value fr the 2022 growing season (by Sept. 09, most trap locations had vine killed). Blue bars indicate the mean number of aphid vectors recovered in all traps at that date. The red line represents the sum of PVY Vector Risk index values summed across all sites at that date. Note the high increase in both vector numbers and associated PVY Vector Risk Index values late in August. This coincides with the appearance in the region of Green Peach Aphid (*Myzus persicae*) at multiple location across MN and ND. Numbers on the x-axis are not dates, but ISO 8610 week numbers.

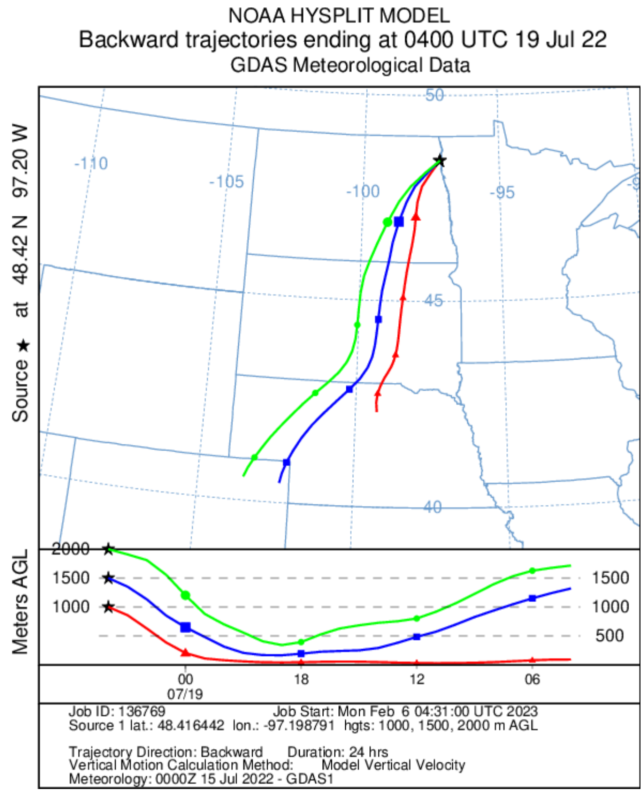

Figure 10. Output for HYSPLIT backtrack model terminating in Grafton, ND, July 19, 2022.

While the tactics used in this detective story provide only an explanation rather than a prevention for what happened, with further refinement it might be a method of within-season prediction of potential PVY vector problems. If source locations close to other potato production areas are identified, there may be opportunities to examine if PVY can be

While aphid flight was comparatively late in 2022, our typical pattern of aphid flight stays low through early summer, rising in mid-late July and peaking in August. While this may vary somewhat from site to site within the region, the pattern is generally applicable. But the general late season flight period of our major PVY vectors does help target scouting, management and harvest activities.

Table 2. NDAWN Weather Monthly Weather Report for Grafton, July 2022.

GRAFTON 10E Daily Observations from July 1, 2021 to July 31, 2021
North Dakota Agricultural Weather Network (NDAWN)

Year	Mo	Da	Max Temp (F)	Min Temp (F)	Avg Soil Temp (F)	Avg Turf Temp (F)	Avg Wind Spd (MPH)	Max Wind Spd (MPH)	Avg Wind Dir (deg)	Avg Wind DirSD (deg)	Total Solar Rad (Lys)	Total PET (inch)	Rain-fall (inch)	Avg Dew Pt (F)
2021	7	1	88.9	58.0	74.8	70.0	2.1	14	55	46	701	0.27	0.00	58
2021	7	2	92.6	58.9	75.3	70.5	3.4	15	145	24	696	0.29	0.00	63
2021	7	3	93.3	68.3	76.3	71.7	6.5	27	175	32	595	0.32	0.08	63
2021	7	4	89.3	64.3	75.7	72.6	4.5	21	312	31	634	0.26	0.00	68
2021	7	5	88.4	60.5	75.6	72.1	4.3	18	345	45	611	0.27	0.00	61
2021	7	6	64.8	56.6	71.3	69.0	5.4	17	8	23	369	0.15	0.00	50
2021	7	7	72.6	50.6	69.0	66.6	2.3	11	37	58	444	0.15	0.00	49
2021	7	8	78.5	50.2	69.2	66.1	3.8	14	159	25	573	0.22	0.00	54
2021	7	9	82.3	51.8	71.2	67.3	2.4	12	138	40	700	0.25	0.00	51
2021	7	10	86.4	50.7	71.8	68.1	1.9	8	141	52	648	0.25	0.00	53
2021	7	11	93.9	60.0	74.2	70.4	4.4	15	206	34	635	0.32	0.00	58
2021	7	12	90.1	59.8	73.7	70.7	6.5	24	206	49	587	0.32	0.00	59
2021	7	13	83.9	57.7	73.4	70.8	3.1	15	345	41	580	0.23	0.00	58
2021	7	14	80.1	56.7	71.6	69.6	1.8	10	25	36	444	0.17	0.00	55
2021	7	15	87.1	53.3	72.0	69.2	4.0	20	183	35	611	0.26	0.00	56
2021	7	16	88.0	57.6	73.5	70.6	5.3	23	171	24	625	0.30	0.00	59
2021	7	17	86.9	55.1	73.1	70.6	4.2	19	159	23	574	0.26	0.00	58
2021	7	18	90.7	55.4	73.9	71.1	4.6	18	167	26	587	0.27	0.00	63
2021	7	19	78.0	65.0	71.8	70.4	3.5	34	59	73	226	0.09	0.92	66
2021	7	20	78.5	61.9	69.2	68.7	3.5	13	114	41	208	0.07	0.00	67
2021	7	21	82.4	67.0	70.4	70.0	6.7	19	137	19	290	0.14	0.00	68
2021	7	22	88.4	70.4	75.8	72.8	5.0	17	149	23	579	0.25	0.00	70
2021	7	23	96.2	68.7	78.4	74.8	4.2	19	271	47	545	0.27	0.00	68
2021	7	24	85.4	54.8	75.5	72.8	6.3	22	286	25	657	0.34	0.00	52
2021	7	25	90.4	55.3	75.0	72.3	4.3	17	280	26	644	0.31	0.00	53
2021	7	26	90.2	55.5	74.9	72.0	3.9	16	84	46	565	0.26	0.00	58
2021	7	27	88.4	54.4	74.7	71.9	3.1	14	107	39	562	0.24	0.00	57
2021	7	28	87.7	59.1	74.0	72.2	4.6	20	7	61	338	0.19	0.00	63
2021	7	29	82.2	52.9	73.1	71.2	3.0	18	350	41	602	0.23	0.00	53
2021	7	30	88.0	57.9	74.2	71.3	4.8	18	245	37	536	0.28	0.00	54
2021	7	31	80.9	55.6	73.3	71.3	4.6	22	342	25	538	0.24	0.00	52
Averages			85.6	58.2	73.4	70.6	4.1	18			545			59
Totals												7.47	1.00	
Max			96.2	70.4	78.4	74.8	6.7	34			701	0.34	0.92	70
Min			64.8	50.2	69.0	66.1	1.8	8			208	0.07	0.00	49
Std. Dev.			6.6	5.4	2.2	1.9	1.3	5			132	0.07		6

E = estimated value
M = missing value
The number of missing values is indicated in parentheses.

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Report Title: 2022 Support of Irrigated Potato Research for North Dakota and Minnesota

Submitted to NPGA & MN Area II

Principle Investigator: Julie S. Pasche, Department of Plant Pathology, North Dakota

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Co-Principle Investigator: Gary A. Secor
Collaborators: Susie Thompson, Andy Robinson and Harlene Hatterman-Valenti

Executive Summary: North Dakota State University has conducted irrigated potato research for over 30 years. Over that time, growers have generously supported this research and have had access to the wealth of information generated in the areas of cultivar development, general cultural management practices such as vine desiccation, herbicide efficacy and damage, nutrient management, physiological defects including sugar ends and disease management, among others. Specifically, trials conducted at the irrigated research site near Inkster, ND have given us a way to track fungicide efficacy for the management of early blight, brown spot, Rhizoctonia, and silver scurf. We evaluate foliar and seed treatment fungicides in a program approach specific for the pathogens and environmental conditions in this region, among other things. Again, allowing us to make timely and relevant grower recommendations. Without the irrigated research site near Inkster, our ability to react to changes in management for irrigated potato productions conditions in our region would be severely impeded. If you have utilized recommendations from NDSU for managing your irrigated potato crop, you have no doubt benefitted from the research conducted at Inkster.

Rationale: Irrigated potato production accounts for more than half of the state's total potato production and differs substantially from non-irrigated production. The majority of the irrigated potato production is used in the production of French fries, and as a result the spectrum of cultivars grown under irrigation differs greatly from those produced under non-irrigated conditions. In addition, the pressure from diseases, insect and weed pests, cultivar selection and use of fertilizer all differ substantially for irrigated potato production compared to potatoes produced under non-irrigated conditions. To be relevant to the many irrigated potato growers in the region, research must be conducted under irrigated conditions, mimicking as closely as possible the grower experience.

The funding for the management of the Inkster irrigated research site facilitates the use of the site by potato research projects. The expenses associated with managing the research site include general maintenance for all research trials (soil tillage, cultivation, scheduling and performing irrigation, fertility management, application of herbicides, fungicides and insecticides, etc.) in addition to assisting in planting and harvest operations as needed. The potato pathology management team monitors soil-borne pathogens to make the irrigated research site useful to everyone. For example, our research team coordinates the fumigation of the Inkster site with Hoverson Farms as needed and has been able to secure Vapam donations from AmVac to offset all expenses associated with this fumigation. This saves the NPGA approximately $7,500 annually. The Inkster management team also plants all cover crops and assists in planning and preparing the site for the annual field day.

The total cost of the general management of irrigated potato research in 2022 at the NPGA research site near Inkster, ND was nearly $75,000. Some notable increases in expenses are due to substantial increases in fertilizer, employee salaries, and vehicle costs. We continue to make a concerted effort to re-evaluate all operations and to increase efficiencies in management of the Inkster research site. For example, in 2022 we enlisted the use of remote soil moisture sensors to more effectively irrigate and potentially reduce travel to the site.

It was wonderful to see full trailers at the NPGA field day and the trial site looked as fabulous as usual thanks to Russell, Dean, and the rest of the team!

We look forward to working with growers and researchers in the future to tackle existing and emerging challenges faced by the industry. Please contact us with any questions concerning this report or any other matters.

An enormous thank you goes out to Russell Benz, Dean Peterson, Hunter Bentten, Cory Ingram, Sunil Shrestha, Arslan Sarwar, and Rachel Selstedt and the entire field staff for their work on this research.

We appreciate the generous cooperation from Forest River Colony for tillage, irrigation, and general support. This effort was generously funded by the MN Area II Potato Growers Association and the Northland Potato Growers Association.

Research Results: In 2022, 38 research trials were conducted on nearly 24 acres at the Inkster research site. As indicated above, these trials span the range of expertise of the potato improvement team. Among other things, data from these trials are helpful for screening registered and novel products to provide statistically unbiased evaluations for the benefit of the potato industry and growers. In many cases the trial results are confidential because products are not registered for use. The Inkster site allows us to generate data under local irrigated growing conditions over several years. Using data generated at Inkster, in part, products that are deemed successful by the cooperator are registered and marketed for use on potatoes in the region. Below we have included some selected results from trials conducted at Inkster. Some results are preliminary and as indicated, some results are confidential.

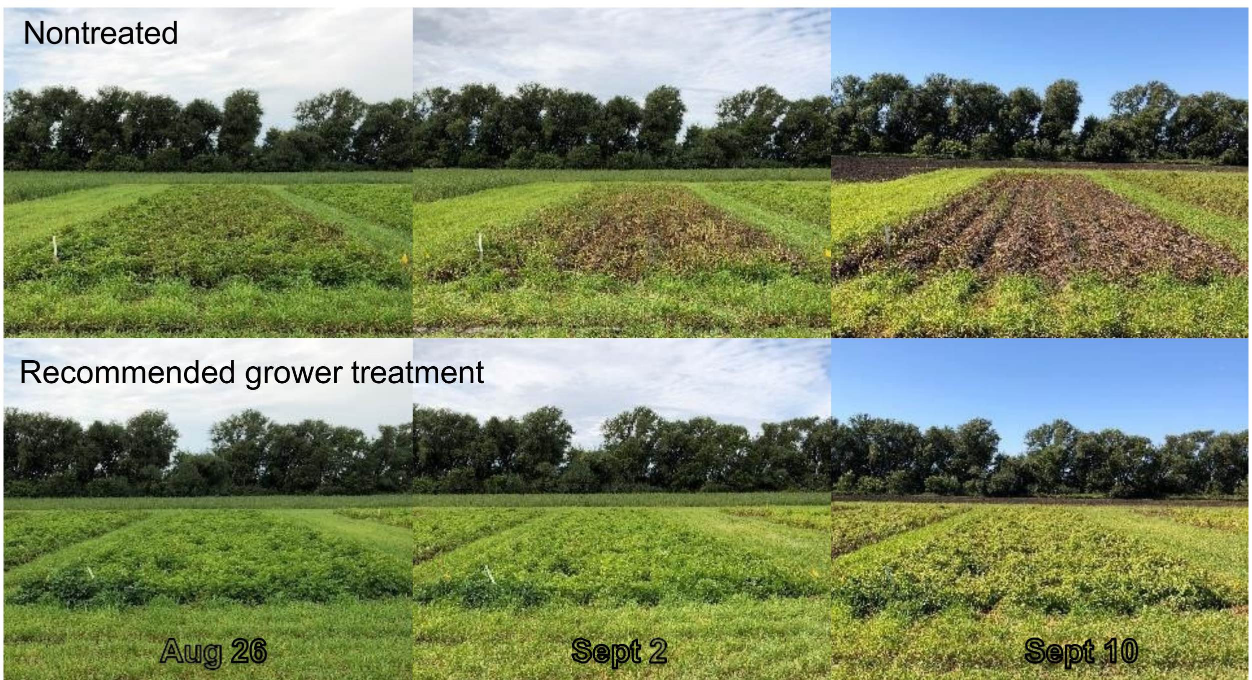

Figure 1. Examples of plots from a foliar disease trial conducted at Inkster in 2020 illustrating the high disease pressure. Plants were inoculated with spores of the early blight pathogen, *Alternaria solani*, twice during the growing season. The grower recommended treatment includes three specialty fungicides (applications 2, 5, and 7) rotated with chlorothalonil (applications 1, 3, 4, 6, 8-10) and tank-mixed with mancozeb. Photos taken by Russel Benz.

We feel strongly that we are generating unbiased, reliable, robust foliar fungicide recommendations for the management of early blight and black dot because of our ability to manage the trials to promote disease the irrigated research site (Figure 1). One example of generating data over several years includes the evaluation of new foliar products / formulations for the management of early blight (Figure 2). Results reported here represent 2 years of data generated at Inkster. Similar data have been generated in other years and reflect the same message. While we have concerns over the development of fungicide resistance, these fungicides remain very effective against the pathogen population in our region.

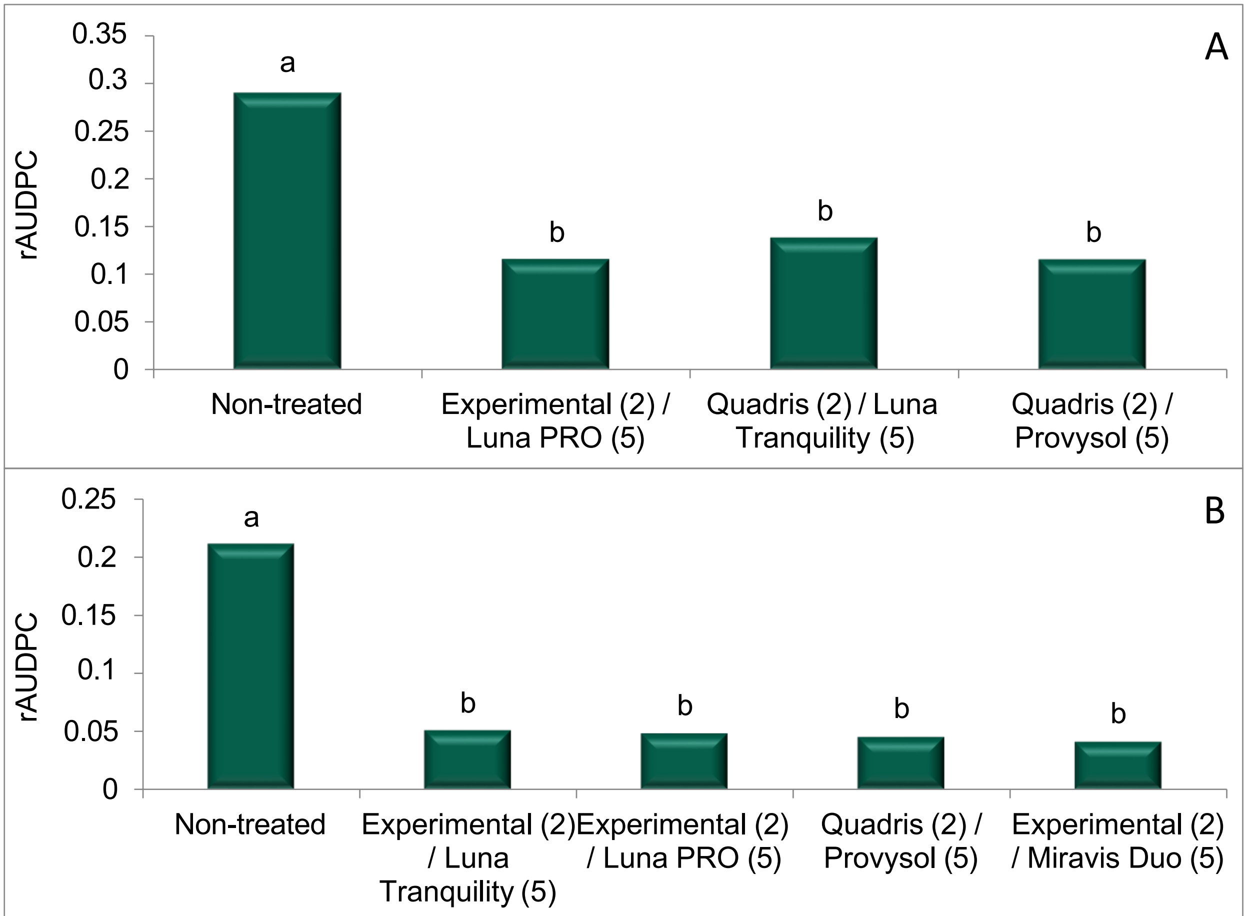

Figure 2. Trial conducted in 2020 under high disease pressure (A) and 2022 under moderate disease pressure (B) at the Inkster research site. Bars with different letters above have significantly different relative area under the disease progress curve (rAUDPC) which represent disease severity across the growing season as determined by visual disease ratings collected weekly for 10 weeks. The number in () represent the application number in a 10-application program. All treatments included Scala @ application 7. The three specialty fungicides (applications 2, 5, and 7) were rotated with chlorothalonil (applications 1, 3, 4, 6, 8-10) and tank-mixed with mancozeb.

At Inkster in 2022, the pathology project conducted six trials to evaluate 36 treatments for managing seed-borne Rhizoctonia. Registered fungicides, experimental fungicides and natural products by seed treatments and in-furrow at planting we evaluated. Most of the treatments were entered as numbered compounds and/or were confidential. Two nontreated controls were included in each trial, a non-inoculated control and a Rhizoctonia seed inoculated control. Many of the products tested did not result in significant reduction of Rhizoctonia 45 days after planting. As in past years, the best control of Rhizoctonia 45 days after planting continued to be Maxim seed treatment at 0.08 fl oz/cwt plus Quadris in-furrow at 9.0 fl oz/acre.

A field trial was conducted at the Inkster site to evaluate efficacy of eight seed treatments and in-furrow at planting treatments to reduce silver scurf of harvested potatoes. Tubers cv. Agata naturally infected with silver scurf were planted at the Inkster site and grown using local agronomic practices. Tubers were harvested and incubated at 50F for three months and evaluated for silver scurf and black dot severity (Table 3). Overall, most treatment reduced incidence and severity of silver scurf, but did not reduce incidence and severity black dot that is naturally present at the site.

Table 3. Summary of results of blemishes observed at harvest in tubers of cultivar Agata grown at Inkster, ND during 2022.

Treatment	Application Rate	Schedule	Incidence (%)			Severity (%)		
			Black dot	Silver scurf	Total**	Black dot	Silver scurf	Total**
Non-treated / Asymptomatic	-	-	14.0	35.0	45.0	0.6	2.4	3.0
Non-treated / Symptomatic	-	-	9.0	30.0	37.0	0.4	2.4	2.8
Minuet*	12.0 fl oz / a	In-furrow	22.3	6.1	27.4	1.5	0.3	1.8
Actinovate AG*	9.0 oz / a	In-furrow	10.0	12.1	22.1	0.6	0.9	1.6
CruiserMaxx Vibrance Potato*	0.5 fl oz / cwt	Seed	13.0	7.0	18.0	0.8	0.5	1.2
Maxim 4FS + Quadris*	0.08 fl oz / cwt + 9.0 fl oz / a	Seed + In-furrow	15.0	26.0	40.0	1.4	1.0	2.3
Emesto Silver*	0.31 fl oz / cwt	Seed	12.0	8.0	19.0	0.9	0.3	1.2
Elatus*	0.5 oz / 1000 row ft	In-furrow	22.0	10.0	31.0	2.3	0.4	2.7
Miravis Prime*	9.2 fl oz / a	In-furrow	17.3	10.7	28.0	1.0	0.3	1.3
Oxidate*	0.39% v/v	Seed	25.0	15.0	39.0	2.1	0.5	2.6
LSD(α=0.05)			11.2	16.6	18.0	1.1	1.5	N.S.

* : using silver scurf symptomatic seed as source. ** : Sum of black dot and silver scurf.

Dr. Harlene Hatterman-Valenti's project examined the use of preplant polysulphate with either potassium sulfate or potassium chloride in comparison to the grower standard of potassium sulfate for Russet Burbank and Bannock. The polysulphate + potassium sulfate mixture provided a 16% yield increase compared to the grower standard with Russet Burbank and a 34% yield increase with Bannock. A separate trial evaluated several calcium products applied to Russet Burbank during the growing season. Foliar applications were made at emergence, pre-hook and pre-bloom. The nontreated control had the lowest calcium percentage when the petioles were tested, but the higher calcium percentages resulted in a 4% marketable yield increase and a 16% increase in the yield for 6-10 oz tubers compared to the nontreated.

Report Title: Adjusting Planting Date for the Management of Verticillium Wilt

Submitted to MN Area II and Northland Potato Growers Associations

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Acknowledgments

An enormous thank you goes out to Dean Peterson, Russell Benz, Kal Larson, Jacory Ingram, Hunter Bentten, Binod Pandey, Rachel Selstedt, Fereshteh Shahoveisi, Arslan Sarwar, and Ipsita Mallik for their work on this trial. We appreciate the generous cooperation from RD Offutt Farm Division at Park Rapids for donating land, irrigation, fungicide and insecticide applications and sample storage. We also thank MN Valley Irrigation at Wadena for assisting with the fumigated strips. This trial was generously funded by the MN Area II Potato Growers Association and the Northland Potato Growers Association.

Executive Summary

Verticillium wilt arguably is the most damaging disease of potatoes when considering reduced yield and quality and the increased cost of management. Seed-tubers planted into colder soils emerge more slowly when compared to a later planted crop. The **objectives of this research** are to determine the effect of planting date on the development of Verticillium wilt utilizing three russet-skinned cultivars planted on three dates. Funding for this project has not been requested elsewhere, this year or in the past.

Trials conducted in west-central MN under irrigated conditions in 2020, 2021, and 2022 evaluated Verticillium wilt severity, total and marketable yield, and grower return ($) / acre. Stem colonization by *V. dahliae* was also collected to aid in elucidating the effect planting date on the return of inoculum to the soil as vines desiccate in the soil. Three russet cultivars varying in Verticillium wilt susceptibility (Russet Burbank, Umatilla Russet, and Alturas Russet) were planted at three dates. Verticillium wilt incidence was low in 2020, at least partially due to our ability to effectively rate after an early frost. Higher Verticillium wilt was observed in 2021, but ratings were again cut short due to excessive heat and bacterial vine rot. Therefore, rigorous conclusions could not be made based on Verticillium wilt severity in the first two years the trial was conducted. Delaying planting resulted in significant total and market yield reductions; however, not always significantly so depending on the number of days planting was delayed and the cultivar. Across years, lower total and market yield can be attributed to reduced time for tuber bulking. While this is not surprising, these yield losses were exacerbated by an early frost and delays in our initial planting date in 2020, and heat stress and bacterial vine rot in 2021. Again, 2022 brought a challenging planting season; therefore, planting dates were shortened to 10-day intervals to stay within a reasonable commercial planting schedule for the region. In 2022, we observed high wilt severity and significant yield consequences for not fumigating. While there was a trend towards lower yields with delayed planting, there effects were generally not significant within cultivar. Combining these data across three-years and developing an intensive data analysis pipeline will allow us to rigorously evaluate the use of planting date as a management tool for Verticillium wilt.

Procedures

Field trials were conducted near Park Rapids, MN in 2022 (third year of the project) under overhead irrigation. Fumigation was applied in strips using commercial equipment at 40 gpa on November 1, 2021. Grower practices, including cultivation, standard fungicide, insecticide, and herbicide regimes were performed by the cooperating grower (Supplemental Table 1). Russet Burbank (susceptible (S)), Umatilla Russet (MS) and Alturas (resistant (R)) were planted on May 7, May 17, and May 27, 2022 into fumigated and non-fumigated strips (Table 1; Supplemental Fig. 1). Seed for all treatments was obtained in March and held at 45F until one week before targeted planting date. Seed was warmed to 55F, cut and suberized 3 to 4 days prior to planting. This procedure was repeated for each planting date to ensure consistent, high seed quality at all planting dates. Plots were replicated four times in a randomized complete block design and split-plot arrangement. Fumigation was the main blocking factor. Cultivar and planting date were randomized within fumigated and non-fumigated strips. Four-row plots were seeded at 14 in. seed spacing and 36 in. row spacing.

Table 1. Cultivar, planting date and metam sodium treatment evaluated for the effect of planting date on Verticillium wilt development in 2022.

Treatment	Cultivar	Planting Date	Fumigation
501	Russet Burbank	7-May	Yes
502	Umatilla Russet	7-May	Yes
503	Alturas Russet	7-May	Yes
504	Russet Burbank	17-May	Yes
505	Umatilla Russet	17-May	Yes
506	Alturas Russet	17-May	Yes
507	Russet Burbank	27-May	Yes
508	Umatilla Russet	27-May	Yes
509	Alturas Russet	27-May	Yes
510	Russet Burbank	7-May	No
511	Umatilla Russet	7-May	No
512	Alturas Russet	7-May	No
513	Russet Burbank	17-May	No
514	Umatilla Russet	17-May	No
515	Alturas Russet	17-May	No
516	Russet Burbank	27-May	No
517	Umatilla Russet	27-May	No
518	Alturas Russet	27-May	No

The number of emerged plants were counted in the center two rows of each plot until 95% emergence was observed. Verticillium wilt was visually assessed weekly beginning at mid-potato vegetative growth and flowering stage (from August 5 to September 21) by counting the number of plants exhibiting symptoms. Soil samples were collected from fumigated and non-fumigated strips on August 5 from each replicate and the *Verticillium* propagules per gram (Vppg) were determined by Pest Pros Inc., Plainfield, WI (Table 2). Two soil samples were taken at a 0-8" depth from each plot (one hill and one valley) for a total of 18 samples/replication, all samples were thoroughly mixed and dried before shipment to Pest Pros for analysis. Five stems were collected from each of the 72 plots (2 fumigation, 3 cultivars, 3 planting dates, 4 replicates) on September 9, 20, and 27, for each planting date, respectively, and returned to the laboratory for *V. dahliae* quantification.

Table 2. *Verticillium* propagules per gram (Vppg) of soil.

Replication	Fumigation	Vppg	Difference (%)
1	no	26	53.8
1	yes	14	
2	no	22	36.4
2	yes	8	
3	no	32	56.3
3	yes	18	
4	no	30	33.3
4	yes	10	

Fumigation conducted on Nov. 1, 2021
Soil samples taken August 5, 2022
Two soil samples were taken at a 0-8" depth from each plot (one hill and one valley) for a total of 18 samples/replication, all samples were thoroughly mixed and dried before shipment to Pest Pros Inc., Plainfield, WI for analysis.

Total yield was collected at harvest on October 3 and 4. Market yield was calculated from tuber grade performed on November 3 and 4 by the USDA in Park Rapids, MN. All disease and yield data were collected from the center two rows only. The outside rows were used to buffer the plots from any competitive advantage that can occur during the early season because of staggered planting dates. Data analysis of disease incidence, yield, grade, pathogen quantification, and grower return were conducted using appropriate statistical procedures for the experimental design.

Results

The mean number (across cultivars and fumigation treatments) of days from planting to reach 95% emergence was reduced by 5 days from the first to second planting dates, and 9 days from the first to third planting dates (Figs. 1 and 2A). The date of emergence was delayed in early planted plots as expected, with 95% emergence recorded at 6/12, 6/17, and 7/1. Combining these data with soil temperatures collected from the data loggers will further clarify the associations of emergence and stem colonization by *V. dahliae*.

Verticillium wilt incidence ranged from 2% to 90%, depending on treatment, by the last rating date (Fig. 2B). Based on relative area under the disease progress curve (rAUDPC), planting date, cultivar, and the interaction among planting date, fumigation, and cultivar were significant (Fig. 3). As expected, susceptible cultivar Russet Burbank had significantly higher levels of visual Verticillium wilt than did moderately susceptible Umatilla and resistant Alturas (Fig. 3A). A significant difference was observed among planting dates across cultivar and fumigation, with the last planting date displaying the lowest disease incidence (Fig. 3B). An interaction among fumigation, planting date and cultivar also was observed. Generally, trends were a reduction in visual disease incidence under fumigation, and as planting date was delayed, but these differences were not always significant (Fig. 3C).

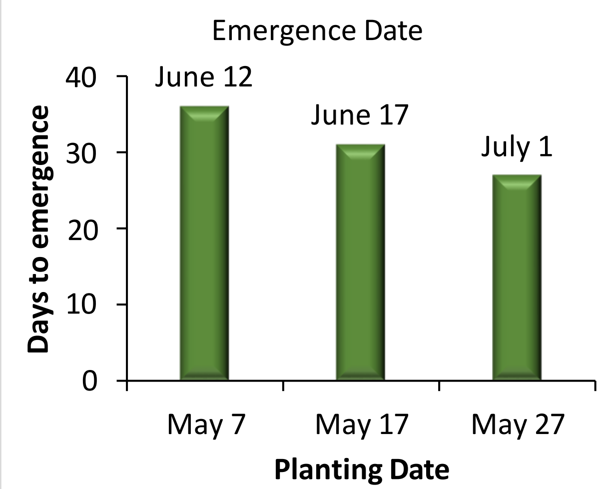

Figure 1. Days to emergence (y axis) and emergence date (above each column) for each planting date. Values represent the means across all three cultivars, fumigated and non-fumigated.

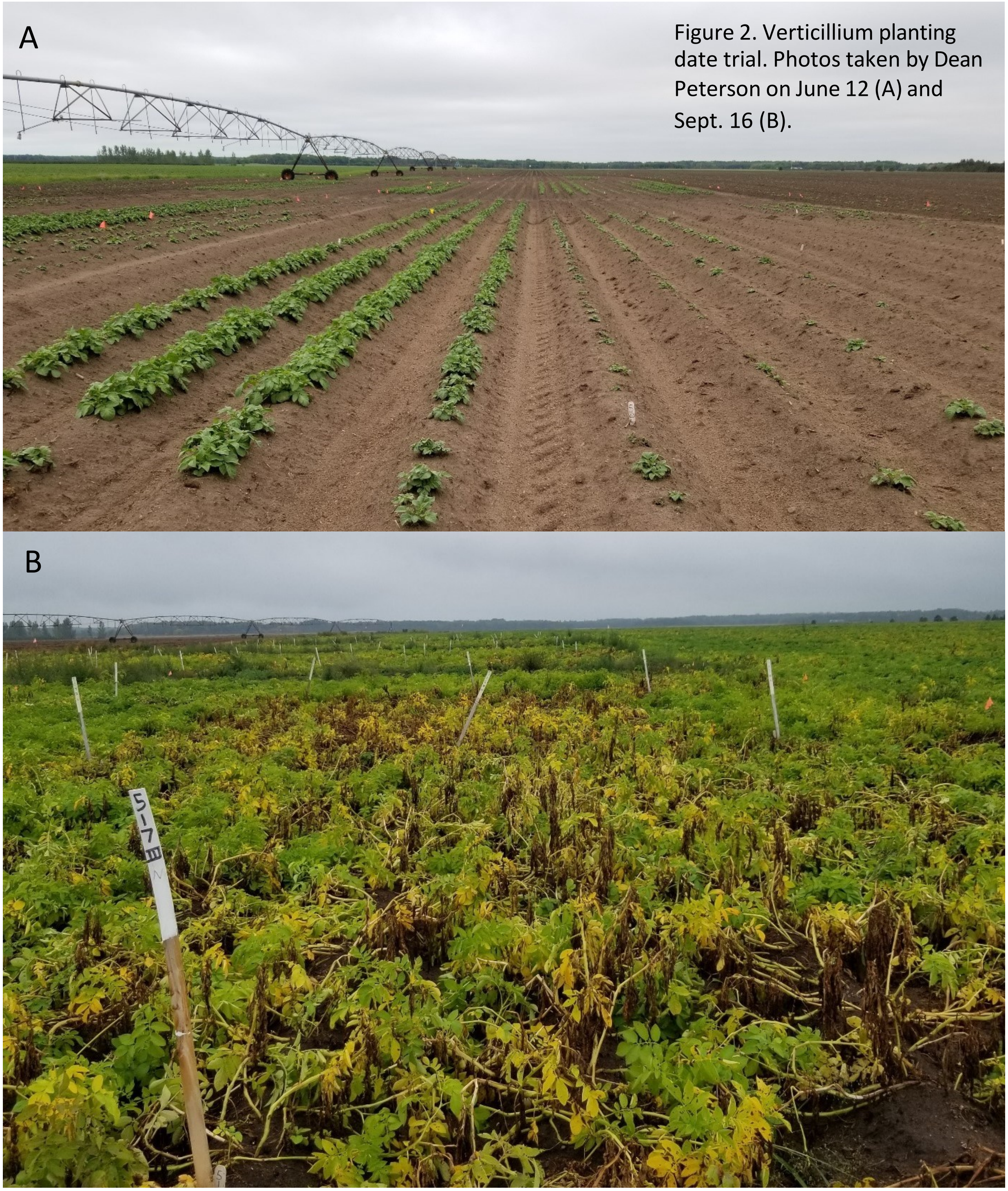

Figure 2. Verticillium planting date trial. Photos taken by Dean Peterson on June 12 (A) and Sept. 16 (B).

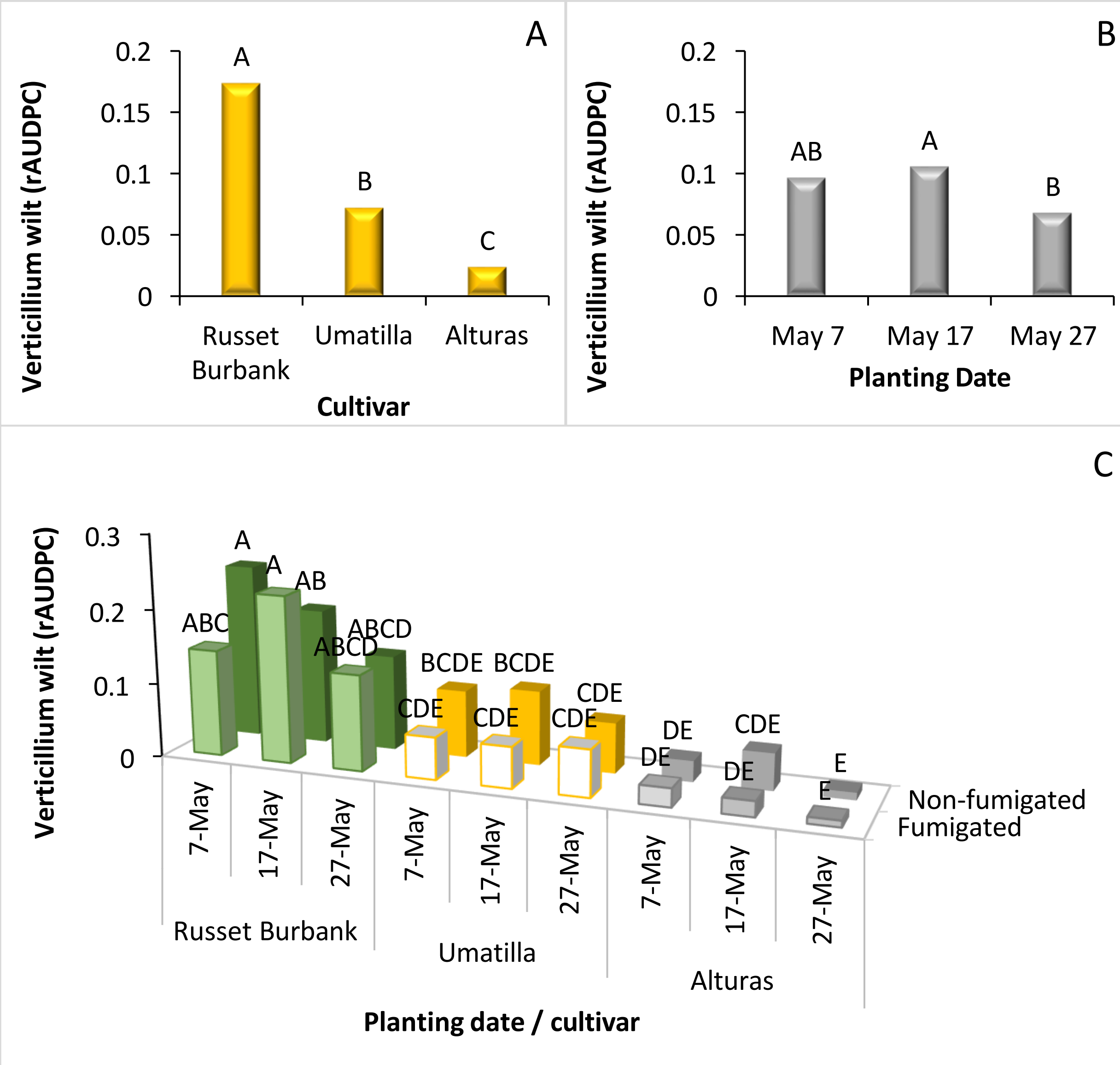

Figure 3. Visual Verticillium wilt incidence as represented by relative area under the disease progress curve (rAUDPC). Cultivar (A), planting date (B) and the interaction among planting date, fumigation, and cultivar (C) were significant. Columns with the same letters are not significantly different.

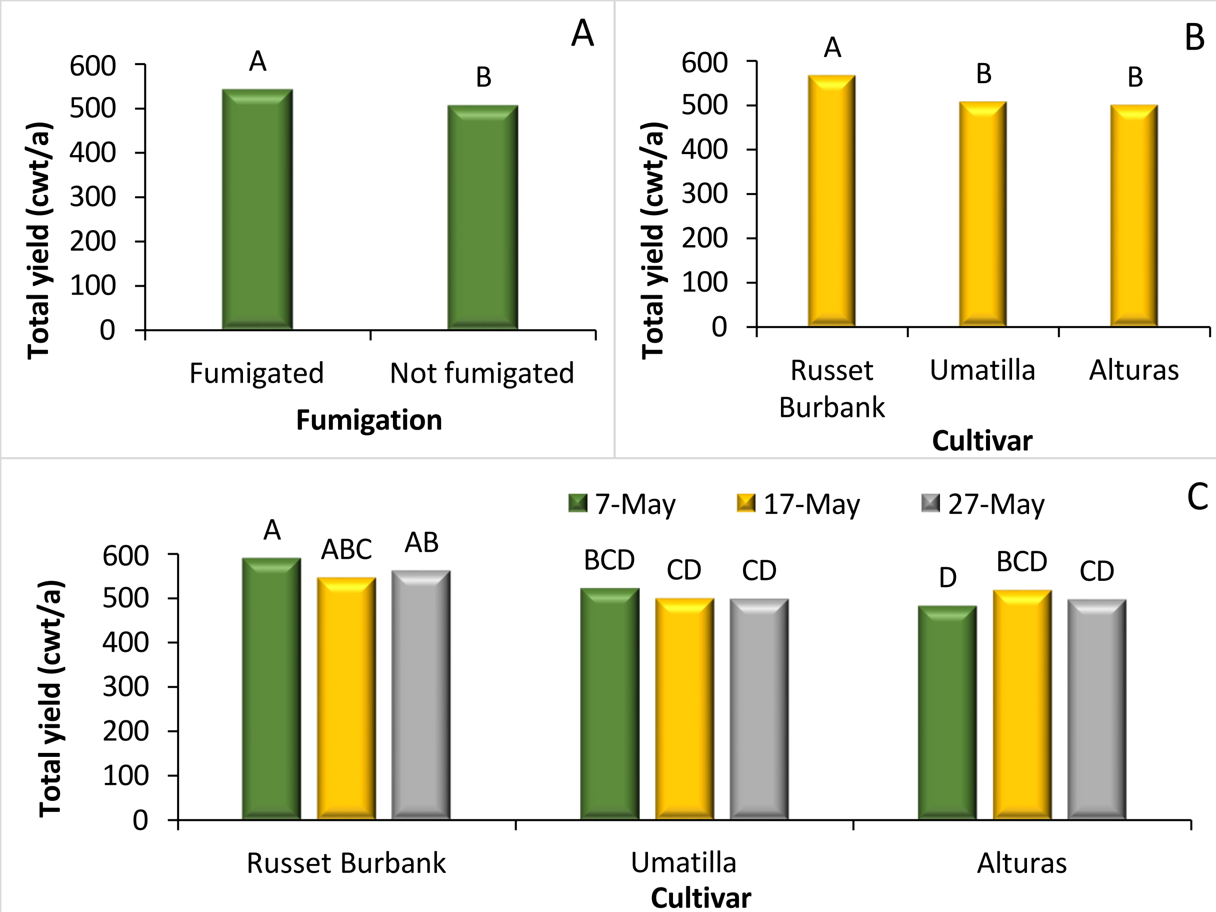

Figure 4. Total yield for the trial conducted in 2022 to evaluate the effect of planting date on Verticillium wilt in three potato cultivars. The main effects of fumigation (A) and cultivar (B) were significant. The interaction between planting date and cultivar was also significant (C). Columns with the same letters are not significantly different.

Total yield was affected by fumigation, cultivar and there was an interaction between planting date and cultivar. Yield was higher in fumigated plots of all three cultivars, regardless of planting date (Fig. 4A). The susceptible cultivar Russet Burbank provided significantly higher yield compared to other tested cultivars, regardless of fumigation and planting date (Fig. 4B). Further, the delay in planting resulted in significant interaction with cultivar for yield (Fig. 4C). While delaying planting generally resulted in lower total yield, these differences were not significant within individual cultivars.

Trends in market yield generally mirrored those of total yield (Fig. 5). The notable difference was significantly reductions in market yield in Russet Burbank as planting dates were delayed (Fig 5C). Market yield was most affected by reductions in tuber bulking in Russet Burbank where the first planting date resulted in significantly larger tuber profile including more tubers greater than 10 oz. and fewer at 4-6 oz. (Table 3). Bulking of Umatilla and Alturas was not significantly affected by planting date. Fumigation increased tubers greater than 10 oz. across cultivars.

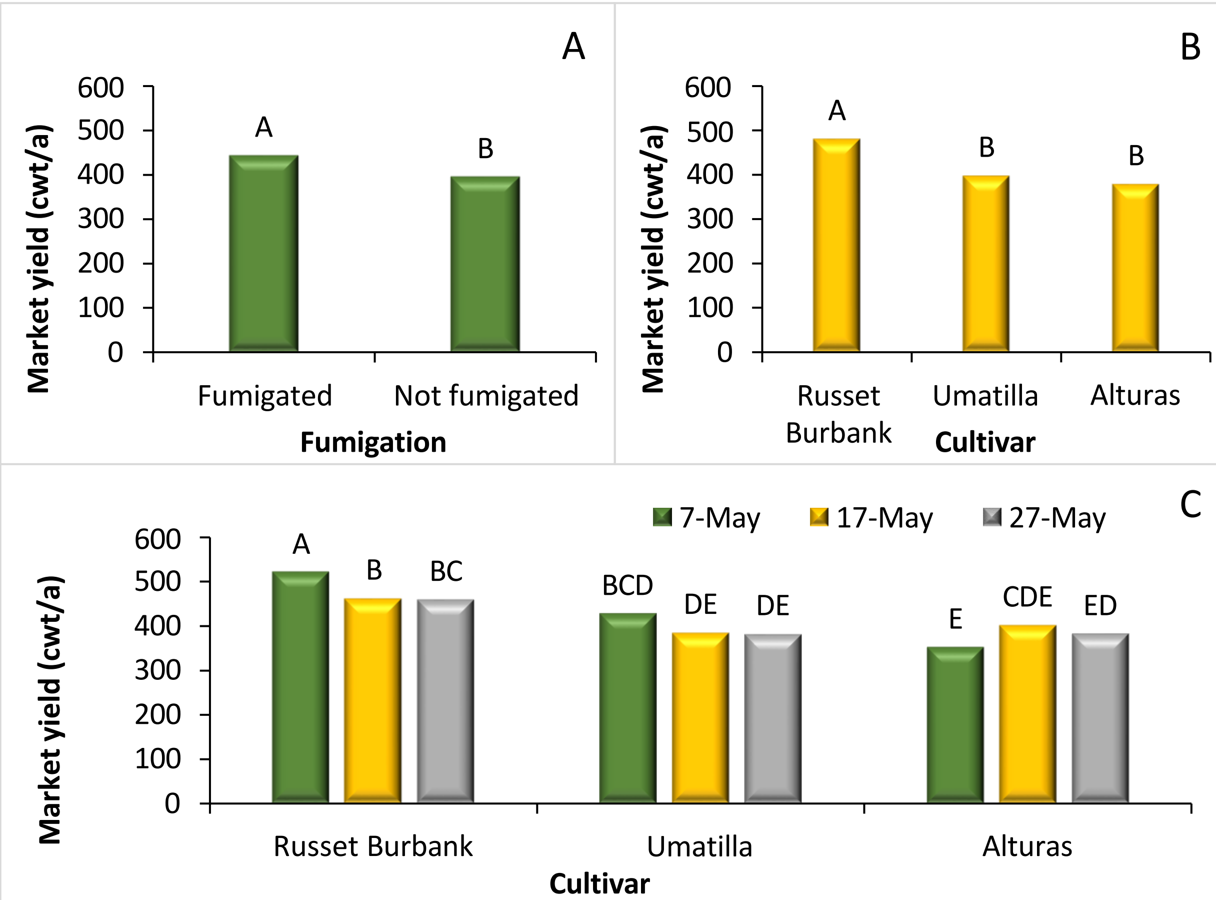

Figure 5. Market yield for the trial conducted in 2022 to evaluate the effect of planting date on Verticillium wilt in three potato cultivars. The main effects of fumigation (A) and cultivar (B) were significant. The interaction between planting date and cultivar was also significant (C). Columns with the same letters are not significantly different.

Gross return per acre was calculated based on a processor contract (Table 3). Grower return was affected by cultivar, planting date and fumigation, with reductions in gross returns coming with lack of fumigation and to some degree planting date, depending on cultivar (Fig. 6). Within cultivars, only planting Russet Burbank early into fumigated plots provided a significantly higher return than other treatments.

Table 3. Yield, USDA grade and grower return for the 2021 trial conducted near Park Rapids, MN evaluating the effect of planting date, cultivar, and fumigation on the effects of Verticillium wilt caused by *V. dahliae* .

Trt	Cultivar	Planting Date	Treatment	Total Yield (cwt/a)	Market Yield (cwt/a)	10 oz. & over (%)			6 - 9 oz. (%)			>6 oz. (%)	4 - 6 oz (%)			Unusables (%)				Specific Gravity	Adjusted price ($/cwt)	Gross $ / acre
						US No. 1	US No. 2	Total	US No. 1	US No. 2	Total	Total	US No. 1	US No. 2	Total	Total	Under-size	Hollow Heart	Other			
501	Russet Burbank	7-May	Vapam	640.6	584.1	26.9	2.0	29.0	36.3	3.3	39.6	68.6	20.6	2.0	22.6	8.8	2.5	3.2	3.2	1.084	11.7	6809.4
502	Umatilla Russet	7-May	Vapam	540.9	437.0	11.7	1.0	12.7	30.8	4.2	34.9	47.7	29.2	3.9	33.1	19.2	6.8	2.9	9.6	1.095	10.5	4603.9
503	Alturas Russet	7-May	Vapam	496.7	361.0	10.4	2.3	12.8	22.6	6.3	28.8	41.6	26.6	4.5	31.1	27.3	8.7	10.9	7.7	1.088	10.3	3709.8
504	Russet Burbank	17-May	Vapam	566.9	481.2	5.6	0.9	6.5	27.3	2.2	29.5	36.0	46.4	2.2	48.6	15.4	10.1	2.4	2.9	1.083	10.7	5144.1
505	Umatilla Russet	17-May	Vapam	521.7	407.1	5.9	0.8	6.7	21.0	2.1	23.1	29.8	45.1	3.1	48.2	22.0	15.7	0.4	6.0	1.091	10.6	4332.8
506	Alturas Russet	17-May	Vapam	514.7	423.4	11.0	1.4	12.5	26.3	6.6	33.0	45.4	30.6	6.1	36.8	17.8	10.0	3.0	4.8	1.077	10.6	4491.6
507	Russet Burbank	27-May	Vapam	576.5	478.6	4.3	0.0	4.3	25.9	1.8	27.7	32.0	48.6	2.4	51.0	17.0	12.0	1.8	3.3	1.084	10.7	5099.8
508	Umatilla Russet	27-May	Vapam	517.0	400.8	3.3	0.8	4.0	25.3	2.4	27.7	31.7	41.8	4.0	45.8	22.5	15.8	2.4	4.2	1.092	10.6	4245.5
509	Alturas Russet	27-May	Vapam	513.8	413.3	7.3	0.7	8.0	30.7	2.0	32.6	40.6	35.3	4.4	39.7	19.7	9.5	6.0	4.2	1.085	10.6	4389.4
510	Russet Burbank	7-May	No Vapam	539.6	458.2	16.8	1.8	18.6	35.8	1.0	36.8	55.4	27.7	1.6	29.3	15.3	5.4	4.7	5.3	1.078	10.9	4995.2
511	Umatilla Russet	7-May	No Vapam	503.9	418.3	7.3	0.9	8.2	27.2	2.3	29.5	37.7	42.0	3.3	45.3	17.0	12.6	0.0	4.3	1.092	10.8	4527.0
512	Alturas Russet	7-May	No Vapam	468.8	342.2	6.4	0.8	7.2	29.1	2.0	31.1	38.3	31.2	3.3	34.5	27.2	11.1	9.2	6.9	1.083	10.2	3493.6
513	Russet Burbank	17-May	No Vapam	537.1	442.7	6.7	0.4	7.1	26.9	0.9	27.8	34.9	44.5	2.9	47.5	17.6	11.0	3.0	3.7	1.083	10.6	4702.1
514	Umatilla Russet	17-May	No Vapam	478.1	362.5	4.3	0.5	4.9	24.2	2.3	26.5	31.4	41.1	3.3	44.4	24.2	18.5	2.3	3.4	1.094	10.5	3819.7
515	Alturas Russet	17-May	No Vapam	522.9	381.0	8.8	0.8	9.6	26.1	4.1	30.3	39.8	28.2	4.4	32.5	27.6	10.7	10.8	6.1	1.084	10.2	3892.3
516	Russet Burbank	27-May	No Vapam	547.0	438.8	2.0	0.0	2.0	28.1	1.2	29.3	31.3	47.4	1.5	48.9	19.8	12.7	5.1	2.0	1.085	10.7	4688.8
517	Umatilla Russet	27-May	No Vapam	479.9	360.7	3.1	0.8	3.8	23.3	2.4	25.7	29.5	41.0	4.5	45.5	24.9	14.3	7.6	3.0	1.094	10.3	3708.9
518	Alturas Russet	27-May	No Vapam	479.9	351.3	2.9	0.0	2.9	27.4	3.7	31.1	34.0	35.0	4.0	38.9	27.1	9.8	13.3	4.0	1.083	10.2	3576.6

Stastical notes: Glimmix was run, therefore Lsmeans were used for mean separation

Since this is a split plot and more than one sources of error could be significant, single P values could not be presented in the table

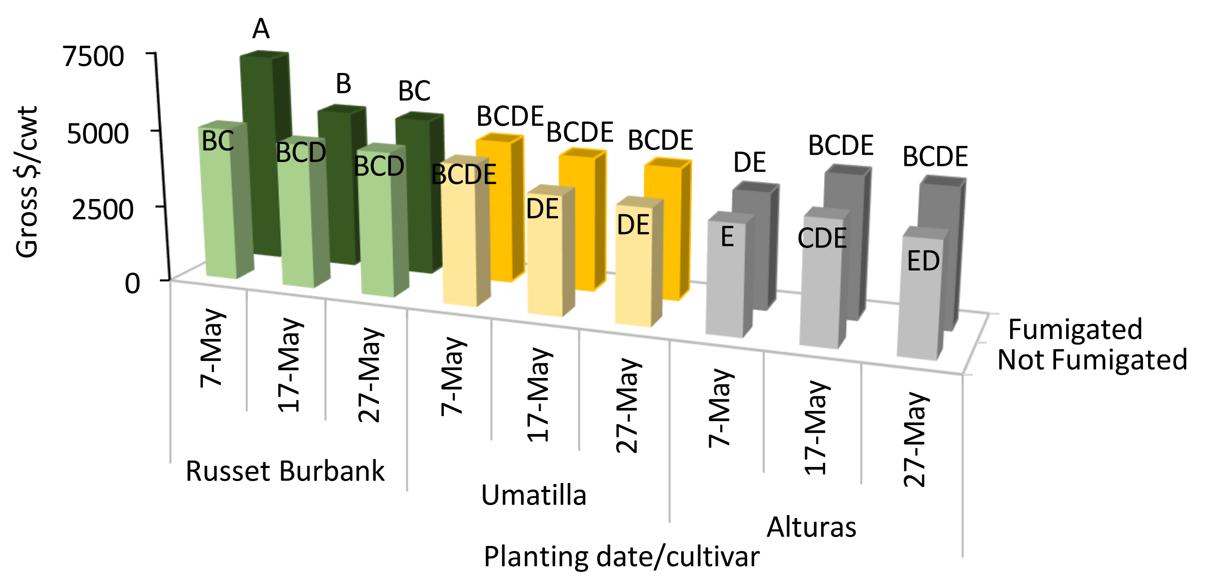

Figure 6. Gross return ($) per acre for the trial conducted in 2022 to evaluate the effect of planting date on Verticillium wilt in three potato cultivars. The interaction of planting date, cultivar, and fumigation was significant. Columns with the same letters are not significantly different. The main effects (fumigation, planting date, and cultivar) and the interaction between planting date and cultivar were significant (data not shown).

It was not part of the original objective to evaluate colonization of stems by the black dot pathogen *C. coccodes*; however, we have developed protocols which require only modest increases in resources to include both pathogens. Therefore, colonization of stem tissue was evaluated for both *V. dahliae* and *C. coccodes*. The main effects of fumigation, planting date and cultivar all significantly affected the colonization of stem tissue by *V. dahliae* (Fig. 7). Additionally, the interaction of fumigation by cultivar, and planting date by cultivar were significant. For Russet Burbank, *V. dahliae* colonization was lower in fumigated plots and higher as planting was delayed. Colonization of Umatilla and Alturas by *V. dahliae* was not affected by fumigation. Umatilla was colonized at higher levels at the May 17 and 27 planting dates when compared to planting on May 7. Colonization by *C. coccodes* was not affected by fumigation, but planting date and cultivar did have an effect. Similar to *V. dahliae* colonization, *C. coccodes* increased as planting was delayed. Umatilla was significantly more susceptible to *C. ccocodes* than the other two cultivars and Russet Burbank was more susceptible that Alturas. Additionally, there was a significant effect of planting date by cultivar, where delaying planting increased the pathogen significantly in Russet Burbank and Umatilla, but not Alturas.

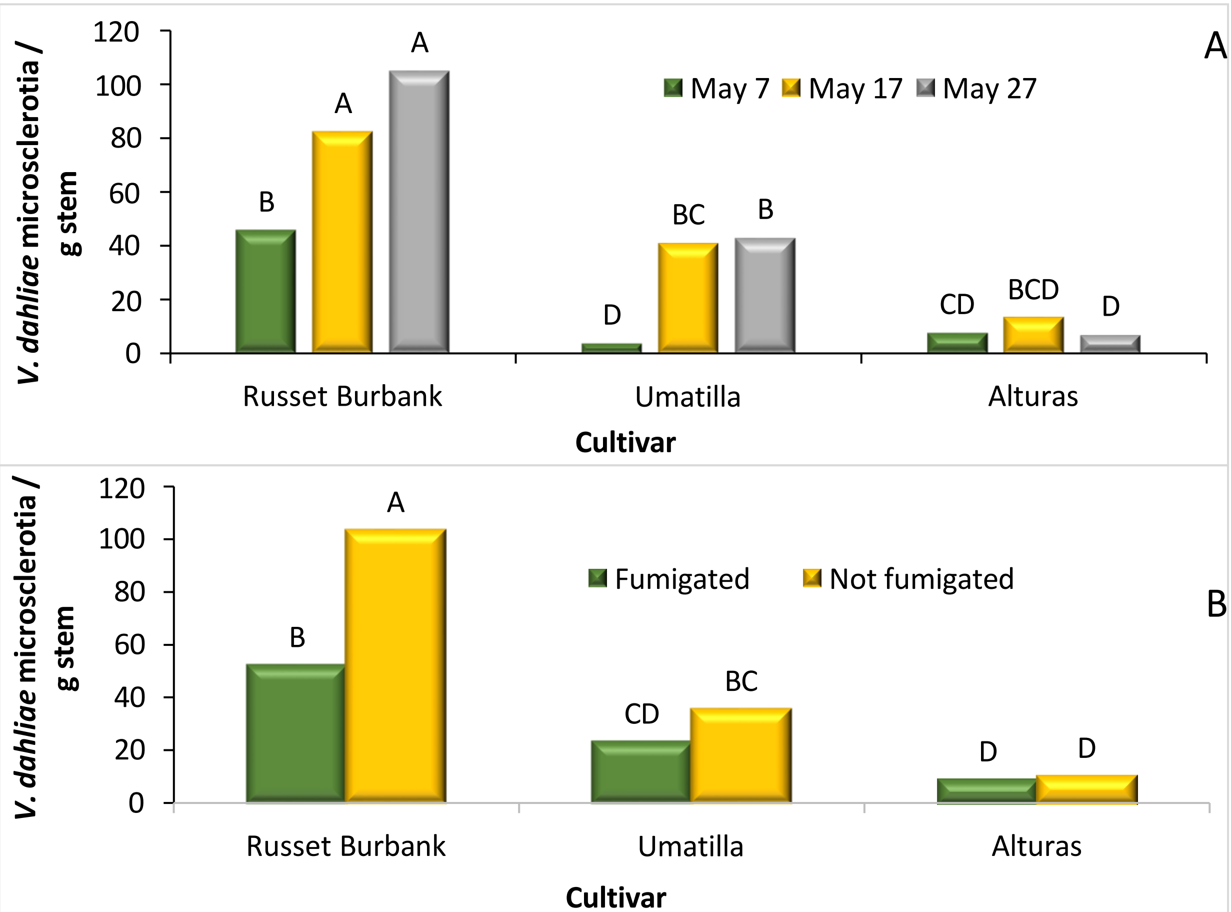

Figure 7. Colonization of stem tissue by *Verticillium dahliae* for the trial conducted in 2022 to evaluate the effect of planting date on Verticillium wilt in three potato cultivars. The interaction of planting date by cultivar (A), and fumigation by cultivar (B) were significant. Columns with the same letters are not significantly different. The main effects (fumigation, planting date, and cultivar) were significant (data not shown).

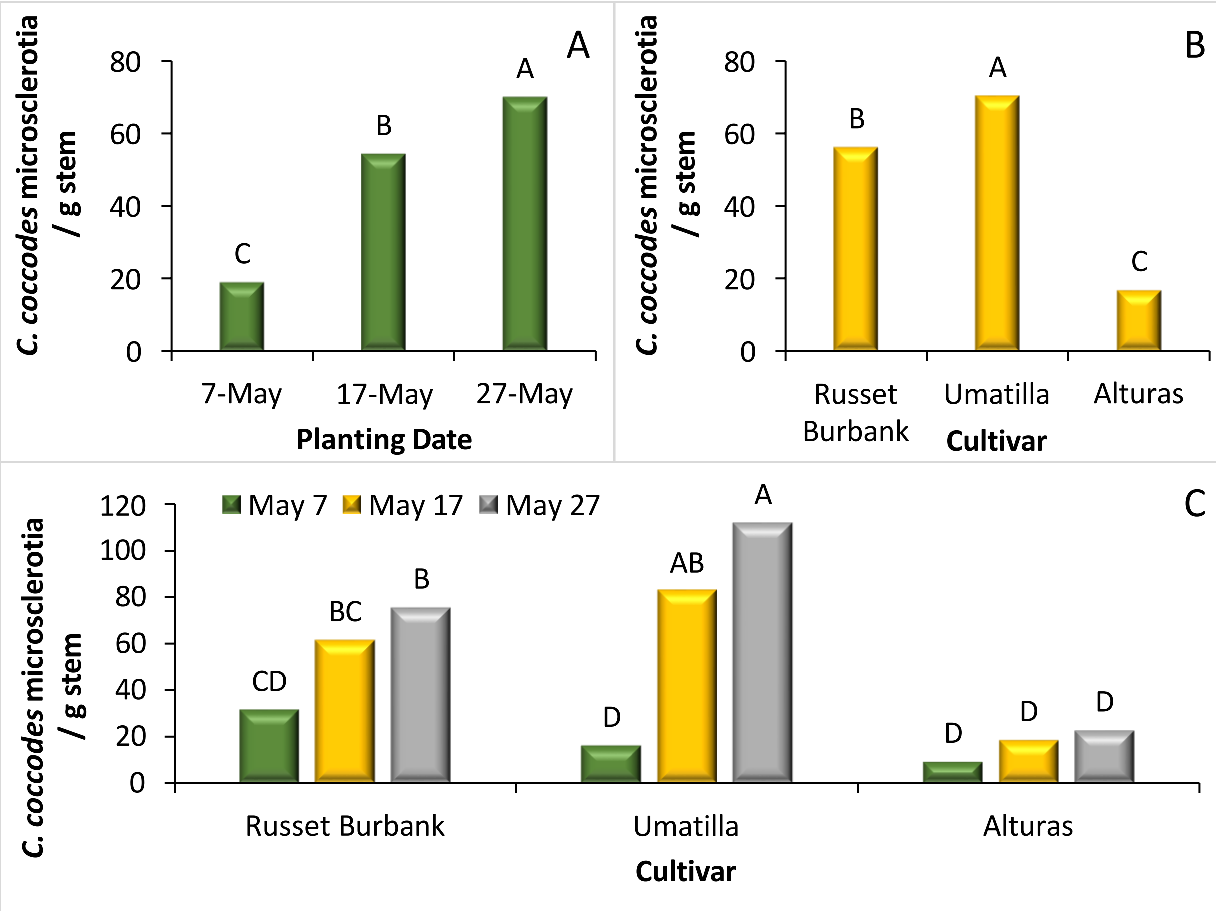

Figure 8. Colonization of stem tissue by *Colletotrichum coccodes* for the trial conducted in 2022 to evaluate the effect of planting date on Verticillium wilt in three potato cultivars. The interaction of planting date by cultivar (A), and fumigation by cultivar (B) were significant. Columns with the same letters are not significantly different. The main effects (fumigation, planting date, and cultivar) were significant (data not shown).

Conclusions

Results of this trial illustrate the risks of lower yields resulting from adjusting planting date. Some reductions in visual Verticillium wilt were observed as planting was delayed, but these were not significant within cultivar. In the trial results reported in 2020, the reductions in yield was noted in the later planning date at 6/3, which was not a good trade-off for the Verticillium reductions. Therefore, we moved planting dates earlier in 2021 to determine if there is a point at which these two factors may balance. However, the result of 2021 trials indicated that even planting at 5/21 instead of 6/3 resulted in a lower yield compared to early planting in April. This is important to note that early dying of the plants due to the extreme heat and bacterial vine rot damage have affected Verticillium wilt development and yield where in absence of those factors the pressure of the disease would have been higher and the results might have been different. Low visual disease incidence in 2020 and 2021 due to environmental extremes was a limiting factor in these experiments. Higher disease was observed in 2022, even in the short growing season. Similar trends were observed across years where yield reductions were recorded, particularly in Russet Burbank. This is our first direct comparison between colonization by *V. dahliae* and *C. coccodes* in replicated field trials. These results provide an excellent framework for expanding our understanding of *C. coccodes* colonization. An intensive, combined analysis of data from all three trial-years will facilitate a greater understanding of the effect of planting date on pathogen colonization. Grower recommendations will be prepared upon final analyses of the data combined across all three trials.

Supplemental Table 1. Agronomic information for the trial conducted to evaluate the effect of planting date on the effects of Veticillium wilt.	
Objective:	To determine the effect of planting date on the development of Verticillium wilt in three russet-skinned cultivars.
Location:	Fisher South - Park Rapids, MN
Plot design:	4 rows × 25 feet × 4 replicates; RCBD; split-plot arrangement. Data taken from the center two rows.
Fumigation date:	November 1, 2021
Fumigant rate:	Vapam @ 40 gpa
Post-fume soil sample	August 5, 2022
Post-fume soil vppg:	Rep 1 Fumigated 14 vppg Rep 1 Non-fumigated 26 vppg
	Rep 2 Fumigated 8 vppg Rep 2 Non-fumigated 22 vppg
	Rep 3 Fumigated 18 vppg Rep 3 Non-fumigated 32 vppg
	Rep 4 Fumigated 10 vppg Rep 4 Non-fumigated 30 vppg
Planting dates:	May 7, May 17, May 27
Row width:	36 inches
Seed spacing:	14 inches
Cultivars:	Russet Burbank, Umatilla Russet, Alturas Russet
In-furrow insecticide:	Platinum (8 fl oz/a); IF at plant
In-furrow fungicide:	Ridomil (6.1 fl oz/a) + Quardris (11.6 fl oz/a)
Herbicide:	
Fertilizer:	Performed by cooperator as applicable for a commercial crop.
Insecticide:	
Fungicide :	
Stem sample date:	September 9, September 20 and September 27, five plants/row sampled.
Vinekill dates:	Rotobeat; September 28
Harvest:	October 3 - 4
Grade:	November 3 - 4
	USDA, Park Rapids, Mn

Can Herbicide Injury be Reversed?

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Executive summary
Herbicide injury continues to be problematic for potato growers. Glyphosate injury has been a constant issue as it is sprayed on corn, soybean, and sugarbeets fields near potato fields. Additionally, the use of dicamba in soybean through late June has caused major problems in potato fields the past few years. When potato plants and tubers are injured from drifting, volatilization, or movement of herbicides in unexpected ways, significant injury to potato plants and tubers can occur. Several products are commercially available that claim to improve plant health or recover plants exposed to herbicides. However, there is little if any scientific data on these products to determine if they are improving plant recovery after being exposed to herbicides. The objective of this project was to determine if plant recovery can be improved following herbicide exposure. This study did not provide good results as the imazamox was applied at too high of a rate and the dicamba was applied at too low of a rate. Future work will adjust herbicide rates to simulate carryover and drift more appropriately.

Procedures
A field study was established at Inkster, ND in a randomized complete block design with four replicates. Plots were planted on 9 June 2022 with Umatilla Russet. Treatments will included Reclaim, Invigorate, and X-Cyte. Herbicide treatments included two herbicides that commonly the cause of injury on potatoes applied at a low dose of the maximum labelled use rate. Greenhouse studies were conducted to help determine the correct rate to apply. These herbicides are imazamox (Raptor) soil incorporated and dicamba applied at tuber initiation. Reclaim is an enzyme, Invigorate is a microbial complex, and X-Cyte is a growth regulator. Testing different types of products will provide understanding if one type has an advantage. Imazamox was applied at 1 oz/a on 8 June 2022 and rototilled in to about 4 inches to incorporate the herbicide. Dicamba was applied as a foliar spray on 29 July 2022 near tuber initiation. Plots were vine killed on 9 September and harvested on 13 September. Tubers were graded according to USDA grading standards for size on 23 November 2022. Specific gravity was measured the same day as grading.

Treatments

1. Non-treated
2. Imazamox (soil incorporated) at 1 pt/a
3. Imazamox (soil incorporated) at 1 pt/a + Reclaim at 1 qt/a PPI + Reclaim at 1 qt/a at 3 weeks after emergence
4. Imazamox (soil incorporated) at 1 pt/a + Invigorate 1 gal/a PPI + Invigorate 1 gal/a at 3 weeks after emergence
5. Imazamox (soil incorporated) at 1 pt/a + X-Cyte 1 pt/a PPI + X-Cyte 1 pt/a at 3 weeks after emergence
6. Dicamba (tuber initiation) at 2.8 oz/a
7. Dicamba (tuber initiation) at 2.8 oz/a + Reclaim at 1 qt/a 1 DAT + Reclaim at 1 qt/a at 3 WAT
8. Dicamba (tuber initiation) at 2.8 oz/a + Invigorate 1 gal/a 1 DAT + Invigorate 1 gal/a at 3 WAT
9. Dicamba (tuber initiation) at 2.8 oz/a + X-Cyte 1 pt/a 1 DAT + X-Cyte 1 pt/a at 3 WAT
10. Dicamba (tuber initiation) at 2.8 oz/a + Reclaim at 1 qt/a 7 DAT + Reclaim at 1 qt/a at 3 WAT
11. Dicamba (tuber initiation) at 2.8 oz/a + Invigorate 1 gal/a 7 DAT + Invigorate 1 gal/a at 3 WAT
12. Dicamba (tuber initiation) at 2.8 oz/a + X-Cyte 1 pt/a 7 DAT + X-Cyte 1 pt/a at 3 WAT

Results
No differences existed for stand and stem number. The rate of imazamox was too high and plants were stunted for the entire growing season (Figure 1). As a result, the yield data from these plots was the lowest compared to the other treatments (Table 1). What was interesting at such a high rate of herbicide, the total yield was numerically less with any additional treatments compared to the imazamox treatment alone. For the dicamba treatments there were no statistical differences among treatments, expect in specific gravity. An analysis was conducted comparing dicamba treatments without the imazamox treatment and a similar result occurred. As expected, the non-treated plot had the numerically highest yield.

Figure 1. Imazamox rate was too high for any additives to help.

Table 1. Yield of Umatilla Russet potatoes treated with herbicide and herbicide recovery options in Inkster, ND 2022.

	Treatment	Total yield		Total marketable		US No 1		US No 2		>6 oz		>10 oz		Specific gravity	
		cwt/a								%					
1	Non-treated check	432	a	421	a	412	a	145	abc	79	ab	41	ab	1.080	a
2	Imazamox 1 pt/a PRE	110	b	104	b	90	b	236	a	75	ab	46	ab	1.074	ab
3	Imazamox 1 pt/a PRE + Reclaim 1 qt/a PPI + Reclaim 1 qt/a 3 WAE	56	b	51	b	37	b	217	a	64	b	25	b	1.070	ab
4	Imazamox 1 pt/a PRE + Invigorate 1 gal/a PPI + Invigorate 1 gal/a 3 WAE	61	b	57	b	46	b	174	ab	83	a	55	a	1.075	ab
5	Imazamox 1 pt/a PRE + X-Cyte 1 pt/a PPI + X-Cyte 1 pt/a 3 WAE	75	b	69	b	54	b	239	a	66	b	34	ab	1.070	ab
6	Dicamba 2.8 oz/a TI	402	a	389	a	381	a	134	abc	75	ab	34	ab	1.067	b
7	Dicamba 2.8 oz/a TI + Reclaim 1 qt/a 1 DAT + Reclaim 1 qt/a 3 WAT	379	a	365	a	361	a	60	bc	67	ab	26	b	1.074	ab
8	Dicamba 2.8 oz/a TI + Invigorate 1 gal/a 1 DAT + Invigorate 1 gal/a 3 WAT	412	a	399	a	391	a	117	abc	77	ab	40	ab	1.071	ab
9	Dicamba 2.8 oz/a TI + X-Cyte 1 pt/a 1 DAT + X-Cyte 1 pt/a 3 WAT	386	a	375	a	372	a	49	bc	74	ab	29	b	1.073	ab
10	Dicamba 2.8 oz/a TI + Reclaim 1 qt/a 7 DAT + Reclaim 1 qt/a 3 WAT	420	a	406	a	404	a	40	c	75	ab	33	ab	1.075	ab
11	Dicamba 2.8 oz/a TI + Invigorate 1 gal/a 7 DAT + Invigorate 1 gal/a 3 WAT	401	a	389	a	382	a	111	abc	71	ab	35	ab	1.074	ab
12	Dicamba 2.8 oz/a TI + X-Cyte 1 pt/a 7 DAT + X-Cyte 1 pt/a 3 WAT	391	a	374	a	366	a	120	abc	71	ab	33	ab	1.080	a

Agronomic performance and storability of Red- and Yellow-Skinned Potatoes

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Executive summary
As consumption of potato cultivars continues to increase, so has the demand for high-quality yellow and red potatoes enlarged. The challenge has been that most yellow-skinned and some red-skinned cultivars come from out-of-state locations and were not bred for a North Dakota/Minnesota environment. An example is some European cultivars tend to express heat-stress in tubers by chaining tubers or causing dumbbell or pointed tubers when they are grown in our environment (the European environment is typically cooler). Or other cultivars are great producers under irrigation but struggle with water stress.

Understanding the performance of new red- and yellow-skinned potato clones grown in the Red River Valley is important for fresh potato growers to stay competitive in the fresh market. With new varieties being released from public and private breeding programs it is important to evaluate these clones to understand their performance in the Red River Valley. The purpose of this work was to evaluate 8 red-skinned and 18 yellow-skinned potato clones for their agronomic performance in the field and in storage. This trial had problems with the soil being too salty and compacted. The data are too variable to provide any good information for growers and will not be shown to prevent misinterpretation of bad data.

Procedures
A randomized complete block, with each treatment replicated four times was established near Hoople, ND in a commercial field grown by JG Halls and Sons. Each cultivar was planted on June 21, 2022 in a single row of 30-feet at 9-inch with-in-row spacing. Typical agronomic practices for Red Norland production occurred, keeping the nitrogen near 120 lb/a. Field measurements included stand count, stem count, and plant height were taken on 25 July 2022. Plots were vine killed on September 5 and 12, 2022 and subsequently harvested on September 26, 2022. Tubers were graded for size using a Kerian Speed Sizer on Decemer 1, 2022. Within a day of harvest, a subsample of potatoes was placed into the pressure bruise chamber to be held for 4 to 5 months. These tubers will be held at 42 F, with 95% relative humidity and an airflow rate of 1.5 cfm/cwt. Pressure bruise areas will be measured for diameter and number per tuber.

Results
Emergence of potato plants was slow. We though this might have been caused by late planting, heat, and low soil moisture. However, as the season progressed it was evident that something more was occurring as 80% of the plots were extremely slow to reach row closure (Figure 1). While the 20% of plants furthest away from the field edge grew normally and appeared like the growth of the commercial field. Differences were clearly seen in the yield and size of tubers at harvest. It seemed that the plots were in an area of higher salt concentration and compaction. Because of this issue in the soil, the graded data is not presented to prevent confusion on which varieties performed best as the data does not show a fair representation of each variety. However, tubers were collected and placed in a the pressure bruise chamber to see if any reliable data may be discovered from this part of the study.

Figure 1. Photo of red variety trials on August 1, 2022. Plants were slow to grow, while the last two ranges of plots nearly had row closure.

Yield and quality responses of Ivory Russet and Russet Burbank potatoes to P rate, banded P application, soil fumigation, and mycorrhizal inoculation in high-P soils:

year three

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Summary

Potato yield often increases with phosphorus (P) fertilizer application even under high soil-test P conditions, suggesting that potato plants do not take up P efficiently. This may be because potato plants have limited root systems or because they are not efficient at forming mycorrhizal associations, possibly as a side effect of soil fumigants used to control soilborne pathogens. If the limited spread of potato plant root systems limits P uptake, plants receiving a banded application of P should respond as if they had received a broadcast application at a higher rate. If the ability to form mycorrhizae limits P uptake, plants inoculated with mycorrhizal fungi at planting should respond as if they had received P at a higher rate. In addition, if potato plants are able to form mycorrhizae with native soil fungi, and if populations of these fungi are suppressed by soil fumigation, then (1) plants grown in plots fumigated with metam sodium should respond positively to P fertilization at higher rates than plants grown in unfumigated plots because more P is required to maximize yield and (2) plants in fumigated plots should respond more positively to inoculation with mycorrhizal fungi at planting than plants in unfumigated plots. Root system reach, ability to form mycorrhizae, and P use efficiency all potentially vary among cultivars. We conducted an experiment to assess the roles soil fumigation, fertilizer placement, inoculation with mycorrhizal fungi, and potato cultivar play in determining P use efficiency. We used a split-split-plot randomized complete block design with four replicates. Whole plots were defined by fumigation treatment (no fumigant or fall-applied metam sodium) and subplots by cultivar (Ivory Russet or Russet Burbank). Sub-subplots were defined by nine P treatments: five in which P was broadcast-applied as triple super phosphate (TSP) at different rates (0, 75, 150, 300, or 450 lbs/ac P_2O_5), two in which the mycorrhizal product MycoGold Liquid was applied in-furrow at planting and P was broadcast at 0 or 150 lbs/ac P_2O_5, and two in which P was banded at planting at 75 or 150 lbs/ac P_2O_5. Initial soil P concentration in the field was 128-146 ppm Bray and 223-238 ppm Mehlich-3, with a P saturation index (PSI; Mehlich-3 P : Mehlich-3 Al) of 21.4-23.0%. Soil fumigation with metam sodium was effective in reducing the number of *Verticillium* propagules per gram of soil (VPPG). In unfumigated plots, VPPG was higher in subplots with Russet Burbank than Ivory Russet. Total, marketable, and U.S. No. 1 yield increased with P rate in both cultivars, but only in plots fumigated with metam sodium. The yield response to P treatment did not differ significantly between the two cultivars, except that U.S. No. 2 yield decreased with increasing P rate in Russet Burbank and increased with increasing P rate in Ivory Russet. The percentage of Ivory Russet yield in tubers over 6 or 10 ounces increased with P rate, but this was not true of Russet Burbank, suggesting that the yield response of Ivory Russet was due to tuber size while that of Russet Burbank was due to tuber number. Tuber specific gravity increased with P rate and was higher in fumigated plots and in Ivory Russet. Contrary to what would be expected if the availability of mycorrhizal partners limits potato plant P use efficiency, the responses of tuber yield, size, and specific gravity to P rate did not depend on whether the soil was fumigated with metam sodium, nor did applying a mycorrhizal product improve these metrics.

Background

Potato yield often increases in response to phosphorus (P) fertilizer application even at high soil-test P. This is especially true in acidic, irrigated soils, where yield responses have been observed at Bray P concentrations of up to 150 ppm. This suggest that potato plants do not take up soil P efficiently. This inefficiency may have two causes, both related to the low mobility of available P in the soil. First, potato plant root systems are not extensive, with few roots extending more than two feet into the soil, limiting the area over which they can access soil P. This issue could be addressed through banded rather than broadcast application of P fertilizer, placing more of the P applied within range of the plants' root systems.

Second, potato plants in agricultural systems may lack mycorrhizal associations, which would improve the plant's ability to access what P is available within reach of their root systems. The lack of mycorrhizae, in turn, may occur because the soil lacks mycorrhizal fungi or because potato plants are inefficient at forming mycorrhizae efficiently even when potential partners are available. In either case, applying mycorrhizal fungi to the soil can be expected to improve P uptake efficiency and tuber yield. Consistent with this expectation, previous studies have found that inoculation with arbuscular mycorrhizal fungi can improve potato plant vigor and yield. Both the extensiveness of potato plant root systems and their efficiency at forming mycorrhizae are likely to depend on plant genetics. Thus, different cultivars of potato plants may be expected to differ in their abilities to exploit available P in the soil and in their responsiveness to banded P application and inoculation of seed with mycorrhizal fungi. Our previous research at the Sand Plain Research Farm in Becker, MN, has indicated that the cultivars Russet Burbank and Ivory Russet have different responses to the application rate of P.

If efficiency in forming mycorrhizal associations limits P uptake in potato plants, soil fumigation might be expected to decrease P use efficiency, if it decreases native populations of mycorrhizal fungi. This effect might be masked by the overall positive effects of fumigation on plant health through the suppression of soil borne pathogens, but its presence may be indicated by a stronger response (e.g., in terms of yield or P uptake) to inoculation with mycorrhizal fungi in fumigated soils than in unfumigated soils.

Bray P concentration does not account for the potential for soluble aluminum (Al) in the soil to fix available P, making it no longer available for plants. This issue tends to become more significant at lower soil pH, as Al becomes more soluble at low pH. Research in Eastern Canada has found that a P saturation index (PSI: Melich-3 P / Melich-3 Al * 100) may be a better indicator of the potential for plants to respond to P fertilization in lower pH soils. The researchers suggest threshold PSI values (19.2% where pH < 5.5 and 14.2% where pH > 5.5) above which P fertilization should be limited to crop requirements in order to reduce P fixation.

The objectives of this study, which is in its third year, are to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying MycoGold Liquid (MycoGold LLC), a mycorrhizal product, in-furrow at planting, and (4) banded versus broadcast application of P fertilizer. These results will be considered in the context of the site's PSI, Bray P, and Mehlich-3 P.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2022 on a Hubbard loamy sand soil. The previous crop was soybeans. A split-split plot randomized complete block design was deployed, with whole plots defined by fumigation treatment, subplots by potato cultivar, and sub-subplots by P application treatment. The fumigation treatments were (1) no fumigation and (2) fumigation with metam sodium the fall before planting. The cultivars used were Russet Burbank and Ivory Russet. The nine P treatments were as follows: (1) a check treatment receiving no P; four treatments receiving (2) 75, (3) 150, (4) 300, or (5) 450 lbs/ac P_2O_5 as triple super phosphate (TSP; 0-45-0-15Ca) broadcast before planting; two treatments inoculated in-furrow with the mycorrhizal product MycoGold Liquid at planting and receiving either (6) zero or (7) 150 lbs/ac P_2O_5 as TSP broadcast before planting; and two treatments receiving either (8) 75 or (9) 150 lbs/ac P_2O_5 as TSP banded at planting. A summary of the P treatments is presented in Table 1.

Soil tests

Soil samples to a depth of six inches were taken from each whole plot in each block on April 22, 2022. These samples were analyzed for Bray P; Melich-3 P, Al, Ca, Mg, Mn, Fe, Zn, and Cu; pH; loss-on-ignition organic matter content; ammonium-acetate-extractable K; hot-water-extractable B; and calcium-phosphate-extractable SO_4^{2-}-S. Samples to a depth of two feet were collected at the same time. These were analyzed for NH_4^+-N and NO_3^--N using a Wescan Nitrogen Analyzer. Results are presented in Table 2.

On July 13, a second set of six-inch soil samples was collected from each half of the field (blocks 1 and 2 in one half and blocks 3 and 4 in the other) and each combination of fumigation treatment and cultivar. These samples were sent fresh to Allied Cooperative (Plainfield, WI) and analyzed for *Verticillium* propagules and root lesion nematodes.

Treatment applications

Metam sodium was shank-injected into the soil in the appropriate plots at a rate of 50 gal/ac on October 20, 2021. The field was irrigated immediately after fumigant application.

On April 25, 2022, 200 lbs/ac MOP (0-0-60) and 200 lbs/ac SulPoMag (0-0-22-21S-11Mg) were broadcast applied to the entire field, providing 164 lbs/ac K_2O equivalent, 42 lbs/ac S, and 22 lbs/ac Mg. TSP was broadcast applied by hand to treatments 2 through 5 and 7. The field was cultivated on April 26 to incorporate the fertilizer.

A mixture of whole and cut 3-ounce seed tubers were planted by hand on May 3 (blocks 1 and 2) and 4 (blocks 3 and 4). Rows were spaced 36 inches apart and tubers were paced twelve inches apart within rows. Each sub-subplot comprised four, 20-foot rows, in which the central 18 feet of the middle two rows were eventually used for harvest samples. Each block was surrounded by a three-foot buffer of additional tubers to reduce field edge effects. After all tubers were placed on each planting day, MycoGold Liquid was applied in-furrow per the manufacturer's directions to treatments 6 and 7. Rows were closed by machine on the day they were planted. TSP was mechanically banded in treatments 8 and 9 at this time. In addition, a blend of 87 lbs/ac urea (46-0-0), 233 lbs/ac MOP, 191 lbs/ac SulPoMag, 2.8 lbs/ac $ZnSO_4$ (35.5% Zn, 17.5% S), and 3.3 lbs/ac Boron 15 (15% B) was banded into all rows, supplying 40 lbs/ac N, 180 lbs/ac K_2O, 40 lbs/ac S, 21 lbs/ac Mg, 1 lb/ac Zn, and 0.5 lbs/ac B.

Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris, and the rows were closed by machine. Weeds, diseases, and insects were controlled using standard practices.

Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling. Rainfall and irrigation amounts are presented in Figure 1.

All treatments received 150 lbs/ac N as ESN (44-0-0, Nutrien, Ltd.) and 60 lbs/ac N as urea mechanically side dressed and then hilled in on May 23, so that 250 lbs/ac N were applied in total.

Petiole sampling

Petioles were collected from each sub-subplot on June 23 and July 7 and 21. The petiole of the fourth mature leaf from the shoot tip was collected from 30 leaves per plot. Petioles were dried at 140°F until their weight was stable and then ground. The ground samples were sent to Agvise Laboratories (Benson, MN) and analyzed for NO_3^--N using a FIALab Fialyzer 1000 Nitrate Analyzer and for P concentration by inductively coupled plasma-mass spectrometry.

Harvest

Vines were chopped with a flail mower on September 15. Tubers were machine-harvested from the central 18 feet of the middle two rows of each plot on September 22. These harvest samples were sorted and graded by machine between September 26 and October 3. A 25-tuber subsample was taken from each harvest sample and assessed for hollow heart, brown center, common scab, specific gravity, and dry matter content. End-of-season soil samples to a depth of 6 inches were collected from each sub-subplot on October 7 to be analyzed for pH and Melich-3 Al and P.

Statistical analyses

Analyses were performed using SAS 9.4 software. Response variables were analyzed as functions of fumigation treatment, cultivar, P treatment, their interactions, block, fumigant*block (whole plot), and fumigant*cultivar*block (subplot), all as fixed effects, using the GLIMMIX procedure. When the effects of fumigation, cultivar, P treatment, or their interactions were significant ($P \leq 0.10$), pairwise comparisons were evaluated using Fisher's LSD using the DIFF option in the LSMEANS statement of the model. Values were considered significantly different if $P \leq 0.10$. Five comparisons among treatments were made using CONTRAST statements. Treatments 1 – 5 were compared in (1) a check-versus-P comparison and (2) linear and (3) quadratic contrasts on the application rate of P; (4) treatments 1 and 3 were compared with treatments 6 and 7 to evaluate the effect of adding mycorrhizae; and (5) treatments 2 and 3 were compared with treatments 8 and 9 to evaluate the effect of broadcast versus banded P application.

Results

Soil <u>Verticillium</u> propagules and root lesion nematodes

Results for soil *Verticillium* propagule population density and root lesion nematode abundance are presented in Table 3. Root lesion nematodes were not detected in any subplot. *Verticillium* propagule density was higher in unfumigated plots than in plots fumigated with metam sodium. Among unfumigated plots, but not the fumigated plots, propagule concentrations were higher in Russet Burbank subplots than Ivory Russet subplots.

Tuber yield

Results for tuber yield are presented in Table 4.

Overall, total and marketable yields, yields of U.S. No. 1 tubers, and the percentages of total yield in tubers over 6 and 10 ounces were higher in plots to which metam sodium had been applied than in unfumigated plots.

Russet Burbank had higher total, U.S. No. 1, U.S. No. 2, and total marketable yield than Ivory Russet, while Ivory Russet had higher percentages of its total yield in tubers over 6 and 10 ounces than Russet Burbank.

The effect of the interaction between fumigation treatment and cultivar on tuber yield and size was significant. While both cultivars showed positive yield responses to metam sodium application, the effect was much more pronounced in Russet Burbank than in Ivory Russet. Russet Burbank also showed a positive response to fumigation in the percentage of total yield represented by tubers over six or ten ounces, while Ivory Russet showed no response of tuber size distribution to fumigation treatment.

Tuber yield and size also responded to P treatment. Based on contrasts, total yield, the yield of U.S No. 1 tubers, and marketable yield increased linearly with the application rate of P. Yields tended to be lower, overall, in treatments receiving MycoGold Liquid (treatments 6 and 7) than in similar treatments receiving no supplemental mycorrhizae (treatments 1 and 3). Based on pairwise comparisons, this difference was only significant when no P was applied (treatment 1 vs. 6). Based on contrasts, total yield was marginally significantly higher in treatments with banded P application (treatments 8 and 9) than corresponding treatments with broadcast P application (treatments 2 and 3), but the difference was not significant in pairwise comparisons.

The percentage of yield in tubers over ten ounces increased linearly with the application rate of P. This relationship was weaker, but still present, for the percentage of yield in tubers over six ounces. Percentages of yield in tubers over six and ten ounces were significantly lower in treatments receiving mycorrhizae (treatments 6 and 7) than in similar treatments receiving no supplemental mycorrhizae (treatments 1 and 3), but in pairwise comparisons, these differences were only significant when no P fertilizer was applied (treatment 1 vs. 6).

The effect of the interaction between fumigation treatment and P treatment was significant for total yield, marketable yield (Figure 2), and the yield of U.S. No. 1 tubers. In plots fumigated with metam sodium, yields in sub-subplots that received P at rates of 300 or 450 lbs/ac P_2O_5 (treatments 4 and 5) were significantly higher than yields at lower P rates (treatments 1-3). In contrast, P rate had no significant effect on yield in non-fumigated plots. In unfumigated plots, the treatments receiving MycoGold Liquid (treatments 6 & 7) had significantly lower yields than corresponding treatments that did not receive this product (treatments 1 & 3). In plots fumigated with metam sodium, a similar, non-significant trend was seen between the treatments receiving no P fertilizer (treatment 1 vs. 6), but this trend was reversed with P applied at 150 lbs P2O5/ac (treatment 3 vs. 7).

The interaction between cultivar and P treatment was significantly related to the yield of U.S. No. 2 tubers and the percentage of yield represented by tubers over six or ten ounces. The yield of U.S. No. 2

tubers in Russet Burbank generally decreased with P rate across all treatments, while U.S. No. 2 yield in Ivory Russet tended to increase with P rate. The percentage of yield in tubers over six or ten ounces did not show a clear relationship to P rate, application method, or the use of MycoGold Liquid in Russet Burbank, while these percentages increased with P rate and decreased with the use of MycoGold Liquid in Ivory Russet.

The percentages of yield represented by tubers over six or ten ounces were related to the three-way interaction among fumigation treatment, cultivar, and P treatment. This may reflect a stronger negative response to the use of MycoGold Liquid (treatments 6 & 7 compared to 1 & 3) in unfumigated Ivory Russet subplots compared to the other combinations of fumigation treatment and cultivar.

Tuber quality

Results for tuber quality are presented in Table 5.

Hollow heart and brown center strongly tended to co-occur. The prevalence of both conditions was significantly related to fumigation treatment, cultivar, and their interaction. Russet Burbank had a much higher prevalence of both conditions than Ivory Russet in both fumigation treatments, and metam sodium fumigation tended to suppress both conditions in both cultivars. Since the prevalence was so much higher in Russet Burbank, the effect of fumigation on prevalence was also much stronger in this cultivar, being statistically non-significant in Ivory Russet. The prevalence of hollow heart and brown center was also related to the interaction among fumigation treatment, cultivar, and P treatment. In Russet Burbank, among treatments that received neither MycoGold nor banded P (treatments 1-5), prevalence was highest in the absence of P fertilizer in unfumigated plots, but prevalence was highest at the highest P rate in plots fumigated with metam sodium. With the same cultivar, between the two treatments receiving mycorrhizae at planting (treatments 6 and 7), fumigation decreased the prevalence of hollow heart and brown center in the absence of P fertilizer (treatment 6), but not in its presence (treatment 7). In contrast, Ivory Russet showed little effect of fumigation treatment or P treatment on the prevalence of these defects, which was low in all cases.

Ivory Russet tubers showed a significantly higher prevalence of common scab than Russet Burbank tubers, though the condition was uncommon in both cultivars. Among Ivory Russet subplots, the prevalence of common scab was also marginally significantly related to P treatment. Based on contrasts, common scab was more prevalent in the banded treatments (treatments 8 and 9) than in the corresponding broadcast treatments (treatments 2 and 3). It was also less prevalent in treatments receiving broadcast P without MycoGold (treatments 2-5) than in the treatment receiving no P fertilizer or MycoGold (treatment 1).

Tuber specific gravity was higher in Russet Burbank subplots fumigated with metam sodium than in unfumigated subplots, but fumigation treatment had no effect on specific gravity in Ivory Russet. Overall, Ivory Russet had higher tuber specific gravity than Russet Burbank. As a result, the effects of fumigation treatment, cultivar, and their interaction on specific gravity were all significant. The effect of P treatment on tuber specific gravity was also significant, with specific gravity increasing linearly with the application rate of P.

Russet Burbank tuber dry matter content, like specific gravity, was higher in plots fumigated with metam sodium than in unfumigated plots. Dry matter content in Ivory Russet showed the opposite trend, resulting in a significant effect of the fumigant*cultivar interaction. Like specific gravity, dry matter content was higher in Ivory Russet than in Russet Burbank. The main effect of P treatment on dry matter content was not significant, but there was a significant effect of the fumigant*P treatment interaction, as well as the three-way interaction among cultivar, fumigation treatment, and P treatment. Both cultivars had higher dry matter contents in fumigated plots than unfumigated plots when P was broadcast-applied at 300 or 450 lbs/ac P_2O_5 (treatments 4 and 5), but lower dry matter in fumigated plots than unfumigated plots at 75 or 150 lbs/ac P_2O_5 (treatments 2 or 3). When no P was applied, regardless of whether MycoGold was applied (treatments 1 and 6), Russet Burbank had higher dry matter content in fumigated plots than unfumigated plots, while the opposite was true of Ivory Russet.

Tuber specific gravity is used as a proxy metric of tuber dry matter content, and the two variables were positively related in a linear regression treating each sub-subplot as an independent unit ($R^2 = 0.3466$).

Discussion

Consistent with the results of our research in previous seasons, total and marketable tuber yield and the yield of U.S. No. 1 tubers, averaged across the two cultivars, increased with the application rate of P within the range of rates evaluated (0 to 450 lbs/ac P_2O_5). This occurred despite the high Bray P and Melich-3 P concentrations (128-146 $mg \cdot kg^{-1}$ and 223-238 $mg \cdot kg^{-1}$, respectively) at this site and the high PSI (21.4-23.0%). For comparison, an application rate of 75 lbs/ac P_2O_5 is expected to maximize yield when Bray P exceeds 51 ppm, and it is recommended that only enough P be applied to replace crop uptake (about 45 lbs/ac) when PSI exceeds 14.2% in soils with pH over 5.5.

Our previous research, including the results of this study in 2020, suggested that Ivory Russet might be more sensitive to P treatment than Russet Burbank. In 2022, however, the responses of total, marketable, and U.S. No. 1 yield to P treatment did not differ significantly between the two cultivars. The yield of U.S. No. 2 tubers was sensitive to P treatment in both cultivars, but in opposite directions, with Russet Burbank U.S. No. 2 tuber yield tending to decrease and Ivory Russet No. 2 yield tending to increase with increasing P rate. In terms of the percentage of yield represented by tubers over 10 ounces, tuber size in Ivory Russet responded positively to P rate while tuber size in Russet Burbank was not related to P rate. The fact that both cultivars showed a positive total and marketable yield response to P rate while only Ivory Russet showed a tuber size response suggests that Russet Burbank responded to higher P rates by producing more tubers while Ivory Russet responded by producing bigger tubers.

If potato plants are inefficient at taking up P because their root systems are not extensive, limiting the volume of soil in which they can access P, tuber yield would be expected to be higher with banded application than with broadcast application at the same rate. Although there was a tendency for total yield to be higher with banded P application than broadcast application, the difference was not significant in pairwise comparisons. This contrasts with results from 2021 where banded P fertilizer at equivalent rates resulted in higher yields than broadcast applications.

If a lack of mycorrhizae limited the ability of potato plants to access soil P, two patterns would be expected as a result. First, responses to P fertilizer rate should extend to higher P rates in fumigated plots than in unfumigated plots because less P fertilizer should be required to meet plant P requirements if plants are exploiting P more efficiently via native mycorrhizal fungi. Second, applying MycoGold should increase plants' access to available P more effectively in fumigated plots than in unfumigated plots, where native mycorrhizal fungi should be more abundant. Thus, yield responses to MycoGold application should be more positive in plots fumigated with metam sodium than in unfumigated plots. In this field and this year, total and marketable yield were highest at the highest two P rates (300 and 450 lbs/ac P_2O_5) in plots fumigated with metam sodium, but did not respond to P rate in unfumigated plots. This is consistent with the hypothesis that low infection with mycorrhizal fungi limits P use efficiency in fumigated soils. However, it could also indicate that endogenous soil P was sufficient to achieve the maximum yield in unfumigated plots because that maximum was low. Yields in unfumigated plots may have been limited by something other than P availability, such as soilborne pathogen loads. Contrary to expectations, marketable yield was more responsive to the application of MycoGold in unfumigated plots than in fumigated plots, and, at least in the absence of P fertilizer, the yield response to MycoGold was negative. Thus, the effects of mycorrhizal inoculation are unclear.

In terms of both tuber yield and tuber size distribution, Russet Burbank showed a stronger positive response to fumigation with metam sodium than Ivory Russet did (with Ivory Russet showing no significant tuber size response to fumigation treatment). This difference in the yield response to fumigation treatment may reflect the higher midseason abundances of *Verticillium dahliae* propagules in unfumigated Russet Burbank subplots compared to unfumigated Ivory Russet subplots, or it may indicate that potato early dying has a greater impact on Russet Burbank yield, due to that cultivar's longer growing season, than Ivory Russet yield.

P availability and application rate have been found in previous research to potentially limit tuber dry matter content and specific gravity. P fertilization with TSP has also been found to decrease the prevalence and severity of common scab. However, P availability and P fertilization appear to have little effect on the prevalence of hollow heart or brown center.

In this study in 2022, P treatment had little net effect on the prevalence of hollow heart and brown center. However, in Russet Burbank, the prevalence of hollow heart tended to decrease with increasing P rate in plots fumigated with metam sodium, while the relationship was reversed in unfumigated plots. This was not observed in the previous two years of this study, and it is not clear whether these apparently contrasting responses to P rate are biologically meaningful.

The prevalence of common scab was lower in Russet Burbank than Ivory Russet, while soil fumigation had no effect on scab prevalence. Common scab prevalence also appeared to be promoted by banded application of P. We found mixed evidence that fertilization with TSP decreased the prevalence of common scab. On one hand, the mean prevalence of common scab among treatments receiving broadcast-applied P without MycoGold was lower than that of the treatment receiving neither P nor MycoGold. On the other hand, among treatments receiving P, there was no tendency for the prevalence of common scab to decrease as the application rate of P increased.

As expected, tuber specific gravity increased with P rate, whether P was broadcast or banded and whether or not MycoGold was applied. Specific gravity was also higher in fumigated plots than unfumigated plots and in subplots with Ivory Russet than in subplots containing Russet Burbank. The specific gravity response to P treatment was not influenced by soil fumigation or potato cultivar.

Ivory Russet tubers had higher dry matter content than Russet Burbank tubers. Russet Burbank tuber dry matter content was higher in fumigated plots than in unfumigated ones, but dry matter was not related to fumigation treatment in Ivory Russet. Overall, dry matter responded differently to P treatment within each fumigation treatment, but there was no clear pattern to how fumigation affected the P response. It is not clear why dry matter, unlike specific gravity, did not show the expected positive response to P rate, though the two metrics were positively related in this study.

Overall, tuber yield (total, marketable, and U.S. No. 1), size, and specific gravity all responded positively to P rate in this study, primarily when fumigation was used. Response to P rate was less evident under nonfumigated conditions. Russet Burbank appeared to produce this positive yield response through higher tuber set, while Ivory Russet did so more through increased tuber size. The P response of specific gravity did not depend on cultivar. Contrary to our expectations if the availability of mycorrhizal partners limits potato plant P use efficiency, the responses of tuber yield, size, and specific gravity to P rate did not depend on whether the soil was fumigated with metam sodium, nor did applying a mycorrhizal product improve these metrics.

Table 1. The nine phosphorus (P) treatments applied to Russet Burbank and Ivory Russet potatoes in unfumigated and metam-sodium-fumigated plots at the Sand Plain Research Farm in 2022.

Treatment			
Number	P rate (lbs/ac)	Application	Mycorrhizae?[1]
1	0	NA	No
2	75	Broadcast	No
3	150	Broadcast	No
4	300	Broadcast	No
5	450	Broadcast	No
6	0	NA	Yes
7	150	Broadcast	Yes
8	75	Banded	No
9	150	Banded	No

[1]Applied in-furrow at planting with a hand sprayer

Table 2. Initial soil characteristics in the study field.

	0 - 6 inches														0 - 2 feet
Fumigation treatment	Bray P (mg/kg)	Melich-3 P (mg/kg)	Melich-3 Al (mg/kg)	PSI (%)	pH	Organic matter (%)	NH_4OAc-K (mg/kg)	Mehlich-3 Ca (mg/kg)	Mehlich-3 Mg (mg/kg)	Mehlich-3 Mn (mg/kg)	Mehlich-3 Fe (mg/kg)	Mehlich-3 Zn (mg/kg)	Mehlich-3 Cu (mg/kg)	Hot water B (mg/kg)	SO_4^{2-}-S (mg/kg)	NO_3^--N (mg/kg)
Control	128	223	1038	21.4	6.5	2.4	269	1852	350	66	168	8.0	2.4	0.4	11	0.4
Metam sodium	146	238	1033	23.0	6.4	2.1	218	1617	302	59	165	6.6	2.2	0.4	20	

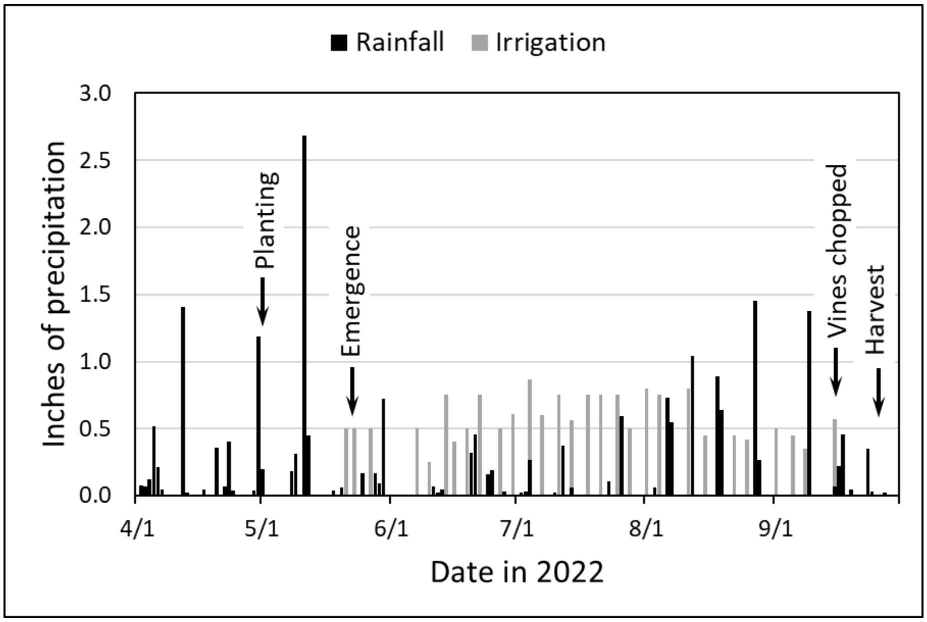

Figure 1. Inches of rainfall and irrigation in the study field in 2022. Irrigation amounts were determined by the checkbook method of irrigation scheduling. Monthly rainfall totals were as follows: April, 4.63 inches; May, 5.08 inches; June, 1.32 inches; July, 1.48 inches; August, 5.64 inches; September, 2.58 inches. Irrigation started on May 21 and ended on September 15. Monthly total irrigation amounts were as follows: May, 1.50 inches; June, 4.25 inches; July, 5.20 inches; August, 3.67 inches; September, 1.80 inches.

Table 3. Abundances of *Verticillium* propagules and root lesion nematodes in the soils of unfumigated plots and plots fumigated with metam sodium, in subplots with either Ivory Russet or Russet Burbank plants.

Fumigant	Cultivar	*Verticillium* propagules / g soil	Root lesion nematodes / 100 cc soil
None	Ivory Russet	16 b	0
	Russet Burbank	33 a	0
Metam sodium	Ivory Russet	7 b	0
	Russet Burbank	8 b	0
ANOVA effects (P-values)	Fumigant	**0.0467**	-
	Cultivar	0.1419	-
	Fumigant*cultivar	0.5133	-

Table 4. Effects of fumigation treatment, cultivar, and P treatment on tuber yield, size, and grade. Within each main effect, values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the main effect the value pertains to (fumigation treatment, cultivar, or P treatment) is significant (P<0.10).

Treatment description						Yield ($CWT \cdot ac^{-1}$)										% yield in tubers over:	
Fumigant	Cultivar	P treatment	P_2O_5 rate	Application	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2	Marketable	6 oz.	10 oz
None	Averaged	Averaged				5.0 a	54	46 b	73 b	53 b	38 b	269 b	175 b	35	210 b	62 b	35 b
Metam sodium						3.6 b	54	50 a	85 a	69 a	50 a	311 a	216 a	27	253 a	66 a	38 a
Averaged	Russet Burbank	Averaged				7.7 a	78 a	61 a	91 a	64 a	40 b	341 a	214 a	42 a	256 a	56 b	30 b
	Ivory Russet					0.8 b	30 b	35 b	67 b	58 b	48 a	238 b	177 b	31 b	207 b	72 a	43 a
Averaged	Averaged	1	0	NA	No	5.9 ab	49	47	77 b	56 bc	43 cde	278 c	182 cd	42	223 c	64 bc	36 bcd
		2	75	Broadcast	No	3.5 c	49	44	76 b	61 b	44 bcd	278 c	190 bc	35	225 c	67 ab	39 ab
		3	150	Broadcast	No	4.8 abc	55	50	79 ab	61 b	45 bcd	295 abc	204 ab	31	234 bc	64 bc	37 bcd
		4	300	Broadcast	No	3.4 c	53	49	81 ab	62 b	52 ab	300 ab	210 ab	34	244 ab	66 ab	39 ab
		5	450	Broadcast	No	4.1 abc	54	43	80 ab	72 a	58 a	311 a	219 a	34	253 a	68 a	42 a
		6	0	NA	Yes	3.2 c	57	49	67 c	49 c	32 f	258 d	162 d	35	197 d	56 d	30 e
		7	150	Broadcast	Yes	3.9 bc	57	52	81 ab	60 b	35 ef	288 bc	192 bc	35	227 c	62 c	33 de
		8	75	Banded	No	3.5 c	56	48	84 ab	64 ab	39 def	294 abc	195 bc	39	235 bc	63 bc	34 cd
		9	150	Banded	No	6.2 a	55	48	86 a	63 b	48 bc	306 a	203 ab	42	245 ab	66 ab	38 bc
ANOVA effects					Fumigant	**0.0295**	0.6936	**0.0077**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.4385	**<0.0001**	**<0.0001**	**0.0050**
					Cultivar	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0183**	**0.0028**	**<0.0001**	**<0.0001**	**0.0002**	**<0.0001**	**<0.0001**	**<0.0001**
					Fumigant*cultivar	*0.0800*	0.9104	0.7370	*0.0648*	**0.0002**	**<0.0001**	**<0.0001**	**0.0071**	**0.0005**	**<0.0001**	**<0.0001**	**<0.0001**
					P treatment	0.2102	0.3052	0.1650	**0.0238**	**0.0213**	**<0.0001**	**0.0002**	**0.0012**	0.6415	**0.0003**	**<0.0001**	**<0.0001**
					Fumigant*P treatment	0.6692	0.3608	0.3962	**0.0272**	0.6522	**0.0045**	*0.0892*	**0.0176**	0.3370	**0.0364**	0.1207	*0.0897*
					Cultivar*P treatment	*0.0956*	0.2645	**0.0241**	0.3001	0.4272	**0.0001**	0.4844	0.7628	**0.0288**	0.4276	**0.0029**	**<0.0001**
					Fumigant*cultivar*P treatment	0.6210	**0.0341**	0.3749	0.4840	**0.0368**	**0.0202**	0.0965	*0.0641*	0.1593	*0.0535*	**0.0011**	**0.0012**
Contrasts					P addition (1 v 2 - 5)	*0.0650*	0.1891	0.8197	0.6123	*0.0770*	0.1045	**0.0420**	**0.0139**	0.1023	*0.0677*	0.1545	**0.0498**
					Linear P rate (1 - 5)	0.2644	0.1451	0.4694	0.3863	**0.0064**	**0.0006**	**0.0005**	**0.0010**	0.3929	**0.0014**	*0.0809*	**0.0086**
					Quadratic P rate (1 - 5)	0.2626	0.4407	*0.0756*	0.7169	0.5362	0.5573	0.8077	0.4525	0.2008	0.9180	0.5801	0.6570
					Mycorrhizae (1&3 v 6&7)	*0.0625*	*0.0826*	0.4456	0.2589	0.2846	**0.0073**	*0.0910*	*0.0713*	0.8268	**0.0336**	**0.0004**	**0.0056**
					Broadcast v band (2&3 v 8&9)	0.4614	0.2625	0.6229	**0.0276**	0.5466	0.8522	*0.0748*	0.7744	*0.0741*	0.1794	0.7850	0.2867

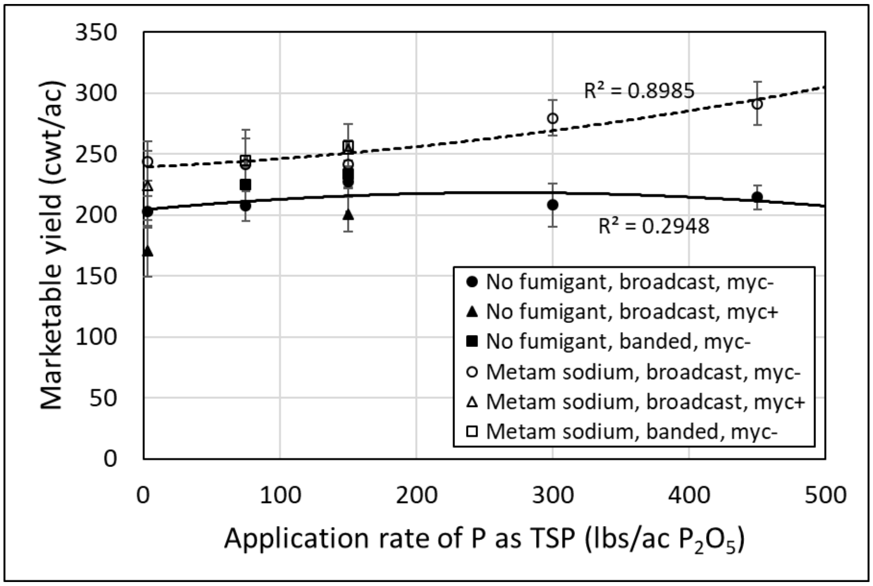

Figure 2. Marketable yield (mean ± S.E.) in each fumigation treatment, averaged between cultivars, as a function of the application rate of P. Curves are fitted on P treatments in which TSP was broadcast and MycoGold Liquid was not applied (treatments 1 – 5; solid circular markers).

Table 5. Effects of fumigation treatment, cultivar, and P treatment on tuber hollow heart, brown center, scab, specific gravity, and dry matter content. Within each main effect, values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the main effect the value pertains to (fumigation treatment, cultivar, or P treatment) is significant ($P<0.10$).

Treatment description			Percent of tubers			Specific gravity	Dry matter (%)
Fumigant	Cultivar	P treatment	Hollow heart	Brown center	Scab		
None	Average of both	Average of all	12 a	11 a	2.1	1.0727 b	20.0
Metam sodium			8 b	8 b	1.8	1.0738 a	20.1
Average of both	Russet Burbank		19 a	18 a	0.7 b	1.0702 b	19.2 b
	Ivory Russet		1 b	1 b	3.3 a	1.0763 a	20.8 a
Average of both	Average of both	1: 0 lbs/ac, myc -	13	13	3.8 a	1.0715 d	20.3
		2: 75 lbs/ac broad myc -	9	9	0.0 d	1.0713 d	19.7
		3: 150 lbs/ac broad myc -	10	10	0.8 cd	1.0740 abc	20.2
		4: 300 lbs/ac broad myc -	9	8	1.8 abcd	1.0753 a	20.3
		5: 450 lbs/ac broad myc -	13	13	3.5 ab	1.0751 a	20.2
		6: 0 lbs/ac, myc +	10	10	1.9 abcd	1.0718 d	19.6
		7: 150 lbs/ac broad myc +	10	9	2.0 abcd	1.0731 bcd	19.5
		8: 75 lbs/ac band myc -	10	9	1.5 bcd	1.0726 cd	20.2
		9: 150 lbs/ac band myc -	9	8	2.8 abc	1.0747 ab	20.2
ANOVA effects		Fumigant	**0.0033**	**0.0051**	0.5938	**0.0430**	0.5040
		Cultivar	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
		Fumigant*cultivar	**0.0245**	**0.0250**	0.4421	**0.0151**	**0.0033**
		P treatment	0.6493	0.5155	***0.0617***	**0.0013**	0.1600
		Fumigant*P treatment	0.4849	0.5977	0.7703	0.7652	**0.0311**
		Cultivar*P treatment	0.8935	0.8868	**0.0349**	0.1912	0.4979
		Fumigant*cultivar*P treatment	0.1544	0.1487	0.6613	0.8659	***0.0568***
Contrasts on P treatment		P addition (1 v 2 - 5)	0.1826	0.1874	**0.0231**	**0.0112**	0.4933
		Linear P rate (1 - 5)	0.8896	0.7928	0.3253	**<0.0001**	0.5700
		Quadratic P rate (1 - 5)	***0.0590***	**0.0322**	**0.0040**	0.1462	0.7833
		Mycorrhizae (1&3 v 6&7)	0.4357	0.3721	0.7246	0.7440	**0.0105**
		Broadcast v band (2&3 v 8&9)	0.7806	0.7365	**0.0448**	0.2162	0.2890

Russet Burbank responses to P rate, timing, and broadcast versus banding application in a field with moderate soil-test P

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Summary

Potato yield is often limited by the availability of phosphate (P), even in soils with high soil-test P. However, excessive P application can increase P losses through erosion, contributing to algal blooms and "dead zones" in surface waterways. In addition, available P from applied fertilizer is rapidly fixed into forms that are unavailable to plants, including organic matter and precipitated minerals. Thus, it may be important to target P application in space and time, placing P where plants are able to access it at a time when their requirements are high. The purpose of this study was to evaluate the responses of Russet Burbank potatoes to P rate, application method, and application timing. At the Sand Plain Research Farm in Becker, MN, in 2022, we evaluated plant responses in terms of tuber yield, size, and quality. Nine treatments were arranged in a randomized complete block design with four replicates: (1-5) triple super phosphate (TSP) broadcast at 0, 75, 150, 300, and 450 lbs/ac P_2O_5 before planting, (6-7) TSP banded at 75 and 150 lbs/ac P_2O_5 at planting, (8) TSP applied at 150 lbs/ac P_2O_5, half broadcast before planting and half banded at planting, and (9) TSP applied at 150 lbs/ac P_2O_5, half banded at planting and half side dressed at emergence. Total tuber yield, but not marketable yield, increased with P rate among the treatments receiving broadcast P alone together with the zero-P check, with the rate response leveling off at the highest two rates (300 and 450 lbs/ac P_2O_5). The percentage of total yield represented by tubers over 6 or 10 ounces decreased linearly with P rate. Tuber specific gravity and the prevalence of hollow heart and brown center increased linearly with P rate. In most respects, treatments receiving at least a portion of their P banded at planting did not differ from treatments receiving broadcast P alone at the same total rates. However, between the two treatments receiving all of their P banded at planting, total yield and tuber specific gravity were significantly lower at the higher rate (150 lbs/ac P_2O_5) than at the lower rate (75 lbs/ac P_2O_5), contrary to the general relationships of total yield and specific gravity as functions of P rate. In addition, the treatment receiving half of its P broadcast before planting and half banded at planting had significantly less of its total yield in tubers over 6 or 10 ounces than the treatment receiving the same total rate (150 lbs/ac P_2O_5) as broadcast P alone. The results of this study indicate that, while P rate had significant effects on total tuber yield, size, hollow heart, and specific gravity in this field, the method and timing of application were less important to tuber yield, size, and quality than the application rate.

Background

Phosphorus (P) fertility management is of vital importance in potato cropping systems. Potato yield is often limited by P availability, and yield responses to P fertilizer are frequently evident even in soils with high soil-test P. However, excessive P application leads to losses through surface runoff. This, in turn can contaminate waterways, contributing to the formation of algal blooms and marine "dead zones." This tension between the high P requirements of potato plants and the need to minimize water pollution from excessive P fertilizer use makes proper P management important.

P is applied by growers in plant-available forms, but available P beyond the long-term equilibrium concentration of the soil solution is rapidly bound up by soil organisms, soil particles, and the formation of insoluble phosphate minerals. This can make it challenging to apply P in a way that makes it available to plants when and where they can access it. More targeted P application may therefore have both spatial and temporal components. Given that potato root systems are not extensive, banded application of P may improve access to plant-available P relative to broadcast application. In addition, given that potato plant P requirements increase greatly after shoot emergence, and that plant-available P is quickly converted in soil to unavailable forms, it may be more effective to apply some P fertilizer at emergence rather than planting.

The purpose of this study was to evaluate P response and the effectiveness of banded P application and P application at hilling for Russet Burbank potatoes. We evaluated plant responses in terms of tuber yield, size, and quality.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2022 on a Hubbard loamy sand soil. The previous crop was soybeans. Nine treatments were arranged in a randomized complete block design with four replicates: (1-5) triple super phosphate (TSP) broadcast at 0, 75, 150, 300, and 450 lbs/ac P_2O_5 before planting, (6-7) TSP banded at 75 and 150 lbs/ac P_2O_5 at planting, (8) TSP applied at 150 lbs/ac P_2O_5, half broadcast before planting and half banded at planting, and (9) TSP applied at 150 lbs/ac P_2O_5, half banded at planting and half side dressed at emergence. These treatments are summarized in Table 1.

Soil sampling

Soil samples to a depth of six inches were taken from each whole plot in each block on April 22, 2022. These samples were sent to the University of Minnesota's Research Analytical Laboratory (St. Paul, MN) and analyzed for pH, loss-on-ignition organic matter content, Bray P, NH_4OAc-extractable K, Ca, and Mg, DTPA-extractable Mn, Fe, Zn, and Cu, hot-water-extractable B, and SO_4^{2-}-S. Two-foot samples were collected on the same day. These will be analyzed for NH_4^+-N and NO_3^--N using a Wescan Nitrogen Analyzer. Results for the six-inch samples are presented in Table 2.

On July 13, a second set of six-inch soil samples was collected from each half of the field (blocks 1 and 2 in one half and blocks 3 and 4 in the other). These samples were sent fresh to Allied Cooperative (Plainfield, WI) and analyzed for *Verticillium* propagules and root lesion nematodes.

Treatment applications

On April 25, 200 lbs/ac MOP (0-0-60) and 200 lbs/ac SulPoMag (0-0-22-21S-11Mg) were broadcast applied to the entire field, providing 164 lbs/ac K_2O equivalent, 42 lbs/ac S, and 22 lbs/ac Mg.

On the same day, P was hand-broadcast as TSP in treatments 2-5 and 8, supplying P at the rates indicated in Table 1.

On April 29, planting rows 36 inches apart were opened by machine. A mixture of whole and cut 3-ounce Russet Burbank seed tubers were planted by hand in all plots with 12-inch spacing between tubers within rows. Each plot was 12 feet (four rows) wide by 20 feet long, and each block was surrounded by a 3-foot buffer of additional tubers to reduce field edge effects. Rows were closed by machine, at which time TSP was banded into treatments 6, 7, 8, and 9, approximately 2 inches below and 4 inches to either side of the seed tubers. In addition, a blend of 87 lbs/ac urea (46-0-0), 233 lbs/ac MOP, 191 lbs/ac SulPoMag, 2.8 lbs/ac $ZnSO_4$ (35.5% Zn, 17.5% S), and 3.3 lbs/ac Boron 15 (15% B) was banded into all rows, supplying 40 lbs/ac N, 180 lbs/ac K_2O, 40 lbs/ac S, 21 lbs/ac Mg, 1 lb/ac Zn, and 0.5 lbs/ac B.

Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris, and the rows were closed by machine. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling. Rainfall and irrigation events are presented in Figure 1.

All treatments received 150 lbs/ac N as ESN (44-0-0, Nutrien, Ltd.) and 60 lbs/ac N as urea mechanically side dressed and then hilled in on May 18, so that 250 lbs/ac N were applied in total. At the same time, 75 lbs/ac P_2O_5 as TSP were side dressed in the plots in treatment 8.

Petiole sampling

Petioles were collected from each sub-subplot on June 16 and 30 and July 11 and 25. The petiole of the fourth mature leaf from the shoot tip was collected from 30 leaves per plot. Petioles were dried at 140°F until their weight was stable and then ground. The ground samples were sent to Agvise Laboratories (Benson, MN) and analyzed for NO_3^--N using a FIALab Fialyzer 1000 Nitrate Analyzer and for P concentration by inductively coupled plasma-mass spectrometry.

Harvest

Vines were chopped with a flail mower on September 19. Tubers were machine-harvested from the central 18 feet of the middle two rows of each plot on October 6. These harvest samples were sorted and graded by machine on October 11 and 12. A 25-tuber subsample was taken from each harvest sample and assessed for hollow heart, brown center, common scab, specific gravity, and dry matter content.

Statistical analyses

Analyses were performed using SAS 9.4 software. Response variables were analyzed as functions of treatment and block, both as fixed effects, using the GLIMMIX procedure. When the effect of treatment was significant ($P \leq 0.10$), pairwise comparisons were evaluated using Fisher's LSD through the DIFF option in the LSMEANS statement of the model. Values were considered significantly different if $P \leq 0.10$. Four comparisons among treatments were made using CONTRAST statements. Treatments 1 – 5 were compared in (1) a check-versus-P comparison and (2) linear and (3) quadratic contrasts on the application rate of P and (4) treatments 2 and 3 were compared with treatments 6 and 7 to evaluate the effect of banded versus broadcast application.

Results

Tuber yield and size distribution

Results for tuber yield and size are presented in Table 3. Among the treatments receiving all TSP broadcast before planting (treatments 2-5) and the zero-P check treatment (treatment 1), total yield generally increased with increasing P rate. This increase in yield leveled off at the highest P rates (300 to 450 lbs/ac P_2O_5). Total yield for the treatment receiving 150 lbs/ac P_2O_5, half broadcast before planting and half banded at planting (treatment 8), was very similar to that of the treatment receiving P at the same rate but entirely broadcast before planting (treatment 3). The same was true of the treatment receiving the same rate of P, half banded at planting and half side dressed at hilling (treatment 9). The treatment receiving 75 lbs/ac P_2O_5 banded at planting (treatment 6) had significantly higher total yield than the treatment receiving twice as much P by the same application method (treatment 7). The treatments receiving the same rates of P broadcast before planting (treatments 2 and 3, respectively) had total yield intermediate between these two banded treatments and not significantly different from either of them.

These effects of P treatment on total yield were not evident in marketable yield, which was not significantly related to P treatment. The yields of U.S. No.1 and No, 2 tubers were also unrelated to P treatment in the ANOVA model, but the results of the contrasts indicated that U.S. No. 1 yield responded to P rate and broadcast versus banded application. U.S. No. 1 yield peaked at an application rate of 150 lbs/ac P_2O_5 (treatment 3) and was numerically lower in the zero-P check than the treatments receiving all P broadcast before planting (treatments 2-5). The treatment receiving banded P at planting at 150 lbs/ac P_2O_5 (treatment 7) had much lower U.S. No. 1 yield than the treatment receiving the same P rate broadcast before planting (treatment 3), resulting in a marginally significant effect of application method. This was true in spite of the treatment receiving banded P at 75 lbs/ac P_2O_5 (treatment 6) having numerically higher U.S. No. 1 yield than the treatment receiving broadcast P at that rate (treatment 2).

The percentage of total yield represented by tubers over 6 ounces decreased linearly with increasing P rate among the treatments receiving broadcast P (treatments 2-5) and the zero-P check treatment. Application method and timing had little effect on this metric, except that the treatment receiving half of its P broadcast and half banded (treatment 8) had significantly less of its yield in tubers over 6 ounces than the treatment that received the same rate of P through broadcast application alone (treatment 3). Results were similar for the percentage of total yield in tubers over 10 ounces.

Tuber quality

Results for tuber quality are presented in Table 4. Among the treatments receiving all of their P broadcast before planting (treatments 2-4) and the zero-P check treatment (treatment 1), the prevalence of both hollow heart and brown center increased linearly with the application rate of P. None of the treatments that received at least a portion of their P banded at planting (treatments 6-9) had a significantly different prevalence of either defect than the treatment receiving only broadcast P at the same total rate (treatment 2 or 3). However, the treatment receiving half of its P banded at planting and half side dressed at hilling (treatment 9) did have a significantly higher prevalence of hollow heart than any other treatment receiving banded P (treatments 6-8) and a higher prevalence of brown center than the treatment receiving half of its

P broadcast before planting and half banded at planting (treatment 8). The prevalence of scab was unrelated to P treatment.

Among treatments receiving all P broadcast before planting (treatments 2-5) and the zero-P check treatment (treatment 1), tuber specific gravity increased linearly with the application rate of P. None of the treatments receiving all or part of their P banded at planting (treatments 6-9) had significantly different specific gravity than the broadcast-only treatment receiving P at the same rate (treatment 2 or 3). However, the treatment receiving 75 lbs/ac P2O5 as TSP banded at planting (treatment 6) had significantly higher tuber specific gravity than the treatment receiving 150 lbs/ac P by the same method (treatment 7), contrary to the general tendency for specific gravity to increase with P rate.

Tuber dry matter did not respond to P treatment except that the treatments receiving all P broadcast before planting (treatments 2-5), as a group, had a higher mean dry matter content than the zero-P check treatment (treatment 1).

Discussion and summary

Overall, total yield, but not marketable yield, increased with increasing P rate, while the percentage of total yield in large size classes decreased. The lack of a marketable yield response may be related to the opposing responses of total yield and tuber size. The benefits of higher P rates to total yield were mostly seen in the smaller tuber size classes, including undersized tubers that were included in total but not marketable yield. Yields of larger tubers tended to decrease as P rate increased. Like total yield, specific gravity and the prevalence of disqualifying hollow heart increased with P rate. The tuber yield, size, and specific gravity results are consistent with those of our previous research on P responses in Russet Burbank. However, we have not previously found hollow heart to be associated with P rate, and it is unusual for hollow heart prevalence to be associated with high specific gravity and fewer large tubers.

Banded or side-dress application of P did not generally produce different results from broadcast application at the same rates. However, there were some treatment differences related to application method. When all P was banded at planting, total yield was lower at 150 lbs/ac P_2O_5 (treatment 7) than at 75 lbs/ac P_2O_5 (treatment 6), contrary to the generally positive relationship between yield and P rate among treatments receiving only broadcast P. The same was true of specific gravity, although the treatments receiving broadcast P at those two rates (treatments 2 and 3) also had numerically lower specific gravity at the higher P rate. In addition, the treatment receiving 150 lbs/ac P_2O_5, half broadcast before planting and half banded at planting (treatment 8), had significantly less of its yield in tubers over 6 and 10 ounces than the treatment receiving all of its P broadcast before planting at the same total rate (treatment 3). It is not clear why this occurred. It was presumably not due to the banded application at planting, since the treatments receiving 75 or 150 lbs/ac P_2O_5 banded at planting (treatments 6 and 7) had percentages of yield in large size classes similar to those of the treatments receiving only broadcast P at those rates (treatments 2 and 3).

The treatment that received half of its P side-dressed at hilling (treatment 9) did not differ in tuber yield, size, or quality from the treatments receiving the same total rate of P (150 lbs/ac P_2O_5) either broadcast before planting (treatment 3) or banded before planting (treatment 7). This suggests that providing some P at shoot emergence confers no advantage over applying all P at or just before planting The results of this study suggest that, while P rate had significant effects on total tuber yield, size, hollow heart, and specific gravity in this field, the method and timing of application were less important.

Table 1. Phosphorus fertilizer treatments applied to Russet Burbank potatoes to evaluate the effects of application rate, method, and timing on tuber yield, size, and quality.

Treatment description		
Number	P rate (lbs/ac P_2O_5)	Application
1	0	NA
2	75	Broadcast before planting
3	150	Broadcast before planting
4	300	Broadcast before planting
5	450	Broadcast before planting
6	75	Banded at planting
7	150	Banded at planting
8	150	Half broadcast before planting, half banded at planting
9	150	Half banded at planting, half side dressed at hilling

Table 2. Soil characteristics before fertilizer application.

0 - 6 inches											
pH	Organic matter (%)	Bray P (mg/kg)	NH_4OAc-K (mg/kg)	NH_4OAc-Ca (mg/kg)	NH_4OAc-Mg (mg/kg)	DTPA-Mn (mg/kg)	DTPA-Fe (mg/kg)	DTPA-Zn (mg/kg)	DTPA-Cu (mg/kg)	Hot water B (mg/kg)	SO_4^{2-}-S (mg/kg)
7.1	1.5	28	111	1081	192	13	16	1.8	0.7	0.2	13

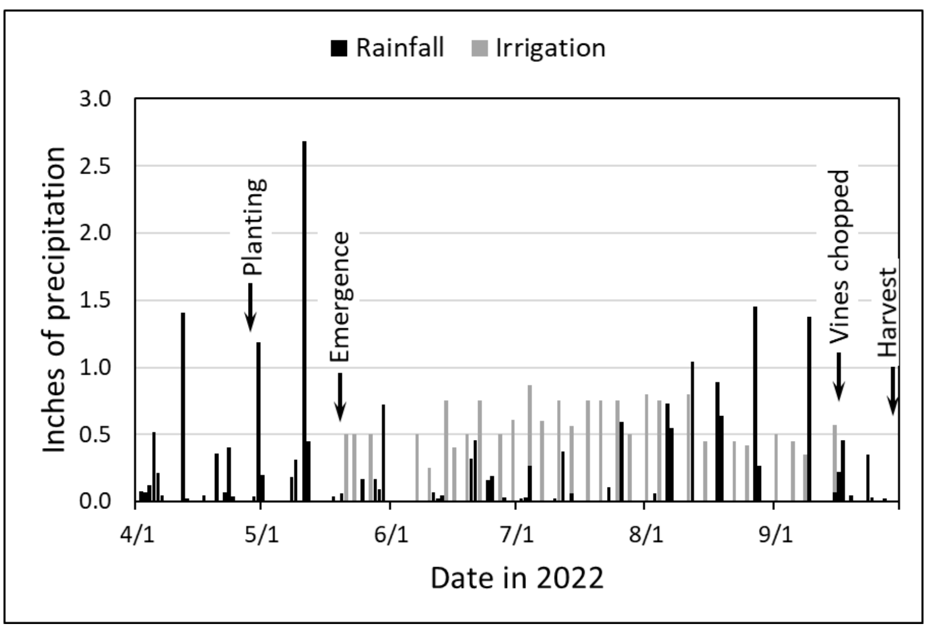

Figure 1. Inches of rainfall and irrigation in the study field in 2022. Irrigation amounts were determined by the checkbook method of irrigation scheduling. Monthly rainfall totals were as follows: April, 4.63 inches; May, 5.08 inches; June, 1.32 inches; July, 1.48 inches; August, 5.64 inches; September, 2.58 inches. Irrigation started on May 21 and ended on September 15. Monthly total irrigation amounts were as follows: May, 1.30 inches; June, 4.45 inches; July, 5.15 inches; August, 3.62 inches; September, 1.87 inches.

Table 3. Effects of P treatment on tuber yield, size, and grade. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant (P<0.10).

Treatment description (rates in lbs/ac P_2O_5)						Yield ($CWT \cdot ac^{-1}$)								
Number	P at planting	Method	P at hilling	Method	Total rate	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2
1	0	-	0	-	0	13	66 e	72 d	150	113	84	484 c	334	84
2	75	Broadcast	0	-	75	10	88 cde	105 bc	161	105	85	544 ab	362	94
3	150	Broadcast	0	-	150	7	86 de	105 bc	177	114	63	545 ab	388	71
4	300	Broadcast	0	-	300	5	119 ab	120 ab	179	101	56	576 a	369	88
5	450	Broadcast	0	-	450	5	134 a	133 a	161	101	44	572 a	349	89
6	75	Banded	0	-	75	6	107 bcd	87 cd	170	122	85	571 a	375	89
7	150	Banded	0	-	150	10	110 bc	88 cd	169	91	63	521 bc	318	93
8	150	1/2 broad, 1/2 band	0	-	150	8	122 ab	114 ab	168	80	61	546 ab	345	78
9	75	Banded	75	Side dress	150	6	106 bcd	117 ab	172	97	57	549 ab	347	95
Effect of P treatment (P value)						0.2175	**0.0010**	**0.0006**	0.7769	0.1627	0.4794	**0.0370**	0.1312	0.8905
Contrasts on P treatment (P values)			P addition (1 v 2 - 5)			**0.0237**	**0.0007**	**<0.0001**	0.1509	0.5269	0.2006	**0.0011**	***0.0792***	0.9332
			Linear P rate (1 - 5)			**0.0101**	**<0.0001**	**<0.0001**	0.4569	0.3601	**0.0323**	**0.0025**	0.7745	0.8037
			Quadratic P rate (1 - 5)			0.2197	0.6995	0.1770	***0.0669***	0.9616	0.7958	***0.0680***	**0.0307**	0.6067
			Broadcast v band (2&3 v 6&7)			0.7605	**0.0323**	***0.0516***	0.9844	0.7534	0.9828	0.9416	***0.0924***	0.4961

Table 4. Effects of P treatment on tuber quality. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant (P<0.10).

Treatment description (rates in lbs/ac P_2O_5)						Hollow heart	Brown center	Scab	Specific gravity	Dry matter (%)
Number	P at planting	Method	P at hilling	Method	Total rate	Percent of tubers				
1	0	-	0	-	0	8 cd	7 bc	10	1.0709 d	17.3
2	75	Broadcast	0	-	75	5 d	4 c	10	1.0726 abcd	19.0
3	150	Broadcast	0	-	150	16 abc	15 ab	5	1.0712 d	19.1
4	300	Broadcast	0	-	300	14 bc	13 abc	7	1.0749 a	19.0
5	450	Broadcast	0	-	450	18 ab	18 a	11	1.0743 ab	18.8
6	75	Banded	0	-	75	14 bc	13 abc	12	1.0737 abc	18.3
7	150	Banded	0	-	150	14 bc	14 ab	12	1.0707 d	18.4
8	150	1/2 broad, 1/2 band	0	-	150	9 cd	8 bc	14	1.0717 cd	19.0
9	75	Banded	75	Side dress	150	23 a	22 a	15	1.0720 bcd	18.6
Effect of P treatment (P value)						***0.0604***	***0.0778***	0.4295	**0.0382**	0.5962
Contrasts on P treatment (P values)			P addition (1 v 2 - 5)			0.2082	0.2196	0.6276	**0.0375**	**0.0274**
			Linear P rate (1 - 5)			**0.0221**	**0.0216**	0.8712	**0.0055**	0.2355
			Quadratic P rate (1 - 5)			0.7242	0.8373	0.1821	0.5366	0.1007
			Broadcast v band (2&3 v 6&7)			0.3511	0.3218	0.1656	0.7442	0.2575

Evaluation of Crystal Green Synchro 50 (Ostara) as a phosphate source for Russet Burbank potatoes

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Summary

Phosphorus (P) management is important in potato cropping systems. Potatoes have been found to show positive responses to increased P rate even at rates above recommendations in soils that test high for P, but excessive use of P fertilizer increases risks of surface water contamination. A possible source of P use inefficiency in crops is that fertilizer P availability may not match the timing of crop needs. Most fertilizer provide immediately-available P, much of which is rapidly fixed in the soil and rendered unavailable before plants can take it up. Crystal Green (Ostara; CG: 5-28-0-10Mg) is a P fertilizer that dissolves poorly in water but releases P in the presence of weak organic acids such as those present in plant root exudates. CG alone may not meet early-season crop needs, but it has been found to be an effective P source in combination with quick-release ammonium phosphate fertilizers. Crystal Green Synchro 50 (Sync50: 9-43-0-4Mg) is a 50:50 cogranulated blend of CG and ammonium phosphate designed to both provide plant-available P immediately (as ammonium phosphate) and release more throughout the growing season (as CG). The purpose of this study was to evaluate the effectiveness of Sync50 as a P source for Russet Burbank potatoes compared to monoammonium phosphate (11-50-0) and a 75:25 blend of MAP and CG. Total and marketable tuber yield were found to increase linearly with the rate of P banded at planting at rates of 0 to 100 lbs/ac P_2O_5, whether the source was MAP or Sync50. U.S. No. 1 yield showed this linear trend for Sync50, but not MAP. The percentage of total yield represented by tubers over 6 ounces decreased with increasing P rate when the P source was MAP but not when it was Sync50. When Sync50 was broadcast at 100 lbs/ac P_2O_5 instead of banded, total yield was significantly lower than if P was supplied at the same rate as banded Sync50 or banded or broadcast MAP. The blend of MAP and CG banded at 100 lbs/ac P_2O_5 produced a significantly lower yield of U.S. No. 1 tubers than Sync50 broadcast or banded or MAP broadcast at the same rate. The prevalence of hollow heart and brown center was not affected by P treatment, but the prevalence of common scab decreased with increasing P rate among treatments receiving Sync50. Tuber specific gravity and dry matter content both increased with the application rate of P banded at planting as either MAP or Sync50. A treatment receiving 200 lbs/ac P_2O_5 as MAP broadcast before planting did not produce significantly improved tuber yield or quality relative to most treatments receiving half that rate, including one receiving 100 lbs/ac P_2O_5 as MAP broadcast before planting. Overall, these results indicate that Sync50 was as effective as MAP as a P source and that Sync50 outperformed a physical blend of CG and MAP in terms of U.S. No. 1 yield. Tuber yield and quality improved with increasing P rate up to 100 lbs/ac P_2O_5, but not 200 lbs/ac P_2O_5.

Background

Phosphorus (P) management is important in potato cropping systems. Potatoes are a P-intensive crop, showing positive responses to increasing P rate even under high soil-test P conditions and at rates above recommendations. However, the yield benefits of P fertilizer show diminishing returns at high P rates, and excessive application of P fertilizer can contribute to pollution of surface waterways.

P is frequently supplied to crops in the form of ammonium phosphate fertilizers, which immediately provide plant-available P. However, this P is rapidly removed from the soil solution by adsorption onto soil particles, incorporation into microbial biomass, and the formation of insoluble phosphate minerals.

Crystal Green (Ostara; CG: 5-28-0-10Mg) is a struvite fertilizer that holds P in a form that dissolves poorly in water but releases it in the presence of weak organic acids such as those present in plant root exudates. It has been found to be an effective P source when applied in combination with an ammonium phosphate fertilizer. Crystal Green Synchro 50 (Sync50: 9-43-0-4Mg) is a cogranulated 50:50 blend of CG and ammonium phosphate designed to both provide plant-available P immediately (as ammonium phosphate) and release more throughout the growing season (as CG).

The purpose of this study was to evaluate the effectiveness of Sync50 as a P source for Russet Burbank potatoes relative to monoammonium phosphate (MAP: 11-50-0) and a 75:35 blend of MAP and CG.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2022 on a Hubbard sandy loam soil. The previous crop was soybeans. Twelve treatments were applied in a randomized complete block design with four replicates. These treatments are summarized in Table 1.

Soil sampling

Soil samples to a depth of six inches were taken from each whole plot in each block on April 22, 2022. These samples were sent to the University of Minnesota's Research Analytical Laboratory (St. Paul, MN) and analyzed for pH, loss-on-ignition organic matter content, Bray P, NH_4OAc-extractable K, Ca, and Mg, DTPA-extractable Mn, Fe, Zn, and Cu, hot-water-extractable B, and SO_4^{2-}-S. Two-foot samples were collected on the same day. These will be analyzed for NO_3^--N using a Wescan Nitrogen Analyzer. Results for the six-inch samples are presented in Table 2.

Treatment applications

On April 25, 200 lbs/ac MOP (0-0-60) and 200 lbs/ac SulPoMag (0-0-22-21S-11Mg) were broadcast applied to the entire field, providing 164 lbs/ac K_2O equivalent, 42 lbs/ac S, and 22 lbs/ac Mg. On the same date, MAP or Sync50 were broadcast-applied by hand according to treatment in plots assigned to treatments 3, 4, and 9.

On April 27, planting rows were opened by machine with 36-inch spacing. A mixture of whole and cut three-ounce Russet Burbank seed potatoes were planted by hand 12 inches apart throughout the field. Each plot was 12 feet (four rows) wide and 20 feet long, with the central two rows were designated as harvest sample rows. The field was surrounded by a three-foot buffer of additional potatoes to reduce edge effects. Rows were closed by machine, at which time MAP, CG, and Sync50 were banded according to treatment approximately two inches below and four inches to either side of the seed tubers in treatments 2, 5-8, and 10-12. In addition to the nutrients provided by the P sources, all treatments received urea (46-0-0), Sul-Po-Mag (0-0-22-22S-11Mg), MOP (0-0-60), ammonium sulfate (21-0-0-24), $ZnSO_4$ (35.5% Zn, 17% S), and Boron 15 (15% B) as needed to provide a total of 50 lbs/ac N, 60 lbs/ac K_2O, 40.5 lbs/ac S, 20 lbs/ac Mg, 1 lb/ac Zn, and 0.5 lbs/ac B.

Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris, and the rows were closed by machine. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling. Rainfall and irrigation events are presented in Figure 1.

All treatments received 150 lbs/ac N as urea mechanically side dressed and then hilled in on May 18. However, based on plant deficiency symptoms and reduced yield, it appears that the harvest rows in one third of the plots did not receive urea at this time. All plots received 20 lbs/ac N as 28% UAN on June 27 and July 28, so that 240 lbs/ac N was applied in total, outside of the two rows missed at emergence.

Harvest

Vines were chopped with a flail mower on September 16. To obtain tuber counts, five-plant samples were harvested from one of the central two rows of each plot. The remaining tubers were machine-harvested from the central 18 feet of the middle two rows of each plot on October 6. In the plots where the middle two rows were believed not to have received emergence N, the two border rows were also machine-harvested, and tuber yield and quality results were derived from these rows. The machine-harvested samples were sorted and graded by machine on October 12 and 13. A 25-tuber subsample was taken from each harvest sample and assessed for hollow heart, brown center, common scab, specific gravity, and dry matter content. The five-plant samples were sorted and graded on October 14.

Statistical analyses

Analyses were performed using SAS 9.4 software. Response variables were analyzed as functions of treatment and block, both as fixed effects, using the GLIMMIX procedure, with denominator degrees of freedom determined by the Kenward-Roger method. When the effect of treatment was significant ($P \leq 0.10$), pairwise comparisons were evaluated using Fisher's LSD through the DIFF option in the LSMEANS statement of the model. Values were considered significantly different if $P \leq 0.10$. Three comparisons among treatments were made using CONTRAST statements: (1) the zero-P treatment (treatment 1) was compared to the remaining treatments to evaluate the effects of applying P in any form; (2) treatments 1-2 and 5-6 were compared to test for linear relationships with P rate among the treatments receiving banded MAP; and (3) treatments 1, 8, and 10-12 were compared to test for linear relationships with P rate among the treatments receiving banded Sync50.

Results

Tuber yield, grade, and size

Results for tuber yield, grade, and size are presented in Table 3. Based on the ANOVA model, P treatment was significantly related to total yield, yield of U.S. No. 1 tubers, and the percentage of total yield represented by tubers over 10 ounces. Based on contrasts, total yield, yield of U.S. No. 1 tubers, and marketable yield all increased in response to P fertilizer application, while P application decreased the percentage of yield represented by tubers over six ounces. Total and marketable yield increased with P rate among the treatments receiving MAP banded at planting (treatments 2, 5, and 6) and the zero-P control (treatment 1), while the percentage of yield in tubers over six ounces declined with P rate among these treatments. Among treatments receiving Sync50 banded at planting (treatments 8 and 10-12), together with the zero-P control, total, U.S. No. 1, and marketable yield all increased with P application rate.

In pairwise comparisons among the treatments receiving 100 lbs/ac P_2O_5, the treatment receiving broadcast Sync50 (treatment 9) had lower significantly total yield than the treatments receiving broadcast MAP (treatment 3) or banded Sync50 (treatment 8). In terms of U.S. No. 1 yield, the treatment receiving a blend of MAP and CG banded at planting (treatment 7) had significantly lower yield than the other treatments receiving 100 lbs/ac P_2O_5 except for the treatment receiving only MAP banded at planting (treatment 2), which had significantly lower yield than the treatment receiving MAP broadcast before planting (treatment 3). The treatment receiving a blend of MAP and CG (treatment 7) also had less of its yield in tubers over ten ounces than any other treatment receiving 100 lbs/ac P_2O_5 except for the treatment receiving only MAP banded at planting (treatment 2).

Based on contrasts, the treatments receiving MAP banded at planting (2, 5, and 6) did not differ from those receiving Sync50 banded at planting at the same rates (8, 11, and 12) in tuber yield, size, or grade. In pairwise comparisons for total yield, U.S. No. 1 yield, and the percentage of yield represented by tubers over ten ounces, the only significant difference between banded MAP treatments and banded Sync50 treatments matched by P rate was see in the percentage of yield in tubers over ten ounces. The treatment receiving banded MAP at 25 lbs/ac P_2O_5 (treatment 6) had significantly less of its yield in tubers over ten ounces than the treatment receiving the same rate of P as Sync50 banded at planting (treatment 12).

The treatment receiving 200 lbs/ac P_2O_5 as MAP broadcast before planting (treatment 4) had similar total tuber yield to the treatments receiving 100 lbs/ac P P_2O_5 as MAP, whether banded (treatment 2) or broadcast (treatment 3), indicating that the positive relationship between P rate and yield had diminishing returns on investment on P at higher rates in this field. None of the contrasts comparing the yields of banded MAP treatments (treatments 2, 5, and 6) to those of banded Sync50 treatments (treatments 8, 11, and 12) were significant.

Tuber quality

Results for tuber quality are presented in Table 2. The prevalence of hollow heart and brown center were unrelated to P treatment. Among treatments receiving Sync50 banded at planting (treatments 8 and 10-12) and the zero-P check treatment (treatment 1), the prevalence of common scab decreased linearly with increasing P rate. This relationship was not significant among treatments receiving banded MAP at planting together with the zero-P check (treatments 2-3 and 5-6), possibly because the zero-P check treatment had a slightly lower prevalence of common scab than the treatments receiving 25 or 50 lbs/ac P_2O_5 as MAP (treatments 5 and 6).

Tuber specific gravity increased with P rate with either MAP or Sync50 banded at planting, based on linear contrasts. The zero-P check treatment (treatment 1) had significantly lower specific gravity than any other treatment except the two receiving the lowest non-zero rate, 25 lbs/ac P_2O_5 (treatments 6 and 12). The treatment receiving 200 lbs/ac P P_2O_5 as MAP broadcast before planting (treatment 4) had numerically lower specific gravity than the treatment receiving 100 lbs/ac P_2O_5 in the same form and by the same method (treatment 3), and it did not have significantly higher tuber specific gravity than any treatment receiving 100 lbs/ac P_2O_5 (treatments 2-3 and 7-9). This suggests that the positive relationship between P rate and specific gravity may not have extended as high at 200 lbs/ac P_2O_5 in this field.

Like specific gravity, tuber dry matter content increased with P rate in linear contrasts, whether MAP (treatments 2 and 5-6) or Sync50 (treatments 8 and 10-12) were considered together with the zero-P control treatment (treatment 1). Numerically, the treatment receiving 200 lbs/ac P_2O_5 broadcast at planting as MAP (treatment 4) had lower tuber dry matter content than all of the treatments receiving 75 or 100 lbs/ac P_2O_5 except the treatment banded with a blend of MAP and CG at planting (treatment 7). The positive relationship between tuber dry matter and P rate may not have extended to this high a rate in this field. None of the contrast comparing the tuber quality of banded MAP treatments (treatments 2, 5, and 6) to that of banded Sync50 treatments (treatments 8, 11, and 12) were significant.

Summary

The application rate of P as MAP or Sync50 banded at planting had a significant effect on tuber yield and quality in this study. Total yield, marketable yield, tuber specific gravity, and tuber dry matter content all increased with P rate with either source, while U.S. No. 1 yield also increased with P rate among treatments receiving Sync50. Common scab prevalence decreased with increasing P rate among treatments receiving Sync50, and the percentage of total yield represented by tubers over six ounces decreased with increasing P rate among treatments receiving MAP banded at planting. While the treatment receiving 200 lbs/ac P_2O_5 as MAP broadcast before planting did not improve tuber yield or quality relative to treatments receiving 100 lbs/ac P_2O_5, at lower rates, tuber yield and quality improved as P rate increased.

There was no significant difference in performance between banded MAP and banded Sync50. However, among treatments receiving 100 lbs/ac P_2O_5, P source and application method did have some significant effects. In terms of total yield, broadcast-applied Sync50 underperformed banded Sync50 and both broadcast and banded MAP. In terms of U.S. No. 1 yield, banded CG + MAP underperformed all other treatments receiving 100 lbs/ac P_2O_5 except for the treatment receiving banded MAP. This treatment also had the lowest dry matter content of any treatment receiving P at any rate.

Overall, Sync50 performed similarly to MAP as a P source in promoting tuber yield and quality. In terms of U.S. No. 1 yield and possibly tuber dry matter content, it outperformed a physical blend of CG and MAP. While increased P rate produced benefits to tuber yield and quality up to a rate of 100 lbs/ac P_2O_5, doubling this application rate conferred no additional benefits in this study.

Table 1. Rates, methods, and sources of phosphorus applied to Russet Burbank potatoes to evaluate the effectiveness of Crystal Green Synchro 50 as a P source for potatoes.

Treatment #	P rate (lbs/ac P_2O_5) by source MAP[1]	Crystal Green[2]	Crystal Green Synchro 50 [3]	Total	Method
1	0	0	0	0	-
2	100	0	0	100	Banded
3	100	0	0	100	Broadcast
4	200	0	0	200	Broadcast
5	50	0	0	50	Banded
6	25	0	0	25	Banded
7	75	25	0	100	Banded
8	0	0	100	100	Banded
9	0	0	100	100	Broadcast
10	0	0	75	75	Banded
11	0	0	50	50	Banded
12	0	0	25	25	Banded

[1] Monammonium phosphate: 11-50-0

[2] Crystal Green: 5-28-0-10Mg

[3] Crystal Green Synchro 50: 9-43-0-4Mg

Table 2. Soil characteristics in the study field before fertilizer application.

0 - 6 inches												0 - 2 feet
pH	Organic matter (%)	Bray P (mg/kg)	NH_4OAc-K (mg/kg)	NH_4OAc-Ca (mg/kg)	NH_4OAc-Mg (mg/kg)	DTPA-Mn (mg/kg)	DTPA-Fe (mg/kg)	DTPA-Zn (mg/kg)	DTPA-Cu (mg/kg)	Hot water B (mg/kg)	SO_4^{2-}-S (mg/kg)	NO_3^--N (mg/kg)
6.9	1.8	24	124	898	185	17	21	1.9	0.9	0.2	15	0.9

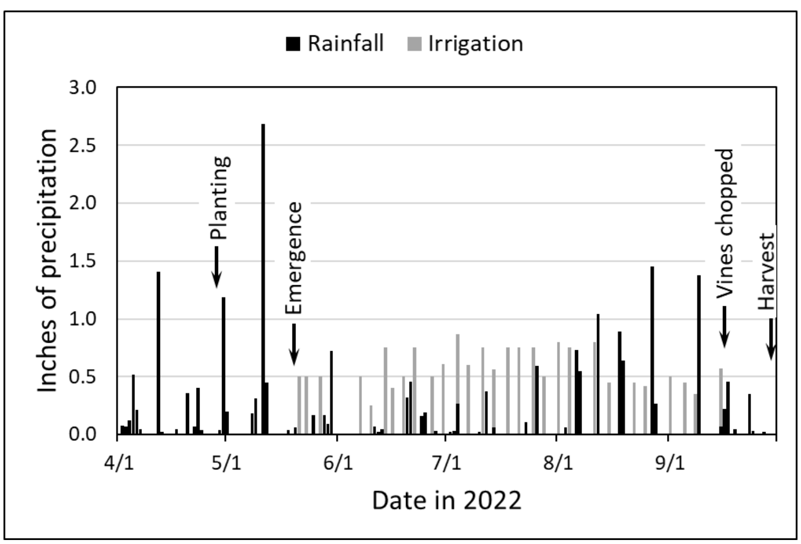

Figure 1. Inches of rainfall and irrigation in the study field in 2022. Irrigation amounts were determined by the checkbook method of irrigation scheduling. Monthly rainfall totals were as follows: April, 4.63 inches; May, 5.08 inches; June, 1.32 inches; July, 1.48 inches; August, 5.64 inches; September, 2.58 inches. Irrigation started on May 21 and ended on September 15. Monthly total irrigation amounts were as follows: May, 1.30 inches; June, 4.45 inches; July, 5.15 inches; August, 3.62 inches; September, 1.87 inches.

Table 3. Effects of P treatment on tuber yield, size, and grade. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant ($P < 0.10$).

	P rate (lbs/ac P_2O_5) by source					Yield ($CWT \cdot ac^{-1}$)										% yield in tubers over:	
Number	MAP	CG	Sync50	Total	Method	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2	Marketable	6 oz.	10 oz
1	0	0	0	0	-	9	74 e	68 e	155 f	103	100	500 d	351 d	76	427	71	39 a
2	100	0	0	100	Banded	7	104 ab	129 a	175 cdef	113	64	585 abc	386 bcd	96	482	61	30 bcd
3	100	0	0	100	Broadcast	3	86 bcde	99 cd	195 abc	129	89	598 ab	454 a	58	512	69	36 ab
4	200	0	0	200	Broadcast	4	104 ab	120 ab	204 a	108	71	606 a	424 abc	79	502	63	29 bcd
5	50	0	0	50	Banded	6	85 bcde	96 cd	172 cdef	126	80	559 abc	423 abc	51	474	67	36 ab
6	25	0	0	25	Banded	7	97 bcd	104 bcd	188 abcd	100	50	538 cd	368 cd	72	441	62	27 cd
7	75	25	0	100	Banded	4	122 a	114 abc	187 abcd	101	40	563 abc	344 d	97	441	58	25 d
8	0	0	100	100	Banded	6	87 bcde	102 bcd	201 ab	130	80	600 ab	448 ab	64	512	68	34 abc
9	0	0	100	100	Broadcast	6	73 e	95 cd	181 abcde	121	77	547 cd	419 abc	55	474	69	36 ab
10	0	0	75	75	Banded	8	79 de	93 d	165 def	137	95	568 abc	439 ab	50	489	70	41 a
11	0	0	50	50	Banded	8	101 abc	103 bcd	179 bcdef	106	66	554 bc	388 bcd	65	453	63	31 bcd
12	0	0	25	25	Banded	8	80 cde	94 cd	162 ef	121	83	540 cd	392 abcd	68	460	67	37 ab
Effect of P treatment (P value)						0.3902	**0.0146**	**0.0045**	**0.0212**	0.4700	0.3253	**0.0297**	*0.0930*	0.4463	0.1991	0.1006	*0.0733*
Contrasts (P values)	P addition (1 v 2 - 12)					0.1961	*0.0517*	**0.0003**	**0.0114**	0.3064	0.1063	**0.0025**	*0.0549*	0.6405	*0.0542*	*0.0824*	0.1059
	Linear P rate, MAP (1, 2, 5, & 6)					0.5425	*0.0543*	**<0.0001**	0.3957	0.4304	0.3245	**0.0052**	0.3110	0.3813	*0.0863*	*0.0628*	0.2907
	Linear P rate, Sync50 (1, 8, 10 - 12)					0.2721	0.3550	**0.0194**	**0.0043**	0.1000	0.5621	**0.0011**	**0.0089**	0.3993	**0.0119**	0.7301	0.6170
	MAP vs. Sync50 (2, 5&6 vs. 8, 11&12)					0.6000	0.4502	0.1644	0.7791	0.5795	0.3932	0.8108	0.4549	0.5604	0.6257	0.2884	0.3487

Table 4. Effects of P treatment on tuber quality. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant (P < 0.10).

	P rate (lbs/ac P_2O_5) by source					Hollow heart	Brown center	Scab	Specific	Dry matter
Number	MAP	CG	Sync50	Total	Method	Percent of tubers			gravity	(%)
1	0	0	0	0	-	4	6	18	1.0647 c	18.1
2	100	0	0	100	Banded	11	8	11	1.0716 ab	20.4
3	100	0	0	100	Broadcast	4	4	10	1.0762 a	20.0
4	200	0	0	200	Broadcast	9	10	10	1.0738 ab	19.4
5	50	0	0	50	Banded	3	3	19	1.0711 ab	18.9
6	25	0	0	25	Banded	5	5	22	1.0679 bc	19.2
7	75	25	0	100	Banded	4	4	17	1.0725 ab	18.3
8	0	0	100	100	Banded	9	9	6	1.0734 ab	20.7
9	0	0	100	100	Broadcast	9	7	8	1.0751 a	20.0
10	0	0	75	75	Banded	10	10	9	1.0757 a	20.3
11	0	0	50	50	Banded	10	10	18	1.0718 ab	19.4
12	0	0	25	25	Banded	5	5	20	1.0703 abc	19.6
Effect of P treatment (P value)						0.5366	0.8403	0.2082	***0.0993***	0.1176
Contrasts (P values)	P addition (1 v 2 - 12)					0.3331	0.8216	0.3723	**0.0040**	**0.0217**
	Linear P rate, MAP (1, 2, 5, & 6)					0.1174	0.6618	0.1841	***0.0523***	**0.0195**
	Linear P rate, Sync50 (1, 8, 10 - 12)					0.1357	0.3202	**0.0218**	**0.0067**	**0.0048**
	MAP vs. Sync50 (2, 5&6 vs. 8, 11&12)					0.5150	0.7409	0.4886	0.4312	0.4252

Evaluation of MicroEssentials S10 and Susterra as phosphorus sources for Russet Burbank potatoes

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Summary

Phosphorus (P) makes an important contribution to potato tuber yield and quality. Consequently, effective P management is vital in potato production. MicroEssentials S10 (Mosaic Co.: 12-40-0-10S) is a slow-release P fertilizer intended to improve P management by matching the timing of P availability more closely to the timing of crop needs. Potato growers are also increasingly concerned with improving the health of their soils. Susterra (Mosaic Co.: 12-24-0-10S) is a recent P fertilizer with 15% organic matter intended to promote soil microbial activity and improve soil health. The purpose of this study was to evaluate these products as P sources for Russet Burbank potatoes. The study was conducted at the Sand Plain Research Farm in Becker, MN, on a Hubbard loamy sand soil with moderate soil-test P (Bray P = 24 ppm). Seven treatments were applied in a randomized complete block design with four replicates: (1) a zero-P control, (2) 100 lbs/ac P_2O_5 as monoammonium phosphate (MAP: 10-52-0), (3) the same P rate as MAP plus ammonium sulfate (AS: 21-0-0-24S), (4) the same P rate MES10, (5) a blend MES10 and Susterra providing 63 and 37 lbs/ac P_2O_5, respectively, (6) a blend of MES10 and Susterra providing 56 and 34 lbs/ac P_2O_5, respectively, and (7) a blend of MAP and Susterra providing 68 and 32 lbs/ac P_2O_5, respectively. Total and marketable yields were highest in the treatment receiving a 63:37 blend of MES10 and Susterra and lowest in the zero-P control treatment. Yield in the treatment receiving 90 lbs/ac P_2O_5 as a 56:34 blend of MES10 and Susterra and in the treatment receiving a blend of MAP and Susterra was significantly lower than that of the 63:37 MES10:Susterra blend and not significantly higher than that of the zero-P control. The MAP-only treatment also had significantly lower yield than the 63:37 MES10:Susterra blend. The zero-P control had significantly more of its yield in tubers over 6 and 10 ounces than any other treatment. P fertilizer treatment did not have any significant effects on the prevalence of hollow heart, brown center, or common scab, nor on tuber specific gravity or dry matter content. Overall at equivalent P rates, MES10 alone and the 63:37 blend of MES10 and Susterra were at least as effective as conventional P sources at promoting total and marketable yield, with no significant differences in tuber size or quality.

Background

Because phosphorus (P) plays critical roles in canopy growth, tuber set, and starch production, thus promoting tuber yield and quality, effective P management is important in potato production. Efficient P management includes providing P when plants are able to take it up, which reduces P losses to fixation and leaching. MicroEssentials S10 (MES10, Mosaic Co.: 12-40-0-10S) is a slow-release P fertilizer. Slow release may increase nutrient availability relative to fertilizer application at planting by increasing the proportion of the supplied nutrients that are made available when the crop is large enough and growing rapidly enough to take them up.

Due to the benefits of soil health to both economic and environmental sustainability, as well as its potential to promote yield and control soilborne pathogens, potato growers are increasingly interested in improving soil health. Susterra fertilizer (Mosaic Co.: 12-24-0-10S) is a recent P product with 15% organic materials that is intended to promote soil microbial activity, support a balanced microbial community, and improve soil health.

The purpose of this study was to evaluate the effectiveness of MES10 and Susterra as P sources for Russet Burbank potatoes relative to the conventional source monoammonium phosphate (MAP: 11-52-0).

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2022 on a Hubbard loamy sand soil, using a randomized complete block design with four replicates. The previous crop was soybeans. Seven treatments were applied in a randomized complete block design with four replications: (1) a zero-P control, (2) 100 lbs/ac P_2O_5 as monoammonium phosphate (MAP: 10-52-0), (3) the same P rate as MAP plus ammonium sulfate (AS: 21-0-0-24S), (4) the same P rate MES10, (5) a blend MES10 and Susterra providing 63 and 37 lbs/ac P_2O_5, respectively, (6) a blend of MES10 and Susterra providing 56 and 34 lbs/ac P_2O_5, respectively, and (7) a blend of MAP and Susterra providing 68 and 32 lbs/ac P_2O_5, respectively. Crop responses to P source were measured in terms of tuber yield, size, and quality. These treatments are summarized in Table 1.

Soil sampling

Soil samples to depths of six inches and two feet were collected from across the study field on April 22. The six-inch samples were sent to the University of Minnesota's Research Analytical Laboratory and analyzed for Bray P, NH_4OAc-extractable K, Ca, and Mg; DTPA-extractable Fe, Mn, Zn, and Cu; hot-water-extractable B; SO_4-S; pH; loss-on-ignition soil organic matter content; and cation exchange capacity. The two-foot samples were analyzed for NH_4^+-N and NO_3^--N concentrations using a Wescan Nitrogen Analyzer. The results of these analyses are presented in Table 2.

Treatment applications

On April 26, 500 lbs/ac MOP (0-0-60) was broadcast-applied to the entire field, providing 300 lbs/ac K_2O. On the following day, the fertilizer treatments were broadcast by hand. The fertilizers indicated in Table 1 were blended with 50 lbs/ac MOP, 160 lbs/ac $MgCl_2$ (25% Mg), 3.1 lbs/ac ZnO (80% Zn), and 6.7 lbs/ac Granubor (15% B), providing 30 lbs/ac K_2O, 40 lbs/ac Mg, 2.5 lbs/ac Zn, and 1 lb/ac B. Enough urea (46-0-0) was added to each blend to bring the total application rate of N to 50 lbs/ac.

The planting rows were opened mechanically with 36-inch spacing between rows. Two- to three-ounce Russet Burbank seed potatoes (a mixture of cut "A" seed and whole "B" seed) were planted by hand with 12-inch spacing, and the rows were closed mechanically. Each plot was four rows (12 feet) wide and 20 feet long.

Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris, and the rows were closed by machine. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling. Rainfall and irrigation events are presented in Figure 1.

At hilling on May 18, 20 days after planting, urea was sidedress applied to the rows at 348 lbs/ac, providing 160 lbs/ac N. On June 28 and July 29, 20 lbs/ac N were applied as 28% urea and ammonium nitrate (UAN: 28-0-0) with irrigation.

Percent stand was assessed for the central 18 plants in each of the middle two rows of each plot on June 1 and 8 (36 plants total). The number of stems per plant was determined for ten plants in one of the middle two rows on June 9. Petioles were sampled from the fourth mature leaf from the shoot tip from 30 plants in the central two rows on June 16 and 30 and July 11 and 26. These were dried at 140°F until their weight was stable, and then ground. They were sent to Agvise Laboratories (Benson, MN), where their nitrate contents were determined using a FIALab Fialyzer 1000 Nitrate Analyzer and their P concentrations were measured using inductively coupled plasma mass spectrometry.

Harvest

Vines were chopped with a flail mower on September 19. Tubers were harvested from the central 18 feet of the middle two rows in each plot on September 29. On October 4 and 5, the tubers were sorted by size and USDA grade, and yield by size class and grade was determined. A 25-tuber subsample was collected from each plot's harvest sample and assessed for hollow heart, brown center, scab, specific gravity, and dry matter content.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the GLIMMIX procedure. Yield and quality metrics were analyzed as functions of treatment and block. To test for effects of P application, the zero-P treatment (treatment 1) was compared with the other six treatments using a CONTRAST statement. Treatment marginal means were determined using an LSMEANS statement, and Fisher's LSD pairwise comparisons were made using the DIFF option. Pairwise comparisons are presented only where the effect of treatment was at least marginally significant ($P \leq 0.10$), and the same standard of statistical significance was applied to determining which pairs of treatments had significantly different values.

Results

Tuber yield and size distribution

Results for tuber yield are presented in Table 3. Total yield was significantly related to P treatment. The treatment receiving 100 lbs/ac P_2O_5 as a blend of MES10 and Susterra (treatment 5) had the highest yield. This treatment had significantly higher yield than the zero-P control treatment (treatment 1), the treatment receiving MAP without an S source (treatment 2), the treatment receiving 90 lbs/ac P_2O_5 as a blend of MES10 and Susterra (treatment 6) and the treatment receiving 100 lbs/ac P_2O_5 as a blend of MAP and Susterra (treatment 7). The zero-P control treatment (treatment 1) had the lowest yield, with significantly lower yield than all other treatments except the treatment receiving 90 lbs/ac P_2O_5 as a blend of MES 10 and Susterra (treatment 6) and the treatment receiving 100 lbs/ac P_2O_5 as a blend of MAP with Susterra. Marketable yield was marginally significantly related to treatment ($P = 0.08$). Values for marketable yield generally paralleled those for total yield, except that the zero-P treatment (treatment 1) did not differ as much the other treatments in terms of marketable yield as it did in terms of total yield.

The zero-P treatment (treatment 1) had significantly lower yields of 0-4-ounce and 4-6-ounce tubers, as well as significantly higher yields of tubers over 14 ounces, than any other treatment. Accordingly, the zero-P treatment had significantly larger percentages of its yield in tubers over 6 and 10 ounces than any other treatment, suggesting that lack of P fertilizer application reduced tuber set. The contrast comparing the zero-P treatment with the other six treatments was statistically significant for every yield variable except the yields of culled tubers and U.S. No. 1 tubers. Overall, this treatment had relatively low total and marketable yields, low yield of U.S. No. 2 tubers, and larger tubers than the other treatments.

Tuber quality

Results for tuber quality metrics (specific gravity and internal disorders) are presented in Table 4. Treatment had no significant effect on any of these metrics, nor did the zero-P control treatment (treatment 1) differ significantly from the other six treatments as a group with respect to metrics of tuber quality.

Conclusions

Our results indicated that MES10 was at least as effective a P source as MAP and at least as effective a source of P and S as MAP blended with AS. A 37:63 blend of Susterra with MES10 produced the highest total and marketable yield, numerically, among the treatments applied. In a related study in 2021, we found that the same blend produced the second highest total and marketable yields, numerically, behind a 20:80 blend of the same products applied at the same rate, although neither blend significantly outperformed other P sources. Clearly, a combination of Susterra and MES10 provides P (and perhaps S) effectively relative to conventional sources. However, the same ratio of Susterra to MES10, applied at a lower P rate (90 versus 100 lbs/ac P_2O_5), did not perform significantly better than providing no P at all. Thus, while MES10 blended with Susterra is an effective source of P, under the condition of this study it was not effective enough to be applied at a rate just 90% that of conventional sources. We observed no effects of P treatment on tuber quality in this study, although P fertilizer application has been known to improve tuber specific gravity or dry matter in previous research.

Table 1. Treatments applied to Russet Burbank potato plants to evaluate MicroEssentials S10 and Susterra as sources of P.

Treatment		P2O5 rate (lbs/ac) from each source:			
Number	Description	MAP[1]	MicroEssentials S10[2]	Susterra[3]	Total
1	Control	0	0	0	0
2	MAP	100	0	0	100
3	MAP/AS[4]	100	0	0	100
4	MicroEssentials S10	0	100	0	100
5	63:37 MES10:Susterra	0	63	37	100
6	56:34 MES10:Susterra	0	56	34	90
7	68:32 MAP:Susterra	68	0	32	100

[1]Monoammonium phosphate: 11-52-0

[2]MicroEssentials S10 (MES10): 12-40-0-10S

[3]Susterra: 14-24-0-10S

[4]Ammonium sulfate: 21-0-0-24S

Table 2. Soil characteristics in the field before fertilizer application.

0 - 2 feet	0 - 6 inches				
Primary macronutrients			Secondary macronutrients		
NO_3^--N	Bray P	K	Ca	Mg	SO_4-S
(mg·kg^{-1} soil)					
0.4	24	95	780	148	11.4

0 - 6 inches							
Micronutrients					Other characteristics		Cation exchange capacity
Fe	Mn	Zn	Cu	B	pH	Organic matter (%)	
(mg·kg^{-1} soil)							
14	12.0	1.7	0.70	0.16	6.9	1.2	6.3

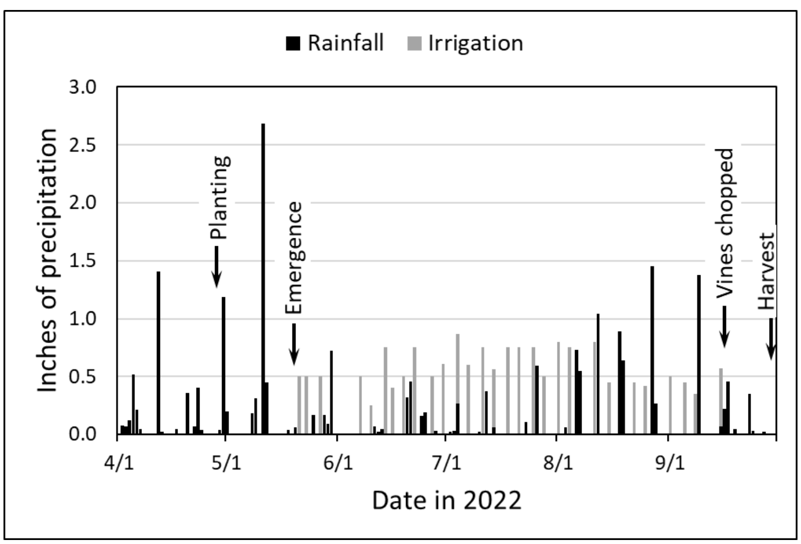

Figure 1. Inches of rainfall and irrigation in the study field in 2022. Irrigation amounts were determined by the checkbook method of irrigation scheduling. Monthly rainfall totals were as follows: April, 4.63 inches; May, 5.08 inches; June, 1.32 inches; July, 1.48 inches; August, 5.64 inches; September, 2.58 inches. Irrigation started on May 21 and ended on September 15. Monthly total irrigation amounts were as follows: May, 1.30 inches; June, 4.45 inches; July, 5.15 inches; August, 3.62 inches; September, 1.87 inches.

Table 3. Effects of P treatments on Russet Burbank tuber yield, size, and grade. Values within a column that have a letter in common are not significantly different from each other (at P ≤ 0.10) based on pairwise comparisons. Pairwise comparisons were only considered where the treatment effect was significant (P ≤ 0.10).

Treatment			Yield ($CWT \cdot ac^{-1}$)									
Number	Description	P_2O_5 (lbs/ac)	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2	Mark
1	Control	0	7	34 b	36 b	108 d	145 d	209 a	532 d	412	87	499
2	MAP	100	8	58 a	57 a	159 abc	165 bcd	139 b	578 bc	414	106	520
3	MAP/AS	100	9	66 a	50 a	151 bc	179 ab	148 b	594 abc	407	122	529
4	MicroEssentials S10	100	7	59 a	56 a	175 a	171 abc	148 b	609 ab	422	128	550
5	63:37 MES10:Susterra	100	6	66 a	57 a	161 ab	190 a	157 b	632 a	439	127	565
6	56:34 MES10:Susterra	90	6	59 a	56 a	143 bc	169 abc	136 b	564 cd	387	118	504
7	68:32 MAP:Susterra	100	7	59 a	61 a	137 c	150 cd	162 b	569 bcd	401	109	510
Effect of treatment (P-value)			0.9348	**0.0090**	*0.0576*	**0.0015**	**0.0264**	**0.0402**	**0.0140**	0.4986	0.2768	***0.***
Contrast: effect of P (1 vs. 2-7)			0.9378	**0.0002**	**0.0020**	**0.0001**	**0.0141**	**0.0012**	**0.0047**	0.9956	**0.0298**	***0.***

Table 4. Effects of P treatments on hollow heart, brown center, scab, specific gravity, and dry matter content of Russet Burbank tubers.

Treatment			Hollow heart	Brown center	Scab	Specific gravity	Dry matter content (%)
Number	Description	P_2O_5 (lbs/ac)	- ----------- Percent of tubers		------------		
1	Control	0	10	11	8	1.0710	20.0
2	MAP	100	10	11	7	1.0706	19.6
3	MAP/AS	100	14	14	8	1.0708	20.6
4	MicroEssentials S10	100	15	15	7	1.0715	20.6
5	63:37 MES10:Susterra	100	17	17	7	1.0740	20.2
6	56:34 MES10:Susterra	90	14	14	9	1.0694	19.3
7	68:32 MAP:Susterra	100	12	10	10	1.0698	19.2
Effect of treatment (P-value)			0.8805	0.8887	0.9971	0.2497	0.6702
Contrast: effect of P (1 vs. 2-7)			0.4315	0.5871	1.0000	0.9606	0.9443

Effects of soil health management strategies, rotation length, and cultivar on disease incidence and potato yield and quality

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Summary

Reducing soil disturbance is among the most effective approaches to improving soil health, but severe soil disturbance is inherent to potato agriculture. The SCRI Potato Soil Health Project is a nationwide, multi-institutional effort to assess the viability of other approaches to improving soil health in potato cropping systems. We present the results of the Minnesota field study from this project, evaluating the effects of rotation length, chemical fumigation, pro-microbial management, and cultivar choice on potato yield, size, and quality in a field with a history of potato early dying and low yield. Effects of rotation length were evaluated using a two-year rotation and a three-year rotation. Within each rotation, three management regimes were evaluated: (1) a conventional regime with soil fumigation before each potato year and limited intervention to improve or maintain soil health, (2) a pro-microbial regime with chemical fumigation replaced with biofumigation in the second potato year, applications of composted poultry manure, and the use of cover crops and alternative rotation crops to improve soil health, and (3) a no-fumigant regime that was identical to the conventional regime except that no chemical fumigant was applied. Russet Burbank and Russet Norkotah were both grown under the conventional and promicrobial regimes, while Russet Burbank and Bannock Russet (which, unlike Russet Burbank, is resistant to *Verticillium* wilt) were grown under the no-fumigant regime. The three-year rotation outperformed the two-year rotation in terms of yield, tuber size and tuber specific gravity, with a lower prevalence of *Verticillium* symptoms in the tubers. Norkotah Russet was especially affected by rotation length. Bannock Russet under the no-fumigant regime performed as well or better than Russet Burbank under the fumigated conventional regime, except that Bannock tubers had a much higher prevalence of hollow heart. For Russet Burbank, the promicrobial treatment generally produced similar or worse results than the fumigated conventional treatment in terms of tuber yield and quality. For Russet Norkotah, the two management regimes performed similarly, overall. Although the prevalence of common scab in this cultivar was numerically higher in the promicrobial treatment, the difference was not significant in pairwise comparisons. However, soil health benefits to tuber yield and quality over a single rotation are expected to be small. Extending the study for at least four more years (two, three-year rotations and three, two-year rotations) would most likely be more informative. Analyses of the effects of these management strategies on soil health are underway and will provide insight into how these regimes influence soil health metrics and the microbial community.

Background

Maintaining and improving soil health in agricultural systems is essential to long-term environmental and economic sustainability. Reducing soil disturbance is among the most effective approaches to improving soil health, but severe soil disturbance is inherent to potato production. The SCRI Potato Soil Health Project is a nationwide, multi-institutional effort to assess the viability of other approaches to improving soil health in potato cropping systems.

Here, we present the results of the Minnesota field study from this project, evaluating the effects of rotation length, chemical fumigation, pro-microbial management, and cultivar choice on potato yield, size, and quality.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2019-2022 on a Hubbard loamy sand soil. Results for 2022 are presented. Prior to this study, the site was used for commercial potato production on a three-year rotation for several decades. The site was selected because it had a history of potato early dying and low yields, suggesting poor soil health. The 2018 crop was soybeans. The study was arranged in a split-plot randomized complete block design with five replicates. Whole plots were defined by rotation length: either two-year or three-year. Subplots were divided among six treatments defined by potato cultivar (Russet Burbank, Russet Norkotah, or Bannock Russet) and management regime (conventional, promicrobial, or no-fumigant). The management plan for each treatment in each rotation is presented in Table 1.

2022 management

Plots under the conventional management regime were fumigated with Vapam on October 20, 2021. Preplant soil samples were collected on April 13, 2022, and sent to Pest Pros and Agvise to be analyzed for pathogens, soil chemistry, and soil health metrics. Penetrometer readings were taken at four locations per plot. Manure was applied to plots under the pro-microbial management regime on April 21. On April 25, 200 lbs/ac MOP (0-0-60) and 200 lbs/ac SulPoMag (0-0-22-21S-11Mg) were broadcast applied to the entire field, providing 164 lbs/ac K_2O equivalent, 42 lbs/ac S, and 22 lbs/ac Mg. All plots were planted on May 5. Rows were spaced 36 inches apart and a mixture of cut and whole 3-oz. seed tubers were planted by hand with 12-inch spacing. Plots in the conventional and no-fumigant treatments received 30 lbs/ac N as urea (46-0-0) along with other nutrients as required. On May 23, 100 lbs/ac N was side dressed as urea and the rows were hilled. On June 28, 60 DAP soil samples were collected and sent to Agvise to be analyzed for soil health metrics and soil chemistry. On June 30, 20 lbs/ac N as 28% UAN was applied to all plots. Plots planted in Russet Burbank and Bannock Russet received additional applications on July 11 and 25.

On August 16, green cover estimates and disease ratings were made in all Russet Norkotah plots. On August 17, Russet Norkotah vines were beaten with a flail mower. The tubers were harvested on August

31 and sorted on September 1. Green cover and disease ratings were performed on Russet Burbank and Bannock Russet plots on September 14. The vines were beaten with a flail mower on September 15, and the tubers were harvested on September 29 and sorted on October 5. A 50-tuber subset of each harvest sample was evaluated for common scab, vascular browning (a symptom of *Verticillium* wilt), and hollow heart. Specific gravity was measured on a 25-tuber subsample.

Results

Tuber yield, size, and grade

Results for tuber yield, size, and grade are presented in Table 3. Total, U.S. No.1, and marketable yield were higher in the three-year rotation than the two-year rotation. In the two-year rotation, Russet Burbank with conventional management and Bannock Russet without fumigation had significantly higher marketable yield than the other treatments, while both Russet Norkotah treatments had significantly lower yield than the other treatments. In the three-year rotation, Bannock Russet without fumigation had significantly higher yield than any treatment but Russet Burbank with conventional management, which had higher yield than Russet Burbank without fumigation or Russet Norkotah under conventional fumigation.

In both rotations, Russet Burbank had higher marketable yield under conventional management than promicrobial or no-fumigant management. In contrast, Russet Norkotah had numerically higher yields under promicrobial management than conventional management. All treatments with Russet Burbank had significantly greater yields of U.S. No. 2 tubers than all treatments with other cultivars.

The percentage of yield in tubers over six or ten ounces was also higher, averaged across cultivar and management, in the three-year rotation than the two-year rotation. This rotation effect was profound in Russet Norkotah in pairwise comparisons but not significant for Russet Burbank under any management regime. In the two-year rotation, Russet Burbank had significantly less of its yield in tubers over six ounces when it was under no-fumigant management than under the other two regimes.

Tuber quality

Results for tuber quality are presented in Table 4. Russet Burbank produced tubers with lower specific gravity than Russet Norkotah, which produced lower specific gravity than Russet Bannock. Overall, specific gravity was higher in the three-year rotation than the 2-year rotation, although Bannock showed a non-significant trend in the opposite direction. In Russet Burbank, the conventional treatment produced higher specific gravity than the other two management regimes, with the difference being significant under the 3-year rotation.

Common scab was rare in Bannock Russet. It was more common, overall, in Russet Norkotah than in Russet Burbank. It was also more common in the promicrobial treatment than the conventional treatment, based on contrasts.

The prevalence of vascular browning due to *Verticillium* was higher, on average, in the two-year rotation than the 3-year rotation. Russet Bannock had a lower prevalence of *Verticillium* than Russet Burbank in the no-fumigant treatment, and Russet Burbank had a lower prevalence than Russet Norkotah, averaged across the conventional and promicrobial treatments. There was no significant difference in *Verticillium* prevalence between the conventional and promicrobial treatments. In the three-year rotations, Russet Burbank had a significantly higher prevalence of *Verticillium* vascular browning in the no-fumigant treatment than the conventional treatment.

Bannock Russet had a much higher prevalence of hollow heart than the other two cultivars. In Russet Burbank, the prevalence of hollow heart was higher in the three-year rotation than the two-year rotation, while in Russet Norkotah, hollow heart was nearly absent in the three-year rotation.

Discussion and Summary

The benefits of using a three-year rotation over a two year rotation were clear in terms of tuber yield, size, specific gravity, and the prevalence of *Verticillium* symptoms in tubers. Bannock Russet, which was selected for its resistance to *Verticillium* wilt, produced yields with no fumigation similar to those of Russet Burbank under conventional management, in which the field was fumigated with Vapam before each potato year. Russet Bannock tubers also had a lower prevalence of vascular browning and higher specific gravity than Russet Burbank, whether Russet Burbank was grown under a conventional or no-fumigant management regime. However, the prevalence of hollow heart in Russet Bannock was quite high. Overall, growing Bannock Russet without fumigation may be a viable alternative to growing Russet Burbank and applying fumigant before every potato year. However high hollow heart incidence, late maturity, and poor skin set in Bannock Russet may reduce acceptability under Minnesota growing conditions.

For Russet Burbank, the promicrobial treatment generally produced similar or worse results than the conventional treatment in terms of tuber yield and quality. For Russet Norkotah, the two management regimes performed similarly, overall. Although the prevalence of common scab in this cultivar was numerically higher in the promicrobial treatment, the difference was not significant in pairwise comparisons. However, soil health benefits to tuber yield and quality over a single rotation are expected to be small. Extending the study for at least four more years (two, three-year rotations and three, two-year rotations) would most likely be more informative. Analyses of the effects of these management strategies on soil health are underway and will provide insight into how these regimes influence soil health metrics and the microbial community.

Table 1. Treatments applied over a single two-year or three-year rotation to Russet Burbank, Russet Norkotah, and Bannock Russet potatoes to evaluate strategies for improving soil health in potato cropping systems.

Rotation	Cultivar	Management	2018	2019	2020	2021	2022
2-year	Russet Burbank	Conventional	Soybeans	Soybeans, fall Vapam	Russet Burbank, fall rye	Soybeans, fall Vapam	Russet Burbank, fall rye
	Russet Norkotah		Soybeans	Soybeans, fall Vapam	Russet Norkotah, fall rye	Soybeans, fall Vapam	Russet Norkotah, fall rye
	Russet Burbank	Pro-microbial	Soybeans	Soybeans, fall Vapam	Manure, Russet Burbank, fall rye	Field peas, then mustard cv 'Caliente 199', fall rye	Manure, Russet Burbank, fall rye
	Russet Norkotah		Soybeans	Soybeans, fall Vapam	Manure, Russet Norkotah, fall rye	Field peas, then mustard cv 'Caliente 199', fall rye	Manure, Russet Norkotah, fall rye
	Russet Burbank	No fumigant	Soybeans	Soybeans	Russet Burbank, fall rye	Soybeans	Russet Burbank, fall rye
	Bannock Russet		Soybeans	Soybeans	Bannock Russet, fall rye	Soybeans	Bannock Russet, fall rye
3-year	Russet Burbank	Conventional	Soybeans, fall Vapam	Russet Burbank, fall rye	Corn, fall Vapam	Soybeans, fall Vapam	Russet Burbank, fall rye
	Russet Norkotah		Soybeans, fall Vapam	Russet Norkotah, fall rye	Corn, fall Vapam	Soybeans, fall Vapam	Russet Norkotah, fall rye
	Russet Burbank	Pro-microbial	Soybeans, fall Vapam	Manure, Russet Burbank, fall rye	Manure, corn	Field peas, then mustard cv 'Caliente 199', fall rye	Manure, Russet Burbank, fall rye
	Russet Norkotah		Soybeans, fall Vapam	Manure, Russet Norkotah, fall rye	Manure, corn	Field peas, then mustard cv 'Caliente 199', fall rye	Manure, Russet Norkotah, fall rye
	Russet Burbank	No fumigant	Soybeans	Russet Burbank, fall rye	Corn	Soybeans	Russet Burbank, fall rye
	Bannock Russet		Soybeans	Bannock Russet, fall rye	Corn	Soybeans	Bannock Russet, fall rye

Table 2. Effects of rotation length, management regime, and potato cultivar on tuber yield, size, and grade in 2022. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant (P<0.10).

Rotation	Management	Cultivar	Yield (CWT·ac^{-1})										% yield in tubers over:	
			Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2	Marketable	6 oz.	10 oz
2-year	Conventional	Russet Burbank	10 bc	48 def	46 d	87 abc	60 b	42 cd	293 bcd	198 bcd	38 a	236 bc	64 b	35 b
		Russet Norkotah	1 f	78 a	49 cd	39 d	13 d	6 h	186 g	100 g	7 b	108 e	30 e	10 f
	Promicrobial	Russet Burbank	9 bcd	45 ef	46 d	74 c	42 c	28 def	245 ef	153 ef	38 a	191 d	59 bc	29 bcd
		Russet Norkotah	1 f	80 a	67 ab	43 d	19 d	3 h	213 fg	124 fg	8 b	132 e	30 e	10 f
	No fumigant	Russet Burbank	7 bcde	60 bc	56 bcd	78 bc	43 c	12 gh	257 de	156 ef	34 a	190 d	51 d	21 e
		Bannock Russet	4 def	58 bcd	61 bc	100 a	50 bc	28 def	299 bc	230 bc	9 b	240 bc	59 bc	26 de
3-year	Conventional	Russet Burbank	17 a	66 b	61 bc	83 abc	59 b	58 b	343 a	223 bc	37 a	260 ab	57 bcd	33 bc
		Russet Norkotah	4 cdef	51 cde	58 bcd	87 abc	46 bc	21 efg	268 cde	208 bcd	4 b	212 cd	57 bcd	25 de
	Promicrobial	Russet Burbank	17 a	57 bcde	53 cd	80 bc	53 bc	50 bc	309 abc	193 cde	42 a	235 bc	59 bc	33 bc
		Russet Norkotah	2 ef	57 bcd	77 a	92 abc	60 b	16 fgh	305 abc	237 b	9 b	246 bc	55 cd	25 de
	No fumigant	Russet Burbank	10 b	63 bc	57 bcd	82 abc	48 bc	32 de	293 bcd	180 de	39 a	220 cd	55 cd	27 cde
		Bannock Russet	0 f	38 f	50 cd	95 ab	77 a	74 a	334 ab	285 a	11 b	296 a	74 a	45 a
AVOVA effects (P-values)	Rotation		**0.0142**	**0.0370**	0.1404	**0.0011**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.6377	**<0.0001**	**<0.0001**	**<0.0001**
	Treatment		**<0.0001**	**0.0010**	**0.0026**	**0.0018**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	Rotation*treatment		0.1306	**<0.0001**	0.2282	**0.0012**	**0.0048**	0.1038	0.4807	**0.0340**	0.9144	**0.0406**	**<0.0001**	**0.0073**
Contrasts (P-values)	Burbank v. Norkotah		**<0.0001**	**0.0008**	**0.0045**	**0.0096**	**<0.0001**	**<0.0001**	**<0.0001**	***0.0502***	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	Conventional v. Promicrobial		0.6895	0.7959	***0.0639***	0.7691	0.7929	***0.0912***	0.7081	0.6478	0.3627	0.7972	0.4885	0.5503

Table 3. Effects of rotation length, management regime, and potato cultivar on tuber quality and disease symptom prevalence in spring 2022. Values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the effect of treatment is significant (P<0.10).

Rotation	Management	Cultivar	Specific gravity	Common scab	*Verticillium* brown ring	Hollow heart
				% of tubers		
2-year	Conventional	Russet Burbank	1.0536 f	31 cd	61 bc	4 cde
		Russet Norkotah	1.0617 d	44 abcd	69 ab	6 cde
	Promicrobial	Russet Burbank	1.0507 f	46 abc	56 bcd	5 cde
		Russet Norkotah	1.0629 cd	54 a	76 ab	7 bcd
	No fumigant	Russet Burbank	1.0513 f	31 d	55 bcd	4 cde
		Bannock Russet	1.0752 a	2 e	44 de	26 a
3-year	Conventional	Russet Burbank	1.0574 e	38 bcd	35 e	12 b
		Russet Norkotah	1.0653 bc	39 bcd	59 bc	0 e
	Promicrobial	Russet Burbank	1.0519 f	38 bcd	53 cd	13 b
		Russet Norkotah	1.0667 b	53 ab	57 bcd	1 de
	No fumigant	Russet Burbank	1.0523 f	45 abcd	62 bc	11 bc
		Bannock Russet	1.0731 a	2 e	15 f	28 a
AVOVA effects (P-values)	Rotation		**0.0107**	0.8321	**0.0003**	0.1847
	Treatment		**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	Rotation*treatment		0.1109	0.5279	**0.0330**	**0.0230**
Contrasts (P-values)	Burbank v. Norkotah		**<0.0001**	**0.0493**	**0.0017**	**0.0098**
	Conventional v. Promicrobial		***0.0978***	**0.0333**	0.2789	0.6416

Data Report for UMN Potato Breeding Program 2022

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Nitrogen Timing

Aim: At the research planning meeting in 2021 growers identified nitrogen efficiency as a crucial target for our breeding program. We've been working on nitrogen efficiency especially in red potatoes since we restarted the breeding program in 2017. In 2017 and 2018 we grew eleven of the red legacy clones and two checks at two nitrogen (N) levels to assess N use efficiency[1]. Although we did not observe a clone specific response, we did see an effect of N on quality traits including lightness. We also found that selecting for NUE in low N environments may reveal genotypes that have a more static N response in varying N environments. Further, we found that response to selection was possible and breeding for improved NUE in red potatoes is an achievable breeding objective.

We hypothesized that the lack of clone specific response was in part due to the extreme difference in the two N rates. Therefore in 2018 and 2019 we grew a smaller number of red legacy clones at five nitrogen rates[2]. Skin color and yield were affected by N rate in a genotype specific manner. These results were encouraging to us by suggesting we can select for potato breeding lines that yield well with good quality at reduced N levels.

Timing of N application has been shown to effect N efficiency in potatoes[3]. We proposed to test generally if the response to the timing of N application is clone specific in red fresh market potatoes, and specifically identify the ideal N rate and timing for our legacy clones with sufficient seed.

Methods: Three replications of eight clones were planted at the University of Minnesota's Sand Plains Research Farm (SPRF), on May 11, 2021 and May 10 in 2022, in three row plots. Each row contained 15 plants with 1 ft spacing. The clones planted were Chieftain, Dark Red Norland, Pontiac, and the five legacy lines MN12006WW-01R, MN13025PLWR-08R, MN13026PLWR-02R, MN14006W-01R, and MN14022W-01R. A starter fertilizer rate of 45 lbs/A was applied to all plots just prior to planting. All plots received a total of 90 lb/A of added N. For 1/3 of the plots N was applied pre-plant and 1 week later. For 1/3 of the plots, N was applied pre-plant, one week later and at emergence, For the remaining plots N was applied pre-plant, one week later, at emergence and at tuber bulking. All N applied after pre-plant was applied over the top of the center row. Plots were vine-killed on August 23, and harvested on September 7 in 2021 and vine-killed August 15, and harvested September 12 in 2022. Harvested tubers were then graded by the Agray tuber grader at the USDA potato research facility in East Grand Forks MN providing yield and size distribution data in 2021. In 2022 the tuber yield was graded in Becker using Exeter grading machine. Finally, Tubers were returned to Saint Paul to be analyzed with our TubAR image analysis protocol, providing skin, color, and shape data[4]. Skin color is measured using a Lab color scheme meaning that it can be broken down into redness (red vs. green) and lightness (white vs. black)[5]. Data was analyzed in R using ANOVAs and LSDs.

Results: Clone significantly contributed to all traits but oversized yield (Table 1). We saw no significant effect of the timing of N application. In general, we did not see a clone specific N response. However we did see a clone specific change in shape as a result of the timing of application (Figure 1). Specifically, clones that were the most oblong over all (low roundness score), MN13025PLWR-008 and MN12006WW-001, had different shapes under different N application schedules. In both cases application at planting and emergence led to the roundest tubers, although for MN12006WW-01 this treatment was indistinguishable from a single N application.

Table 1. Significance table from ANOVA analysis of N timing experiment.

Phenotype	Clone	N applications	C*N Interaction	Year
Total yield	p<0.001	NS	NS	P<0.001
<4 oz yield	p<0.001	NS	NS	P<0.001
4-6 oz yield	p<0.001	NS	NS	P<0.05
6-10 oz yield	p<0.001	NS	NS	NS
>10 oz yield	P<0.001	NS	NS	P<0.001
Lightness	P<0.01	NS	NS	P<0.001
Redness	P<0.001	NS	NS	P<0.001
Roundness	p<0.001	NS	P<0.001	NS

The highest yielders were Pontiac, MN13025PLWR-08R, MN12006WW-01R, and MN14006W-01R (Figure 2). This pattern was consistent for both mediums and larges suggesting marketable tubers are driving yield. However while Pontiac had the lightest tubers MN13025PLWR-08R, MN12006WW-01R, and MN14006W-01R had the darkest (Figure 3) and all the legacy lines tested were redder than the checks (Figure 4).

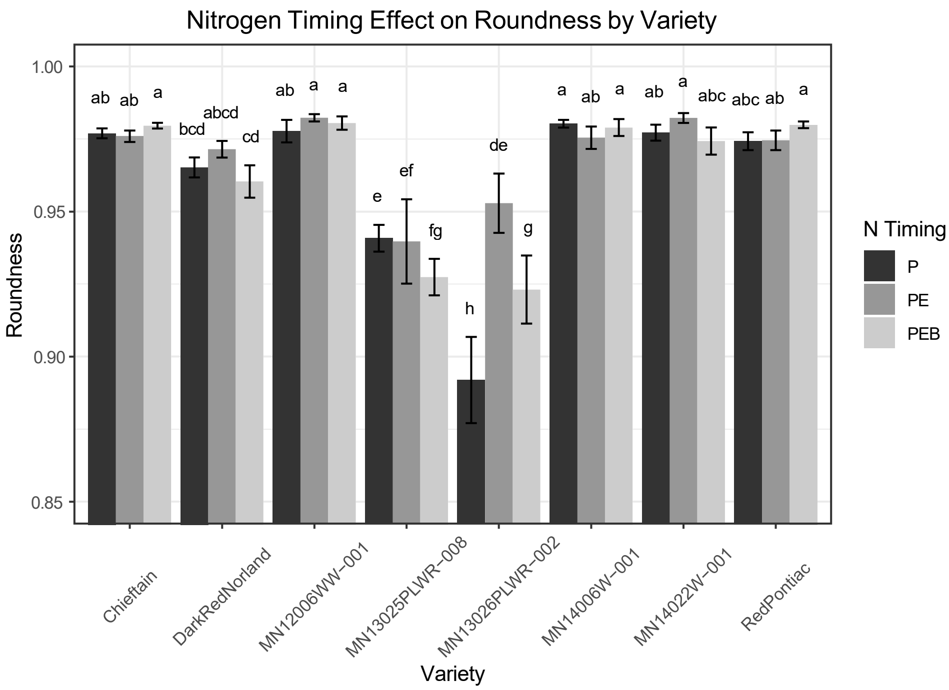

Figure 1. The interaction between the effect of variety and nitrogen timing in determining tuber shape. Tuber shape was scored using image analysis on a scale from 0-1 where 1 was a perfect circle. The three N timing treatments were 100% application at planting (P), 50% application at planting and 50% at emergence (PE), and three equal applications at planting, emergence, and bulking (PEB)

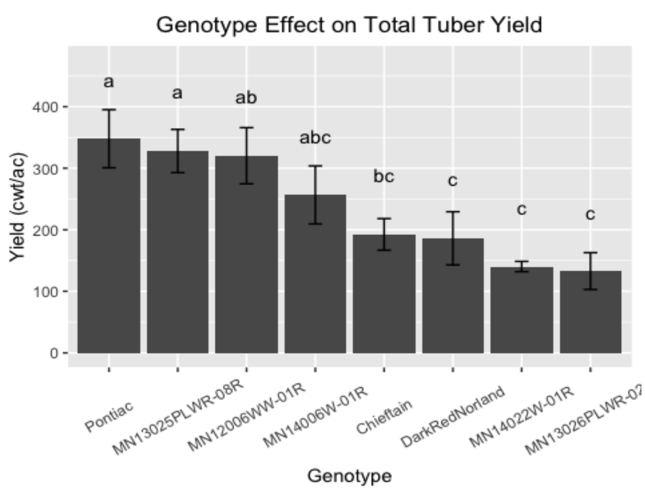

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Figure 2. Total yield by genotype N timing experiment

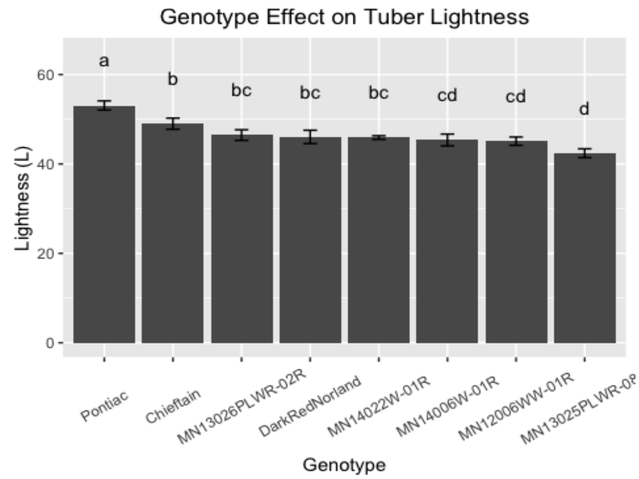

Figure 3. Lightness by genotype N timing experiment

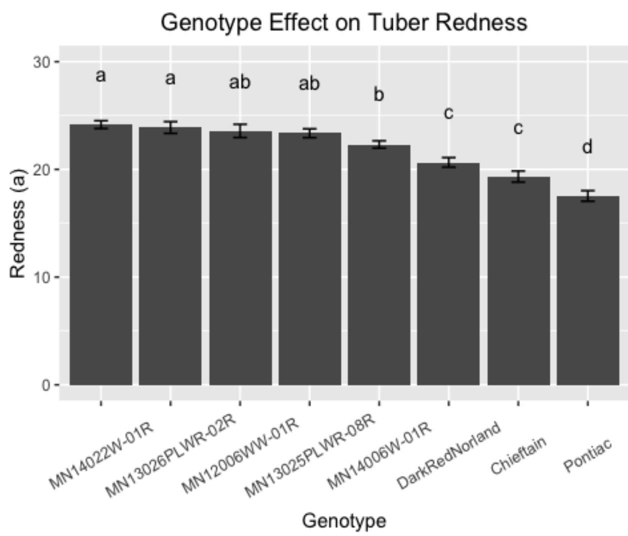

Figure 4. Redness by genotype N timing experiment

Conclusion: While clones differ in their N requirements as observed in previous reports[1, 2], our results suggest that ideal N application timing is consistent across clones. These results were pooled over two years providing us with confidence that the easiest N timing (all at hilling), is effective for our selection environment. The exception to this, is that oval clones may become rounder if N application is split between hilling and emergence. This observation should be tested in a wider range of genotypes.

This experiment also let us collect additional data on some of our red fresh market legacy clones three of which outperformed the checks by most measures.

Data Tracking

Aim: Breeding programs, including ours, generate large amounts of data. As we add trials for things like nitrogen use efficiency, analyzing and organizing this data to make selections becomes increasingly computationally intense. To maximize our, and our collaborators use of the data we are generating we needed a database. We chose the Breedbase system originated at Cornell University because it is designed for complicated data including that generated by genomic breeding and high through-put phenotyping[6]. Additionally, it is browser based so that it is easy to access by multiple users even on their phones in the field. It is low cost, with a single price for any number of users. It is currently being used by the Agriculture Agrifood Canada Breeding Group, so unlike other breeding software it has already been adapted for use with clonal crops. There is a team actively working on maintaining the software and adding new features for their own research in other crops and our instance of the database will benefit from this research as well. Although it will be straightforward to use, the initial set-up steps are time intensive. In order to make this system work for our lab and open it to the other breeders in the North Central Region we had to establish trait ontologies, enter accessions and pedigrees, set up trials and locations, and re-load historical data.

Methods: We hired a technician who set up accessions and locations in Breedbase, loaded historical data, and wrote a trait ontology. We collaborated with the Endelman lab at University of Wisconsin to write a wrapper script that converts genotype data to a single variant call format so that all the data generated in different programs can be used in concert.

In talking to other groups which use Breedbase we discovered it works best with Field Book App, which allows us to take data in the field on a tablet and directly upload to the database. We purchased tablets and barcode printers and set up Field Book for phenotyping in the field, at grading, and during early generation selection. We are also configuring our new Exeter grader to work with the barcode system from Field Book and Breedbase.

Results: The North Central Region instance of Breedbase is set up and ready for use. We have uploaded all of the UMN breeding program data from the last three years. We are working with collaborating programs to upload their data. The next step is adding genotypic data which we expect to add in the next month or so. This will facilitate data organization, use, and sharing in the University of Minnesota Breeding program and with our collaborators in the region.

Generation of Germplasm

Aim: The UMN potato breeding program works to develop new cultivars in four distinct market classes (red, yellow, chip, and russet) with increased resistance to biotic and abiotic stress. We also aim to develop cultivars which require fewer inputs (fertilizer, pesticides, irrigation, etc.) Potatoes are highly responsive to their environment, so while we test cultivars for broad adaptability, we select specifically for Minnesota and North Dakota environments, growers, and markets.

Potatoes are highly heterozygous, meaning that even a cross between two high performing cultivars largely produces plants with no or low commercial value. Therefore, new cultivars are developed through a process of winnowing from a large number of unselected offspring from a cross, to a small number of promising clones. In the early stages of the breeding program we focus on generating a large pool of germplasm from which to select. 2022 marks the fifth field season of the re-vamped Minnesota Potato Breeding Program.

Methods:

FY1

We planted 26,000 single hills the majority of which were provided to us by collaborators at University of Maine, North Dakota State University, Texas A&M University, and the University of Colorado. All single hills were planted at the NCROC and selected using visual selection.

FY2

We evaluated 771 FY2 clones this year in 12-hill plots. Of these clones, 39% were chips, 22% were russet, 32% were red, and 7% were specialty. All clones were planted at the NCROC and selected using visual selection. Additionally, post-harvest we collected quantitative measures of: tuber shape, tuber color, and skin set, for each selected clone.

This was accomplished by arranging a subset of 10 tubers in a 3x4 grid in a Photosimile 200 lightbox, and images were taken with a Canon Rebel T6i camera using a 24mm lens, ISO 100, 1/30 sec shutter speed and aperture f/5.6. Following the methods of Caraza-Harter and Endelman[5]. Image analysis was performed in-house using the R package TuBAR[4]. These tubers were cut in half and internal defects were counted.

FY3

While FY3 is generally our preliminary yield trials we lost a lot of clones to PVY. We were able to identify clean seed for only 37 clones. For 8 of these we had sufficient seed to grow them in un-replicated 15-hill plot trials at Becker. The others were only grown for seed increase. Modoc, Chieftan, Red Norland, Dark Red Norland, Red Pontiac and Red LaSoda were used as checks for the red potatoes. Atlantic, Snowden, Cascade, Superior, and Lamoka were used as checks for the chippers. Russet Norkotah, Russet Burbank, Umatilla Russet, and Goldrush were used as checks for the russets. Vines were desiccated after 97 days for the red potatoes and 120 days for processors. Fresh market tubers were harvested 4 weeks after vine desiccation while processing tubers were harvested 3 weeks after desiccation. They were graded to obtain yield and size profile data. At grading two sub samples of 10 individuals were taken. The first for photography as described in FY2, the second to test specific gravity and chip and fry color.

In order to test specific gravity, we took a sample of ten tubers per clone which were weighed on a balance while suspended in the air in a mesh bag. The sample was then weighed while suspended in a sink containing about ten liters of tap water. Specific gravity was calculated as SG = weight in air /(weight in air – weight in water).

Chipping and russet potatoes were analyzed separately for chip/fry color. For the chipping potatoes, each potato in the sample was cut transversely, perpendicular to the stem-bud end axis. One cut was first made and discarded to provide a flat surface. Then that half was sliced three times to provide three slices per tuber for frying. The slices were blotted dry to remove surface moisture and then fried at 185° C for 2.0 minutes. For the frying potatoes, each potato was placed in a plank cutter longitudinally along the bud-stem end axis. A pneumatic piston forced the potato into the cutting grid cutting the potatoes into 9.0 x 21.0 mm planks. The planks were notched at the bud end, blotted dry, then fried at 190° C for 3.5 minutes.

Both chip and fry samples were photographed in a light box for visual evaluation. After photographing the chip samples were crushed by hand to a consistency of about 1.0 cm per “crumble”. These samples were then assessed in a Hunterlab analyzer which quantifies “darkness”.

All clones were genotyped using KASP technology from Intertek for two sources of PVY resistance (RYsto and RYadg) and Verticillium wilt resistance (Ve2). These three genes were chosen as targets for selection, due to the availability of low cost genotyping technology. Additionally 31 of the chipping clones were evaluated in 8-hills North Carolina as part of the Early Generation Southern Strategy Trial.

FY4-5

We grew both FY4 and FY5 as a replicated field trial in Becker MN with two 15-hill plots each. These were grown with both the FY3 plots and single replicate samples from North Dakota, Wisconsin, and Michigan. For each market class FY3-5, checks, and the clones from the North Central Region were grown in a partially replicated randomized design. The trial included 97 FY4 individuals: 47% fresh market, 29% russet, and 24% chip and 57 FY5 individuals: 46% fresh market, 40% chip, and 14% fresh market. They were phenotyped as above. Thirty of these clones were also grown in North Dakota, Wisconsin, and Michigan as part of the North Central Regional Trial and six were entered into the National Chip Processing Trial.

Results:

FY1

We selected 1.2% of the individuals over all to continue on in the program to year 2, resulting in 316 clones to be evaluated in 12 hills in 2022.

FY2

We selected 59.1% of the clones, resulting in 456 clones to be evaluated in preliminary yield trials in 2022.

FY3

We lost a lot of FY3 seed due to PVY and so we were not able to trial most of it at Becker. We will observe 29 clones for the first time next year. Of the 8 we were able to evaluate, we selected 6 chipping clones which will be evaluated as FY4 in summer 2023 (Table 2). They will also be evaluated in North Carolina as part of the EGSS. The mean specific gravity from our selections was 1.074, higher than all checks but Snowden. The mean yield for our selections was 107.25% of Atlantic yield.

Table 2. 2021 FY3 Chipping Selections (yield in % Atlantic)

Clone	Yield MN 2022	SG MN 2022
MN20CO18127-003	127	1.072
MN20AF7145-002	110	1.071
Atlantic	100	1.073
MN20CO18192-001	98	1.085
MN20ND17100-001	94	1.068
Cascade	82	1.060
Lamoka	59	1.071
Superior	27	1.064
Snowden	19	1.075

FY4-5

We selected 13 FY4 chips (Table 3) and 19 FY5 chips (Table 4) all of which out yielded Lamoka, Superior and Snowden. On average the FY4 selections yield 91.7% of Atlantic, and 5 out yielded Atlantic. The FY5 selections yielded 85.4% of Atlantic on average, and 3 out yielded Atlantic. The average specific gravity of the FY4 selections was 1.074 which is higher than all checks but Snowden. The average specific gravity of the FY5 selections was 1.077 which is higher than all checks.

Clone	Yield MN 2022	SG MN 2022	Yield MI 2022	SG MI 2022	Yield WI 2022	SG WI 2022	Yield NC 2022	SG NC 2022	Yield MN 2021	SG MN 2021	Yield NC 2021	SG NC 2021	Vert	PVY
MN19TX18093-001	165	1.071	160	1.068	125	1.063	172	1.062	147	1.073	26	NA	Tol	No
MN19TX18304-001	119	1.068	134	1.078	106	1.080	161	1.073	118	1.077	256	1.060	No	No
MN19AF6866-014	106	1.075	NA	NA	NA	NA	NA	NA	90	1.069	16	NA	Yes	No
MN19AF6892-009	102	1.089	NA	NA	NA	NA	NA	NA	80	1.074	129	1.070	No	Yes
MN19TX18211-001	102	1.070	NA	NA	NA	NA	NA	NA	88	1.064	200	1.054	yes	No
Atlantic	100	1.073	100	1.075	100	1.079	100	1.076	100	1.075	100	1.064	NA	NA
MN19AF6867-003	90	1.076	NA	NA	NA	NA	NA	NA	70	1.070	136	1.062	No	No
MN19TX18032-005	85	1.076	NA	NA	NA	NA	NA	NA	73	1.057	87	1.057	No	No
Cascade	82	1.060	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
MN19TX18032-007	75	1.074	NA	NA	NA	NA	NA	NA	58	1.069	127	1.078	No	No
MN19AF6869-013	74	1.083	NA	NA	NA	NA	NA	NA	75	1.062	31	NA	No	No
MN19TX18032-001	74	1.066	NA	NA	NA	NA	NA	NA	85	1.067	162	1.057	Yes	No
MN19AF6866-001	68	1.069	NA	NA	NA	NA	NA	NA	37	1.058	31	NA	Yes	No
MN19AF6866-009	67	1.079	NA	NA	NA	NA	NA	NA	49	1.056	83	1.053	No	No
MN19TX18280-002	66	1.063	NA	NA	NA	NA	NA	NA	72	1.074	56	NA	No	No
Lamoka	59	1.071	81	1.074	76	1.075	NA	NA	77	1.068	NA	NA	NA	NA
Superior	27	1.064	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Snowden	19	1.075	123	1.082	95	1.076	134	1.073	92	1.071	142	1.066	NA	NA

Several FY5 selections were part of Dr. Darrin Haagenson's storage trials at East Grand Forks. The stand out is MN18W17043-12 which produces very light chips after 8 months at 40 degrees (Figure 5). MN18W17037-33 will be entering Tier 2 of the National Chip Processing Trial and we will be submitting 9 additional chips to Tier 1.

Table 3. 2022 FY4 Chipping Selections (NAs indicate unmeasured phenotypes, "Tol" indicates a tolerant result in field testing but without a known resistance gene, Yields are presented as % Atlantic)

Table 4. 2022 FY5 Chipping Selections (NAs indicate unmeasured phenotypes, Yields are presented as % Atlantic)

Clone	Yield MN 2022	SG MN 2022	Yield MN 2021	SG MN 2021	Yield MN 2020	SG MN 2020	Yield NC 2021	SG NC 2021	Yield WI 2021	SG WI 2021	Yield MI 2021	SG MI 2021	PVY	Vert
MN18W17037-033	153	1.075	87	1.070	88	1.067	94	1.069	NA	NA	NA	NA	Yes	No
MN18W17039-005	123	1.078	89	1.072	122	1.070	NA	NA	108	1.084	103	1.080	Yes	No
MN18W17043-012	120	1.084	153	1.081	113	1.067	NA	NA	NA	NA	NA	NA	No	No
Atlantic	100	1.073	100	1.075	100	1.064	100	1.079	100	1.085	100	1.088	NA	NA
MN18TX17730-008	100	1.074	NA	NA	NA	NA	NA	NA	81	1.074	93	1.072	No	No
MN18AF6730-005	96	1.066	68	1.068	98	1.063	NA	NA	74	1.070	96	1.079	No	Yes
MN18TX17748-002	95	1.076	77	1.068	151	1.068	NA	NA	NA	NA	NA	NA	No	No
MN18W17043-002	93	1.091	93	1.072	63	1.067	103	1.079	NA	NA	NA	NA	Yes	No
MN18W17052-004	89	1.094	98	1.082	82	1.063	NA	NA	96	1.098	72	1.098	No	No
MN18W17037-027	85	1.071	59	1.065	103	1.062	NA	NA	NA	NA	NA	NA	No	Yes
Cascade	82	1.060	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
MN18W17043-006	82	1.078	76	1.069	125	1.071	NA	NA	100	1.078	71	1.085	Yes	Yes
MN18W17065-004	71	1.074	91	1.063	91	1.061	NA	NA	NA	NA	NA	NA	Yes	Yes
MN18AF6717-006	71	1.065	80	1.056	113	1.047	NA	NA	135	1.074	82	1.072	No	No
MN18W17037-034	68	1.085	117	1.066	88	1.062	NA	NA	93	1.076	85	1.081	Yes	Yes
MN18W17039-025	67	1.083	94	1.069	70	1.060	NA	NA	79	1.087	76	1.088	No	No
MN18AF6658-005	65	1.073	71	1.067	93	1.056	NA	NA	116	1.075	76	1.080	No	No
MN18AF6643-013	63	1.070	68	1.069	100	1.066	NA	NA	89	1.082	48	1.072	No	No
MN18AF6648-010	62	1.064	36	1.060	NA	1.057	NA	NA	NA	NA	NA	NA	No	No
MN18W17052-006	61	1.087	74	1.065	84	1.073	NA	NA	70	1.084	84	1.082	No	Yes
MN18W17043-017	59	1.085	95	1.069	133	1.067	83	1.077	102	1.085	102	1.084	No	No
Lamoka	59	1.071	77	1.068	NA	NA	NA	NA	98	1.084	87	1.081	NA	NA
Superior	27	1.064	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Snowden	19	1.075	92	1.071	NA	NA	NA	NA	104	1.081	88	1.087	NA	NA

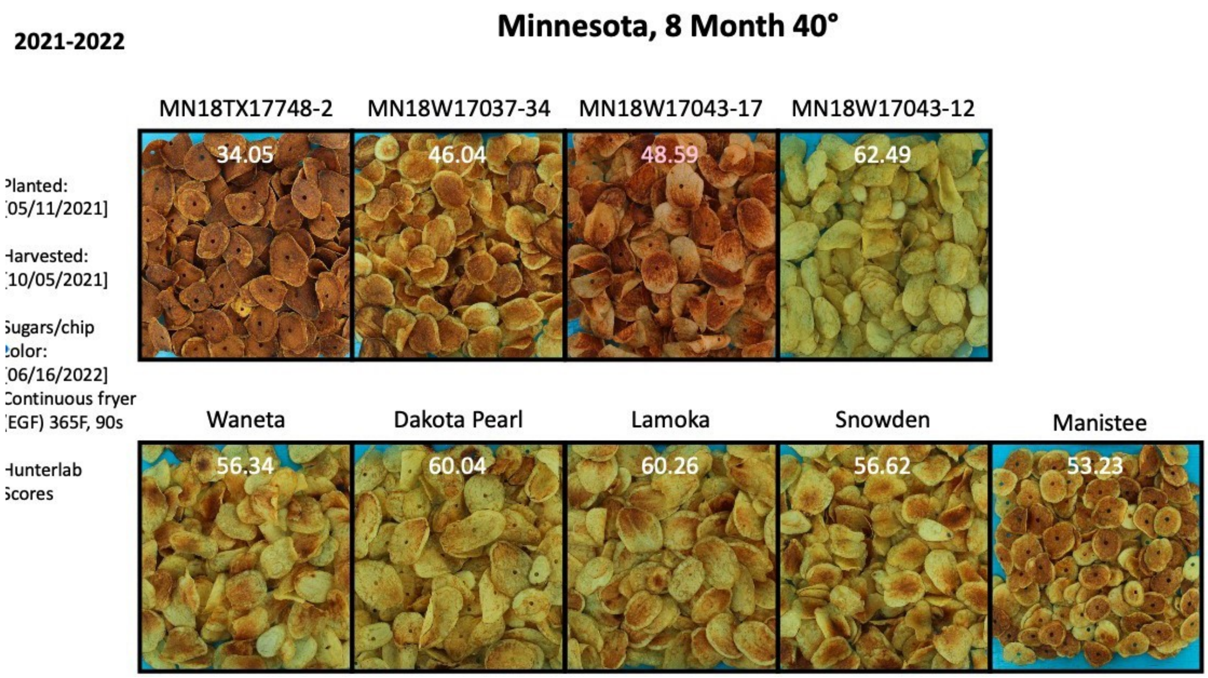

Figure 5. East Grand Forks storage trial data from 2021 showing images of chips made from tubers kept in storage for 8 months at 40 degrees.

We selected 10 FY4 russets (Table 5) and 3 FY5 russets (Table 6). All FY4 russets out yielded Goldrush (Table). On average they yielded 117% of Russet Burbank. The average specific gravity was 1.069, which is higher than all checks. Of the FY5 russets, two out yielded Russet Burbank and two show specific gravities suitable for chipping while the third shows potential as a high yielding fresh market variety.

Table 5. 2022 FY4 Russet Selections (NAs indicate unmeasured phenotypes, Yields are presented as % Russet Burbank)

Clone	Yield MN 2022	SG MN 2022	Yield MI 2022	SG MI 2022	Yield WI 2022	SG WI 2022	Yield MN 2021	SG MN 2021
MN19CO17066-001	137	1.068	NA	NA	NA	NA	68	1.063
MN19AOR16061-002	136	1.071	75	1.072	80	1.066	127	1.061
MN19CO17021-003	134	1.074	NA	NA	NA	NA	130	1.061

MN19AF7015-005	133	1.061	NA	NA	NA	NA	59	1.053
MN19AOR16061-007	129	1.066	67	1.066	101	1.066	63	1.056
Umatilla Russet	114	1.066	NA	NA	NA	NA	NA	NA
Russet Norkotah	113	1.060	54	1.061	112	1.070	54	1.055
MN19AOR16038-002	102	1.073	NA	NA	NA	NA	81	1.057
MN19AOR16065-001	101	1.068	NA	NA	NA	NA	136	1.065
Russet Burbank	100	1.067	100	1.075	100	1.071	100	1.060
MN19AF7015-002	100	1.073	NA	NA	NA	NA	67	1.057
MN19CO17072-005	99	1.066	NA	NA	81	1.078	116	1.068
MN19CO17072-004	99	1.066	NA	NA	NA	1.073	84	1.065
Goldrush	98	1.058	NA	NA	113	1.064	98	1.054

*Table 6. 2022 FY5 Russet Selections (NAs indicate unmeasured phenotypes, Yields are presented as percent Russet Burbank except for the * Yield which is presented as percent Russet Norkotah)*

Clone	Yield MN 2022	SG MN 2022	Yield MN 2021	SG MN 2021	Yield MN 2020*	SG MN 2020	Yield WI 2021	SG WI 2021	Yield MI 2021	SG MI 2021
MN18W17091-015	165	1.066	NA	NA	135	1.062	NA	NA	NA	NA
MN18W17091-005	128	1.045	133	1.054	206	1.057	80	1.074	79	1.072
Umatilla Russet	114	1.066	NA	NA	NA	NA	NA	NA	NA	NA
Russet Norkotah	113	1.067	54	1.055	100	1.052	92	1.069	73	1.073
Russet Burbank	100	1.067	100	1.060	NA	NA	100	1.077	100	1.072
Goldrush	98	1.058	98	1.054	NA	NA	89	1.071	76	1.070
MN18W17079-011	95	1.068	72	1.065	193	1.061	88	1.079	81	1.079

We selected 6red skinned white fleshed potatoes from FY4 (Table 7) and 5 from FY5 (Table 8). Only one out yielded Red Norland in 2022 although several had in previous years or other locations. All out yielded Modoc. Where these selections shine is quality traits. Color is made up of two components, redness (on a red to green scale) and lightness (on a black to white scale). These components should be looked at in combination, for instance while Dark Red Norland is not very red it is very dark and the combination creates the dark red color. Both redness and lightness are in part dependent on environment with 2022 producing lighter less red tubers than 2021 (Figure 6). The most desirable tuber phenotypes are in the upper left hand corner of the plot and are selections from the breeding program.

Table 7. 2021 FY4 Red Selections (NAs indicate unmeasured phenotypes. Yields are presented as percent Red Norland. Redness, roundness, lightness, and skinning were measured with TubAR digital imaging software. Redness is measured on a scale from

green -100 to red 100. Roundness is measured on a scale from 0 to 1, with 1 being a perfect circle. Lightness is measured on a scale from black 0 to white 100. Skinning is measured in percent area skinned.)

Clone	Yield MN 2022	Yield WI 2022	Yield MI 2022	Red 2022	Light 2022	Round 2022	Yield MN 2021	Red 2021	Light 2021	Round 2021	Skinning 2021	Vert
Red Norland	100	100	100	20.7	45.6	0.963	100	9.9	50.4	0.939	0	NA
Red LaSoda	92	90	137	22.8	44.9	0.982	54	11.2	NA	0.967	0.345	NA
Red Pontiac	85	NA	NA	NA	NA	NA	NA	8.6	55.6	0.958	0.020	NA
Dark Red Norland	84	106	97	21.2	47.2	0.977	101	11.6	48.5	0.952	0	NA
MN19ND1756-002	80	NA	NA	24.3	40.4	0.926	21	13.0	53.0	0.962	0.030	No
MN19ND1759-001	70	NA	NA	23.8	50.2	0.982	95	15.8	53.3	0.985	0	No
MN19AF6942-004	65	NA	NA	22.9	50.1	0.963	104	11.2	58.2	0.977	0.010	No
MN19ND14342-003	61	103	111	24.6	44.0	0.991	65	14.9	49.2	0.980	0.010	Yes
Chieftain	59	NA	NA	21.1	49.7	0.984	NA	12.0	52.8	0.979	0.570	NA
MN19ND1759-002	56	NA	NA	24.4	50.1	0.979	125	18.9	45.8	0.974	0.052	No
MN19AF6933-006	53	97	93	25.7	45.3	0.943	54	NA	NA	0.982	0.333	No
Modoc	39	NA	NA	NA	NA	NA	NA	11.9	53.2	0.965	0.220	NA

Table 8. 2021 FY5 Red Selections (NAs indicate unmeasured phenotypes. Yields are presented as percent Red Norland. Redness, roundness, lightness, and skinning were measured with TubAR digital imaging software. Redness is measured on a scale from green -100 to red 100. Roundness is measured on a scale from 0 to 1, with 1 being a perfect circle. Lightness is measured on a scale from black 0 to white 100. Skinning is measured in percent area skinned.)

Clone	Yield MN 2022	Red 2022	Light 2022	Skinning 2022	Round 2022	Yield MN 2021	Yield WI 2021	Yield MI 2021	Red 2021	Light 2021	Round 2021	Yield MN 2020	PVY
MN18CO15083-006	120	19.0	62.4	0.215	0.977	107	120	172	22.6	46.5	0.982	64	Yes
Red Norland	100	9.9	50.4	0	0.939	100	100	100	20.7	45.6	0.963	100	NA
Red LaSoda	91	NA	NA	0.345	0.967	54	89	82	22.8	44.9	0.982	NA	NA
Red Pontiac	85	11.2	55.6	0.020	0.958	NA	NA	NA	NA	NA	NA	NA	NA
Dark Red Norland	84	8.6	48.5	0	0.952	101	84	86	21.2	47.2	0.977	NA	NA
MN18W17026-004	81	9.9	63.0	0.005	0.978	117	NA	NA	18.2	51.4	0.980	42	No
MN18W17026-002	76	9.0	56.1	0	0.961	168	138	153	22.7	41.6	0.971	99	No
MN18CO15117-002	72	12.4	52.7	0	0.981	142	109	109	21.2	44.3	0.985	66	No
MN18W17009-001	60	13.8	56.5	0.035	0.980	123	131	136	20.3	46.3	0.986	48	No
Chieftain	59	12.0	52.8	0.052	0.974	NA	NA	NA	21.1	49.7	0.984	NA	NA
Modoc	39	11.9	53.2	0	0.980	NA	NA	NA	NA	NA	NA	NA	NA

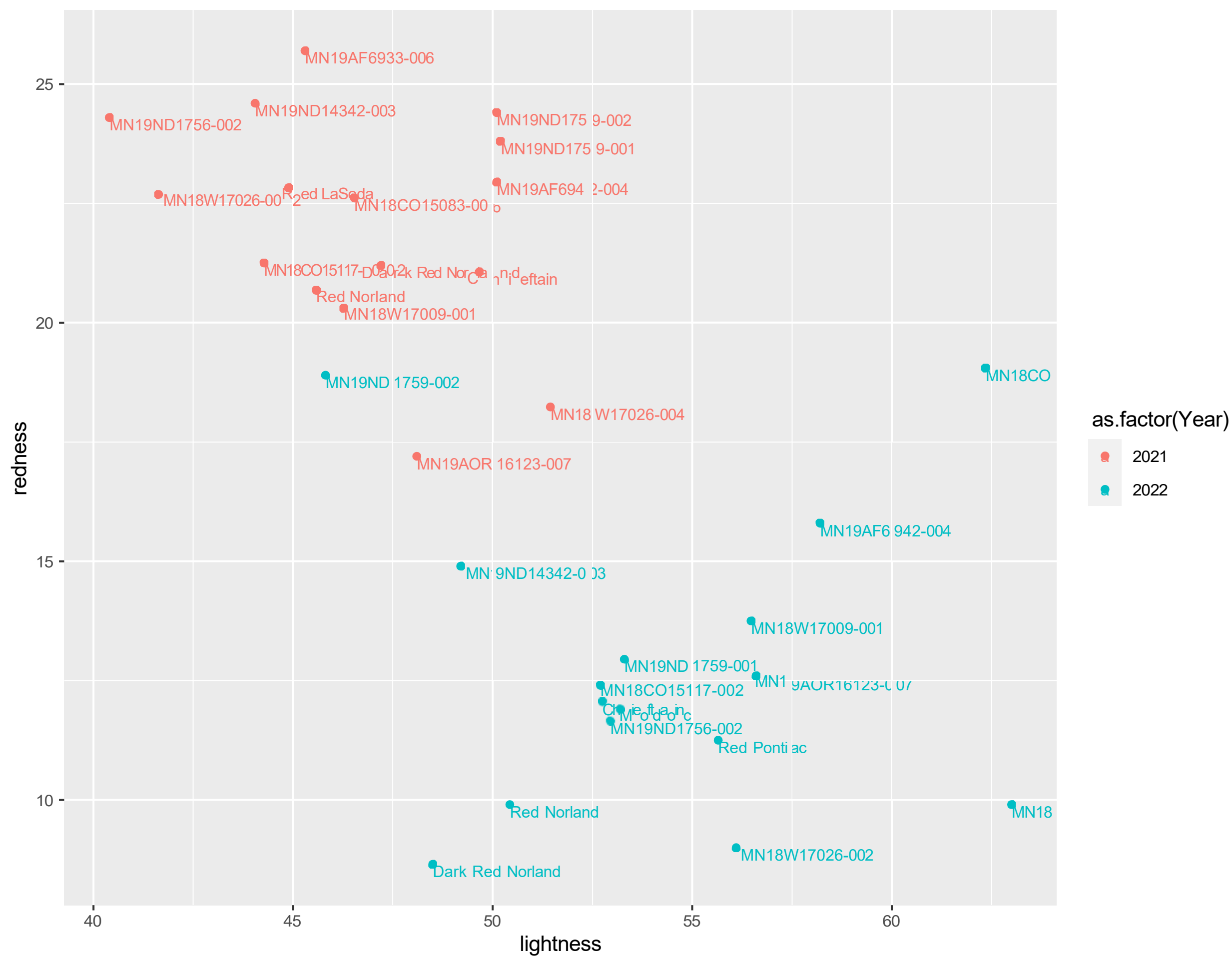

Figure 6. Tuber color phenotypes from red fresh market selections. Redness is measured on a scale of -100 (green) to 100 (red) and lightness is measured on a scale from 0 (black) to 100 (white). Desirable tuber phenotypes are to the upper left.

We selected 5 FY4 yellow skin and yellow flesh clones (Table 4) and 6 from FY5 (Table 5). All but 1 out yielded Yukon Gold and that clone performed well in previous years.

Table 9. 2022 FY4 Fresh market yellow selections (NAs indicate unmeasured phenotypes, Yield in 2022 is percent Yukon Gold while Yield 2021 is percent Red Norland)

Clone	Yield MN 2022	Yield MN 2021	PVY
MN19AF6945-003	162	168	Yes

MN19AF6945-005	194	111	No
MN19TX17722-003	178	101	No
Red Norland	211	100	NA
Yukon Gold	100	NA	NA
MN19TX18215-005	137	NA	NA

Table 10. 2022 FY5 Fresh market yellow selections (NAs indicate unmeasured phenotypes, Yield in 2022 is percent Yukon Gold while Yield 2021 is percent Red Norland)*

Clone	Yield MN 2022	Yield MN* 2021	Yield MN 2020	Yield WI 2021	Yield MI* 2021	Vert
MN18TX17760-4	66	132	193	NA	NA	No
Red Norland	211	100	100	114	352.5	NA
MN18CO16154-9	141	93	57	95	441	Yes
MN18CO16212-3	145	62	103	NA	NA	No
MN18CO16212-002	167	NA	108	NA	NA	No
MN18CO16213-002	112	78	37	75	72	No
MN18TX17760-002	115	52	241	138	154	No
Yukon Gold	100	NA	100	100	NA	NA

Polaris Gold

We have released a fresh market yellow skin yellow fleshed late season potato, Polaris Gold[7]. The inventor was the late Dr. Christian Thill, and the cross from which it was selected was W2257-2 x Dakota Pearl. This clone was being maintained by Dr. Tom Michaels, the interim breeder when I took over the program in 2017. At that time I had heard from several seed growers that there was demand for this clone. These anecdotes identify Polaris Gold as excellent for soups, stews, lefse, chips and au gratin. The release of Polaris Gold marks the first release of a potato by UMN since I took over the program. Seed is available through Kent Mason and Sandi Aarestad.

Conclusions

We have developed multiple generations of new germplasm that segregate for a variety of traits of interest. This material will continue to be evaluated, in 2023 and beyond, in order to identify promising new clones for Minnesota and North Dakota growers. We are excited to begin to make these varieties available through release and plan to release two legacy clones: a specialty purple and a long storing dual purpose russet in 2023.

Acknowledgements

Team: Our breeding program logistics were managed at by Dr. Thomas Stefaniak. Dr. Stefaniak also lead the N timing trial, although data was analyzed by Megan Harder. Megan Harder also set up Breedbase which is a database system run by Lukas Mueller at Cornell University. Other members of the lab who assisted in these projects include: Dr. Xiaoxi Meng, Husain Agha, Heather Tuttle, Michael Miller, Yusuf Muyideen, Adynn Stedillie, Ian Spencer, Julia Lau, Jessi Huege, John Larsen, Ena Vigil, Miranda Gregory, Dat Vo, and Adalyn Pederson.

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Turkey Manure for Potato Nutrition 2021 - 2022

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Executive summary

Turkey manure is a local source of N that has been used in potato production. With fertilizer prices increasing substantially in 2021 and 2022, alternative sources of fertilizer are important. The focus of this study was to evaluate turkey manure and Environmentally Smart Nitrogen (ESN) on Russet Burbank potato production. The overall objective of this project is to increase payable yield for potato growers in Minnesota and North Dakota. The use of 3 tons/a turkey manure with ESN or 5 tons/a turkey manure with or without ESN had similar yield to the grower standard. Based on these results and previous work, turkey manure has proven to be a suitable option for potato fertilizer.

Rationale for conducting the research

In 2019 and 2020 research was conducted to compare turkey manure with ESN or urea. At about a third of the total nitrogen, turkey manure had numerically lower yield but not a significantly different yield than ESN and urea in 2019 and in 2020. Describing the benefits of turkey manure as a source of nitrogen is important as the potato industry continues to seek more sustainable sources for plant nutrition. Building upon the previous work, we focused on different rates of turkey manure and the mixture of turkey manure with ESN. The objective of this study was to determine the best nitrogen fertilization option utilizing turkey manure as the major source of nitrogen and compare this to the grower standard fertilizer program.

Procedures

Field studies were established near Perham, MN in a commercial potato field in 2021 and 2022. A randomized complete block with four replications was utilized. Plots were planted on 28 April 2021 and on 28 May 2022 with Russet Burbank at 12 inch with-in-row spacing on 36-inch spaced rows. Prior to planting turkey manured was spread over the plot areas. The planting equipment and hilling was used to incorporate the turkey manure. In 2021, turkey manure was analyzed and found to have 51 lb N/ton, 49 lb P_2O_5/a, and 34 lb K_2O/a. In 2022 turkey manured had 47 lb N/ton, 37 lb P_2O_5/a, and 28 lb K_2O/a. Environmentally Smart Nitrogen was applied on 9 May 2021 and on 6 June 2022 and hilled in the following day. Vines were removed with a vine chopper on 7 September 2021 and harvested with a single row plot harvester on 9 September 2021. In the second year of the study vines were removed on 12 September and harvested on 16 September 2022. Following harvest, tubers were graded and sized according to USDA standards.

Yield differences between 2021 (434 cwt/a) and 2022 (392 cwt/a) were found because of the late planting in 2022. Because of this difference, yield data converted to a percent of the grower standard to combine data from 2021 and 2022. Data were analyzed in SAS with an analysis of variance. Differences in data were separated utilizing a Tukey pairwise comparison at p=0.05.

Results

Stand, stems per plant, and specific gravity were similar between treatments. Differences in 6-10 oz tubers, total yield, marketable yield, and the percent of tubers >6 oz were found between treatments (Table 1). When compared to the grower standing, the no nitrogen and 3 tons/a turkey manure treatments had fewer larger tubers. As a result, the total marketable yield and percentage of tubers >6 oz was less than the grower standard. Numerically, the additions of ESN to turkey manure increased the percent of tubers >6 oz and >10 oz. Tuber number echoed the results found by tuber yield. Based on these results and previous work, turkey manure has proven to be a suitable option for potato fertilizer. This work has found that turkey manure with the addition of ESN can benefit total yield and increase tuber size. An economic analysis should be conducted based on current fertilizer prices to determine what combination of turkey manure and ESN would be optimal for growing Russet Burbank.

Figure 1. Turkey manure trial near Perham, MN on August 31, 2022. Grower standard is on the left, 3 tons/a turkey manure in center, and no nitrogen on the right.

Table 1. Yield by size of Russet Burbank potato grown in 2021 and 2022 near Perham, MN with turkey manure treatments. Data are presented as a percentage of the grower standard (Treatment 1), except for specific gravity.

Treatment	Turkey manure	N	<3 oz	3-6 oz	6-10 oz		>10 oz	Total yield		Total marketable		>6 oz		>10 oz	Specific gravity
	tons/a	lb/a	% compared to grower standard												
1	0	250	0	0	0	ab*	0	0	a	0	ab	0	ab	0	1.074
2	0	0	37	4	-44	c	-38	-27	c	-30	c	-22	b	-22	1.070
3	3	0	28	6	-21	bc	-17	-17	bc	-18	bc	-13	ab	-4	1.074
4	3	50	21	16	-3	abc	42	-5	ab	-3	ab	4	ab	41	1.071
5	3	100	31	11	4	ab	20	-2	a	-1	ab	3	ab	18	1.070
6	5	0	53	8	-7	abc	8	-8	ab	-9	ab	-5	ab	11	1.071
7	5	50	16	0	17	a	78	0	a	3	a	18	a	72	1.070
8	5	100	19	-1	11	a	54	3	a	5	a	14	ab	48	1.069

*Means within the same column followed by the same letter are not significantly different according to Tukey pairwise comparison (P ≤ 0.05). No letters in a column indicate no differences between treatments.

Vine Kill Timing Effects on Skin Set of Russet Burbank and Umatilla Russet (2022)

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Executive summary

Skinning of tuber skins allow disease entry and water loss. However, it can cut the growing season short and potentially affect yield. A field trial was established near Clitherall, MN within a commercial field. Two nitrogen rates were applied grower standard (295 lb N/a) and grower standard + 60 lb N/a (355 lb N/a). Vines were desiccated at 21, 14, 10, 7, and 0 days before harvest. Skin set of Russet Burbank was best when vines were desiccated 21 days before harvest, but yield was significantly less compared to vine killing at 0-10 days before harvest. From this first year of research it appears that vine killing at 10 days prior to harvest can improve skin strength and reduced yield losses.

Rationale for conducting the research

When harvesting potato tubers, it is difficult to not damage potato tuber skins because of the quantity and speed of moving tubers. Skinning of tuber occurs when the periderm is not fully developed and it is easily rubbed off, broken, or peeled during handling. Potato skins are especially vulnerable to skinning when overfertilized with nitrogen (Figure 1). Skin set is important for potato tubers, because the skin protects tubers from water loss and disease entry. Infected tubers that are put into storage risk the storability of the entire bin as diseases can spread in storage. Understanding skin set of russet tubers following different periods of time after vine kill can assist in reducing storage diseases. Lulai and Orr (1993) reported in non-irrigated Russet Burbank the torque pressure needed to shear the skin was greatest at 14 to 28 days after vine kill, followed by 7 days after vine kill, and the least amount of force needed was at 0 days after vine kill (Figure 2). Less information is available on nitrogen rate and timing of skin set strength of irrigated Russet Burbank potatoes. The objective of this project was to determine skin set strength of Russet Burbank following different lengths of vine desiccation.

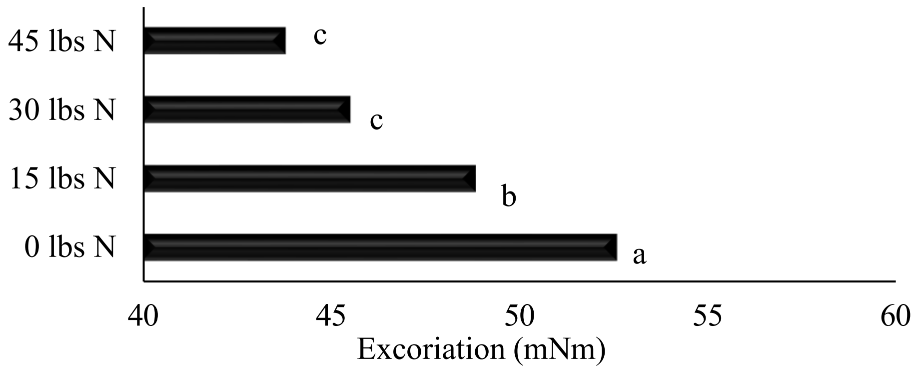

Figure 1. The resistance to skinning (force in milliNewton meters, mNm) of Red Norland potatoes 2 hours post-harvest among treatments with additional nitrogen rates above commercial N of 235 lb N/a. Treatments with the same letter are not significantly different according to Fisher's protected least significant difference test (P=0.05) (Bauske and Robinson, 2017).

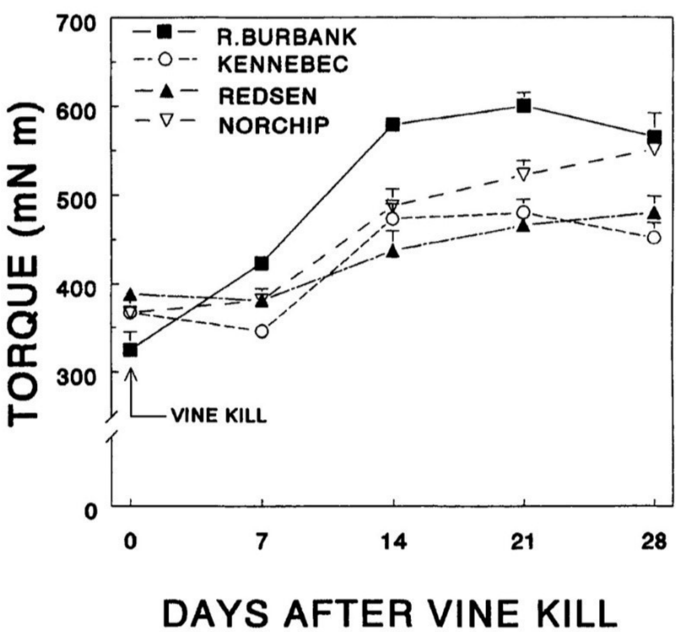

Figure 2. Differences in skin strength of four potato cultivars in 1991 non-irrigated research (Lulai and Orr, 1993).

Procedures

A field study was setup in a commercial field near Clitherall, MN as a randomized complete block design with a factorial arrangement of treatments. Factor A was nitrogen rates at 1) Grower standard and 2) grower standard nitrogen plus an additional 60 lb N/a. Factor B is time after vine kill (Reglone at 1.5

pt/a) at 0, 7, 10, 14 and 21 days. Vine kill at 10, 14, and 21 days received a second treatment of Reglone at 1.5 pt/a one week following the first treatment. The resistance to skinning was tested using a Halderson periderm shear tester fitted with a flywheel attached to a torquemeter equipped with a follow-up pointer as described by Lulai and Orr (1993). Skin strength was measured by testing the resistance to skinning 2-hours after digging tubers. At the end of the season, plots were harvested and tubers graded according to USDA grading standards for size. Skin strength data was analyzed to determine if differences exist between vine kill timings and nitrogen rate. An analysis of variance was conducted to determine differences. A Tukey-pairwise comparison was used to separate differences at p=0.05.

Results

Vine kill timing and nitrogen rate had an effect on skin strength (Figure 3). Skin strength was strongest (higher excoriation value) when vine were killed 21 days before harvest compared to other vine kill timings. The vine kill timings of 7 to 14 days before harvest were generally similar. While no vine kill resulted in the least resistance needed to tear tuber skin. Differences were found between nitrogen rates for skin strength. As expected, the higher nitrogen rate required less force (38.7 mN m) to shear the skin than the lower nitrogen rate (39.3 mN m).

Tuber yield was affected by vine kill timing but not nitrogen rate. Thus, data are presented by vine kill date (Table 1). The highest total yield, marketable yield, and tubers >6 oz was found when vine kill occurred ≤10 days before harvest. Vine killing at 14 or 21 days before harvest resulted in a yield loss and smaller tubers.

Vine killing at 10 days prior to harvest can improve skin strength and reduced yield losses. Although skin strength can improve from 14- or 21-day desiccation, yield losses were significant. Repeating this work is important to validate results from the one-year study.

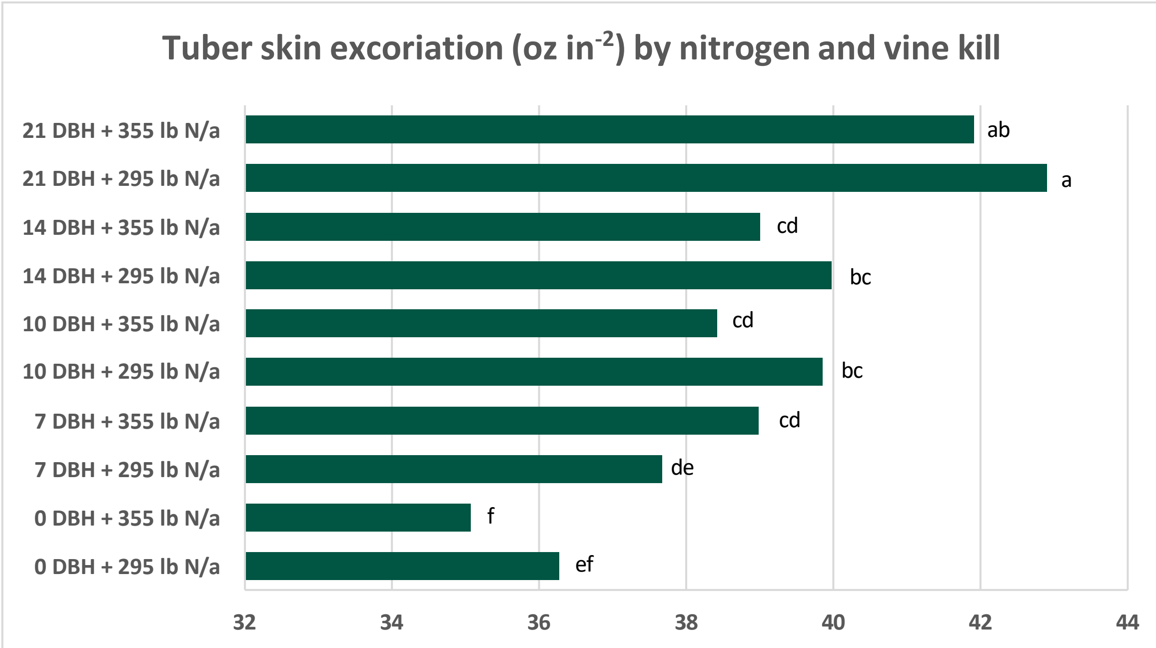

Figure 3. Russet Burbank Tuber skin excoriation (mNm) as affected by nitrogen rate and days before harvest (DBH) at Clitherall, MN. Treatments followed by the same letter are not significantly different according to Tukey pairwise comparison (P ≤ 0.05).

Table 1. Graded yield of Russet Burbank grown near Clitherall, MN in 2022 as affected by vine kill timing.

Vine kill	<3 oz	3-6 oz	6-10 oz	10-14 oz	>14 oz	Total yield	Total marketable yield	>6 oz	>10 oz	Specific gravity
days before harvest				cwt/a				%		
0	33	131	125 a	48 a	19	356 a	323 a	53 a	19 a	1.071 a
7	33	135	125 a	43 a	13	349 ab	317 a	51 ab	16 ab	1.068 ab
10	34	139	126 a	39 ab	10	349 ab	314 a	50 abc	14 ab	1.064 bc
14	43	134	88 b	29 ab	8	302 bc	259 b	41 bc	12 ab	1.061 cd
21	42	129	81 b	21 b	7	281 c	238 b	39 c	10 b	1.058 d

Means within the same column followed by the same letter are not significantly different according to Tukey pairwise comparison (P ≤ 0.05).

Table 2. Tuber number of graded yield of Russet Burbank grown near Clitherall, MN in 2022 as affected by vine kill timing.

Vine kill	<3 oz	3-6 oz	6-10 oz	10-14 oz	>14 oz	Total yield	Total marketable yield	>6 oz	>10 oz
days before harvest						tuber number/a		%	
0	22,234	42,834	23,414 a	5,808 a	1,634	95,923	73,689 ab	33 a	8 a
7	21,689	46,827	24,593 a	5,627 a	1,180	99,916	78,227 a	31 ab	7 ab
10	23,595	46,373	24,503 a	4,810 ab	908	100,188	76,593 a	30 abc	6 ab
14	29,675	46,918	17,878 ab	3,812 ab	726	99,008	69,333 ab	23 bc	5 ab

21	27,134	44,558	15,881	b	2,632	b	635	90,841	63,707	b	21	c	4	b

Means within the same column followed by the same letter are not significantly different according to Tukey pairwise comparison (P ≤ 0.05).

Developing Efficient Nitrogen Management Strategies for Potato in Minnesota

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Summary

Nitrate leaching in Minnesota is a dire issue in agricultural production. A statewide program funded by the Minnesota Department of Agriculture called Township Testing Program found that 4.7% of the private wells exceeded the Health Risk Limit. Because of a shallow root system, irrigation on coarse-textured soils and high N requirements, potato production can play an important role in mitigating nitrate leaching by employing efficient nitrogen (N) management strategies. The improvement in N use efficiency will also benefit potato growers financially through better marketable yield and tuber quality. One strategy is to employ N efficient cultivars such as Hamlin Russet, which has not been studied extensively in Minnesota, and another strategy is to adopt precision N management strategies using nondestructive N status diagnostic methods to guide in-season N management according to potato N demand. In 2021, we conducted a study comparing Russet Burbank and Hamlin Russet at the Sand Plain Research Farm (SPRF), Becker MN and showed that Hamlin Russet requited less N to produce a marketable crop than Russet Burbank. We expanded this study in 2022 with the following objectives: 1) to further evaluate the response of Hamlin Russet to N rate and management in comparison with the commonly planted Russet Burbank, 2) to determine the N uptake characteristics of Hamlin Russet through the growing season, and 3) to develop and evaluate proximal and remote sensing-based precision N management strategies for Hamlin Russet and Russet Burbank. A field experiment was conducted in 2022 that included two cultivars (Russet Burbank and Hamlin Russet) and nine N management treatments (five response curve N rates: 40, 80, 160, 240, 320 lbs N /acre and four precision N management treatments). Dualex Scientific+ and Crop Circle Phenom sensor data were collected at key growth stages during the growing season along with the SPAD chlorophyll meter data for comparison. Plant samples were collected after sensor data collection in each plot to measure petiole nitrate-N concentration, vine biomass and N concentration, and tuber biomass and N concentration at different growth stages. Tuber yield (total and marketable) and quality data (specific gravity, tuber dry matter, and tuber size) were determined at harvest time. The preliminary results showed that the optimum N rate was 160 lbs N/acre for both Hamlin Russet and Russet Burbank. Hamlin Russet produced larger tubers and had higher specific gravity than Russet Burbank regardless of the N rates. One of the precision N management treatments based on the Dualex sensor achieved higher total and marketable yields to the treatment of 240 lbs N/acre with less N fertilizers. Most of the precision N management treatments had higher partial factor productivity and higher or similar yield compared with the treatment of 240 lbs N/acre, demonstrating higher N use efficiency. In summary, the preliminary result demonstrated the potential of using N efficient cultivars and real-time nondestructive prediction of potato N stress indicators to improve potato N management.

Background

Nitrate leaching continues to be an environmental concern for crop production. The Minnesota Department of Agriculture tested 28,932 private wells across Minnesota between 2014 and 2020 through Township Testing Program and reported that 4.7% of the private wells are potentially impacted by a fertilizer source and exceeded the Health Risk Limit of 10 ppm (Kaiser, 2022). Irrigated potato production on course-textured soils is often involved in nitrate leaching for reasons including low nutrient and water retention, shallow root system (Lesczynski & Tanner, 1976), and a high N requirement (Rosen & Bierman, 2008). Errebhi et al. (1998) found that 100 to 257 kg N ha^{-1} in heavy leaching year and 71 to 96 kg N ha^{-1} in moderate leaching year was lost under various N management strategies for Russet Burbank in Minnesota. Effective N management strategies to mitigate nitrate leaching in potato production is therefore crucial to prevent adverse health effects such as methemoglobinemia (also known as blue baby syndrome) and eutrophication. One of the strategies is to employ nitrogen (N) efficient cultivars such as Hamlin Russet, a potato clone recently released by the Maine potato breeding program. In addition, the adoption of precision N management strategies developed according to cultivar differences in N response, different soil and weather conditions, and crop N demand estimated by proximal or remote sensing technologies during the season could offer a solution (Li et al., 2021). The right quantity and timing of N application will also be financially beneficial for potato growers by ensuring good marketable yield (Errebhi et al., 1998) and tuber quality (Sun et al., 2020).

Proximal or remote sensing technologies include SPAD chlorophyll meter, Dualex Scientific+, Crop Circle Phenom, Altum multispectral camera, etc. The SPAD chlorophyll meter (SPAD) has been commonly used in plant N status diagnosis. Dualex Scientific+ (Dualex) is a new innovative handheld leaf sensor capable of non-destructively and accurately measuring leaf chlorophyll (Chl), flavonoid (Flav), and anthocyanin (Anth) contents with GPS location information. The N balance index (NBI) is also calculated as the ratio of Chl over Flav. These parameters were found to be related to corn plant N stress. (Dong et al., 2020, 2021). Crop Circle Phenom (CCP) is a new integrated multi-parameter proximal active canopy sensor capable of measuring reflectance at three wavebands (red, red-edge, and near-infrared) and climatic parameters such as canopy and air temperatures, relative humidity, and air pressure (Cummings et al., 2021). Reflectance can be used to calculate vegetative indices related to plant N stress. Air and canopy temperature difference is related to both plant water and N stresses (Cummings et al., 2021). These sensors were evaluated for corn N status diagnosis, but little has been reported about the performance of these sensors for estimating potato N status. Altum multispectral camera is equipped with red (R), green (G), blue (B), Red-Edge, near infrared (NIR), and thermal capabilities, which can be used to calculate vegetative indices related to plant N stress too.

In 2021, we conducted a study using Russet Burbank and Hamlin Russet at the Sand Plains Research Farm (SPRF), Becker MN. We used Environmentally Smart Nitrogen (ESN) as the primary N source and found that the optimum N rate was 80 lbs N/acre for Hamlin Russet and 160 lbs N/acre for Russet Burbank. Proximal and remote sensing data were collected at key growth stages along with plant samples to develop precision N management strategies. Additional studies were needed with various rates and timings of N applications to characterize the N response of Hamlin Russet and to evaluate precision N management strategies developed using proximal or remote sensing technologies. Thus, the objectives of this study are to 1) further evaluate the response of Hamlin Russet to N rate and management in comparison with the commonly planted Russet Burbank, 2) determine the N uptake characteristics of Hamlin Russet through the growing season, and 3) develop and evaluate proximal and remote sensing-based precision N management strategies for Hamlin Russet and Russet Burbank.

Materials and Methods

Experimental design

A field experiment including two cultivars (Russet Burbank and Hamlin Russet) and nine N rates (five response curve N rates: 40, 80, 160, 240, 320 lbs N /ac, one fix-rate split application and three precision N management treatments) was conducted using a randomized complete block design with three replications on a Hubbard loamy sand soil at the SPRF, Becker MN in 2022. The potatoes were planted after soybean on May 23 and harvested on October 6, and each plot consisted of 7 rows with a 36-inch row spacing. The plot dimensions were 21 feet by 20 feet except for the first and last plots having 25 feet in length for the borders. Russet Burbank and Hamlin Russets were spaced at 12 inches and 9 inches within the row, respectively. Between the planting and harvesting, the rainfall was 310 mm, and supplemental irrigation was applied. Dualex (Figure 1) and CCP sensor (Figure 2) data were collected at key growth stages (4 times) during the growing season along with SPAD data for comparison. Remote sensing imagery was collected twice using the Altum camera mounted on DJI Matrice 100. Plant samples were collected after sensor data collection in each plot to measure petiole nitrate-N concentration, vine biomass and N concentration, and tuber biomass and N concentration. Petiole nitrate-N concentration was measured in the fourth leaf from the top of the plant, together with the Dualex and SPAD sensor readings. Tuber yield (total and marketable) and quality data (specific gravity, tuber dry matter, and tuber size) were determined at harvest time.

Figure 1. The Dualex leaf fluorescence sensor (left) and field data collection (right).

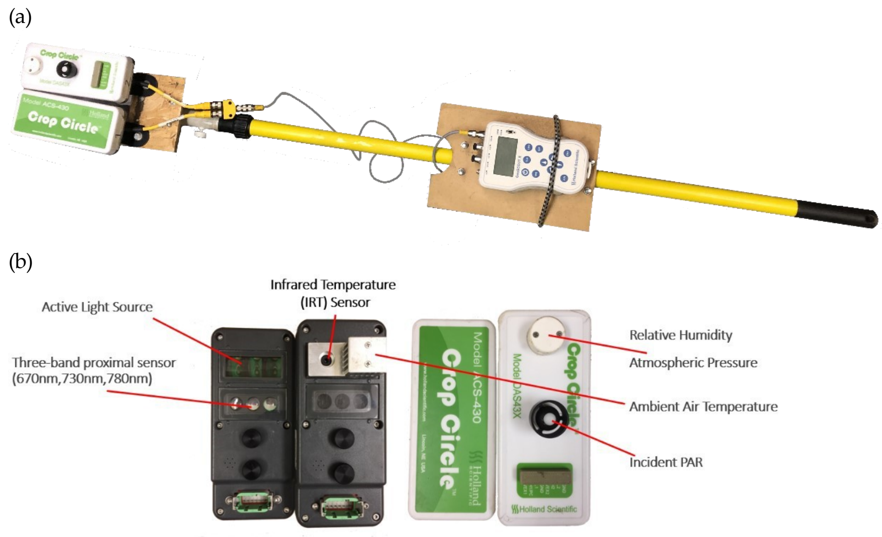


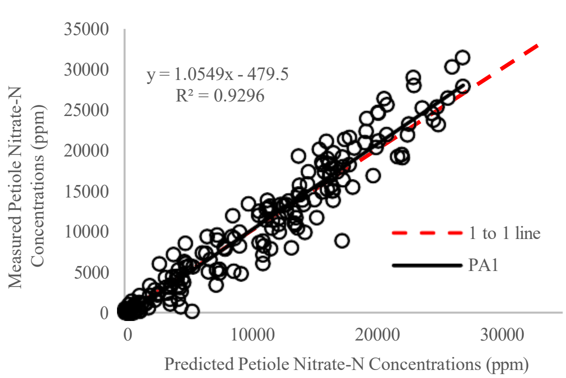
Figure 2. Crop Circle Phenom sensor (a) custom assembly with extendable pole and (b) close-up view of ACS-430 and DAS43X sensor components (from Cummings et al., 2021).

The response curve N rates received 40 lbs N/acre as diammonium phosphate (DAP) at planting on May 23, and the rest of N as ESN at emergence on June 6. The fixed rate split N application treatment was scheduled to receive 140 lbs N/acre for Hamlin Russet and 220 lbs N/acre for Russet Burbank with 40 lbs N/acre as DAP at planting on May 23, 40 or 120 lbs N/A as ESN at emergence on June 6, and four post-hilling split applications of 15 lbs N/acre as urea ammonium nitrate (UAN) on July 7, 14, 28, and August 4. The three precision N management treatments received the same at-planting and at-emergence N rates as the fixed rate split N application treatment. However, the post-hilling N was variably applied according to in-season prediction of N status indicators including petiole nitrate-N (PNN) concentration (Rosen & Bierman, 2008), Nitrogen Nutrition Index (NNI) (Bélanger et al., 2001), and Nitrogen Sufficiency Index (NSI) (Bohman et al., 2019; Nigon et al., 2014) (Table 1). Preliminary analysis was performed to evaluate machine learning models for their abilities to predict PNN concentrations and NNI using the plant sample and proximal sensing data along with cultivar, temperature, and as-applied N rate information collected at the SPRF in 2018, 2019, and 2021. Dualex-based Random Forest (RF) model and Dualex-based Support Vector (SV) model with RBF kernel were found to predict PNN concentrations and NNI most accurately, respectively (Figure 3). The examination of this dataset also showed that SPAD is the most appropriate sensor for NSI calculation with 160 lbs N/acre and 240 lbs N/acre as the sufficient N rates for Hamlin Russet and Russet Burbank, respectively. Consequently, Dualex-based RF model for PNN concentration prediction (PA1), SPAD-based NSI calculation (PA2), and Dualex-based SV model for NNI prediction (PA3) were used for in-season diagnosis of potato N status. The sufficiency ranges of PNN concentrations were mainly based on Rosen & Bierman (2008), while the 0.95 – 1.05 range was used as the NNI and NSI sufficiency range. When N deficiency was detected, 15 lbs N/acre of UAN was applied.

Table 1. The description of nine N rates for each cultivar (* 15 lbs N/A as UAN was prescribed when N stress was indicated)

Cultivar	Treatment	At Planting (lbs N/A)	At Emergence (lbs N/A)	Post-hilling (lbs N/A)			
Hamlin Russet	Control	40 DAP	-	-	-	-	-
Hamlin Russet	80 lbs/A	40 DAP	40 ESN	-	-	-	-
Hamlin Russet	160 lbs/A	40 DAP	120 ESN	-	-	-	-
Hamlin Russet	240 lbs/A	40 DAP	200 ESN	-	-	-	-
Hamlin Russet	320 lbs/A	40 DAP	280 ESN	-	-	-	-
Hamlin Russet	140lbs/A (Split)	40 DAP	40 ESN	15 (UAN)	15 (UAN)	15 (UAN)	15 (UAN)
Hamlin Russet	PA1 (PNN)	40 DAP	40 ESN	*	*	*	*
Hamlin Russet	PA2 (NSI)	40 DAP	40 ESN	*	*	*	*
Hamlin Russet	PA3 (NNI)	40 DAP	40 ESN	*	*	*	*
Russet Burbank	Control	40 DAP	-	-	-	-	-
Russet Burbank	80 lbs/A	40 DAP	40 ESN	-	-	-	-
Russet Burbank	160 lbs/A	40 DAP	120 ESN	-	-	-	-
Russet Burbank	240 lbs/A	40 DAP	200 ESN	-	-	-	-
Russet Burbank	320 lbs/A	40 DAP	280 ESN	-	-	-	-
Russet Burbank	220 lbs/A (Split)	40 DAP	120 ESN	15 (UAN)	15 (UAN)	15 (UAN)	15 (UAN)
Russet Burbank	PA1 (PNN)	40 DAP	120 ESN	*	*	*	*
Russet Burbank	PA2 (NSI)	40 DAP	120 ESN	*	*	*	*
Russet Burbank	PA3 (NNI)	40 DAP	120 ESN	*	*	*	*

PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model



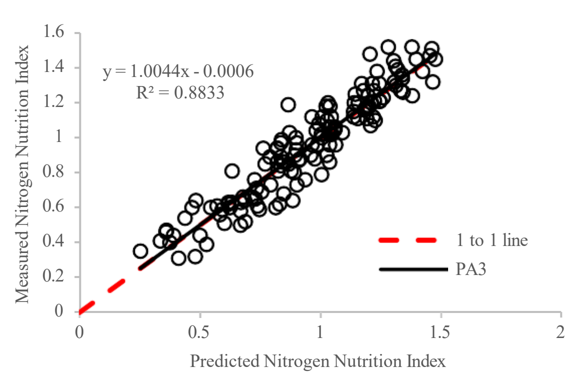


Figure 3. The correlations between the measured and predicted petiole nitrate-N concentrations or Nitrogen Nutrition Index based on Dualex-based machine learning models.

Data analysis

The plant samples collected in 2022 are still being analyzed in the lab for petiole nitrate-N and vine N concentrations etc. This report shows cultivar difference in tuber yields and quality across the response curve N rates. Tuber size and specific gravity were reported as quality parameters. Comparisons will also be made in tuber yields and quality between the recommended N rate of 160 or 240 lbs N/acre and the precision N management treatments.

Results and discussion

Tuber yield and quality responses to N for the two cultivars

Hamlin Russet produced similar or slightly higher total yield than Russet Burbank at 80, 160, and 240 lbs N/acre. Similarly, Hamlin Russet produced higher marketable yields than Russet Burbank except at 320 lbs N/acre (Figures 4 & 5). Total and marketable yields of Hamlin Russet increased with N rates to 160 lbs N/acre and decreased after. Total and marketable yields of Russet Burbank also increased with N rates to 160 lbs N/acre and decreased after except at 320 lbs N/acre (Figures 4 & 5). The achieved total and marketable yields for Russet Burbank were lower than last year. This should be attributed to this year's late planting due to inclement weather and a resultant shorter growing season, which must have affected a late maturing cultivar, Russet Burbank, more than medium-early maturing cultivar, Hamlin Russet. Regardless, the optimum N rate of Russet Burbank for the achieved yields was lower than expected (Rosen & Bierman, 2008). The potential reasons include less nitrate leaching due to drier weather and high N concentrations in the irrigation water (about 10 ppm nitrate-N based on previous analysis). Further analysis is required to better determine the N uptake characteristics of Hamlin Russet.

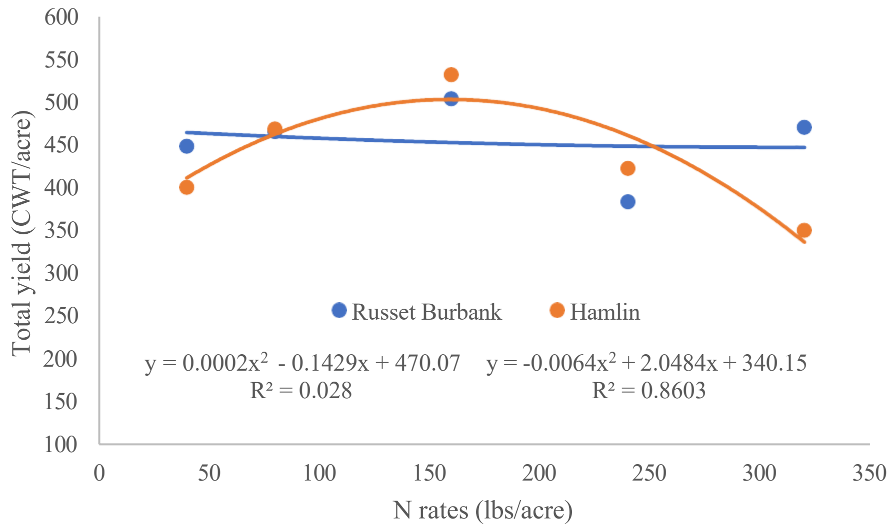


Figure 4. Total yield responses to N rates for Russet Burbank and Hamlin Russet

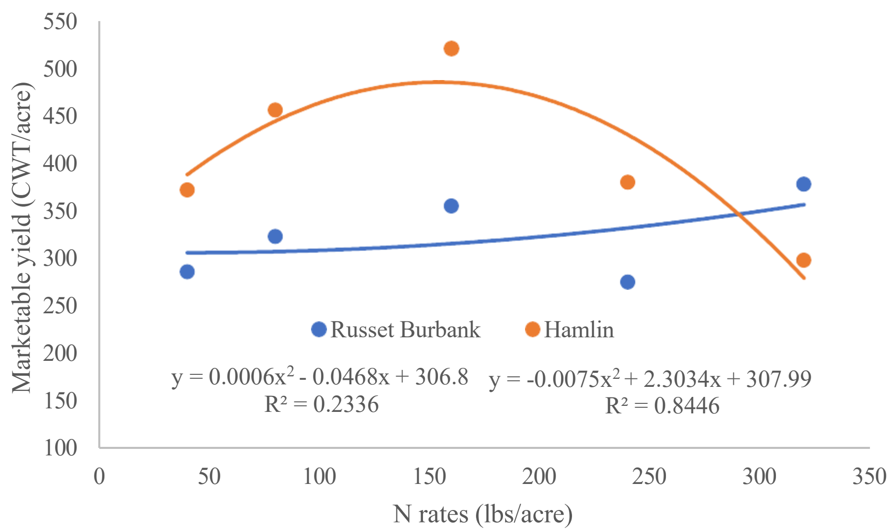


Figure 5. Marketable yield responses to N rates for Russet Burbank and Hamlin Russet**.**

Tuber size and specific gravity for both cultivars are shown in Figures 6 & 7. At most N rates, Hamlin Russet produced larger tubers than Russet Burbank. However, the difference in average tuber size between the two cultivars is not as distinct as last year because the spacing within rows for Hamlin Russet was adjusted from 12 inches to 9 inches given last year's result. Hamlin Russet tended to produce large tubers more frequently at 80 and 160 lbs N/acre, whereas Russet Burbank produced small tubers across all N rates. Additionally, Hamlin Russet had higher specific gravity than Russet Burbank across all N rates.

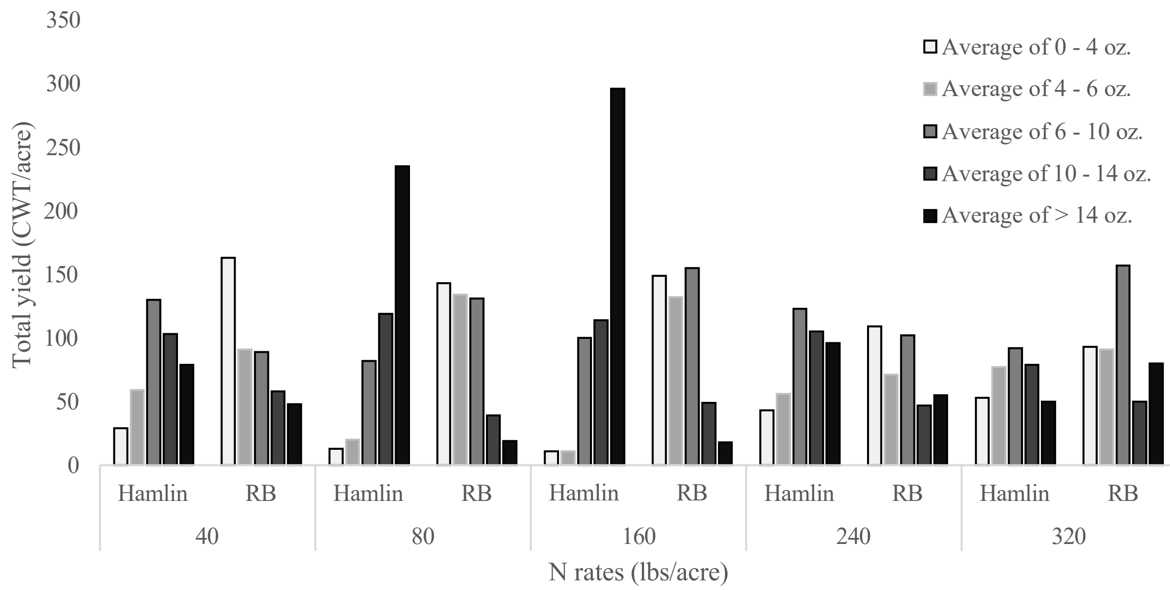


Figure 6. Total yields (CWT/acre) of Hamlin Russet and Russet Burbank in five size categories at the five response curve N rates.

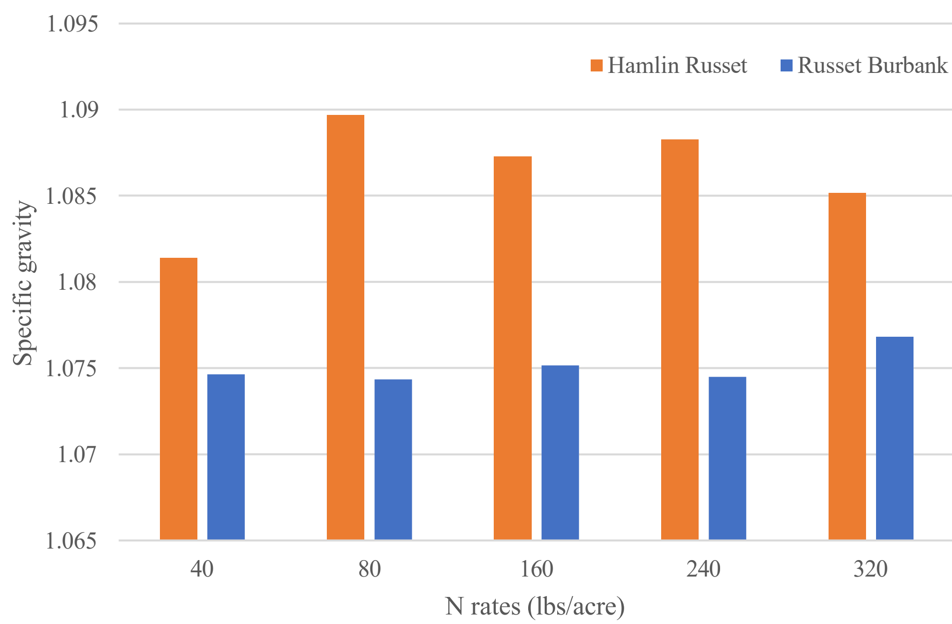


Figure 7. Specific gravity of Hamlin Russet and Russet Burbank at the five response curve N rates.

Post-hilling N prescriptions and their yield/quality effects in precision N management treatments

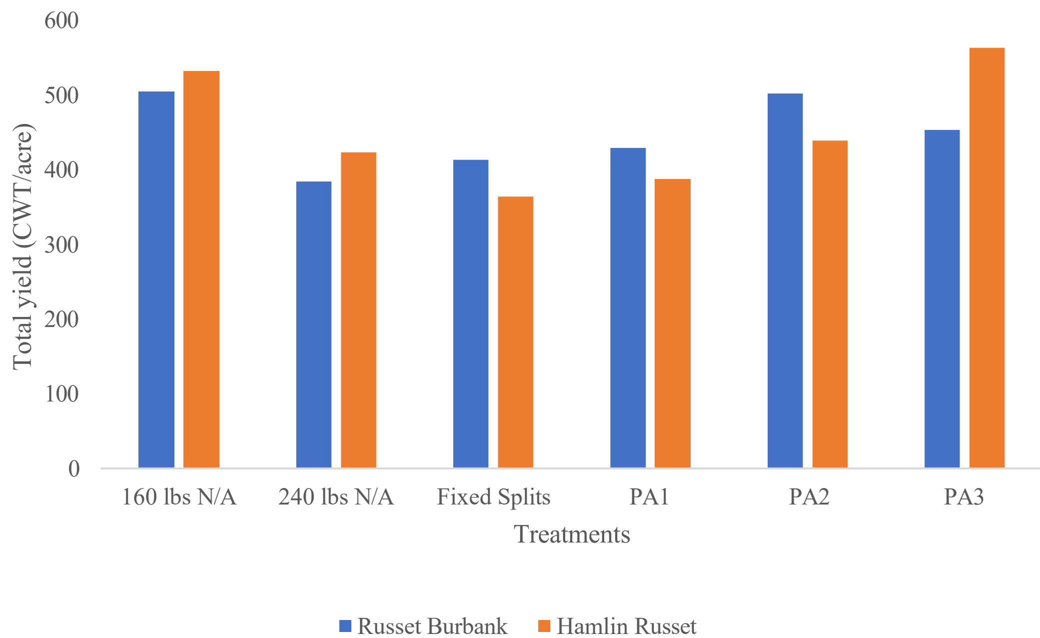
Table 2 shows the timings of post-hilling N applications according to PA1, PA2, and PA3 treatments. Prescription decisions were made on July 7, 14, 28, and August 4 following the proximal/remote sensing data collection. Total N application rates were averaged across three replications for each cultivar-treatment pair to make a comparison with the optimum N rate. Figures 8 & 9 show the total and marketable yields of each cultivar in the fixed rate split N application and precision N management treatments in comparison with 160 and 240 lbs N/A for Hamlin Russet and Russet Burbank, respectively (farmer practice). Dualex-based SV model for NNI prediction (PA3) showed the most similar total and marketable yields to those of farmer practice for both cultivars. It is noteworthy that PA1 and PA3 had similar post-hilling application timings but resulted in a large yield difference for Hamlin. The N applications made for PA3 on July 7 might have contributed to better tuber bulking given the optimum N rate for Hamlin Russet was lowly estimated at 80 lbs N/acre based on last year's result. Figures 10 & 11 show the tuber size and specific gravity for each cultivar-treatment pair in comparison with the optimum N rates. Figure 12 & 13 shows partial factor productivity and economic returns of the fixed rate split N application and precision N management treatments in comparison with farmer practice. Partial factor productivity (PFP), calculated by dividing total tuber yield by total N rate, shows N use efficiency of each treatment. Economic returns were derived by subtracting the N fertilizer cost from the tuber sales value. The following prices were used for the calculation according to (Quinn, 2022): $8 for a hundredweight of processing potatoes, $1.28/lbs N for ESN, and $1.13/lbs N for UAN28. The N attribution from the at-planting DAP application was taken into account in net returns calculations. It should be noted that all of the precision N management treatments had similar or higher PFP than not only the fixed rate split N application treatment but the 160 and 240 lbs N/acre treatments.

Table 2. Precision N management treatment prescriptions

Plot	Treatment	Variety	Pre-hilling (lbs N/A)	Post-hilling (lbs N/A)				Total N (lbs N/A)	Ave N (lbs N/A)
				7-Jul	14-Jul	28-Jul	4-Aug		
108	PA1	Hamlin Russet	80	0	15	15	15	125	
211	PA1	Hamlin Russet	80	0	15	15	15	125	125
310	PA1	Hamlin Russet	80	0	15	15	15	125	
111	PA1	Russet Burbank	160	0	15	15	0	190	
208	PA1	Russet Burbank	160	0	15	15	0	190	190
307	PA1	Russet Burbank	160	0	15	15	0	190	
102	PA2	Hamlin Russet	80	0	0	15	15	110	
213	PA2	Hamlin Russet	80	0	0	0	15	95	100
306	PA2	Hamlin Russet	80	0	0	0	15	95	
113	PA2	Russet Burbank	160	0	0	0	15	175	
210	PA2	Russet Burbank	160	0	0	15	15	190	180
301	PA2	Russet Burbank	160	0	15	0	0	175	
112	PA3	Hamlin Russet	80	0	15	15	15	125	125
203	PA3	Hamlin Russet	80	15	0	15	15	125	

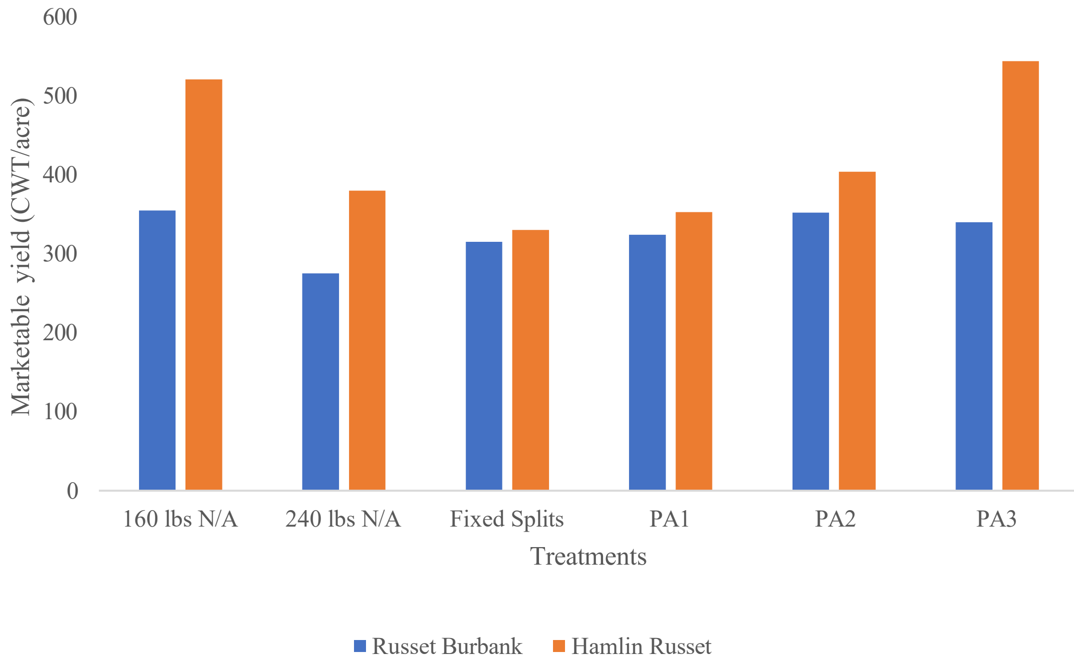
304	PA3	Hamlin Russet	80	15	0	15	15	125	
101	PA3	Russet Burbank	160	0	0	0	15	175	
218	PA3	Russet Burbank	160	0	0	15	15	190	175
305	PA3	Russet Burbank	160	0	0	0	0	160	

PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model



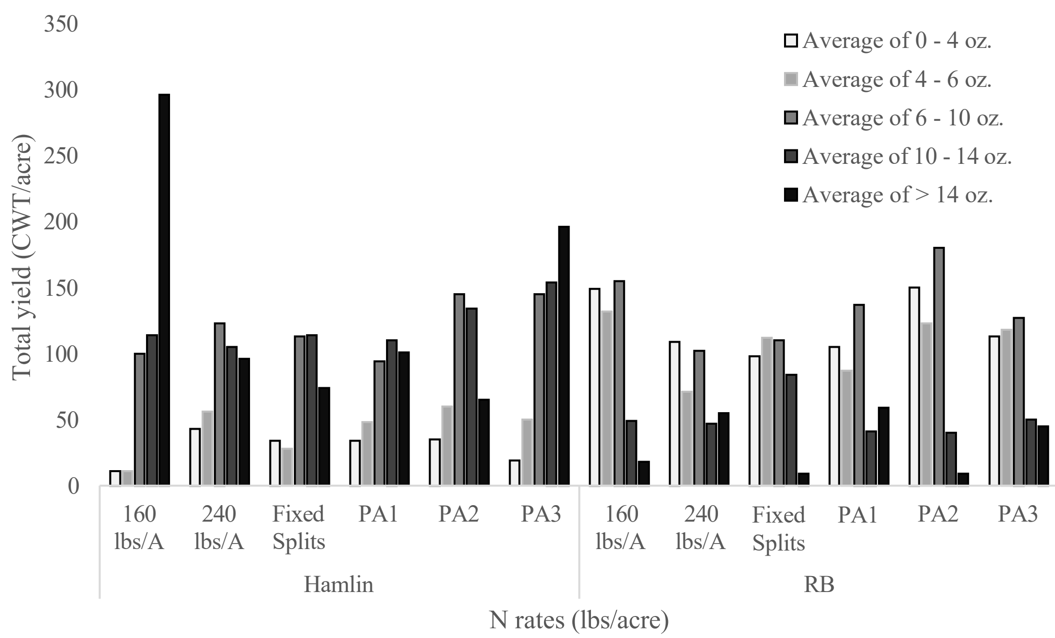
PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 8. Total yields of Hamlin Russet and Russet Burbank in precision N management treatments



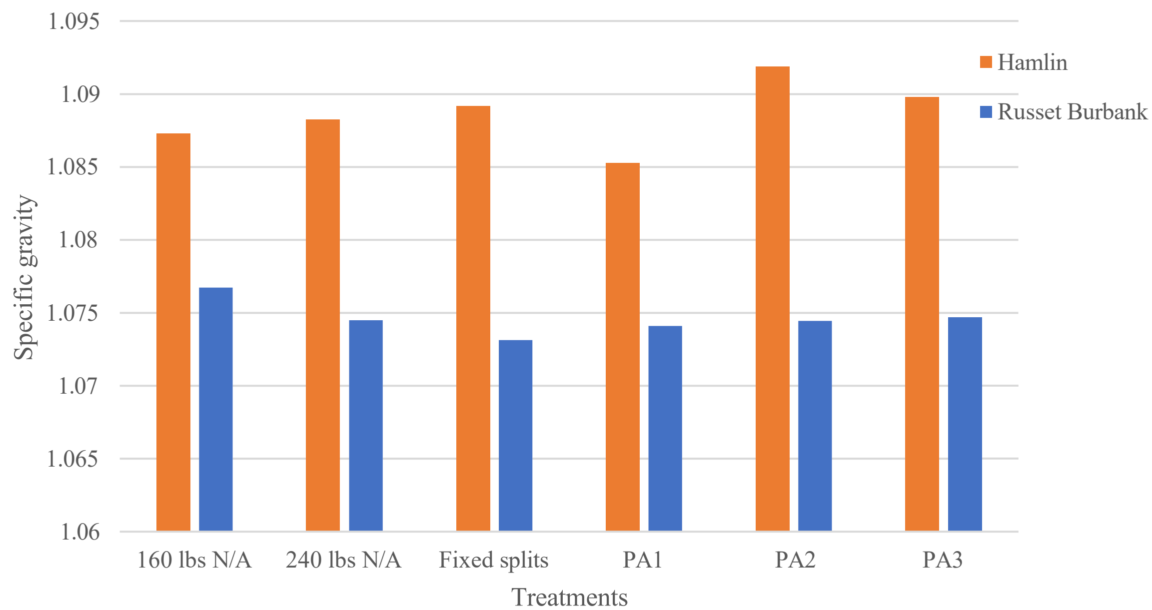
PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 9. Marketable yields of Hamlin Russet and Russet Burbank in precision N management treatments



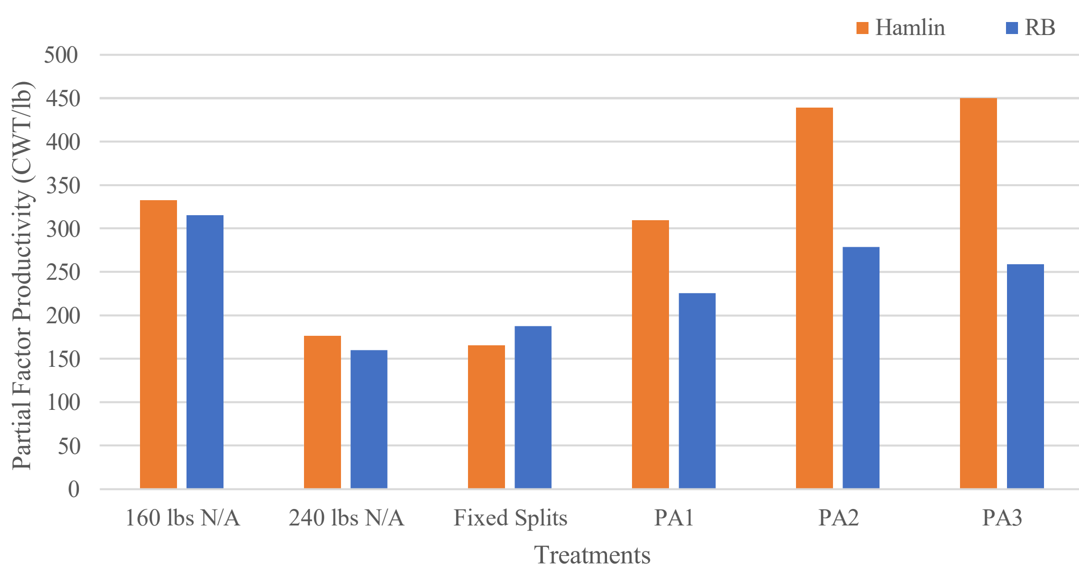
PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 10. Total yields (CWT/acre) of Hamlin Russet and Russet Burbank in five size categories in precision N management treatments



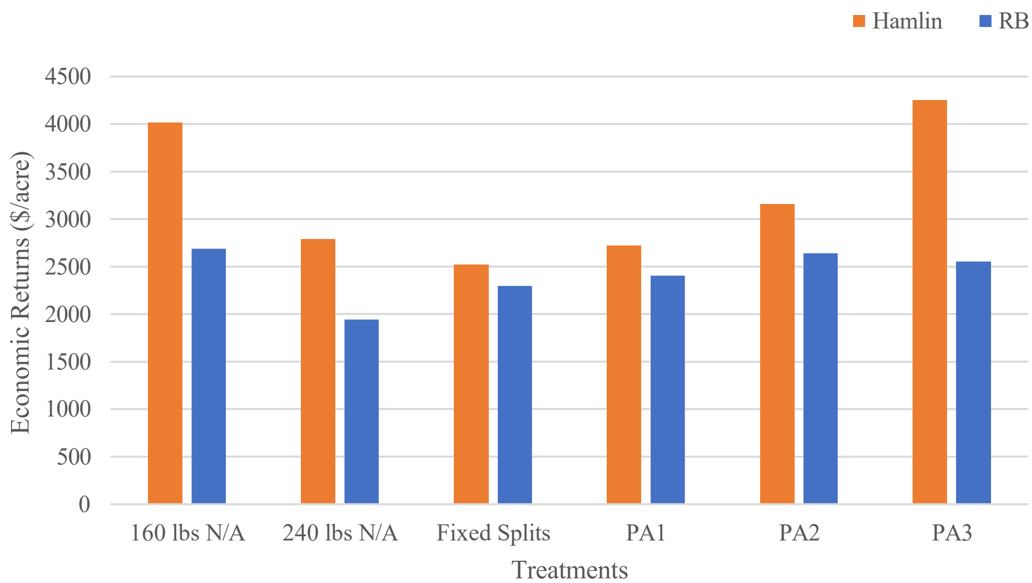
PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 11. Specific gravity of Hamlin Russet and Russet Burbank in precision N management treatments



PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 12. Partial factor productivity of Hamlin Russet and Russet Burbank in precision N management treatments

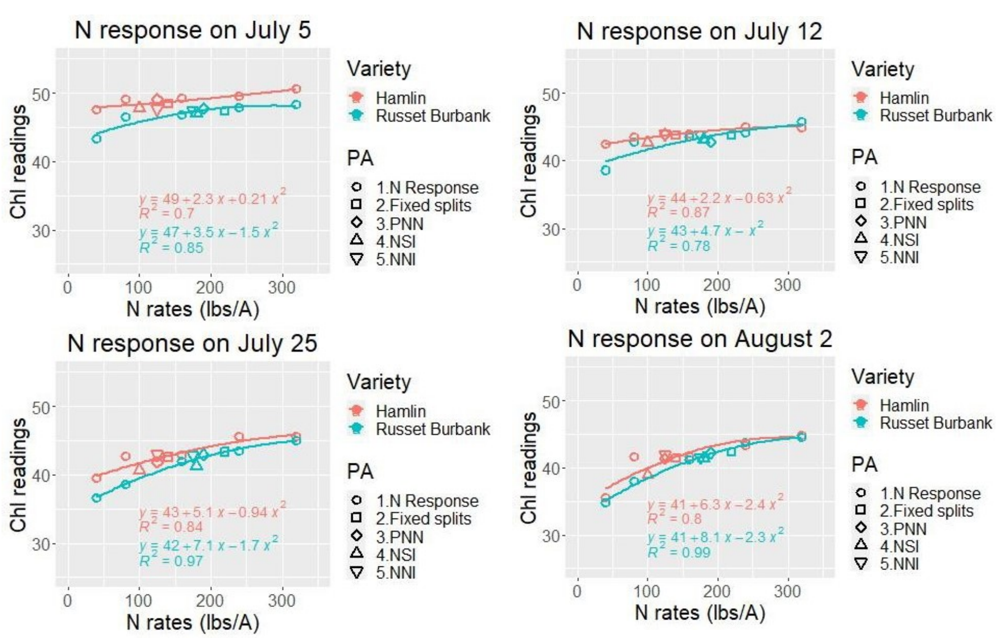


PA1: Petiole nitrate nitrogen prediction using Dualex-based random forest model, PA2: Nitrogen sufficiency index calculated using SPAD, PA3: Nitrogen nutrition index prediction using Dualex-based support vector model

Figure 13. Economic returns of Hamlin Russet and Russet Burbank in precision N management treatments

Leaf sensor data response to N rates at different growth stages

Figures 14, 15, & 16 show the relationships between SPAD, Dualex Chl, or Dualex NBI readings and N rates for each cultivar on different measurement dates, respectively. All leaf sensor readings increased



with N rates up to the highest N rate (320 lbs N/acre), where Dualex NBI varied the most dynamically. These relationships between leaf sensor readings and N rates do not seem to reflect the relationships between tuber yields and N rates directly. Analytical approaches including machine learning should be explored to relate leaf sensor readings to tuber yields.

Figure 14. Relationships between N rates and SPAD readings on four measurement dates for Hamlin and Russet Burbank

Figure 15. Relationships between N rates and Dualex Chl readings on four measurement dates for Hamlin and Russet Burbank

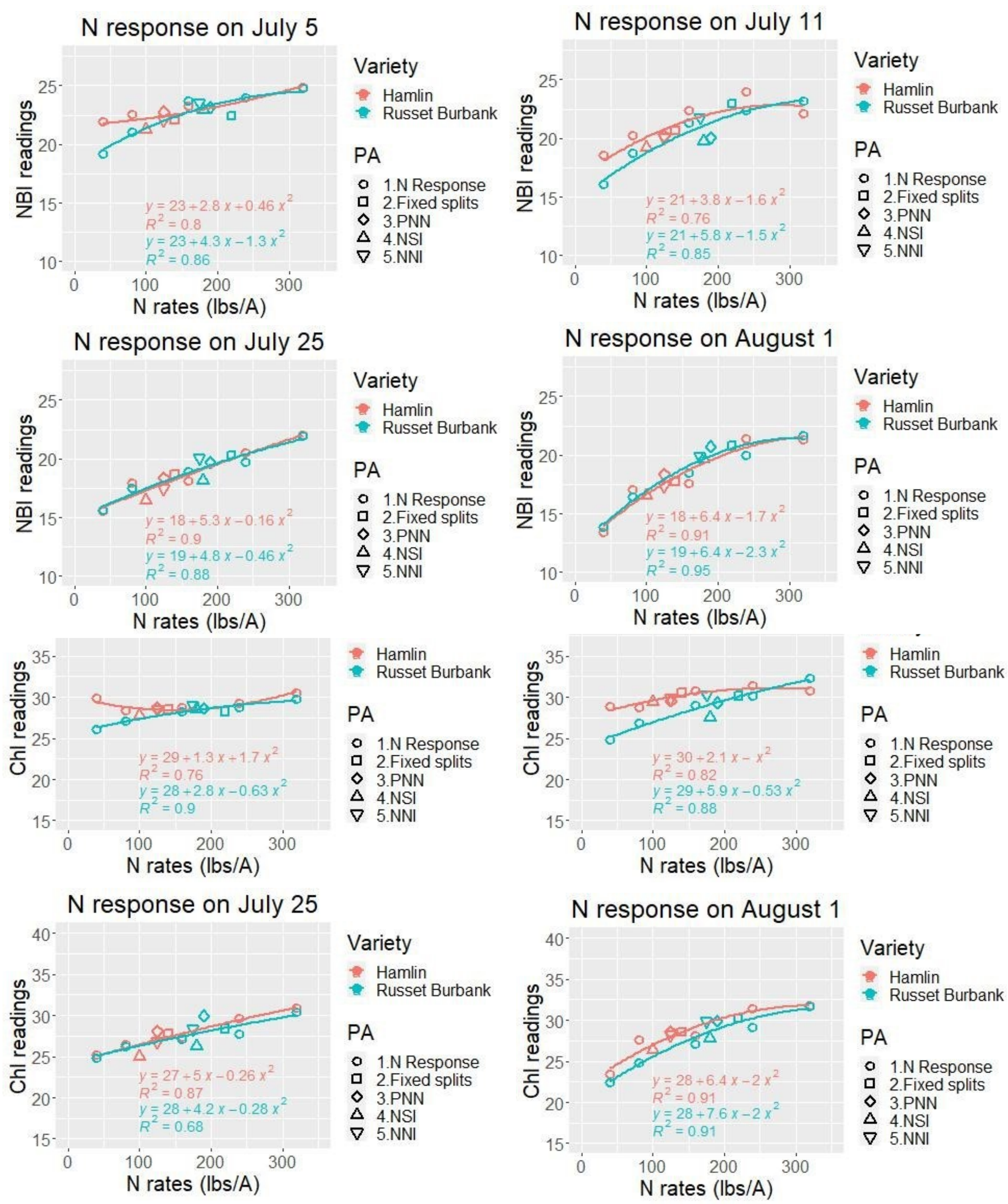


Figure 16. Relationships between N rates and Dualex NBI readings on four measurement dates for Hamlin and Russet Burbank

Active Canopy Sensor data response to N rates at different growth stages

Figures 17 & 18 show the relationships between CCP sensor-based normalized difference vegetation index (NDVI) or normalized difference red-edge (NDRE) index and N rates for each cultivar on different measurement dates, respectively. The NDVI values are irresponsive to N rates (saturation), especially on the last two measurement dates. NDRE, on the other hand, overcomes this problem, but it does not correlate well with tuber yields.

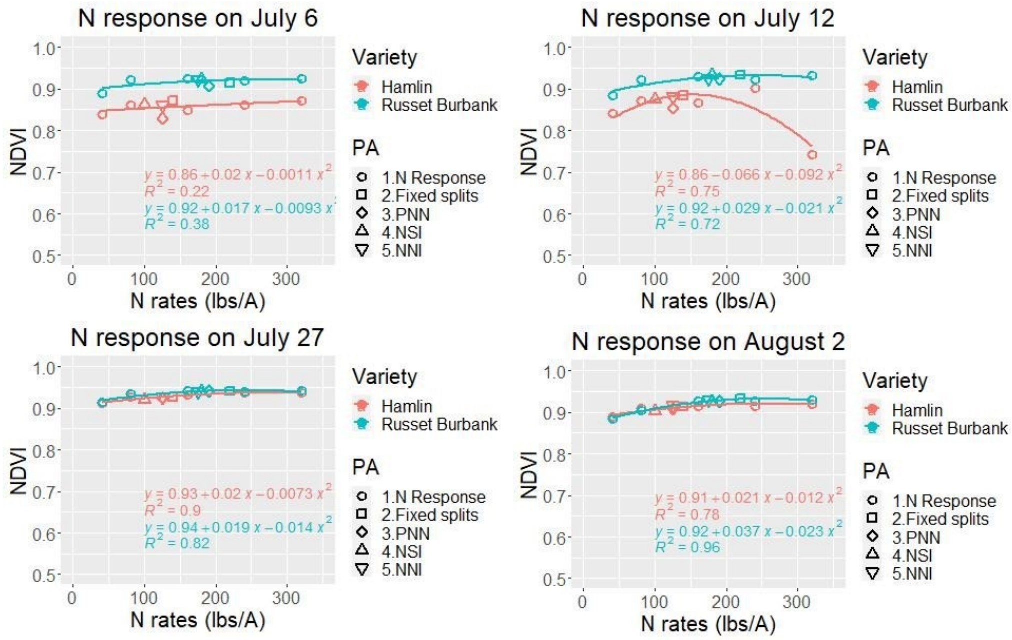


Figure 17. Relationships between CCP NDVI and N rates and on four measurement dates for Hamlin and Russet Burbank

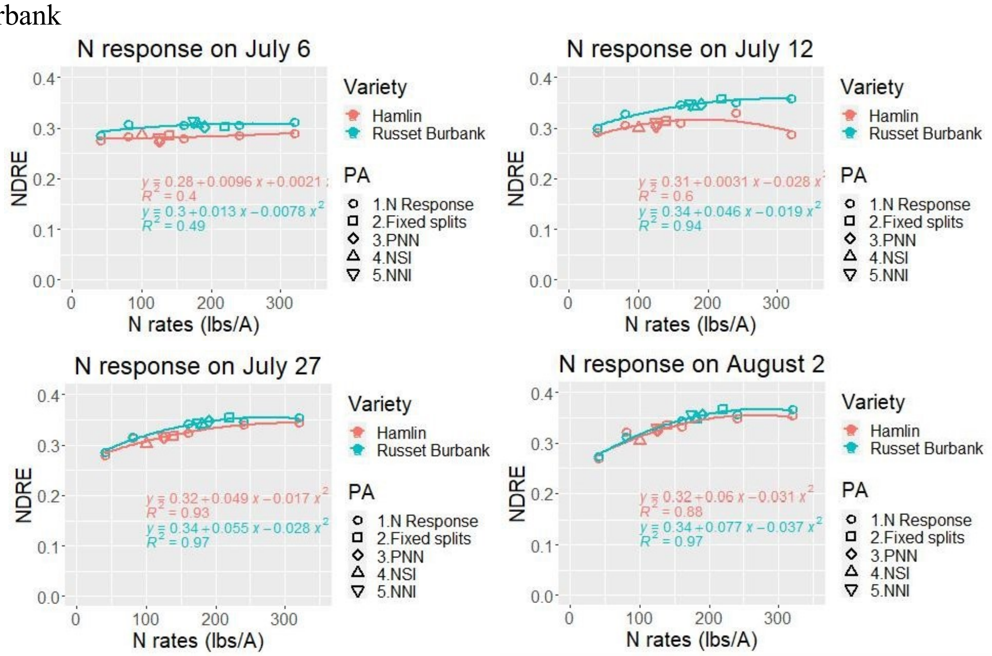


Figure 18. Relationships between CCP NDRE and N rates on four measurement dates for Hamlin and Russet Burbank

Figure 19 shows the air and canopy temperature differences for both cultivars at each N rate. With sufficient water supply, canopy temperature should be lower than air temperature due to the cooling effect of evapotranspiration. When there is water stress, canopy temperature may be similar to or even higher than the air temperature. It seems that on July 6, the potato plants experienced water stress. This sensor may be a good indicator of plant water stress and will be used to guide variable rater irrigation in the future study.

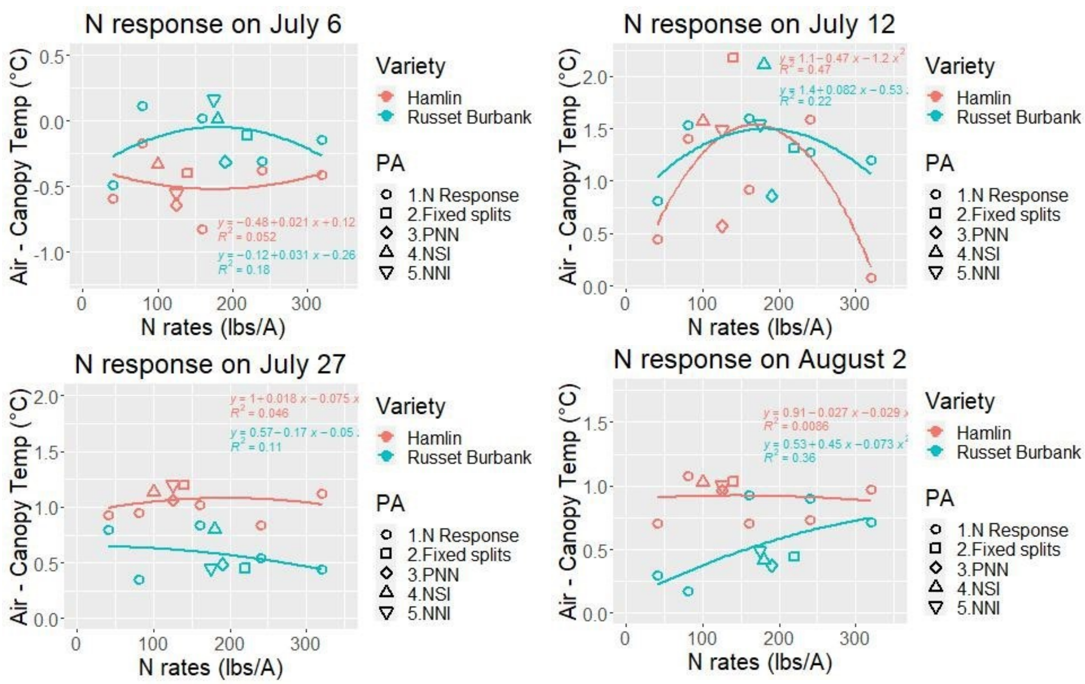


Figure 19. Air and canopy temperature differences for both cultivars at each N rate

Implications for potato N management

Hamlin Russet had a higher marketable yield than Russet Burbank with 160 lbs N/acre as the optimum N rate. This result could be the demonstration of N efficiency by Hamlin Russet. Meanwhile, a longer growing season would have promoted a more distinct N response of Russet Burbank and made clear the comparison in N efficiency between the two cultivars. Moreover, the N efficiency of Hamlin Russet should be evaluated in wetter weather conditions as well because this year was another dry year, similar to 2021.

The precision N management approaches showed promising results but require further assessments and improvements, especially for cultivars other than Russet Burbank. Dualex-based RF model for PNN concentration prediction (PA1) could have guided the N management of Hamlin Russet better for a higher yield. One of the potential problems could be the use of PNN concentration sufficiency ranges designed for Russet Burbank. Based on the comparison in last year's PNN concentrations between the two cultivars, Hamlin Russet seemed to show higher PNN concentrations across all the response curve N rates. Adjustments to N sufficiency ranges might be necessary based on cultivars. Lastly, the machine learning models are expected to incorporate a wider range of management conditions including rainfall/irrigation and weed prevalence. This could have improved our N prescription decisions given the very dry conditions and a large presence of weeds in some of the plots this year.

Conclusion

The preliminary results of this study indicated that the optimum N rate for Hamlin Russet and Russet Burbank was 160 lbs N/acre whether based on total or marketable yield. Both total and marketable yields of Russet Burbank were lower than last year, possibly due to a shorter growing season. Hamlin Russet produced larger tubers and had higher specific gravity than Russet Burbank regardless of the N rates. The precision N management treatment based on Dualex-based support vector model for Nitrogen Nutrition Index prediction (PA3) had very similar total and marketable yields to the optimum N rate treatments (160 lbs N/acre). Most of the precision N management treatments had higher partial factor productivity than the farmer practice N rates, demonstrating higher N use efficiency. Further analysis to better characterize the N efficiency of Hamlin Russet in comparison to Russet Burbank is in progress. The machine learning models including PA3 also need further assessments and improvements in determining sufficiency ranges of predicted N status indicators and accounting for a wider range of management conditions such as irrigation/rainfall and weed prevalence. In summary, the preliminary result demonstrated the potential of using N efficient cultivars and real-time nondestructive prediction of potato N stress indicator to improve potato N management.

Acknowledgement

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Potato Breeding and Cultivar Development for the Northern Plains Region

2022 Summary

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Potato, a nutritious foodstuff high in potassium, vitamin C, and other nutrients, is an important horticultural crop in North Dakota, Minnesota, and the Northern Plains. Potato is susceptible to a myriad of disease, insect and nematode pests, and abiotic stresses. Additionally, stringent specifications exist for each market type. Breeding and cultivar development are long-term processes involving years of evaluation and seed production. The NDSU potato breeding program conducts conventional breeding efforts, germplasm enhancement, selection, evaluation, and development of improved cultivars for stakeholder adoption. In cooperation with the potato improvement team, emphasis is placed on incorporating durable, long-term resistance to biotic and abiotic stressors, early maturity, high yield potential, and identification of genotypes with reduced needs for inputs, in an effort to address the shortcomings of industry standards. Ultimately the goal is to provide potato producers, industry partners, and consumers with environmentally resilient and economically sustainable cultivars across market types. Two research objectives were established for 2022:

1. Develop economically viable and sustainable potato cultivars and germplasm adapted to the Northern Plains region.
2. Evaluate and develop breeding tools and emerging technologies for improving potato breeding efficiency.

The potato breeding program conducts potato research and production in the greenhouse, field and laboratory. In 2022, 63 parental genotypes were used in 1,344 conventional hybridizations, to create 179 new families during winter/spring 2022. Parental genotypes included named cultivars, wild-species hybrids, and advancing selections from NDSU, USDA-ARS Prosser/Aberdeen, Texas A & M University (TAMU), and University of Maine. Emphasis was placed on early maturity and introgression of resistance genes to disease, insect, and nematode pests, and quality traits including nutritional attributes, high specific gravity, low sugar content, and others associated with chip and frozen/French fry processing, all important for producers in North Dakota, Minnesota and beyond.

The single-hill nursery, clone maintenance and increase lots of promising selections were grown at Baker, MN. In 2022, 40,394 single hills were grown in the seedling nursery, with 22,685 representing 111 NDSU families; the remaining 17,709 were received from potato breeding collaborators at USDA-ARS

Aberdeen (ID), University of Maine, and TAMU. Five hundred eighty-four selections were made from NDSU seedlings, and 157 from the out-of-state seedlings. Unselected seedling tubers produced during the summer/fall 2021 and winter/spring 2022 greenhouse crops were shared with collaborating breeding programs in CO, ID, ME, MN, OR and TX. In maintenance lots, 513 second year selections were grown, with 180 retained; 121 third year selections were evaluated and 54 retained, and of the 312 fourth year and older selections produced, 182 were retained. As selections were brought into storage, specific gravity was determined, light box imagery obtained, and chip/frozen processing selections sampled for chip processing evaluations from the field and from 3.3C (38F) and 5.5C (42F) following 8 weeks storage and again following seven months storage. About 0.4 acres (0.15 ha) of increase lots were also entered into certification; these materials are used for our trials, regional and national trials, research collaborator trials, and evaluation by potato growers/industry. Two tetraploid (4x) mapping populations, one segregating for tuber skin set and one for *Verticillium* wilt resistance, were increased for trialing in 2023. These research efforts are collaborations with Dr. Dogramaci and Drs. Pasche and Shannon, respectively.

Field research trials were conducted at irrigated & non-irrigated trial sites in 2022. Trials at Larimore, ND (grower cooperator field) included a replicated processing trial with 15 advancing selections compared to 7 commercial standards (please see results in Tables 1-3 and Figure 1), a preprocessing trial with 58 dual-purpose russet selections compared to eight check cultivars, the North Central (NC) Regional trial with 126 entries from MSU, NDSU, UMN and UW compared to nine check cultivars, the National French Fry Processing trial (NFPT), and several agronomic trials, including a trial utilizing a caterpillar tunnel to increase heat/moisture stress and electronics to monitor impacts on root, tuber and canopy growth, in collaboration with Drs. Dogramaci, Hatterman-Valenti and Panigrahi (Purdue University). Processing trial entries (chip and frozen/French fry) are submitted to Dr. Darin Haagenson (USDA-ARS) for serial processing evaluations from storage. Hoverson Farms hosts these trials at a research pivot site south east of Larimore. Two trials were grown at the Oakes Research Extension Center, a processing trial with 11 selections compared to eight industry standards (Tables 4-6 and Figure 2), and a fresh market trial evaluating 10 red- and yellow-skinned selections compared to four industry standards (Tables 7-8 and Figure 3). At Park Rapids, MN, a replicated *Verticillium* wilt resistance screening trial was conducted in collaboration with Dr. Julie Pasche's program evaluating 25 genotypes; stems were collected for determination of colonization in the fumigated and non-fumigated blocks. A common scab screening trial assessed 68 genotypes. These trials are hosted by RD Offutt Farms.

Non-irrigated trial locations were near Crystal, Hoople, and at Fargo, ND. The Crystal fresh market trial had 30 entries, 24 advancing red-, yellow-, and purple-skinned selections compared to six fresh market standards (Tables 9-10 and Figure 4); the Crystal trials are hosted by Dave and Andy Moquist. The preliminary fresh market trial has evolved into a two replicate trial focused on second year genotypes; in 2022, there were 27 entries with red- and purple-skin and white or yellow flesh compared to six fresh market controls. The focus at the Hoople trial site, hosted by Lloyd, Steve and Jamie Oberg are chip processing trials. The ND state chip trial had 15 NDSU advanced selections compared to nine commercial chip processing cultivars in the four-replicate trial (please see Tale 11-13). Several performed better than the standards including

ND13220C-3 which out yielded all entries as it had in 2021 a drought year when it out yielded all genotypes by two times. The preliminary chip processing trial evaluated 19 selections compared to seven commercial chip processing standards. The National Chip Processing Trial was also grown at this location; it included 176 selections compared to commercial chip standard cultivars Atlantic, Lamoka, Pike, and Snowden. NDSU had 16 entrants. An organic demonstration trial was grown on the NDSU campus with a focus on urban agriculturalists; it had 15 selections with multiple skin and flesh colors compared to five specialty cultivars. Additional trial information will be submitted to the Valley Potato Grower magazine, and will be presented at potato industry meetings in 2023.

The NDSU potato breeding program is supported by Kelly Peppel (research specialist), Dick (Richard) Nilles (research technician), undergraduate students Elizabeth Krause and Hunter Gallagher, and graduate students Tannis Anderson and David Ngure.

Sincere thanks to the Northland Potato Growers Association, the Minnesota Area II Research and Promotion Council, JR Simplot, Cavendish Farms, Lamb Weston and RDO Frozen, to our many grower cooperators, and many others, for research funding, hosting trials, supplying certified seed, and for all you do in support of the NDSU potato breeding and potato research efforts.

Table 1. Agronomic evaluations for advanced processing selections and cultivars grown at Larimore, ND, 2022. The processing trial was planted on June 7, flailed on September 30 (115 DAP), and harvested October 1, 2022, using a single-row Grimme harvester. A randomized complete block design with four replicates was utilized; plots were twenty feet long, with a within-row spacing of 12 inches and 36 inches between rows.

Clone	Stand %	Stems per Plant	Vine Size[1]	Vine Maturity[2]	Tubers per plant	General Rating[3]
ND050032-4Russ	93	1.6	3.5	3.0g	5.1	2.6
ND060735-4Russ	85	2.3	3.5	2.8	6.2	3.9
ND091933ABCR-2Russ	95	3.3	3.5	2.5	6.4	3.4
ND091933ABCR-7Russ	84	3.2	3.3	1.8	9.7	3.0
ND092355CR-2Russ	83	2.3	2.8	1.8	7.9	2.9
ND113096-1Russ	89	3.5	3.5	1.4	9.9	2.8
ND12154AB-2Russ	94	3.4	3.8	3,.0	5.2	2.9

ND12241YB-2Russ	83	2.3	4.0	4.0	4.6	3.6
ND14110B-3Russ	84	2.4	3.8	2.4	7.3	2.4
ND14130C-4Russ	96	3.0	4.1	3.3	7.2	2.5
ND14172B-1Russ	93	2.6	4.1	4.0	6.3	3.6
ND14173-2Russ	91	2.6	3.5	2.4	4.9	3.3
ND1714Y-1Russ	98	3.4	3.5	3.5	6.3	2.8
ND1760-23Russ	80	1.7	3.0	3.0	4.5	3.3
ND1762-19Russ	75	2.3	3.4	2.4	5.4	3.3
Bannock Russet	83	2.7	4.0	4.0	5.0	3.4
Dakota Russet	86	2.4	3.5	3.1	5.6	4.1
Dakota Trailblazer	95	2.5	4.3	4.0	4.9	3.9
Ranger Russet	86	2.5	3.5	4.0	5.6	2.6
Russet Burbank	80	2.8	4.0	3.0	7.8	2.4
Shepody	94	2.3	3.3	2.4	4.7	2.8
Umatilla Russet	81	2.9	4.0	3.6	8.5	3.1
Mean	88	2.7	3.6	3.0	6.3	3.1
LSD ($\propto$=0.05)	19	0.5	0.4	0.5	1.1	0.4

[1] Vine size – scale 1-5, 1 = very small, 5 = very large.

[2] Vine maturity – scale 1-5, 1 = very early, 5 = very late.

[3] General rating based on yield, appearance, tuber size profile, shape, set, defects; scale of 1 to 5; 1 = very poor, 5 = excellent.

Table 2. Yield and grade for advanced processing selections and cultivars grown at Larimore, ND, 2022. The processing trial was planted on June 7, flailed on September 30 (115 DAP), and harvested October 1, 2022, using a single-row Grimme harvester. A randomized complete block design with four replicates was utilized; plots were twenty feet long, with a within-row spacing of 12 inches and 36 inches between rows.

Clone	Total Yield Cwt./A	US No. 1 Cwt./A	US No. 1 %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	US 2s & Culls %
ND050032-4Russ	328	174	54	9	16	10	27	38
ND060735-4Russ	312	230	73	18	33	15	25	9
ND091933ABCR-2Russ	253	153	60	29	31	15	14	11
ND091933ABCR-7Russ	273	137	50	48	37	11	2	2
ND092355CR-2Russ	235	123	53	43	36	10	7	4
ND113096-1Russ	346	177	50	32	32	11	7	19
ND12154AB-2Russ	313	229	73	11	23	13	36	16
ND12241YB-2Russ	299	248	83	8	28	17	38	9
ND14110B-3Russ	358	179	49	17	22	10	17	34
ND14130C-4Russ	361	220	58	15	24	12	22	27
ND14172B-1Russ	333	241	72	13	32	15	24	15
ND14173-2Russ	305	213	69	11	22	13	33	20
ND1714Y-1Russ	270	168	61	23	31	11	20	15
ND1760-23Russ	245	189	77	12	35	17	26	11
ND1762-19Russ	309	232	74	13	27	16	31	13
Bannock Russet	236	175	75	19	31	12	32	7
Dakota Russet	320	248	77	14	29	12	36	8
Dakota Trailblazer	280	210	75	10	33	15	27	15
Ranger Russet	306	188	58	17	20	10	28	26
Russet Burbank	337	161	48	22	27	11	9	30

Shepody	315	225	70	9	22	12	37	20
Umatilla Russet	300	155	52	31	30	9	12	17
Mean	301	194	64	19	28	13	23	16
LSD (∝=0.05)	38	34	6	4	4	2	6	5

Table 3. French fry evaluations following grading for advanced processing selections and cultivars grown at Larimore, ND, 2022. The processing trial was planted on June 7, flailed on September 30 (115 DAP), and harvested October 1, 2022, using a single-row Grimme harvester. A randomized complete block design with four replicates was utilized; plots were twenty feet long, with a within-row spacing of 12 inches and 36 inches between rows.

			Field Fry			Following 45F (7.7C) Storage		
Clone	Specific Gravity[1]	Hollow Heart[2] %	Fry Color[3]	Stem-end Color	% Sugar Ends[4]	Fry Color[3]	Stem-end Color	% Sugar Ends[4]
ND050032-4Russ	1.0889	3	0.4	0.7	8	0.3	0.5	8
ND060735-4Russ	1.0878	0	0.5	0.5	0	0.3	0.3	0
ND091933ABCR-2Russ	1.0779	0	0.4	0.4	0	0.3	0.3	0
ND091933ABCR-7Russ	1.0906	3	0.5	0.5	0	0.3	0.3	25
ND092355CR-2Russ	1.0921	4	0.4	1.3	33	0.6	0.6	0
ND113096-1Russ	1.0836	0	0.5	2.6	67	0.5	3.3	75
ND12154AB-2Russ	1.0856	1	0.4	0.4	0	0.8	0.8	0
ND12241YB-2Russ	1.1035	5	0.3	0.3	0	0.5	0.5	0
ND14110B-3Russ	1.0849	2	0.8	1.3	30	0.6	2.1	65
ND14130C-4Russ	1.0920	1	1.0	1.0	0	0.9	1.2	25
ND14172B-1Russ	1.0789	0	1.0	1.5	42	1.2	1.2	0
ND14173-2Russ	1.0908	0	2.4	2.5	8	1.7	2.4	33
ND1714Y-1Russ	1.0996	0	1.8	2.1	25	0.8	0.9	0
ND1760-23Russ	1.0888	1	0.6	0.8	17	0.4	1.6	42
ND1762-19Russ	1.0987	0	0.3	0.4	4	0.2	0.3	0
Bannock Russet	1.0958	0	0.7	0.9	8	0.9	1.1	8
Dakota Russet	1.0884	1	0.5	0.8	8	0.3	0.3	0
Dakota Trailblazer	1.1098	0	0.8	0.8	0	0.4	0.4	0

Ranger Russet	1.0928	1	1.3	1.3	0	1.8	1.8	0
Russet Burbank	1.0879	1	1.2	1.9	33	0.9	1.4	42
Shepody	1.0891	0	0.9	1.8	34	0.6	2.9	50
Umatilla Russet	1.0937	0	1.6	1.7	8	1.1	1.3	8
Mean	1.0907	1	0.8	1.2	15	0.7	1.2	17
LSD ($\propto$=0.05)	0.0072	2	0.5	1.0	41	0.8	1.1	42

[1] Determined using weight-in-air, weight-in-water method.

[2] Hollow heart and brown center combined.

[3] Fry color scores: 0.1 corresponds to 000, 0.3 corresponds to 00, 0.5 corresponds to 0, 1.0 equals 1.0; subsequent numbers follow French fry rating scale 000 to 4.0. Scores of 3.0 and above are unacceptable because adequate sugars cannot be leached from the tuber flesh to make an acceptable fry of good texture.

[4] Any stem-end darker than the main fry is considered a sugar end in these evaluations, thus mirroring the worst-case scenario. The processing industry defines a sugar end as a 3.0 or darker.

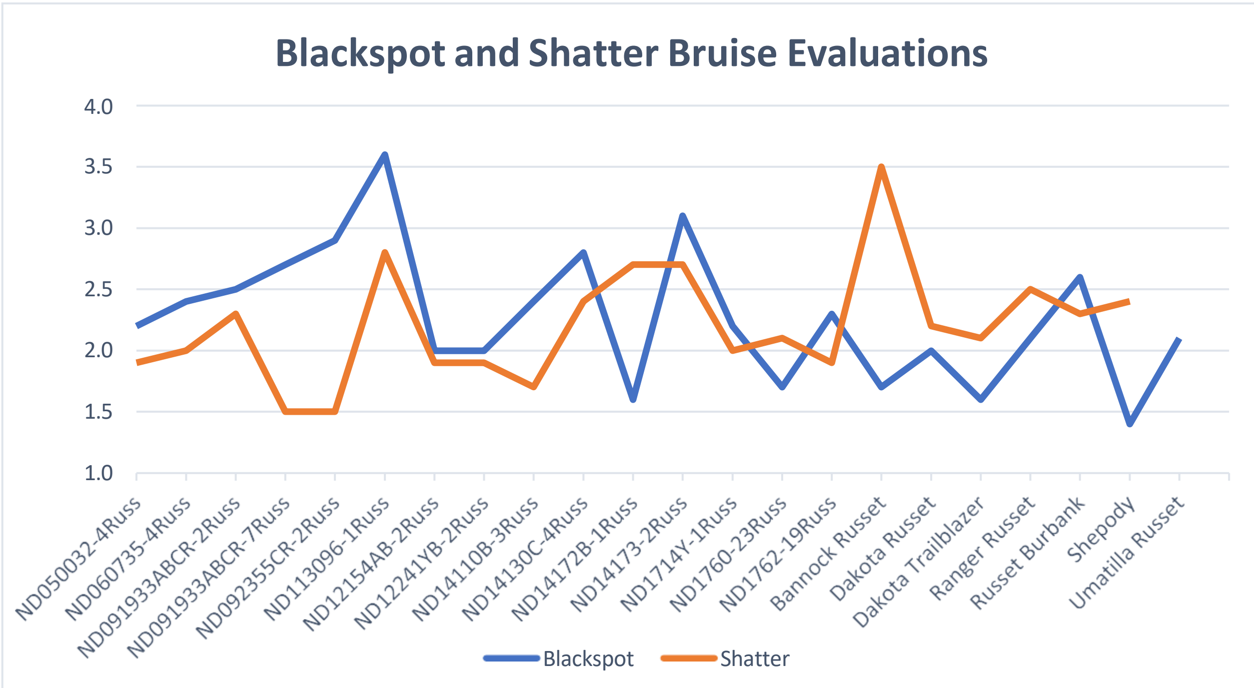

Figure 1. Blackspot and shatter bruise evaluations for advanced processing selections and cultivars grown at Larimore, ND, 2022. The processing trial was planted on June 7, flailed on September 30 (115 DAP), and harvested October 1, 2022, using a single-row Grimme harvester. A randomized complete block design with four replicates was utilized; plots were twenty feet long, with a within-row spacing of 12 inches and 36 inches between rows. Blackspot bruise determined by the abrasive peel method (Pavek et al. 1985), scale 1-5, 1 = none, 5 = severe. The mean for blackspot was 2.2, and the LSD = 0.9. Shatter bruise is evaluated using a bruising chamber with digger chain link baffles. Tubers are stored at 45F prior bruising. Shatter bruises are rated on a scale of 1-5, with 1 = none and 5 = many and severe. Mean shatter bruise was 2.2, and the LSD = 1.0.

Table 4. Agronomic evaluations for advanced processing selections and cultivars grown at Oakes, ND, 2022. The trial was planted on May 24, flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Stand %	Stems per Plant	Vine Size[1]	Vine Matur-ity[2]	Tubers per plant	General Rating[3]
AND08380-1Russ	94	3.1	3.3	2.4	9.8	3.0
AND15394-2Russ	100	3.7	3.5	2.8	10.8	3.0
ND050032-4Russ	93	1.2	3.3	3.0	4.8	3.6
ND060735-4Russ	99	2.7	3.8	3.8	7.1	4.3
ND102642C-2	96	2.0	3.3	2.0	4.9	3.8
ND12154AB-2Russ	99	2.5	3.3	2.6	5.4	3.4
ND14110B-3Russ	95	2.3	3.3	2.0	6.1	3.0
ND14130C-4Russ	98	1.7	3.0	1.9	7.8	2.9
ND14172B-1Russ	95	2.2	4.3	4.0	5.3	3.8
ND14248C-5	99	2.6	3.3	2.6	11.2	2.0
ND1714Y-1Russ	99	3.4	3.5	3.1	8.7	3.3
Bannock Russet	93	2.4	4.3	4.0	5.9	4.0
Dakota Russet	95	2.1	3.3	3.6	5.7	3.9
Dakota Trailblazer	100	2.0	4.8	4.0	4.0	4.0
Goldrush	98	2.7	3.5	1.8	7.3	3.8
Ranger Russet	96	2.2	3.5	3.8	5.0	3.0
Russet Burbank	96	2.4	3.8	2.8	6.3	2.9
Shepody	99	2.2	3.3	2.3	5.9	2.4
Umatilla Russet	89	1.9	4.0	3.8	6.3	3.0
Mean	96	2.4	3.6	2.9	6.8	3.3
LSD ($\propto$=0.05)	5	0.3	0.7	0.6	1.0	0.4

[1] Vine size – scale 1-5, 1 = very small, 5 = very large.

[2] Vine maturity – scale 1-5, 1 = very early, 5 = very late.

[3] General rating based on yield, appearance, tuber size profile, shape, set, defects; scale of 1 to 5; 1 = very poor, 5 = excellent.

Table 5. Yield and grade for advanced processing selections and cultivars grown at Oakes, ND, 2022. The trial was planted on May 24, flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Total Yield Cwt./A	US No. 1 Cwt./A	US No. 1 %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	US 2s & Culls %
AND08380-1Russ	350	229	65	31	41	16	9	4
AND15394-2Russ	476	347	73	23	44	20	9	4
ND050032-4Russ	364	304	83	5	19	10	53	12
ND060735-4Russ	405	345	85	13	37	18	29	3
ND102642C-2	310	250	80	10	25	15	39	10
ND12154AB-2Russ	424	315	74	8	16	9	48	19
ND14110B-3Russ	301	173	57	17	27	16	16	26
ND14130C-4Russ	286	302	77	16	38	19	21	6
ND14172B-1Russ	322	270	84	9	29	15	40	7
ND14248C-5	492	201	41	24	25	8	8	35
ND1714Y-1Russ	382	262	68	23	34	14	20	8
Bannock Russet	301	231	78	16	35	17	26	7
Dakota Russet	327	278	85	11	32	17	37	4
Dakota Trailblazer	343	300	87	5	19	13	56	8
Goldrush	390	275	71	14	31	16	24	15
Ranger Russet	349	279	78	6	23	14	41	16
Russet Burbank	362	258	71	11	30	15	27	18
Shepody	306	149	48	14	25	11	13	38
Umatilla Russet	366	151	50	21	26	9	14	30
Mean	366	258	71	14	29	14	28	14
LSD ($\propto$=0.05)	102	69	10	6	7	4	9	10

Table 6. French fry evaluations following grading for advanced processing selections and cultivars grown at Oakes, ND, 2022. The trial was planted on May 24, flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

			Field Fry			Following 45F (7.7C) Storage		
Clone	Specific Gravity[1]	Hollow Heart[2] %	Fry Color[3]	Stem-end Color	% Sugar Ends[4]	Fry Color[3]	Stem-end Color	% Sugar Ends[4]
AND08380-1Russ	1.0811	15	0.6	1.0	17	0.8	1.6	59
AND15394-2Russ	1.0995	3	0.4	0.7	17	0.4	0.7	25
ND050032-4Russ	1.0946	6	0.3	1.1	25	0.3	0.4	8
ND060735-4Russ	1.0993	1	0.4	0.4	0	0.3	0.3	0
ND102642C-2	1.0870	9	0.4	0.4	0	0.2	0.2	0
ND12154AB-2Russ	1.0813	5	0.7	0.7	0	0.8	0.8	0
ND14110B-3Russ	1.0985	4	0.6	1.5	58	0.5	1.5	67
ND14130C-4Russ	1.0870	3	0.4	0.7	17	0.5	0.5	8
ND14172B-1Russ	1.1039	1	0.5	0.6	8	0.5	0.5	0
ND14248C-5	1.0887	3	0.4	0.4	0	0.3	0.3	0
ND1714Y-1Russ	1.1012	19	0.8	1.5	42	0.5	0.7	8
Bannock Russet	1.1097	9	0.5	0.6	8	0.4	0.4	0
Dakota Russet	1.0916	16	0.4	0.9	17	0.3	0.6	8
Dakota Trailblazer	1.1153	4	0.4	0.4	0	0.3	0.3	0
Goldrush	1.0830	3	1.2	1.7	67	1.3	2.0	42
Ranger Russet	1.1081	5	0.5	1.0	8	0.5	0.8	25
Russet Burbank	1.0808	14	1.0	2.3	42	1.1	2.2	50
Shepody	1.0915	1	0.5	2.3	75	0.5	2.8	75

Umatilla Russet	1.0970	5	0.4	1.0	25	0.3	0.4	8
Mean	1.0947	7	0.5	1.0	22	0.5	0.9	20
LSD (∝=0.05)	0.0069	11	0.3	1.0	42	0.4	0.7	33

[1] Determined using weight-in-air, weight-in-water method.

[2] Hollow heart and brown center combined.

[3] Fry color scores: 0.1 corresponds to 000, 0.3 corresponds to 00, 0.5 corresponds to 0, 1.0 equals 1.0; subsequent numbers follow French fry rating scale 000 to 4.0. Scores of 3.0 and above are unacceptable because adequate sugars cannot be leached from the tuber flesh to make an acceptable fry of good texture.

[4] Any stem-end darker than the main fry is considered a sugar end in these evaluations, thus mirroring the worst-case scenario. The processing industry defines a sugar end as a 3.0 or darker.

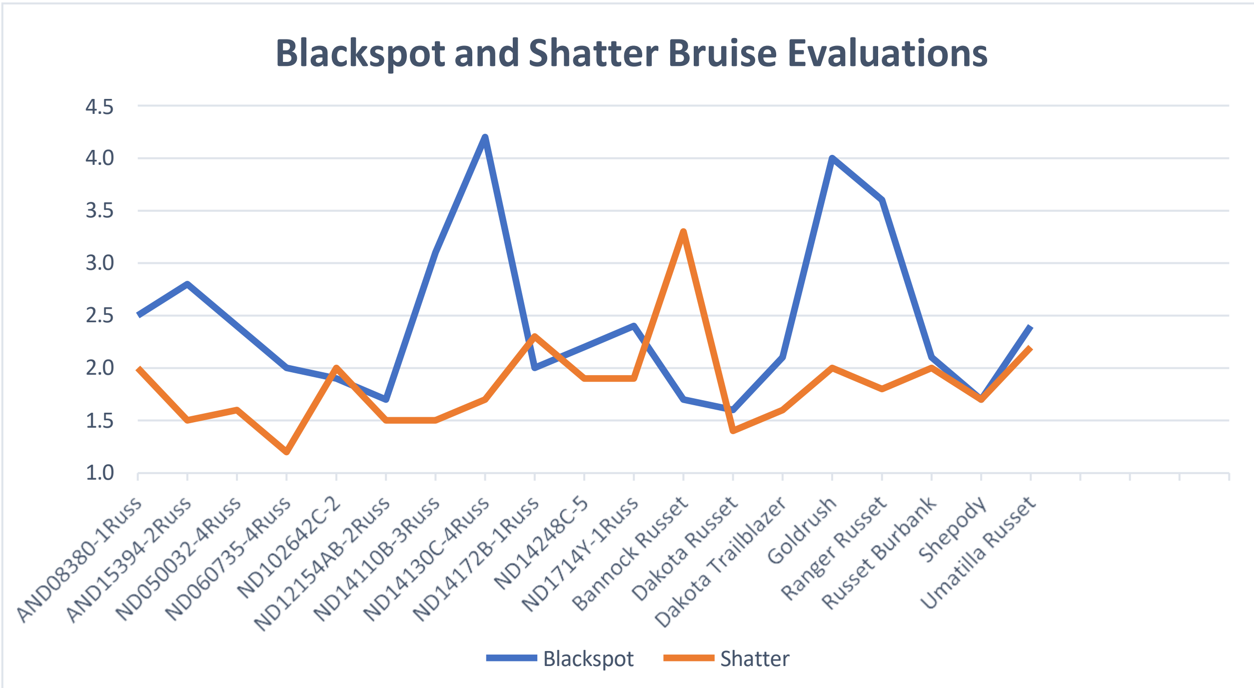

Figure 2. Blackspot and shatter bruise evaluations for advanced processing selections and cultivars grown at Oakes, ND, 2022. The trial was planted on May 24, flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows. Blackspot bruise determined by the abrasive peel method (Pavek et al. 1985), scale 1-5, 1 = none, 5 = severe. The mean for blackspot was 2.4, and the LSD = 0.8. Shatter bruise is evaluated using a bruising chamber with digger chain link baffles. Tubers are stored at 45F prior bruising. Shatter bruises are rated on a scale of 1-5, with 1 = none and 5 = many and severe. Mean shatter bruise was 1.8, and the LSD = 0.6.

Table 7. Agronomic and quality attributes (skin color, scurf, specific gravity, and general rating (breeder merit score) for advanced fresh market selections and cultivars, Oakes, ND, 2022. The trial was planted May 24, flailed on September 16, and harvested on September 24 using a single-row Grimme harvester. A randomized complete block design was utilized with four replicates; plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Stand %	Stems per Plant	Vine Size[1]	Vine Maturity[2]	Tubers per Plant	Color[3]	Scurf[4]	Specific Gravity[5]	General Rating
AFND7090-2R	95	3.3	2.5	2.3	14.8	3.8	2.3	1.0792	3.3
AFND7090-7R	95	2.5	2.8	2.5	9.9	3.4	3.0	1.0704	2.8
AFND6938-3R	98	2.7	2.8	2.1	5.6	3.6	3.8	1.0803	2.9
ND1241-1Y	99	3.2	3.5	1.9	9.1	Y	4.0	1.1146	4.3
ND14338-1R	85	2.6	2.3	1.1	6.6	3.5	3.8	1.0710	3.6
ND14339C-2R	98	3.2	2.3	2.0	6.4	2.8	2.0	1.0716	3.4
ND1727Y-3R	95	2.5	3.3	3.4	8.2	3.5	3.5	1.0799	2.8
ND1757-5R	99	3.2	3.0	2.5	12.1	3.9	3.0	1.0770	3.7
ND17119-9R	96	3.0	3.0	1.1	12.7	3.0	2.9	1.0799	3.0
ND17129-5R	98	3.0	3.0	3.5	7.9	3.9	3.8	1.0801	3.7
Dakota Ruby	96	3.5	2.8	2.0	13.0	4.0	3.8	1.0748	2.8
Red LaSoda	95	2.3	3.0	2.1	6.1	3.3	3.0	1.0748	2.9
Red Norland	100	3.0	2.8	1.4	10.0	3.0	2.0	1.0700	3.1
Yukon Gold	94	1.9	3.3	1.9	3.8	Y	4.0	1.0884	3.4
Mean	95	2.8	2.9	2.1	8.9	na	3.2	1.0794	3.2
LSD ($\propto$=0.05)	7	0.6	0.7	0.6	3.4	0.5	0.6	0.0095	0.5

[1] Vine size – scale 1-5, 1 = very small, 5 = very large.

[2] Vine maturity – scale 1-5, 1 = very early, 5 = very late.

[3] Color = 1-5; 1 = white/buff, 2 = pink, 3 = red, 4 = bright red, 5 = dark red, RSY = Red splashed yellow, Y = yellow, P = purple.

[4] Scurf incidence – scale 1-5, 1 = completely covered, 5 = none (not determined if silver scurf or blackdot sclerotia).

[5] Determined using weight-in-air, weight-in-water method.

[6] General Rating = 1-5; 1 = poor and unacceptable, 3 = fair, 5 = excellent.

na = not applicable.

Table 8. Yield and grade for advanced fresh market selections and cultivars, Oakes, ND, 2022. The trial was planted on May 24, flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Total Yield Cwt./A	A Size Tubers Cwt./A	A Size %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	% Defects
AFND7090-2R	451	210	47	43	35	11	8	2
AFND7090-7R	348	168	48	38	36	13	12	2
AFND6938-3R	275	102	37	18	24	12	11	34
ND1241-1Y	272	137	49	48	37	11	3	1
ND14338-1R	199	95	48	43	38	10	3	8
ND14339C-2R	190	94	46	48	37	9	3	3
ND1727Y-3R	306	176	58	31	42	15	9	2
ND1757-5R	383	194	50	41	39	12	7	2
ND17119-9R	213	45	21	77	17	4	2	1
ND17129-5R	339	221	64	24	44	20	12	0
Dakota Ruby	403	185	46	43	36	10	5	5
Red LaSoda	440	137	31	8	19	12	40	22
Red Norland	503	262	53	16	35	18	24	7
Yukon Gold	311	106	35	5	21	13	47	14
Mean	329	151	45	34	33	12	13	7
LSD ($\propto$=0.05)	122	64	10	9	7	4	8	5

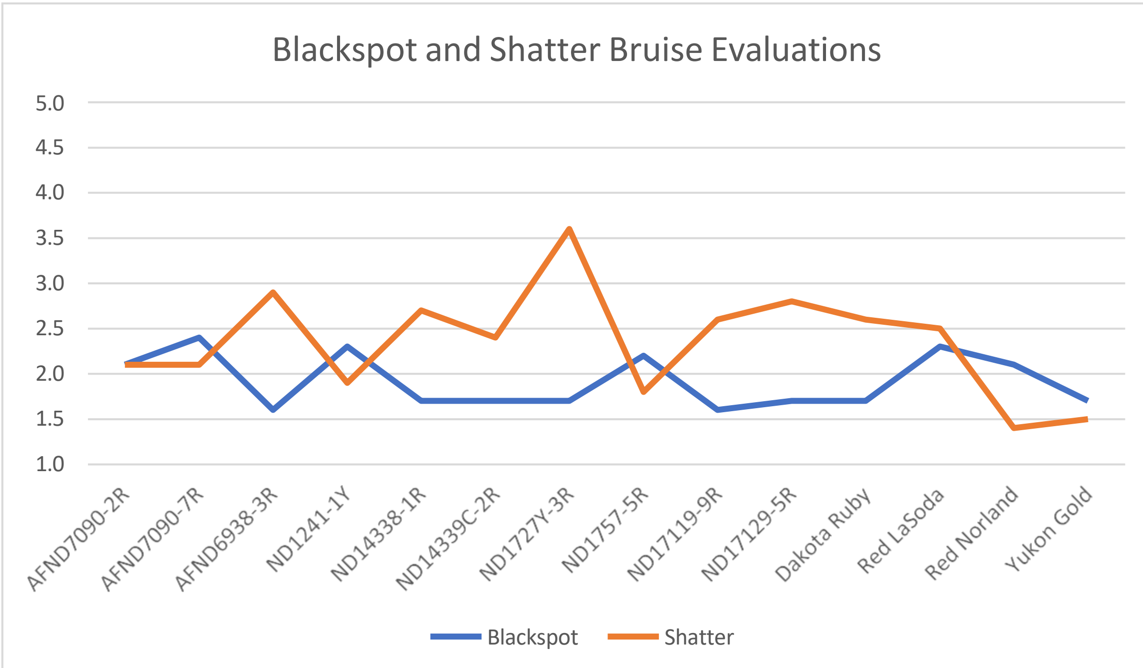

Figure 3. Blackspot and shatter bruise evaluations for advanced fresh market selections and cultivars, Oakes, ND, 2022. The trial was planted on May 24, vines were flailed on September 16, and harvested with a single-row Grimme harvester on September 24. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows. Blackspot bruise determined by the abrasive peel method (Pavek et al. 1985) following storage at 45F, using a scale of 1-5, 1 = none, 5 = severe. As an example, Ranger Russet typically rates as a 4.0 or greater. The mean for blackspot was 1.9, with an LSD of 0.7. Shatter bruise is evaluated using a bruising chamber with digger chain link baffles. Tubers are stored at 45F prior bruising. Shatter bruises are rated on a scale of 1-5, with 1 = none and 5 = many and severe. Mean shatter bruise was 2.3, with an LSD of 0.9.

Table 9. Agronomic and quality attributes (skin color, scurf, specific gravity, and general rating (breeder merit score) for advanced fresh market selections and cultivars, Crystal, ND, 2022. The trial was planted May 25, vines shredded on approximately September 6 (104 DAP), and harvested on September 27 using a single-row Grimme harvester. A randomized complete block design was utilized with four replicates; plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Stand %	Stems per Plant	Vine Size[1]	Vine Maturity[2]	Tubers per Plant	Color[3]	Scurf[4]	Specific Gravity[5]	General Rating
ND081571-2R	95	3.4	3.0	2.5	12.5	4.0	4.0	1.0764	4.1
ND018571-3R	96	3.9	3.5	2.9	11.2	3.5	3.5	1.0989	3.6
ND113207-1R	95	2.7	3.0	2.9	12.3	4.0	3.5	1.0849	3.8
ND1232-1RY	100	3.1	3.6	2.4	17.2	3.9	4.1	1.0918	3.9
ND1232-2RY	95	3.1	3.5	2.9	14.1	4.0	3.5	1.0936	3.9
ND1240-2R	96	3.4	3.5	2.6	16.9	4.0	3.8	1.0917	3.8
ND1241-1Y	95	2.9	3.0	2.6	14.8	Y	4.4	1.1157	4.1
ND1243-1PY	93	2.4	4.0	4.0	10.3	P	3.4	1.0905	3.9
ND12128B-1R	90	3.6	2.8	3.3	14.0	3.8	4.0	1.1029	3.8
ND1382-2R	93	3.2	3.5	3.1	15.9	4.0	4.0	1.0840	3.9
ND1393Y-3R	93	2.3	3.5	3.8	9.3	4.0	3.8	1.0899	3.2
ND13302-1RY	99	3.5	3.5	2.8	11.6	3.8	3.6	1.0844	3.8
ND1455Y-1R	91	3.2	2.5	2.6	9.4	3.4	3.8	1.0883	3.5
ND1455Y-2R	95	3.3	3.0	2.5	9.7	3.4	3.8	1.0874	3.4
ND1465-2R	96	3.5	3.0	2.8	21.0	3.9	3.8	1.0771	3.1
ND14113Y-3R	99	3.2	4.1	3.4	9.3	4.0	3.8	1.0909	3.6
ND14113Y-5R	99	4.0	3.5	2.9	18.3	3.9	2.3	1.0835	3.4
ND14151-9R	94	3.2	3.3	3.4	13.1	3.9	3.9	1.0908	3.9
ND14151-15R	100	3.5	3.3	3.8	14.0	4.0	3.3	1.0966	3.8
ND14151-20R	87	3.0	3.9	3.1	13.1	4.0	3.9	1.0879	3.9
ND14151-24R	95	3.0	3.5	2.9	11.6	4.0	4.4	1.0804	3.9

ND14212Y-1R	93	3.3	2.8	2.3	11.6	3.5	2.3	1.0922	3.1
ND14282CB-4R	98	4.6	2.8	2.3	19.8	3.9	3.3	1.1045	3.5
ND14284CB-4R	94	2.7	3.0	2.9	7.2	3.9	3.6	1.0925	3.6
All Blue	100	3.4	3.0	2.8	13.1	P	2.0	1.0892	3.0
Dakota Ruby	98	3.4	3.5	3.4	14.3	4.0	4.5	1.0936	3.9
Red LaSoda	93	3.1	3.0	3.0	9.2	3.1	4.3	1.0840	3.2
Red Norland	98	4.2	2.8	1.8	9.4	3.0	2.0	1.0853	3.1
Sangre	94	2.1	4.0	3.6	8.3	3.5	2.3	1.0828	2.7
Yukon Gold	93	2.0	3.0	1.6	5.6	Y	4.0	1.0985	3.8
Mean	95	3.2	3.3	2.9	12.6	Na	3.5	1.0903	3.6
LSD ($\propto$=0.05)	9	0.5	0.6	0.6	2.2	0.3	0.6	0.0075	0.4

[1] Vine size – scale 1-5, 1 = very small, 5 = very large.

[2] Vine maturity – scale 1-5, 1 = very early, 5 = very late.

[3] Color = 1-5; 1 = white/buff, 2 = pink, 3 = red, 4 = bright red, 5 = dark red, RSY = Red splashed yellow, Y = yellow, P = purple.
[4] Scurf incidence – scale 1-5, 1 = completely covered, 5 = none (not determined if silver scurf or blackdot sclerotia).

[5] Determined using weight-in-air, weight-in-water method.

[6] General Rating = 1-5; 1 = poor and unacceptable, 3 = fair, 5 = excellent.
na = not applicable.

Table 10. Yield and grade for advanced fresh market selections and cultivars, Crystal, ND, 2022. The trial was planted on May 25, vines shredded on approximately September 6 (104 DAP), and harvested on September 27. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows.

Clone	Total Yield Cwt./A	A Size Tubers Cwt./A	A Size %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	% Defects
ND081571-2R	262	58	22	78	21	1	0	0
ND018571-3R	259	65	25	75	23	2	0	0
ND113207-1R	321	133	41	57	33	7	2	0
ND1232-1RY	363	50	14	86	13	1	0	0
ND1232-2RY	319	70	22	78	20	1	0	0
ND1240-2R	357	55	15	84	14	1	0	0

ND1241-1Y	290	70	23	77	21	2	0	0
ND1243-1PY	355	206	58	39	43	15	2	1
ND12128B-1R	281	37	12	87	12	0	0	1
ND1382-2R	258	12	5	95	5	0	0	0
ND1393Y-3R	254	101	40	57	33	7	2	1
ND13302-1RY	332	155	46	51	38	8	2	0
ND1455Y-1R	219	66	30	98	26	4	2	0
ND1455Y-2R	244	93	39	60	34	5	0	1
ND1465-2R	333	30	9	91	8	1	0	0
ND14113Y-3R	312	183	58	41	45	13	1	0
ND14113Y-5R	368	65	18	81	16	2	0	0
ND14151-9R	225	22	10	90	9	1	0	0
ND14151-15R	231	17	7	93	7	0	0	0
ND14151-20R	261	18	7	93	7	0	0	0
ND14151-24R	287	109	38	61	31	7	1	0
ND14212Y-1R	209	30	14	85	13	1	0	0
ND14282CB-4R	286	13	5	95	5	0	0	0
ND14284CB-4R	170	43	25	75	23	2	0	0
All Blue	272	58	21	77	20	1	0	2
Dakota Ruby	291	55	19	81	17	2	0	0
Red LaSoda	398	227	57	20	39	18	19	4
Red Norland	380	243	64	27	46	18	6	3
Sangre	305	180	59	32	44	15	7	2
Yukon Gold	235	150	64	25	44	19	11	1
Mean	289	87	29	69	24	5	2	1
LSD ($\propto$=0.05)	43	30	8	8	7	3	4	2

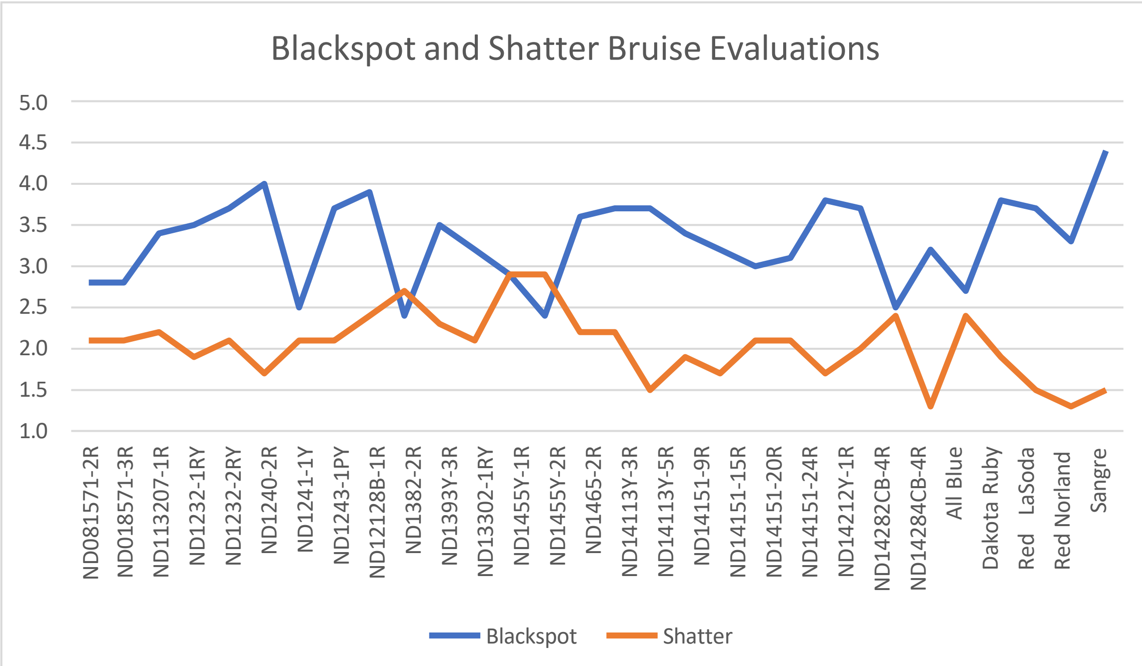

Figure 4. Blackspot and shatter bruise evaluations for advanced fresh market selections and cultivars, Crystal, ND, 2022. The trial was planted on May 25, vines shredded on approximately September 6 (104 DAP), and harvested on September 27. A randomized complete block design was utilized with four replicates. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows. Blackspot bruise determined by the abrasive peel method (Pavek et al. 1985) following storage at 45F, using a scale of 1-5, 1 = none, 5 = severe. As an example, Ranger Russet typically rates as a 4.0 or greater. The mean for blackspot was 3.3, with an LSD of 0.8. Shatter bruise is evaluated using a bruising chamber with digger chain link baffles. Tubers are stored at 45F prior bruising. Shatter bruises are rated on a scale of 1-5, with 1 = none and 5 = many and severe. Mean shatter bruise was 2.0, with an LSD equal to 0.7.

Table 11. Agronomic, bruising and merit assessments for advancing chip processing selections and cultivars, Hoople, ND, 2022. The chip processing trial was planted on June 3, vines were flailed on September 26, and harvested September 28 and 29, using a single-row Grimme harvester. The field design was a randomized complete block, with four replicates; plots were 20 feet long, with a 12-inch with-in row spacing, and 38 inches between rows.

Clone	Stand %	Stems per Plant	Vine Size[1]	Vine Maturity[2]	Tubers per plant	Scab % Area	General Rating[3]
ND4100C-19	80	3.5	1.0	1.3	7.6	14	3.3
ND7519-1	98	3.7	2.5	1.8	4.2	2	3.6
ND7799c-1	93	2.4	1.8	1.4	4.8	1	3.8
ND8331Cb-2	93	2.9	1.8	1.3	6.7	1	3.7
ND092018C-2	84	2.6	2.0	1.6	7.5	8	3.1
ND102631AB-1	91	2.6	1.5	1.0	6.0	1	3.4
ND1241-1Y	96	2.7	2.3	1.6	10.7	9	3.4
ND12209C-2	98	2.9	2.0	1.6	7.0	12	3.4
ND1336-5	95	3.1	1.3	1.0	6.0	8	3.7
ND13220C-3	98	3.6	3.5	2.6	8.7	1	3.4
ND13321CAB-2	93	2.4	2.3	2.4	6.0	14	3.3
ND1462ABC-1a	86	2.2	1.3	1.3	5.9	8	3.6
ND14291CAB-9	83	1.9	1.0	1.1	5.9	4	3.5
ND14316CABY-4	98	3.1	1.0	1.0	6.4	14	3.3
Lady Claire	94	2.9	1.8	1.0	9.5	1	2.9
Lady Liberty	89	2.0	3.0	3.0	6.4	8	3.6
ND1789-1	75	2.3	1.8	1.9	7.7	15	3.4
Atlantic	96	2.7	2.5	2.1	4.7	5	3.3
Dakota Crisp	74	2.8	2.3	2.4	6.4	8	3.5
Dakota Pearl	80	2.9	1.0	1.1	7.4	0	3.8
Lamoka	93	2.0	2.3	1.5	4.0	2	3.4

Pike	98	2.2	2.3	2.4	6.0	0	3.5
Snowden	73	3.0	2.0	2.4	4.5	8	3.3
Waneta	76	1.4	2.0	2.0	5.6	8	3.4
Mean	89	2.6	1.9	1.7	6.5	6	3.4
LSD ($\propto$=0.05)	18	0.9	0.8	0.7	2.0	8	0.5

[1] Vine size – scale 1-5, 1 = small, 5 = large.

[2] Vine maturity – scale 1-5, 1 = early, 5 = late.

[3] General rating based on yield, appearance, tuber size profile, shape, set, defects; scale of 1 to 5; 1 = poor, 5 = excellent.

Table 12. Yield and grade for advancing chip processing selections and cultivars, Hoople, ND, 2022. The chip processing trial was planted on June 3, 2022, vines were flailed on September 26, and harvested September 28 and 29, using a single-row Grimme harvester. The field design was a randomized complete block, with four replicates; plots were 20 feet long, with a 12-inch with-in row spacing, and 38 inches between rows.

Clone	Total Yield cwt./a	Yield A Size cwt/a	A Size %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	US 2s & Culls %
ND4100C-19	170	70	40	50	31	10	6	4
ND7519-1	218	121	56	16	37	18	24	4
ND7799c-1	216	109	50	21	35	15	27	2
ND8331Cb-2	188	83	43	53	36	7	3	1
ND092018C-2	202	94	45	48	37	9	3	2
ND102631AB-1	155	59	38	50	30	8	3	9
ND1241-1Y	202	50	22	77	19	4	0	0
ND12209C-2	212	99	45	46	34	11	4	5
ND1336-5	218	111	51	31	37	13	10	8
ND13220C-3	331	177	53	33	42	11	11	3
ND13321CAB-2	218	111	50	32	38	12	11	7
ND1462ABC-1a	155	75	46	50	35	10	2	5
ND14291CAB-9	129	49	38	56	29	9	6	0
ND14316CABY-4	170	69	41	58	33	8	1	1
Lady Claire	215	69	32	61	26	6	2	5
Lady Liberty	248	148	60	23	43	17	16	1
ND1789-1	202	17	53	32	38	15	13	2
Atlantic	254	139	55	12	37	18	23	9
Dakota Crisp	233	117	52	17	36	17	24	7
Dakota Pearl	165	63	37	55	28	9	4	3
Lamoka	165	97	59	23	41	18	16	1
Pike	177	81	46	53	36	10	1	0

Snowden	148	82	56	23	39	16	19	3
Waneta	189	109	60	19	40	20	20	1
Mean	199	95	47	39	35	12	10	3
LSD (∝=0.05)	59	35	13	14	10	5	8	5

Table 13. Specific gravity and chip color after grading (USDA chip chart) and following 8-weeks storage at 3.3C (38F) and 5.5C (42F) for advancing chip processing selections and cultivars, Hoople, ND, 2022. The chip processing trial was planted on June 3, 2022, flailed on September 26 (115 DAP), and harvested September 28 and 29, using a single-row Grimme harvester. The field design was a randomized complete block, with four replicates; plots were 20 feet long, with a 12-inch with-in row spacing, and 38 inches between rows.

Clone	Black-spot Rating[1]	Shatter Bruise Rating[2]	Specific Gravity[3]	Field Chip Chart[4]	38 F (3.3C) Storage Chart[4]	42F (5.5C) Storage Chart[4]
ND4100C-19	2.0	2.2	1.0955	4.8	8.3	4.8
ND7519-1	2.7	2.5	1.1086	3.0	7.0	4.0
ND7799c-1	1.3	2.8	1.0919	3.0	8.0	4.3
ND8331Cb-2	1.9	1.9	1.1121	4.3	5.5	3.0
ND092018C-2	3.3	2.2	1.1146	4.3	9.8	5.3
ND102631AB-1	1.8	2.8	1.1084	3.3	8.0	4.5
ND1241-1Y	2.7	2.1	1.1176	3.5	7.3	3.8
ND12209C-2	2.2	1.9	1.1089	3.0	7.8	5.0
ND1336-5	2.5	2.8	1.0978	3.0	8.1	4.0
ND13220C-3	3.2	2.7	1.1117	4.8	8.8	4.3
ND13321CAB-2	2.0	2.2	1.1047	2.8	7.8	5.0
ND1462ABC-1a	2.5	2.0	1.0882	2.0	7.6	3.0
ND14291CAB-9	3.2	2.4	1.0868	5.0	9.5	7.3
ND14316CABY-4	2.2	1.7	1.0920	3.5	6.5	4.8
Lady Claire	2.2	1.6	1.1166	3.5	8.0	4.8
Lady Liberty	3.7	1.6	1.1066	4.8	8.3	5.3
ND1789-1	3.7	2.8	1.1003	4.0	8.3	4.8
Atlantic	2.4	2.3	1.1031	4.8	9.3	5.8
Dakota Crisp	2.1	2.2	1.0967	4.5	8.8	7.0
Dakota Pearl	1.3	1.6	1.0969	2.8	7.8	6.5
Lamoka	2.5	2.2	1.1049	3.8	9.0	5.8
Pike	2.4	1.6	1.1057	5.5	10	7.4

Snowden	3.0	2.5	1.1017	4.3	9.8	5.8
Waneta	2.0	1.6	1.0998	2.5	8.0	5.5
Mean	2.4	2.1	1.1030	3.8	8.2	5.0
LSD ($\propto$=0.05)	0.9	0.6	0.0066	2.1	1.3	2.6

[1] Blackspot bruise determined by the abrasive peel method (Pavek et al. 1985) following storage at 45F, using a scale of 1-5, 1 = none, 5 = severe. As an example, Ranger Russet typically rates as a 4.0 or greater.

[2] Shatter bruise is evaluated using a bruising chamber with digger chain link baffles; tubers are stored at 45F prior bruising. Shatter bruises are rated on a scale of 1-5, with 1 = none and 5 = many and severe.

[3] Determined using weight-in-air, weight-in-water method.

[4] USDA Potato Chip Color Reference Standard, Courtesy of B.L. Thomas, B.L. Thomas and Associates, Cincinnati, Ohio, Potato Chip Institute International. 1 = white, 10 = very dark; 4 and below acceptable.

Preliminary Report Title: Monitoring population dynamics of *Verticillium* wilt and developing *Verticillium* wilt screening nursery in an irrigated potato field at Becker, MN

Principle Investigator: Ashish Ranjan, 495 Borlaug Hall, 1991 Upper Buford Circle
Department of Plant Pathology, University of Minnesota - Twin Cities, St. Paul MN 55108

Executive Summary-

Potato is one of the most economically important crops impacted by *Verticillium* wilt in MN. *Verticillium* wilt, also called potato early dying disease of potato is caused primarily by three species of fungal pathogens called *Verticillium dahliae, Verticillium albo-atrum,* and *Verticillium isaacii* (Inderbitzin et al. 2011; Wheeler, D.L et al. 2019). *Verticillium* wilt is a recurring problem for Minnesota and northern plains potato growers. The cultural management strategies such as crop rotation with non-host and fumigation have limited economic success. One of the most sustainable and economical ways to control crop diseases is to identify and generate resistant varieties of plants. For the identification of resistant varieties, it's crucial to have disease nurseries for screening potato lines. The breeding effort at UMN (currently led by Dr. Laura Shannon) has led to the generation of several potato lines. Disease screening plots were established at an irrigated potato field at Sand Plain Research Farm, Becker, MN, in 2022 (Fig1). Seventeen potato entries, including susceptible cultivar Superior, were screened for resistance to *Verticillium* wilt. The study identified five verticillium-tolerant potato lines (Table 1 and Figure 2).

Understanding pathogen variability and genetics is essential for managing the disease and ultimately breeding resistant lines of the host. Another critical aspect of the disease is the knowledge about the diversity of the pathogen isolates and their local adaptation. Therefore, monitoring and determining the population dynamics of locally adapted Verticillium strains in MN is important. Our lab has standardized the protocol for isolating these strains from infected potato stems (Figure 4). We have also surveyed and collected the infected potato stem samples from different locations in Sherburne and Benton counties to monitor and identify the diversity of *Verticillium* isolates (Figure 4). We have used molecular biology techniques to confirm the verticillium species by using *Verticillium*-specific primers (Inderbitzin et al. 2011) to amplify the isolated DNA from these samples. We hope to perform our second year of the field trial in 2023 and continue collecting more Verticillium-infected potato stem samples to identify the prevalent Verticillium species/races in MN. A few years of study will provide comprehensive identification

of Verticillium tolerant lines and provide standard material for further breeding efforts to breed elite Verticillium tolerant potato lines.

Rationale:

Our rationale for the proposed study is to develop an in-home disease nursery for screening potato lines for *Verticillium* wilt resistance. One of the major aims of the study is to find genetic disease management solutions that can reduce dependency on fungicides and fumigants and also secure yield loss in a sustainable way. The proposed research plan will lead to the identification of new *Verticillium* wilt-resistant potato verities, ultimately leading to potato improvement for resistance against *Verticillium* wilt.

Surveying and identifying locally adapted *Verticillium* pathogen isolates might provide a better understanding of its population's dynamics and diversity, which might contribute to a differential degree of pathogenicity. These strains will be an important resource for future studies, including understating their differential pathogenicity and fungicide resistance. The understanding will help inform growers about region-specific planting of potato varieties and help decide about Verticillium control strategies.

Objectives:

For our first year of study, we had the following two primary objectives –

1. Evaluating UMN potato breeding lines for *Verticillium* wilt resistance and standardizing screening protocols in the irrigated potato field.
2. Surveying and collecting the infected potato stem samples from several locations in Mn to monitor and identify the diversity of *Verticillium* isolates.

Materials and methods/procedure:

For objective 1. We screened approximately 17 lines of potato lines bred at the UMN potato breeding group led by Dr. Laura Shannon. We planted four replicates of 10 potato hills in each replicate in the *Verticillium* wilt nursery at the Sand Plain Research Farm, Becker, MN, on 12th May 2022 in a completely randomized block design. Superior potato varieties were used for susceptible checks of Verticillium wilt disease. *Verticillium* wilt was visually assessed at seven-day intervals beginning at the mid-potato vegetative growth and flowering stage (from 22nd July to 11th August) by scoring the plants exhibiting symptoms. We noted the severity of *Verticillium* wilt symptoms at different intervals. We rated them for the percentage of foliage exhibiting senescence using the following scale: 1 - No disease symptoms, 2 - Slight wilting and unilateral discoloration of lower leaves (1-25% wilt), 3 - Moderate wilting involving less than one-half of the plant (25-50% wilt), 4 - Severe wilting involving more than one-half of the plant (51-75%), and 5 - Plant dead or dying from wilt (75-100% wilt) (Hoyos et. al., 1991). We also visited the disease nursery early on and later in the season to check for potato growth stages and perform destructive sampling of the infected potato stems. We calaculated area under the disease progress curve (AUDPC) and Relative Area under the disease progress curve (RAUPDC) in Superior and sixteen potato lines using percentage disease severity foliage (DS%) from 28th July symptoms (Table 1). The stem colonization was validated by *Verticillium*-specific primers (Inderbitzin et al. 2011). Data analysis was conducted using standard statistical procedures.

Objective 2: We collected the infected potato stem samples 10 cm from the bottom of the plant from each replicate and stored them in a cooler until we reached the lab. Further samples were stored at 4^{0}c until we performed the surface sterilization of the samples and isolated the *Verticillium* using semi-selective media (Inderbitzin et al. 2011). Isolate was stored at -80^{0}c as glycerol stocks for further study. Genomic DNA from the *Verticillium* isolates was isolated using the CTAB method. By using *Verticillium*-specific primers, DNA was amplified. The PCR product was purified using a PCR/gel purification kit (Inderbitzin et al. 2011). The PCR-purified products were sent for sequencing to ACGT sequencing services. The sequence was blasted against NCBI (National Center for Biotechnology Information) database to confirm *Verticillium*.

Results:

Disease screening plots were established at an irrigated potato field at Sand Plain Research Farm, Becker, Mn, in 2022 (Fig1).

Figure 1. Becker *Verticillium* wilt disease nursery 28th July 2022.

In our first year of the research project that started in May 2022, we screened ~ 650 potato hills for resistance to *Verticillium* wilt. The study included seventeen entries, including susceptible cultivar Superior, in four replicates. Comparisons were made between Superior and sixteen potato lines for disease symptom expression using the disease severity scoring as discussed above. The study identified five *Verticillium*-tolerant potato lines (Table 1 and Figure 2). Below we have also shown the progression of *Verticillium* wilt disease in MN18CO15083-006 (119, **tolerant**) and MN19TX18304-001(33, **susceptible**) potato variety on 21st July, 28th July, and 11th August 2022.

Table 1. Area under the disease progress curve (AUDPC) and Relative Area under the disease progress curve (RAUPDC) in Superior and sixteen potato lines using percentage disease severity foliage (DS%) from 12th July, 21st July, 28th July, and 11th August. The letter in bold indicates tolerant lines (**in Bold**).

Potato Lines	**AUDPAC**	**RAUPDC**
Superior	1661.75	55.39
MN18CO15083-006	**921.71**	**30.72**
MN18CO16154-009	**1082.99**	**36.1**
MN18CO16212-003	1547.76	51.59
MN18TX17748-002	**1028.15**	**34.27**
MN18W17037-034	1169.55	38.99
MN18W17039-025	1107.27	36.91
MN18W17065-004	**1072.63**	**35.75**
MN18W17089-002	**927.135**	**30.9**
MN19AF6945-004	1449.97	48.33

MN19AF6945-005	1507.37	50.25
MN19CO17027-001	1261.15	42.04
MN19TX17722-003	1118.09	37.27
MN19TX18032-010	1417.94	47.26
MN19TX18073-001	1514.31	50.48
MN19TX18093-001	1124.97	37.5
MN19TX18304-001	1586.96	52.9

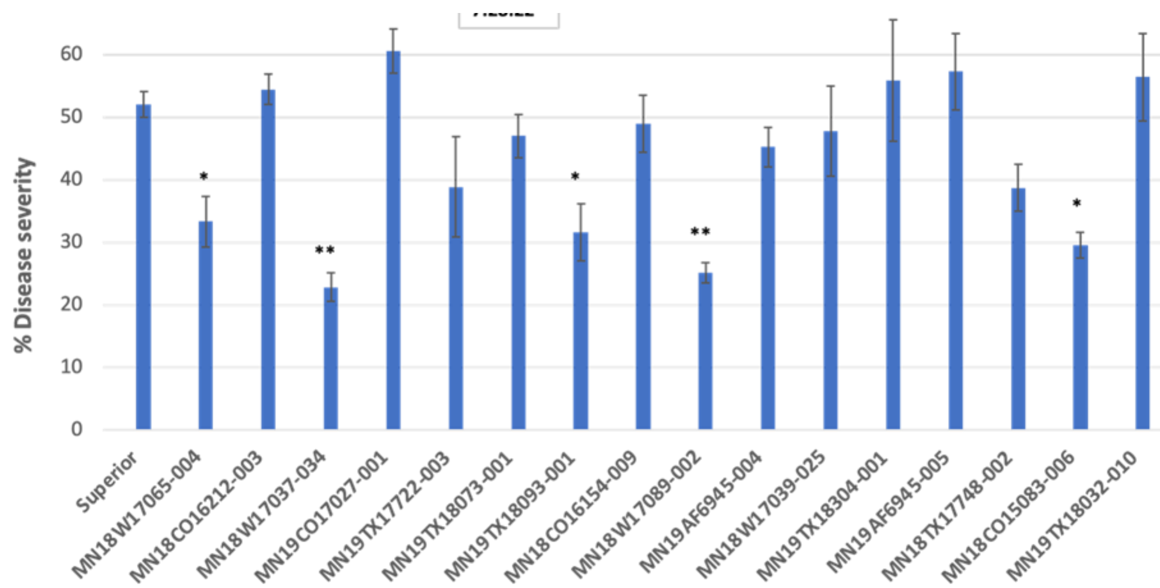

Figure 2. *Verticillium* wilt symptoms (percent disease severity) in Superior and sixteen potato lines on 28th July, * significant effect (P<0.05)

Figure 3. Progression of *Verticillium* wilt disease in MN18CO15083-006 (119, tolerant) and MN19TX18304-001(33, susceptible) potato variety at Sand Plain Research Farm, Becker, MN. Photographed on (A, B) 21st July, (C, D) 28th July, and (E, F) 11th August, respectively.

The *Verticillium* wilt disease was confirmed by isolating the pathogen and DNA from infected stems and validated by PCR and Sequencing. We have also surveyed and collected the infected potato stem samples from different locations in Becker and Rice counties to monitor and identify the diversity of *Verticillium* isolates (Figure 4).

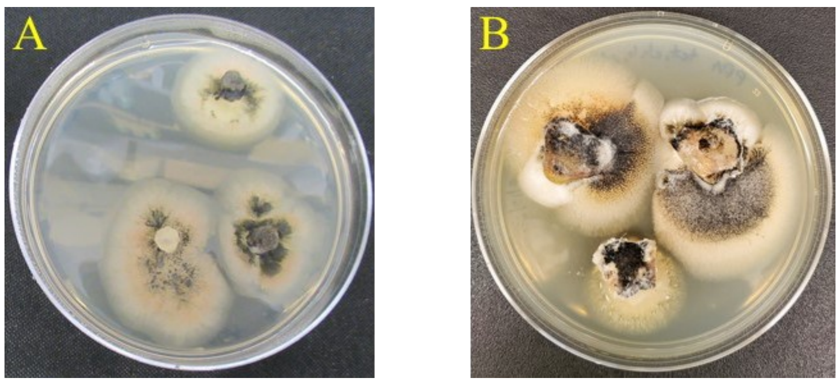

Figure 4. Isolation of *Verticillium* strain from infected potato stems from Becker and Rice county (A) and (B).

Preliminary conclusions:

From first year of *Verticillium* field screening, we can preliminarily conclude that we have identified five tolerant potato lines MN18CO15083-006, MN18CO16154-009, MN18TX17748-002, MN18W17065-004 and MN18W17089-002 to *Verticillium* wilt. To check the consistency of the phenotype, we might have to perform a few years of field evaluation. First-year filed trial suggest measurable VW resistance is apparent in U of MN potato breeding programs. We need to standardize the controlled growth chamber/greenhouse disease screening method to further screen for resistance. Continuation of our experiments for the next two years will increase our sample size and give a comprehensive understanding and conclusive results. These lines can also be used to perform genetics studies to identify important potato genes involved in resistance or for breeding improved *Verticillium*-resistant potato lines.

We have isolated multiple *Verticillium* isolates from different Minnesota sites. A preliminary sequencing study indicates the prevalence of *Verticillium dahliae* in these sites. We need to sample from more sites and counties to monitor *Verticillium* species/race in MN.

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