MINNESOTA AREA II POTATO RESEARCH AND PROMOTION COUNCIL

AND

NORTHERN PLAINS POTATO GROWERS ASSOCIATION

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RESEARCH REPORTS

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Evaluation of MN13142: An Advanced Breeding Clone with Long Dormancy and Other Desirable Traits

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Summary:

Providing crops with adequate levels of nutrients ensures the best yield and quality possible. It has been proposed that N fertilization levels influence tuber sugar content and processing ability at harvest by interfering with tuber chemical maturation ((Bélanger et al., 2000; Harris, 1978; Herman et al., 1996; Iritani and Weller, 1977). The consequences of elevated N fertilization have also caused negative impacts on the environment and have led policymakers and society in search of mitigating options. Balancing economic with environmental concerns is often challenging. Therefore, it is imperative to evaluate new potato cultivars for improved yield per unit fertilizer (kg yield/kg N applied). The development of new potato cultivars with optimum N fertilizer use, low reducing sugar accumulation potential, and long dormancy will meet the current potato industry demand and mitigate negative impacts on the environment.

A field trial was conducted in 2020 at Becker, MN, with two cultivars to evaluate the effect of N fertilizer levels (120, 240, and 360 lb N/A) and seed spacing (9, 12, and 15") on tuber physiology and yield and quality attributes. After harvest, tuber yield, size distribution, and tuber quality components were evaluated. In terms of N absorption, the MN13142 clone had slightly higher petiole nitrate-N compared to Russet Burbank. The control cultivar Russet Burbank had a slight decline in total and marketable yield at the higher N application of 360 lbs-ac$^{-1,}$ but MN13142 showed slight but statistically non-significant yield improvement with higher N fertilizer. Overall, the effect of the N rate was not significant for total or marketable yield. The effect of N fertilizer rate was found significant for percent tubers over 6 oz and 10 oz. The effect of plant spacing in MN13142 had similar trends. MN13142 clone had a significantly higher percentage of 6 oz and 10 oz tuber than control Russet Burbank. In terms of tuber quality, the MN13142 clone had significantly higher specific gravity than control Russet Burbank. Tubers were stored at 40 and 48°F after reconditioning for further physiological and biochemical studies. Storage evaluations are underway.

Background

Providing crops with adequate levels of N fertilizer ensures the best yield possible. However, the soil-plant-atmosphere system inefficiencies prevent complete N utilization, leaving residual N in the soil. Commercial potato production is especially prone to environmental contamination when N fertilizer, irrigation, and unpredictable rainfall results in nitrate leaching (Sharifi et al., 2007). The risks of not applying enough N can be substantial. Balancing economic with environmental concerns is often challenging. Farmers usually apply higher levels of nitrogenous fertilizer to ensure profitable potato production as most N in the soil is present in soil organic matter and crop residues and not readily available for plant uptake. Optimum N fertilizer rates for potatoes are generally based on the traditional cultivar Russet Burbank. New potato cultivars may not be as responsive to N fertilizer as Russet Burbank. In addition to environmental concerns, excessive available N stimulates top growth and delays tuber formation and maturity. Nitrogen use efficiency has been shown to decrease in a curvilinear manner with increasing crop N supply (Sun et al., 2017; Zebarth et al., 2004).

The role of N fertilization on plant establishment, tuber growth, and yield has been extensively studied in traditional commercial cultivars like Russet Burbank. Moreover, N fertilization influences tuber sugar content and fry color by interfering with tuber chemical maturation (Belanger et al., 2000; Iritani and Weller, 1977). It has been proposed that a higher N fertilization rate influences tuber sugar content and chip color at harvest by interfering with tuber chemical maturation. The reports on potato post-harvest storage and reducing sugar (RS) accumulation in response to N fertilization rates during the plant's growth is limited and inconclusive, especially in new potato cultivars with high resistance to cold-induced sweetening (CIS).

Systematic studies are lacking on the effect of N fertilization on the expression of various enzymes related to carbohydrate metabolism in potato tubers. Studies have shown a close association of key enzymes with reducing sugar (RS) accumulation. Changes in carbohydrate metabolizing enzyme expression in response to N status may significantly affect tuber RS accumulation during storage. Management strategies to reduce N losses to the environment from potato production while maintaining profitable yields have been focused on the right time, rate, source, and N application place. However, not much effort has been put into the performance of new potato cultivars on N fertilizer requirement, increasing tuber yield and quality and avoiding N losses. Therefore, the new potato clone MN13142 has been evaluated for N fertilizer rate in relation to total and marketable yield, tuber size distribution, and specific gravity. The new clone MN13142 is under evaluation for long term storability, reducing sugar accumulation and processing quality. Various biochemical parameters will be investigated to gain an understanding of physiological response to plant N status.

For decades, the processing industry has had a high demand for potatoes with long dormancy, high solids, low, reducing sugar potential, and tough skin set, traits important for storability and good processing quality. The sprout inhibitor CIPC is routinely used on potatoes to improve long term storage. However, CIPC is a health concern, and European countries have banned the use of CIPC for potatoes, which has increased the demand for potato varieties with long dormancy. The new clone MN13142 has several of the needed desirable traits, like, high solids, tough skin, low temperature sweetening resistance, post-harvest quality retention, etc. The MN13142 clone could be an attractive alternative for future potato production systems. The current study's overall objective was to evaluate the response of new clone MN13142 to N management and other agronomic traits associated with yield and long-term storability.

Methods:

To better understand N fertilizer response, the MN13142 clone was evaluated under three N fertilizer regimes. Russet Burbank was used as a control cultivar. Cut, 2-3 oz certified seeds were used for both clones. In 2020, the cultivars were planted on May 04, 2020, at the Sand Plain Research Farm, Becker, MN, in a Hubbard loamy sand soil. A randomized complete block design with four replications was used. Each cultivar was subjected to three N rates treatments120, 240, and 360 lbs acre^{-1}. All plots received 40 lb N acre^{-1} as DAP (18-46-0) at planting (05/04/2020) in a band 8 cm to the side and 5 cm below the seed tuber. At emergence, N was side-dressed at 80, 200, and 320 lbs N acre^{-1} as ESN (Agrium, Inc., Calgary, AB, Canada; 44-0-0) at each specific N rate treatment, respectively, and then hilled in on 22 May 2020. to achieve total N rates of 120, 240, and 360 lb N acre^{-1} rates. To investigate the effect of planting spacing, MN13142 clone at N rate of 240 lbs ac^{-1} was planted at three different in-row spacings of 9, 12, and 15 inches. All potatoes were harvested on October 2, 2020, and suberized for three weeks at room temperature. At harvest, yield and yield attributes were recorded. Tubers were stored at 40 and 48°F cold storage for evaluations at 3 and 6 months intervals. Baseline sugar, fry color, and other biochemical analysis were performed in tubers before cold storage.

Five tubers from each plot were analyzed for sugars, fry color, and other traits for storage evaluations. Sugars, glucose, and sucrose were analyzed using a YSI model 2000 Industrial Analyzer (Yellow Springs Instruments Co., Inc., Yellow Springs, OH). The concentration of sugar is expressed in mg g^{-1} FW.

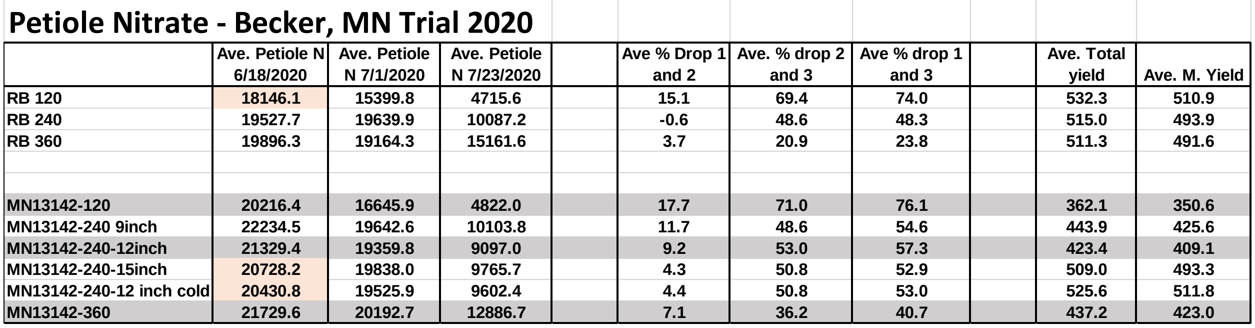
Results and Discussion: To investigate N absorption and utilization by the cultivars in this study, plant N status in terms of petiole nitrate-N was recorded during three plant growth stages viz 1) Vegetative (50 DAP), 2) tuber initiation and tuber setting (50 to 60 DAP), 3) tuber bulking (64 DAP to 87 DAP). To understand N utilization at harvest, mature tubers were evaluated for total tuber N content. Percent drop in petiole nitrate-N in each physiological stage of tuber development was investigated. Mature tubers are currently being evaluated for storability at 40 and 48°F cold storage.

Petiole nitrate-N showed a clear trend under both the high and low N fertilization rates in all cultivars (Figure 2). Petiole nitrate was highest before tuber initiation, which then declined rapidly in both cultivars as the growing season progressed. This trend is consistent with the previously published reports (Love et al., 2005; Zebarth and Rosen, 2007). Regardless of cultivar, petiole nitrate levels were higher when plants were grown at higher N rates. Porter and Sisson reported similar results for Russet Burbank and Shepody potato cultivars (Porter and Sisson, 1991).

Petiole N drop during tuber growth stages:

The number of tubers increases physiologically during the tuber setting stage, and tuber size increase during the tuber bulking stage. There was a consistent trend of less N partitioning as N fertilization increased from 120 to 360 lbs ac^{-1}. The percentage drop in petiole nitrate-N in Russet Burbank and MN13142 at 120 lbs ac^{-1} rate was 15.1 and 17.7% (Table 1). Which decline to 3.7% in Russet Burbank and 7.1% for MN13142 clone grown at 360 lbs ac^{-1} N rate. Between cultivars, Russet Burbank seems to partition less N, possibly to developing tubers compared to MN13142. This could be related to the clone's maturity and the sink demand and need in-depth investigation. Higher petiole nitrate-N at tuber initiation had no significant effect on tuber yield (Fig. 1) in Russet Burbank. This suggests that each cultivar or clone has its optimum N requirement. In our experiment, the optimum petiole nitrate-N for Russet Burbank is around 18000 ppm. Whereas, MN13142 clone had an optimum petiole nitrate-N of 22000 ppm. But within the same fertilizer rate, the MN13142 clone translocated more N than Russet Burbank. Early N partitioning could be related to tuber set provided plants have optimum petiole N. Petiole nitrate-N changes over the season too. Porter and Sisson reported critical petiole nitrate levels of 1.6% (16,000 ppm) for Russet Burbank at 50 DAP. Petiole nitrate levels above 2.2% (22,000 ppm) at 50 DAP resulted in lower Russet Burbank yields (Porter and Sisson, 1991). This trend in percent petiole N drop at different physiological stages and N contents accumulation in developing tubers needs further investigation.

Table 1: Petiole nitrate (mg kg^{-1}) in four cultivars supplied with 120, 240, and 360 lbs N ac^{-1} at three growth stages.



Petiole Nitrate - Becker, MN Trial 2020

	Ave. Petiole N 6/18/2020	Ave. Petiole N 7/1/2020	Ave. Petiole N 7/23/2020		Ave % Drop 1 and 2	Ave. % drop 2 and 3	Ave % drop 1 and 3		Ave. Total yield	Ave. M. Yield
RB 120	18146.1	15399.8	4715.6		15.1	69.4	74.0		532.3	510.9
RB 240	19527.7	19639.9	10087.2		-0.6	48.6	48.3		515.0	493.9
RB 360	19896.3	19164.3	15161.6		3.7	20.9	23.8		511.3	491.6
MN13142-120	20216.4	16645.9	4822.0		17.7	71.0	76.1		362.1	350.6
MN13142-240 9inch	22234.5	19642.6	10103.8		11.7	48.6	54.6		443.9	425.6
MN13142-240-12inch	21329.4	19359.8	9097.0		9.2	53.0	57.3		423.4	409.1
MN13142-240-15inch	20728.2	19838.0	9765.7		4.3	50.8	52.9		509.0	493.3
MN13142-240-12 inch cold	20430.8	19525.9	9602.4		4.4	50.8	53.0		525.6	511.8
MN13142-360	21729.6	20192.7	12886.7		7.1	36.2	40.7		437.2	423.0

Effect of N fertilizer rate on tuber size distribution and yield:

Cultivars showed a differential response to N fertilizer rates in terms of the tuber size distribution (Table 3). The industry recommendation for tuber size is 68-74% 6 oz tubers and 28-40% 10 oz tubers. At the N fertilizer rate of 240 lbs ac^{-1}, Russet Burbank had 6 oz and10 oz tubers of 72 and 42 %, respectively. MN13141 had 78% 6 oz tubers and 50% 10 oz tubers at the same fertilizer rate, which increased slightly with a planting distance of 15 inches (82% and 55%, respectively). It is interesting to note that at N fertilization of 360 lbs ac-1, Russet Burbank had 65% off 6 oz tubers and 35% of 10 oz tubers. But MN13142 had 80 and 51%, respectively. The effect of spacing was significant for tubers larger than 10oz.

The effect of N rate on total tuber yield and marketable yield was not significant. MN13142 clone was quite comparable to Russet Burbank in terms of total and marketable yield. The highest total yield of 532 cwt-ac^{-1} was recorded in Russet Burbank at 120 lbs ac^{-1} N fertilizer, followed by 526 cwt-ac^{-1} in MN13142 fertilized with 240 lbs ac^{-1}. The highest marketable yield of 512 cwt ac^{-1} was recorded in MN13142, followed by 511 cwt ac^{-1} in Russet Burbank.

Effect of N fertilizer rate on tuber quality:

Various tuber quality parameters like hollow heart, scab, specific gravity, and dry matter content were recorded for all three N rates (Table 3). The effect of N rate and its interaction with cultivar was not found significant for scab, hollow heart, specific gravity, or tuber dry matter content. MN13142 had significantly higher dry matter content and specific gravity than Russet Burbank. This year MN13142 had a slightly higher incidence of scab and hollow heart than Russet Burbank.

Tuber specific gravity (SG) is a crucial trait for the acceptability of new cultivars. MN13142 had a SG range from 1.0772 to 1.0798. The SG range for Russet Burbank was 1.0706 to 1.0732. MN13142 had acceptable SG. Irrespective of the cultivars, there was a decline in specific gravity in response to increasing N fertilizer levels though statistically not significant. That is often one of the adverse effects of a high N fertilization rate. A similar pattern has been reported previously (Sun et al., 2019).
The effect of N rate on tuber dry matter content was significant. The highest dry matter content of 22.4% was recorded in MN13142 fertilized with 240 lbs N ac$^{-1,}$ and the lowest dry matter content of 18.2% was recorded in Russet Burbank fertilized with an N rate of 360 lbs ac^{-1}.

Conclusion:

The use of certified seeds of MN13142 showed much better yield performance compared to previous years. The higher percentage of petiole nitrate-N partitioning at the tuber setting stage could have affected total and marketable yield. Yield, specific gravity, and dry matter contents of MN13142 were quite comparable to the control cultivar, Russet Burbank. Being a midterm maturing clone, MN13142 was not very responsive to a higher fertilizer rate of 360 lbs ac^{-1}. In our field, MN13142 had higher optimum petiole nitrate-N and higher partitioning, possibly to developing tubers in our trial. In terms of tuber quality, MN13142 had a higher incidence of scab and hollow heart than Russet Burbank.

Acknowledgment:

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Table 2: Effect of N fertilizer rate and plant spacing on yield attributes and yield.

Treatment #	Cultivar	N rate (lbs/ac)	Seed spacing (in.)	Seed warmed?	Yield (CWT·ac^{-1})										% yield in tubers over:	
					Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	U.S. No. 1	U.S. No. 2	Marketable	6 oz.	10 oz
1	Russet Burbank	120	12	Yes	9	21	158 a	177	120	57 c	**532**	471	40 ab	**511**	66 d	33 e
2	MN13142	120	12	Yes	32	12	75 e	129	88	82 abc	387	362	12 c	374	77 abc	44 bcd
3	Russet Burbank	240	12	Yes	9	21	124 b	157	109	105 ab	**515**	450	44 a	**494**	72 c	42 cd
4	MN13142	240	9	Yes	24	22	107 bc	172	119	87 abc	507	465	19 bc	485	75 bc	41 cde
5	MN13142	240	12	Yes	18	16	91 cde	138	122	121 a	488	462	10 c	473	78 ab	50 abc
6	MN13142	240	15	Yes	21	16	76 de	138	158	122 a	509	467	26 abc	493	82 a	55 a
7	MN13142	240	12	No	14	14	104 bcd	159	134	114 a	526	484	28 abc	512	77 ab	47 bc
8	Russet Burbank	360	12	Yes	12	20	159 a	150	114	69 bc	**511**	447	44 a	**492**	65 d	35 de
9	MN13142	360	12	Yes	15	15	86 cde	148	142	116 a	507	471	21 bc	492	80 ab	51 ab
				Effect of treatment (P-value)	0.3493	0.1313	**<0.0001**	0.2713	0.1592	**0.0914**	0.2048	0.1416	**0.0693**	0.2071	**<0.0001**	**0.0022**
Treatments 1 - 3, 5, 8 - 9				**Effect of cultivar (P-value)**	**0.0314**	**0.0034**	**<0.0001**	**0.0321**	0.5833	0.1454	0.1142	0.3219	**0.0001**	0.1392	**<0.0001**	**<0.0001**
				Effect of N rate (P-value)	0.6198	0.9153	0.4368	0.7225	0.7729	0.3332	0.9744	0.9678	0.8912	0.9693	0.3607	0.3871
				Effect of cultivar*N rate (P-value)	0.4434	0.7090	0.1807	0.7739	0.9703	0.4598	0.9800	0.9772	0.7733	0.9850	0.1243	0.4415
Treatments 4 - 6				**Effect of spacing (P-value)**	0.8294	0.1342	0.4040	**0.0826**	0.3536	**0.0205**	0.8560	0.8459	0.5739	0.7891	0.1628	**0.0057**

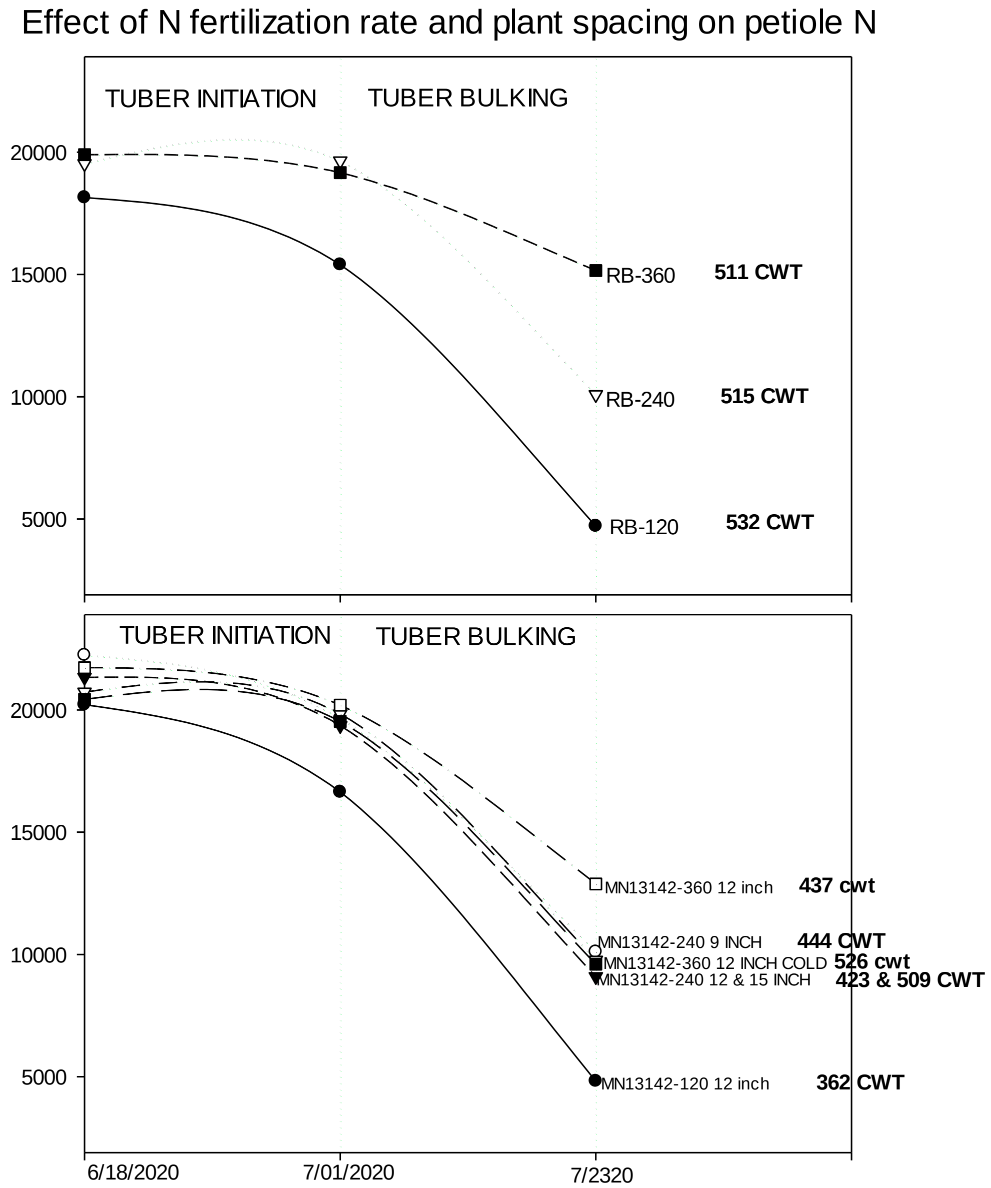
Note: values with same letters indicate no significant difference.

Table 3: Effect of N fertilizer rate and plant spacing on tuber quality.

Treatment #	Cultivar	N rate (lbs/ac)	Seed spacing (in.)	Seed warmed?	Percentage of tubers			Specific gravity	Dry matter content (%)
					Hollow heart	Brown center	Scab		
1	Russet Burbank	120	12	Yes	7	0	5 bc	1.0732 c	20.0 bcd
2	MN13142	120	12	Yes	9	0	21 a	1.0812 a	21.9 ab
3	Russet Burbank	240	12	Yes	8	0	4 bc	1.0716 c	19.2 cd
4	MN13142	240	9	Yes	10	0	8 bc	1.0798 ab	22.1 a
5	MN13142	240	12	Yes	16	0	7 bc	1.0788 ab	21.0 abc
6	MN13142	240	15	Yes	9	1	2 c	1.0792 ab	22.4 a
7	MN13142	240	12	No	13	0	9 bc	1.0775 b	21.9 a
8	Russet Burbank	360	12	Yes	12	0	5 bc	1.0706 c	18.2 d
9	MN13142	360	12	Yes	14	1	12 ab	1.0783 ab	22.2 a
Effect of treatment (P-value)					0.7246	0.4331	0.0709	**<0.0001**	**0.0069**
Treatments 1 - 3, 5, 8 - 9		**Effect of cultivar (P-value)**			0.1102	0.2977	**0.0241**	**<0.0001**	**0.0016**
		Effect of N rate (P-value)			0.2396	0.2696	0.2087	0.1393	0.6249
		Effect of cultivar*N rate (P-value)			0.5578	0.2696	0.2867	0.9237	0.2995
Treatments 4 - 6		**Effect of spacing (P-value)**			0.8565	0.5102	0.5600	0.7500	0.3633

Note: values with same letters indicate no significant difference.

Fig. 1.
of petiole N
potatoes
yield.



Effect
on
total

Two potato cultivars Russet Burbank and MN13142 were grown at three N fertilizer levels of 120, 240 and 360 lbs ac-^{1}.

Evaluating bruising in storage among new fresh-market and processing varieties.

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Summary:

Pressure bruise susceptibility in storage was assessed among several fresh market and processing clones. Included in this evaluation were several advanced public breeding lines and commercial checks for comparison. A hydraulic press simulated pile height, and water loss and bruise incidence was assessed after six months of storage. Varietal differences in water loss and bruising were detected among fresh market and dual market russet varieties, but no differences in chip potato bruising or chip quality were detected from chip fields evaluated in 2020.

Plant Material.

Red and yellow evaluation.

Tubers were collected from a Hoople, ND variety trial led by Dr. Andy Robinson. Samples were placed into pressure totes immediately after grading on October 10, 2019. Each variety was evaluated across field replicates and treatment bags contained 5 tubers/bag. Tuber water loss, bruise incidence, and bruise area was assessed after six months of storage (March, 2020).

Dual-market russet evaluation.

Fourteen russet clones were sampled from the USDA-ARS irrigated field location (Hoverson Farms, Larimore, ND). The clones represent ten advanced public breeding lines including the Minnesota clone: MN13142. Sample harvest occurred on October 9th, 2019, and duplicate treatment bags containing 10 tubers/ bag were placed into storage totes within 48 hours of harvest. Tuber water loss, bruise incidence, and bruise area was assessed after six months of storage (March, 2020).

Chip variety evaluation.

On September 25, 2019 samples from three chip fields were collected from Hoople, ND grower facilities. All samples were harvested that morning and the pulp temperature was 54-56°F at the time of sampling. Samples were brought to the EGF lab and immediately sorted into eight replicate mesh bags per field with each bag containing eight tubers. Initial bag weights were recorded, and sample bags were positioned inside the macrobin totes in replicated layers. Water loss and bruise incidence was assessed after six months of storage. To assess the impact of storage sample management on bruise severity and chip processing quality, a fluming test treatment was also conducted. Immediately following the six-month weight loss measurement designated samples were submerged in water for 15 minutes to examine the impact of fluming on chip processing quality. Chip quality was measured following continuous processing at

365°F, 90 seconds using the USDA-ARS Pilot Scale Chip Line. Chip photos and Hunterlab scores were collected to examine the impact of fluming on chip defect rating.

Pressure adjustment and sampling.

All storage evaluations were conducted in 1000# totes (Macroplastic 32-S Pro-bin; external dimension 48’’l x 44’’w x 30’’h). Totes were stored in one of three storage towers possessing temperature and humidity control. To ensure proper air flow (1.5 cfm/cwt), the tote floor was modified by drilling 5/32’’ holes in a 2’’ grid pattern. Temperature and humidity was controlled and monitored with Techmark Inc. 755 Controller and StorTrac™ software.

A pressure plate fabricated from ½’’ thick UHMW equipped with a 12 ½ ton bottle jack w/ gauge port (Norco model #76412BG) was placed on the potatoes within the tote. Applied tote pressure equaled 2.1 lb/in^2 and is the estimated force exerted within an 18’ pile height. The desired gauge pressure was achieved by directing the ram into the shelving support structure; pressure was monitored and adjusted as needed. Daily adjustment was required during initial storage, and pressure was routinely monitored every 48hr -72h throughout the entire storage duration.

Humidified air flow through the tote was monitored with a hot-wire anemometer. Reds and yellows were stored at 40°F and processing varieties (russet and chips) were stored at 46°F. Bruise incidence and water loss was assessed at 6 months of storage (March 2020).

Results:

Reds and Yellows

Reds. Of the 17 red varieties examined, Sangre was far superior in low bruise incidence and severity. On average, Sangre had 1.2 bruises per tuber with an average bruised area of only 0.8 in^2. In comparison, Red Norland had 2.5 bruises per tuber with an impacted area of 1.6 in^2, which was similar to the experimental mean for bruise number per tuber (3.3) and average bruise area per tuber (2.0 in^2). In agreement with previous studies, increasing tuber water loss was associated with increased bruise number and severity. Autumn Rose and ‘Public -2’ clone had the highest six-month weight loss of 9.8 and 10.2%, respectively. The weight loss from these two varieties corresponded with the highest bruise number of 4.9 and 4.8 bruises per tuber. Please refer to Table 1 for complete list of red variety 2019-20 storage performance. A second year of this field study is being repeated in the 2020-21 storage cycle and bruising notes will be collected in March 2021.

Yellows.

Of the 25 yellow varieties reported, little significant differences in bruising incidence and bruise severity were detected among yellow varieties examined in 2019-20. On average, 3.2 bruises per tuber were measured with an average bruise area of 1.6 in^2. The range in bruise incidence was 1.9 to 4.5 bruises/tuber, and range in bruise area was 0.7 to 2.5 in^2, respectively. Although significant differences in bruising were difficult to detect among the yellow varieties examined in 2019-20, significant water losses were observed. At six months of storage at 40°F, 6 of the 25 varieties had a >9% weight loss. In contrast, 8 varieties had less than 7% weight loss. Please refer to Table 2 for a complete list of yellow variety six-month storage performance. A second year of this field study is being repeated in the 2020-21 storage cycle and bruising notes will be collected in March 2021.

Russets

Significant differences in weight loss, bruise incidence, and bruise area were detected among the 14 Russet varieties examined in 2019-20 (Table 3). Three numbered breeding lines (MN13142, Public -9, and Public -2) had less than 7% water loss at six months of storage, in contrast to Bannock that lost 14.2%. MN13142 and Public-9 had the lowest bruise number (0.9, 1.4) and impacted area per tuber (0.3 and 0.7 in^2). Although MN13142 and Public -9 had had the lowest reported bruising (0.9 and 1.4), this bruise incidence was not significantly different than Russet Burbank's bruise incidence (2.2) and area (1.8in^2).

Although effort was taken to sample tubers of uniform size and shape, it must be noted that tubers of MN13142 and Public -9 were generally smaller than that from other varieties. Tuber size is reported as a percentage of Burbank area (Table 3). However, the impact of tuber size on bruising is unclear as bruise incidence from smaller tubers of 'Public -8' (85% of Burbank size) had significantly higher bruise number (5.6 bruise/tuber) and bruise area (4.1 in^2) when compared to Burbank.

Chips

In 2018, we observed a close association between increased water loss and increased bruising from chip samples stored at four months. However, during this four-month storage examination, pressure bruising did not impact tuber flesh discoloration and no chip defects were observed. In the 2019-20 storage evaluations, the storage duration was extended from four to six months and the impact of post storage fluming time on tuber discoloration and chip color (Hunterlab score) was investigated.

No significant differences in water loss and bruising were detected among the chip fields sampled in 2019-20. However, unlike the 2018-19 storage campaign, a flesh coloration response was observed in the 2019-20 study (Figure 1). An orange/yellow flesh color is observed in flattened areas. Bruising also resulted in off color chips, but no significant differences in HunterLab scores were detected from the field samples examined in 2020 (Figure 2). In addition, there was no impact of fluming on bruise color development and chip defect rating (data not shown).

Although no differences were detected among the three fields samples, this study is being repeated in 2020-21. In addition to three grower fields, 11 advanced chip lines participating in the 2020 Potatoes USA SNAC trial are also included in the current study that will conclude in March, 2021.

USDA-ARS Grading Update Funding Acknowledgement

In January 2020, a new grading line was installed at the USDA-ARS East Grand Fork's Facility. With grower funds, warehouse grading lighting improvements were made in the summer of 2020. This permitted successful use of grader in the Fall of 2020 by NDSU and UMN research groups: Robinson, Thompson, Shannon, and Hatterman-Valenti.

Table 1. Weight loss and bruising after 6 months of storage_Reds (2019-20)

Variety[1]	Water loss (%)[2]	Bruise/tuber	Bruise area / tuber (in^2)
Public - 8	5.8	3.3	1.7
ND13282C-1R	6.2	2.6	1.4
Red Norland	6.4	2.5	1.6
Roko	6.4	2.4	1.2
Public - 7	6.5	2.5	1.7
Sangre	7.0	1.2	0.8
ND081571-2R	7.3	3.7	2.3
Dark Red Norland	7.4	3.4	2.0
ND113207-1R	7.5	3.5	2.0
Red Pontiac	8.0	2.8	2.1
Red Prairie	8.1	3.9	2.2
Cerata	8.9	3.7	2.8
ND13241C-6R	8.9	3.4	2.5
ND102990B-3R	8.9	3.9	2.7
Public - 1	9.1	3.8	2.3
Autumn Rose	9.8	4.9	2.4
Public -2	10.2	4.8	3.0
Mean	7.8	3.3	2.0
LSD ($P \leq 0.05$)[3]	2.0	1.4	1.0
CV (%)	1.5	1.9	1.3

[1] Eight numbered clones from Public breeding lines were included in the study.

[2] Varieties were sorted by increasing water loss at 6 months of storage.

[3] An F-protect LSD was calculated for variety mean comparison

Table 2. Weight loss and bruising after 6 months of storage_Yellows (2019-20)

Variety[1]	Water Loss (%)[2]	Bruise/Tuber	Bruise area / tuber (in^2)
Public - 5	5.3	2.3	1.2
Obama	5.3	2.3	0.7
Public - 4	6.0	3.4	1.1
Electra	6.4	3.1	0.9
Public - 2	6.4	2.7	1.0
Public - 7	6.7	3.5	1.8
Noelle	6.9	2.3	0.9
Public - 3	6.9	1.9	1.0
Mariola	7.1	3.0	1.4
Public - 6	7.2	3.0	1.4
Actrice	7.3	4.1	2.5
Public - 1	7.3	3.3	1.4
ND1241-1Y	8.1	2.4	1.3
Milva	8.1	4.0	1.5
Crop 58	8.1	3.3	1.7
Agata	8.2	3.7	2.5
NDA081451CB-1CY	8.2	3.2	1.3
Crop 49	8.3	3.4	1.9
Crop 80	8.4	4.2	2.0
Musica	9.0	4.5	2.0
Arizona	9.1	3.8	2.2
Lanorma	9.4	3.1	2.4
Nicola	9.6	2.4	1.2
Alegria	9.6	3.9	2.4
Belmonda	9.6	4.3	2.2
Mean	7.7	3.2	1.6
LSD ($P \leq 0.05$)	1.5	2.0	0.9
CV (%)	2.3	3.0	1.4

[1] Nine numbered clones from Public breeding lines were included in the study.

[2] Varieties were sorted by increasing water loss at 6 months of storage.

[3] An F-protect LSD was calculated for variety mean comparison

Table 3. Weight loss and bruising after 6 months of storage_Russet (2019-20)

Variety[1]	Water Loss (%)[2]	Bruise/Tuber	Bruise area / tuber (in^2)	Tuber size[4]
MN 13142	6.1	0.9	0.3	77.7
Public -9	6.4	1.4	0.7	83.1
Public - 1	6.8	2.7	1.5	91.8
Public -2	7.4	2.1	1.0	97.4
Russet Burbank	8.5	2.2	1.8	100.0
Prospect	8.9	4.9	2.7	95.7
Public -3	8.9	4.4	4.2	121.1
Dakota Russet	9.4	4.2	3.4	108.2
Public - 4	9.5	4.1	3.3	94.7
Public -5	9.6	3.4	2.6	82.5
Public -6	10.1	3.6	2.3	100.4
Public - 7	10.2	3.4	1.3	84.6
Public -8	10.6	5.6	4.1	85.4
Bannock	14.2	4.1	1.9	102.0
Mean	9.0	3.4	1.9	
LSD ($P \leq 0.05$)[3]	2.6	1.3	1.8	
CV (%)	10.9	5.6	7.4	

[1] Nine numbered clones from Public breeding lines were included in the study.

[2] Varieties were sorted by increasing water loss at 6 months of storage.

[3] An F-protect LSD was calculated for mean comparison

[4] Tuber size is reported as a size percentage of Russet Burbank

Table 4. Weight loss and bruising after 6 months of storage_Chip (2019-20)

Variety	Field	Flume[1]	Water Loss (%)	Bruise/Tuber	Bruise area / tuber (in^2)
‘X’[3]	H	No	11.0	4.4	2.4
‘X’	H	Yes	10.8	4.1	2.0
‘X’	L	No	10.8	3.9	2.8
‘X’	L	Yes	10.8	4.1	2.4
Waneta	E	No	10.7	3.8	2.1
Waneta	E	Yes	10.2	4.1	3.2
Mean			10.7	4.1	2.5
LSD ($P \le 0.05$)			ns[2]	ns	ns

[1] After six-month weight loss was recorded, tubers were submerged in water for 15 minutes.

[2] An F-protect LSD was calculated for mean comparison and no significant (ns) differences were detected in water loss and bruising.

[3] Variety ‘x’ is a coded proprietary variety.

Figure 1.
Fluming for 15 minutes did not impact bruised tissue color development. After bruise notes were recorded, steam peeling revealed similar flesh discoloration under flattened areas between both flume (+) and unflumed (-) samples.

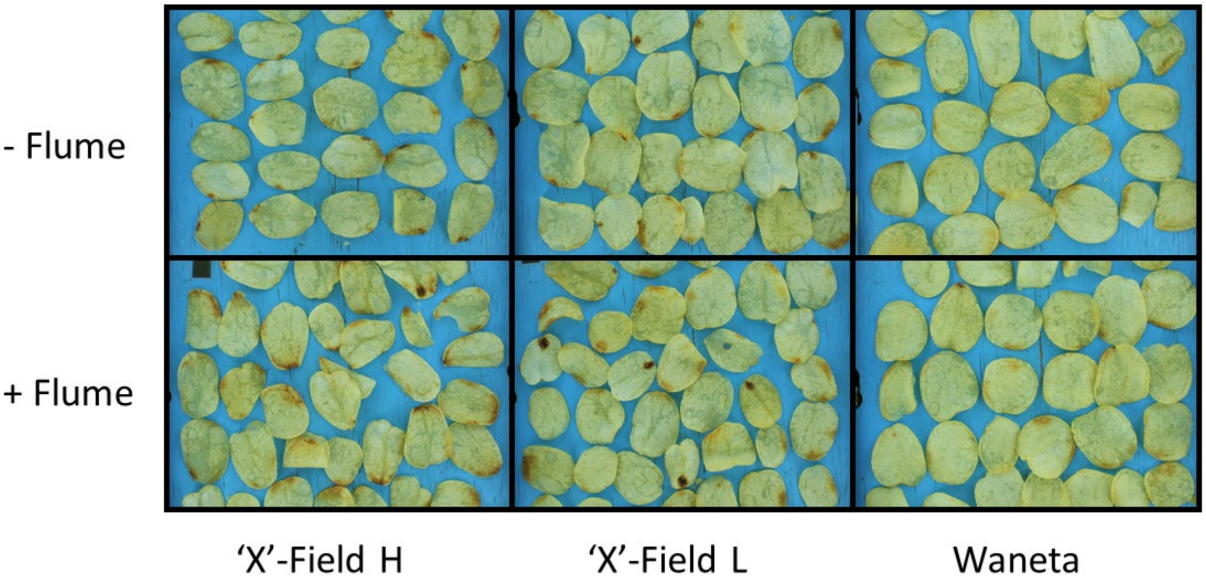

Figure 2.
Fluming did not impact chip defect ratings as quantified by Hunterlab score (data not shown).

Management of Colorado Potato Beetle 2020

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Executive Summary – This is a project to develop and refine management tactics for Colorado Potato Beetles 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) Evaluating the efficacy of registered insecticides with the addition of Piperonyl Butoxide, including the efficacy over 2-3 generations, and 3) Evaluate the efficacy of CPB as a vector of potato virus disease (esp, Potato Virus Y). 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 insect has a pronounced ability to develop insecticide resistance (Weisz et al. 1994, Alyokhin et al. 2007, Huseth et al. 2014). Resistance issues have been documented in Central MN for several years, and recent data on CPB populations in the Red River Valley (RRV) also indicate increasing tolerance for neonicotinoid insecticides (Table 1).

Populations of CPB in MN and ND show varying levels of resistance (MacRae, NPPGA & Area II Research reports 2012-14, 2017-19) and control failures and decreased efficacy with at least three neonicotinoid insecticides (imidacloprid, thiomethoxam and clothianidin) have been reported. Data from 2012-14 and 2017-19 indicate that tolerance to neonicotinoids varies by location within the two states but is increasing in both. This building resistance is not the only challenge to the continued use of neonicotinoid insecticides. Issues with pollinators and data linking the leaching of neonicotinoids into ground-water systems (Goulson 2013, Huseth & Groves 2014, Hladik et al. 2014) has precipitated regulatory issues. In 2016, a Governor's directive ordered increased regulation of neonicotinoids in Minnesota. The Environmental Protection Agency will soon be completing their review on Imidacloprid, Clothianidin, thiomethoxam and acetamiprid later in 2020 and have already announced their Interim regulatory decisions.

In addition, an extended summer emergence of overwintered adult CPB has stretched the presence of adults later in the summer. This has resulted in an erosion of 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, precipitating the need for additional within season foliar applications of insecticides.

This extended emergence is thought to be a behavioral form of resistance. The late emerging beetles are susceptible to neonicotinoid insecticides and represent that portion of the susceptible population that is genetically programmed to emerge later in the season (Szendrei et al. 2012). If a beetle susceptible to neonicotinoid insecticides emerges early in the season into a field treated at-plant with a neonicotinoid, they will die. However, later in the season, the

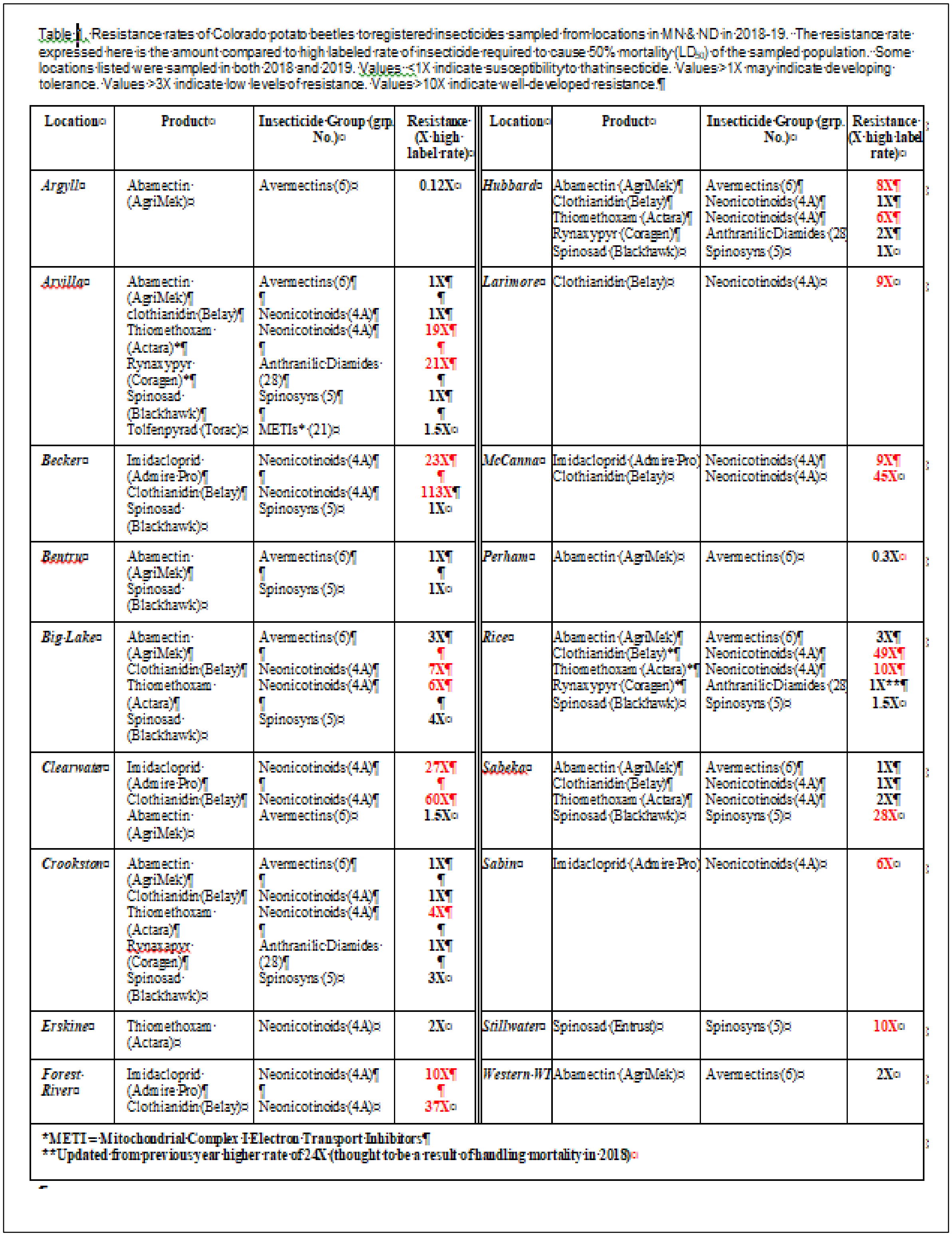


Table 1. Resistance rates of Colorado potato beetles to registered insecticides sampled from locations in MN & ND in 2018-19. The resistance rate expressed here is the amount compared to high labeled rate of insecticide required to cause 50% mortality (LD_{50}) of the sampled population. Some locations listed were sampled in both 2018 and 2019. Values ≤1X indicate susceptibility to that insecticide. Values >1X may indicate developing tolerance. Values >3X indicate low levels of resistance. Values >10X indicate well-developed resistance.

Location	**Product**	**Insecticide Group (grp. No.)**	**Resistance (X high label rate)**	**Location**	**Product**	**Insecticide Group (grp. No.)**	**Resistance (X high label rate)**
Argyll	Abamectin (AgriMek)	Avermectins (6)	0.12X	*Hubbard*	Abamectin (AgriMek) Clothianidin (Belay) Thiomethoxam (Actara) Rynaxypyr (Coragen) Spinosad (Blackhawk)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Anthranilic Diamides (28 Spinosyns (5)	8X 1X 6X 2X 1X
Arvilla	Abamectin (AgriMek) clothianidin (Belay) Thiomethoxam (Actara)* Rynaxypyr (Coragen)* Spinosad (Blackhawk) Tolfenpyrad (Torac)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Anthranilic Diamides (28) Spinosyns (5) METIs* (21)	1X 1X 19X 21X 1X 1.5X	*Larimore*	Clothianidin (Belay)	Neonicotinoids (4A)	9X
Becker	Imidacloprid (Admire Pro) Clothianidin (Belay) Spinosad (Blackhawk)	Neonicotinoids (4A) Neonicotinoids (4A) Spinosyns (5)	23X 113X 1X	*McCanna*	Imidacloprid (Admire Pro) Clothianidin (Belay)	Neonicotinoids (4A) Neonicotinoids (4A)	9X 45X
Bentru	Abamectin (AgriMek) Spinosad (Blackhawk)	Avermectins (6) Spinosyns (5)	1X 1X	*Perham*	Abamectin (AgriMek)	Avermectins (6)	0.3X
Big Lake	Abamectin (AgriMek) Clothianidin (Belay) Thiomethoxam (Actara) Spinosad (Blackhawk)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Spinosyns (5)	3X 7X 6X 4X	*Rice*	Abamectin (AgriMek) Clothianidin (Belay)* Thiomethoxam (Actara)* Rynaxypyr (Coragen)* Spinosad (Blackhawk)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Anthranilic Diamides (28 Spinosyns (5)	3X 49X 10X 1X** 1.5X
Clearwater	Imidacloprid (Admire Pro) Clothianidin (Belay) Abamectin (AgriMek)	Neonicotinoids (4A) Neonicotinoids (4A) Avermectins (6)	27X 60X 1.5X	*Sabeka*	Abamectin (AgriMek) Clothianidin (Belay) Thiomethoxam (Actara) Spinosad (Blackhawk)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Spinosyns (5)	1X 1X 2X 28X
Crookston	Abamectin (AgriMek) Clothianidin (Belay) Thiomethoxam (Actara) Rynaxapyr (Coragen) Spinosad (Blackhawk)	Avermectins (6) Neonicotinoids (4A) Neonicotinoids (4A) Anthranilic Diamides (28) Spinosyns (5)	1X 1X 4X 1X 3X	*Sabin*	Imidacloprid (Admire Pro)	Neonicotinoids (4A)	6X
Erskine	Thiomethoxam (Actara)	Neonicotinoids (4A)	2X	*Stillwater*	Spinosad (Entrust)	Spinosyns (5)	10X
Forest River	Imidacloprid (Admire Pro) Clothianidin (Belay)	Neonicotinoids (4A) Neonicotinoids (4A)	10X 37X	*Western WT*	Abamectin (AgriMek)	Avermectins (6)	2X

*METI = Mitochondrial Complex I Electron Transport Inhibitors
**Updated from previous year higher rate of 24X (thought to be a result of handling mortality in 2018)

concentration of insecticide in plants will drop because the insecticide is starting to degrade and the remaining insecticide is being diluted by continued growth of the plant (Huseth & Groves 2010). Consequently, the use of neonicotinoids applied at-plant has selected against early emerging susceptible CPB. The end result is that the later emerging adults survive, mate and lay eggs later in the season, leading to the extended presence of eggs, larvae and adults into the mid season.

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 (Table 1). 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, CPB from a site in ND showed increased tolerance of the Diamide, Chloratraniliprole (Rynaxypyr = Coragen). Populations from two sites in MN showed significant levels of resistance to Spinosyns (Spinosad = Blackhawk & Spintor). These latter sites, however, were isolated organic production fields which had relied heavily on Spinosad for several years.

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.

One of the most frequent methods whereby insects gain tolerance of insecticide activity is through enzymatic degradation. In insects, Cytochromes P-450 (CYPs) are a family of mixed function oxidases; enzymes that use oxidative reduction to break down a wide variety of compounds, including xenobiotics . Xenobiotics are chemical substances found in a body that was not produced or expected to even be in that organism, including environmental pollutants, toxins, drugs and pesticides. The CYPs in certain insect species can denature and metabolize insecticides before they can reach their target site. Neurotoxins, for example, would be broken down before they can reach the area on the neuron that they attack. Piperonyl Butoxide (PBO) is a synergist that suppresses the activity of CYPs. So when PBO is added to insecticides, it acts as a synergist, reducing enzymatic degradation and resulting in more of the active ingredient reaching the target site, increasing the insecticide’s efficacy. The use of PBO has recently been linked to lower dose but increased efficacy of several insecticides including AgriMek (Sygenta Crop Protection) and Torac (Nichino America).

Colorado Potato Beetle are efficient defoliators with adults consuming up to 10cm^2 of plant material /day and they are highly mobile when feeding. After row and canopy closure, CPB larvae and adults often move from plant to plant spreading areas of defoliation from points of initial colonization. The mechanical transmission of certain potato diseases, (e.g. Potato Virus Y or PVY) has been demonstrated on cutting tables (e.g. Bradley 1954, Fageria et al 2015) and by a variety of post-emergent crop management activities (MacKenzie et al 2018). In fact, transmission of PVY by aphids can be described as mechanical transmission as it involves virus particles adhered to the aphid’s mouthparts that get wiped off when the aphid feeds on a new plant. While Colorado Potato Beetle is generally assumed to be a non-vector of PVY and other potato virus diseases, there are few, if any, published databases providing evidence of this. Other beetle species have been shown to transmit non-persistent virus, as is PVY, in a variety of cropping systems (Fulton et al. 1987). The newly demonstrated ease with which PVY can be mechanically transmitted by operational activities and the aggressive feeding and movement habits of CPB do, however, raise questions. The potential role of CPB in potato epidemiology should be examined.

This project proposes to:

1. Continue monitoring for CPB resistance to different insecticide modes of actions, especially foliar applied classes of insecticide,

2. Evaluate the potential for improving insecticide efficacy through the use of PBO in various insecticide modes of action
3. Assess the potential role of Colorado Potato Beetle in potato disease epidemiology

Procedures

1) Monitoring for insecticide resistance in Colorado Potato beetle - CPB adults will be sampled by UMN personnel from potato production areas within Minnesota and North Dakota. Samples will also be solicited from locations in the two states (especially from producers experiencing a failure), shipping materials will be supplied to anyone wishing to supply sufficient numbers of beetles to be tested. To adequately test each insecticide with adequate replication, approximately 1500-2500 beetles per location will be required.

Previous results and within-season insecticide failures reported by producers and ag professionals will target locations to be sampled in 2020. Overwintering and summer adults (when available) will be sampled, although higher resistance levels are expected to be found in summer adults of the same location (the beetles' detoxification systems are somewhat impaired by overwintering). Larvae will not be sampled due to the difficulty in successfully transporting and maintaining this life stage of the beetle (handling mortality is extremely high).

Sampled beetles will be assessed for susceptibility to representative registered insecticides; in 2020 the focus will be on abamectins, spinosyns and other modes of action will be tested as indicated from field failures. We will only test for neonicotinoid resistance upon request, increasing tolerance in MN and ND has already been well documented for this mode of action.

Resistance / tolerance of CPB from each area will be assessed using direct exposure tests. A gradient of concentrations of active ingredient (ai), the actual toxin in the insecticide, will be used in trials to create a dose curve that indicates the amount of ai necessary kill 50% of the population (i.e. the Lethal Dose 50% or 'LD_{50}'). Direct exposure trials are conducted by applying 10µl (microliter) drops of insecticide directly to the insect using a micro-applicator (Fig 1). After the insecticide has dried, beetles will be placed onto a potato leaf in Petri plates and left to feed for 5-7 days (120h). Beetles will be 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 will again be assessed 5-7 days post application (min. of 120h). Mortality is assessed by placing beetles on their backs and evaluating movement. Any insect not righting itself is assessed as dead or moribund.

Figure 1. Microapplicator; dispenses 10 microliters per button push.

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 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.

Regional levels of insecticide insensitivity for each insecticide will be calculated and mapped for Minnesota and North Dakota. To facilitate management decisions in the next growing season, annual maps will be made available for publication in Valley Potato grower and available on a potato entomology website to be established at University of Minnesota.

2) Improving insecticide efficacy through PBO – with limited modes of action available for managing Colorado Potato beetle and some of those beginning to demonstrate decreasing efficacy, obtaining limited use of some older, less effective chemistries may be worthwhile. If tolerance to some of these older chemistries can be ameliorated with the addition of PBO, they may be a worthwhile and economically viable addition to the resistance management ‘ mode of action rotation’. In addition, several newer chemistries have potential to be highly effective at their lower label rates when used with PBO. Obtaining the same control using lower rates has definite environmental benefits and, depending on the relative costs, provide an added economic benefit.

Table 2. Insecticide classes (and products) to be tested for potential synergism with Piperonyl Butoxide.

Class & grp no. (product)	Label Rate	PBO
Abamectin grp6 (AgriMek)	3.5 oz/ac	No
Abamectin grp 6 (AgriMek)	3.5 oz/ac	Yes
Abamectin grp 6 (AgriMek)	1.75 oz/ac	Yes
METI[1] grp 21A (Torac)	21 oz/ac	No
METI[1] grp 21A (Torac)	21 oz/ac	Yes
METI[1] grp 21A (Torac)	14 oz/ac	Yes
Diamides grp 28 (Coragen)	7.5 oz/ac	No
Diamides grp 28 (Coragen)	7.5 oz/ac	Yes
Diamides grp 28 (Coragen)	3.5 oz/ac	Yes
Spinosyns grp 5 (Blackhawk)	3.3 oz/ac	No
Spinosyns grp 5 (Blackhawk)	3.3 oz/ac	Yes
Spinosyns grp 5 (Blackhawk)	1.7 oz/ac	Yes
Synthetic Pyrethroid grp3 (Warrior II or other)	1.92 oz/ac (Warrior)	No
Synthetic Pyrethroid grp 3 (Warrior II or other)	1.92 oz/ac (Warrior)	Yes
Synthetic Pyrethroid grp 3 (Warrior II or other)	1.28 oz.ac (Warrior)	Yes

Replicated small plots (4 row x 25’) will be established at the NWROC in Crookston and the UMN Sand Plains Research Farm in Becker. Naturally established populations of CPB will be treated with foliar applications of insecticides representing 5 different classes (modes of action) (Table 2). Three different application treatments for each class will be applied: the high label rate, without PBO (mirrors current application practice), high label rates with PBO (to see if there is a synergistic improvement in efficacy), low label rate with PBO (to evaluate potential for economic and environmental savings.

Populations of some insects have shown resistance to PBO synergized insecticides. This may be through genes whereby the CYP system is ‘supercharged’ or because the genes for an alternative resistance mechanism have been magnified in the population through selection pressure. To assess if this will be an immediate concern, laboratory trials will be conducted on more limited scales, examining the potential for development of resistance to products with PBO. Lab colonies will be started from local CPB populations involved in the field trials. This lab colony will be maintained over 2-3 generations and fed on greenhouse plants treated with representative insecticides mixed with PBO. Survivors will be used to mix into the lab colony to mirror field populations over time. Any tolerance to the insecticides with PBO added will be noted and populations will be assessed for resistance rates to insecticides with PBO.

3) Assess role of CPB in potato disease – this research will incorporate both a greenhouse component and field tests. Potato plants, both infected with PVY and non-infected, will be established in the greenhouse at the NWROC in Crookston. Infected plants will be grown in cages and kept separate from non-infected plants. Plants will be tested prior to trials and after for PVY infection using Enzyme-Linked Immunosorbent Assay (ELISA) strips to confirm disease status. Beetles from lab colonies will be allowed to feed on infected plants for 2 days. This will ensure adequate defoliation to expose the beetles to PVY virus within infected plants. Virus transmission will be assessed by percent of plants infected with PVY by beetle feeding.

Rates of virus transmission in the lab are often not reflected by what is seen in the field. Field plots will established at the NWROC in Crookston with both PVY infected and non-infected (clean) plants. Infected plants will be established either by planting infected seed or infecting emerged plants with PVY inoculum, depending on the availability of seed. Clean plants will be caged (4 plants per cage in 16 cages) at emergence to exclude beetles and known PVY vectors to prevent inoculation prior to the trial. Naturally established beetles (i.e. local populations) will be allowed to feed on PVY infected plants for 2 weeks (shorter if excessive defoliation occurs). Cages on non-infected plants will be removed at a rate of 4 cages per week for 4 weeks and plants confirmed to still be PVY free with ELISA strips. CPB will then be allowed to transfer and feed on clean plants over the next several weeks. Prior to complete defoliation, CPB will be removed with insecticides. Plants will allowed to complete development. Tubers will be collected at harvest, held in cold storage and then treated with gibberellic acid to encourage sprouting. Tubers will planted in the greenhouse and daughter plants tested for PVY using ELISA.

Field trials for CPB transmission of PVY will be conducted in June and will not continue into July. This is decrease the potential of having aphid vectored PVY transmission.

This laboratory portion of this trial has additional funding from a MDA Specialty Crops Block Grant. If the field work provides positive data, however, it will provide the preliminary data for a larger field study that will be submitted to a competitive, federal funding source.

Results & Discussion:

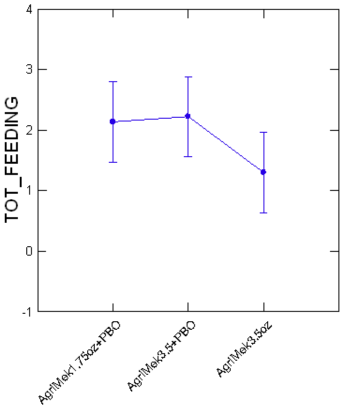
COVID-19 Impacts – the University of Minnesota's COVI-19 restrictions put in place to safeguard the health and welfare of their Students, staff and faculty prevented establishing and maintaining a research effort at the Sand Plains Research Farm in Becker. All field research in 2020 was therefore conducted at the NWROC in Crookston, limiting space available for field trials. Trials focusing on responses in individual insects (e.g. disease transmission, etc), were conducted in the laboratory or greenhouse when possible.

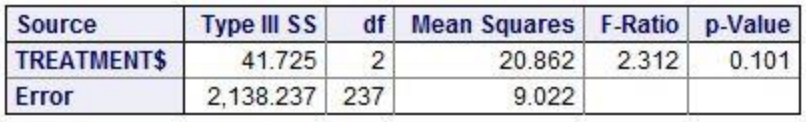
1) Monitoring for insecticide resistance in Colorado Potato beetle – The above mentioned ravel difficulties prevented widespread sampling of MN and ND beetle populations. There were two locations sampled, fields near Clearwater and Rice, MN were sampled in early August.

2) Improving insecticide efficacy through PBO – This trial was conducted in the field at the NWROC in Crookston. The effect of including PBO varied among the modes of action tested, and included some surprising results. Consequently, it's best to consider the impacts of each independently. The insect counts differentiated between adults, large larvae, small larvae, and eggs per plant. The feeding stages (adults and both larval stages) were also combined into Total Feeding Stages / plant at each date. The percent defoliation in each plot was recorded at each date. Cumulative feeding stages (the accumulated average number of feeding staged beetles per plant throughout the entire trial). It is important to remember that Piperonyl Butoxide (PBO) works by decreasing an insect's ability to enzymatically degrade the active ingredient before it reaches its target site (the location in the insect that is affected by the active ingredient). If an insecticide is enzymatically degraded by the Cytochrome P-450 group, PBO can increase the amount of toxin to reach the target site. Consequently, there are circumstances where PBO will not be effective. If the insecticide is not broken down byt the P-450 CYPs and insects are susceptible to the insecticidal mode of action being used, there should be minimal additional activity from adding PBO. In addition, if the enzymatic degradation of an insecticide is being expressed at a very high level (i.e. the insect is highly resistant to the insecticide), the inclusion of PBO may not significantly increase the efficacy of an insecticide to the point where it matters (there may already be a lot of insects surviving). Yield data was obtained but cannot be correlated to treatment. This is because the trial was ended prior to the end of the growing season in an attempt to use the plots in other trials due to the shortage of plot space. This may have confounded the relationships of yields to treatments in this trial so they are not included in this report. The most important data, however, are the relationships between the insecticide treatments and insect numbers.

Abamectins (AgriMek): Results of incorporating PBO with AgriMek were not expected. While PBO has been documented as increasing the efficacy of AgriMek in Central MN, similar results were not seen in the Red River Valley populations. This is likely due to the fact that these populations remain susceptible to Abamectins. At all sample dates, the inclusion of PBO in Abamectin applications did not effect the number of any life stage or the total feeding stages of CPB (Table 3). Neither was there any effect on the percent defoliation in plots sprayed with either Abamectin alone or Abamectin & PBO (Table 4)

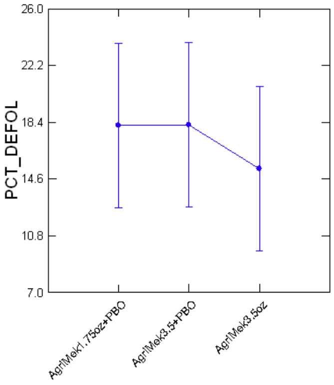
Table 3. Analysis of Variance (ANOVA) of all feeding stages of Colorado Potato Beetle in plots treated with either AgriMek or AgriMek with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO to AgriMek did not improve it's efficacy.

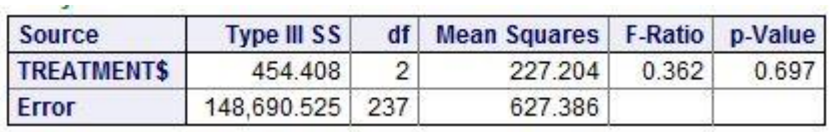




Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	41.725	2	20.862	2.312	0.101
Error	2,138.237	237	9.022		

Table 4. Analysis of Variance (ANOVA) of the percentage of defoliation of plants in plots treated with either AgriMek or AgriMek with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO to AgriMek did not prevent any additional defoliation.

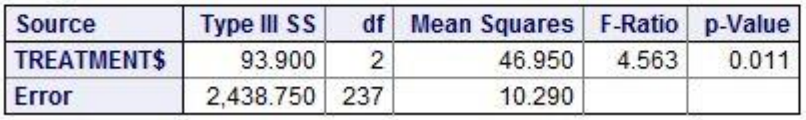




Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	454.408	2	227.204	0.362	0.697
Error	148,690.525	237	627.386		

Mitochondrial Electron Transfer Inhibitors (METI) (Torac): The addition of PBO to Torac provided a significant improvement in efficacy. The 21oz rate of Torac with PBO had sigficantly fewer total feeding stages at each sample date than either the 21oz rate alone or the 14oz rate with PBO (Table 5). This was reflected by the Torac 21oz with PBO treatment plots having significantly less defoliation than the plots treated with Torac 14oz with PBO (Table 6). In fact plots treated with Torac at a 21oz rate with PBO added had significantly fewer feeding stages of CPB throughout the trial and suffered less defoliation than did plots treated with either of the other treatments.

Table 5. Analysis of Variance (ANOVA) of all feeding stages of Colorado Potato Beetle in plots treated with either Torac or Torac with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO tot Torac 21oz improved the efficacy of this treatment.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	93.900	2	46.950	4.563	0.011
Error	2,438.750	237	10.290		

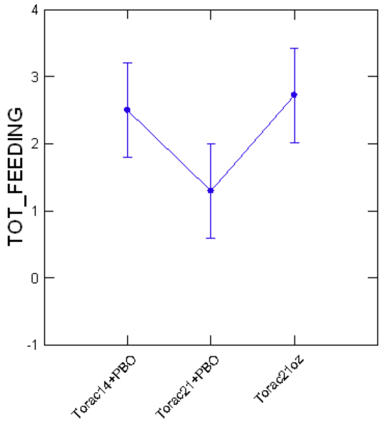
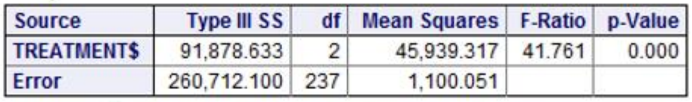
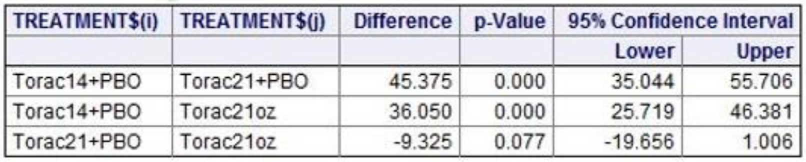


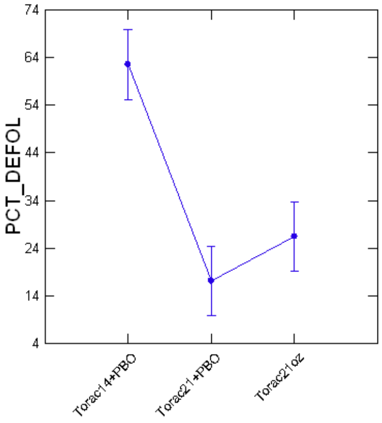
Table 6. Analysis of Variance (ANOVA) of the percentage of defoliation of plants in plots treated with either Torac or Torac with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO to Torac 21oz decreased defoliation; plots treated with Torac at a 21oz rate with PBO added had less defoliation than did plots treated with either Torac at 14oz with PBO or Torac 21oz without PBO.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	91,878.633	2	45,939.317	41.761	0.000
Error	260,712.100	237	1,100.051		

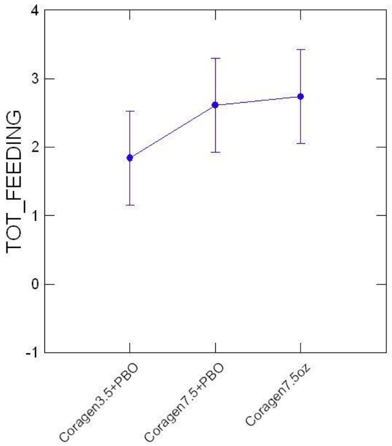


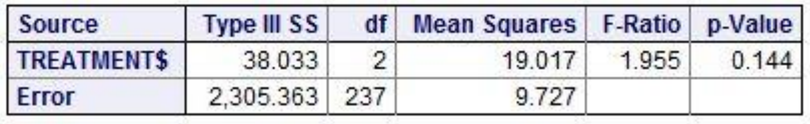
TREATMENT$(i)	TREATMENT$(j)	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
Torac14+PBO	Torac21+PBO	45.375	0.000	35.044	55.706
Torac14+PBO	Torac21oz	36.050	0.000	25.719	46.381
Torac21+PBO	Torac21oz	-9.325	0.077	-19.656	1.006



Anthrenilic Diamides (Coragen): The addition of PBO to Coragen did not improve its efficacy. Plots treated with Coragen with PBO had similar numbers of feeding stages and suffered similar levels of defoliation as did plots treated with Coragen without PBO. The addition of PBO to Coragen did not incrase the insecticide’s efficacy (Table 7). Consequently, the addition of PBO to Coragen had no effect on defoliation either (Table 8). This was not surprising; the diamides are probably not enzymatically degraded quickly enough to decrease the amount of active ingredient reaching the target site. The P-450 group has not been well documented as being involved in the detoxification of diamides; it's thought that diamide resistance is the result of another mechanism. There is some evidence that there is potential for cross resistance between the diamides and the neonicotinoids.

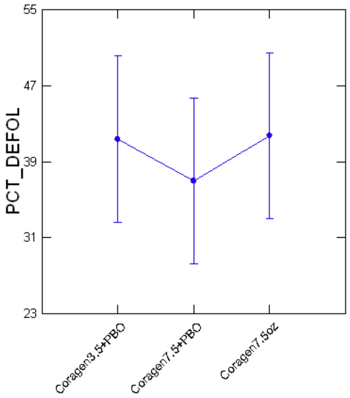
Table 7. Analysis of Variance (ANOVA) of all feeding stages of Colorado Potato Beetle in plots treated with either Coragen or Coragen with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO tot Coragen did not improve its efficacy.

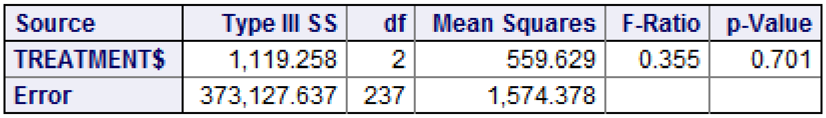




Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	38.033	2	19.017	1.955	0.144
Error	2,305.363	237	9.727		

Table 8. Analysis of Variance (ANOVA) of the percentage of defoliation of plants in plots treated with either Coragen or Coragen with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Plots treated with Coragen with PBO suffered the same amount of defoliation as did plots treated with Coragen alone.

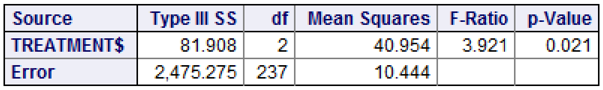




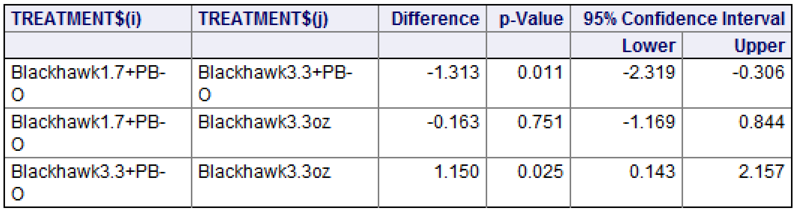
Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	1,119.258	2	559.629	0.355	0.701
Error	373,127.637	237	1,574.378		

Spinosyns (Blackhawk): The addition of PBO to Blackhawk had an antagonistic effect, it decreased the efficacy of this insecticide. There was no difference in the number of feeding stages of CPB in plots sprayed with either Blackhawk at a 1.7oz rate with PBO added and Blackhawk at a 3.3oz rate without PBO. But when PBO was added to the 3.3oz rate of Blackhawk, these plots had significantly more feeding stages on average than either of the other treatments (Table 9). Piperonyl butoxide decreased the toxicity of Blackhawk. Oddly, this did not completely correspond with defoliation data. Plots treated with Blackhawk 3.3oz with PBO did suffer significantly more defoliation than did plots treated with Blackhawk1.7oz with PBO, but there was no difference in defoliation of plots treated with either of the 3.3oz Blackhawk rates (i.e. with or without PBO). An antagonistic effect with PBO has been documented in several insecticides, including Chlorpyrifos (Lorsban) in several cropping systems. Piperonyl Butoxide can in some insects cause a number of physiological responses other than suppression of the P-450 CYPs, some of which can result in decreasing the efficacy of the active ingredient on that insect.

Table 9. Analysis of Variance (ANOVA) of all feeding stages of Colorado Potato Beetle in plots treated with either Blackhawk or Blackhawk with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO to Blackhawk actually decreased its efficacy.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	81.908	2	40.954	3.921	0.021
Error	2,475.275	237	10.444		



TREATMENT$(i)	TREATMENT$(j)	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
Blackhawk1.7+PB-O	Blackhawk3.3+PB-O	-1.313	0.011	-2.319	-0.306
Blackhawk1.7+PB-O	Blackhawk3.3oz	-0.163	0.751	-1.169	0.844
Blackhawk3.3+PB-O	Blackhawk3.3oz	1.150	0.025	0.143	2.157

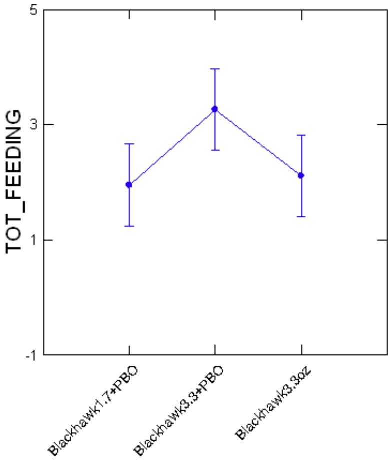
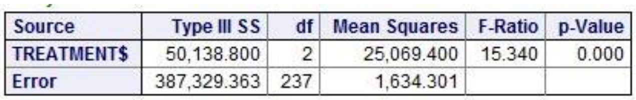
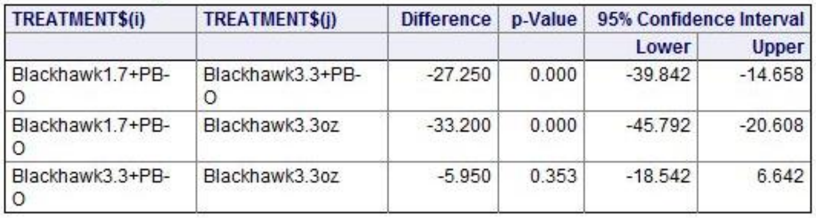


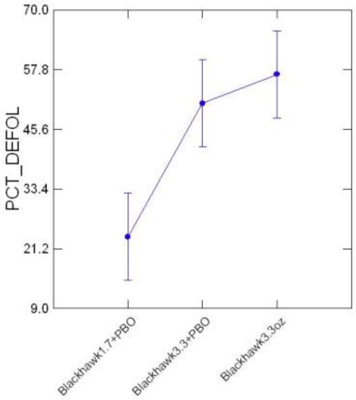
Table 10. Analysis of Variance (ANOVA) of the percentage of defoliation of plants in plots treated with either Blackhawk or Blackhawk with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Plots treated with Blackhawk at a 3oz rate with PBO added suffered more defoliation than did plots treated Backhawk at a 1.7oz rate with PBO Added. There was no difference in defoliation between plots treated with Blackhawk 21oz with or without PBO.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	50,138.800	2	25,069.400	15.340	0.000
Error	387,329.363	237	1,634.301		

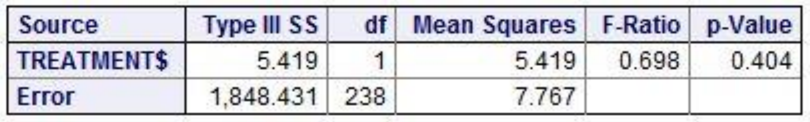


TREATMENT$(i)	TREATMENT$(j)	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
Blackhawk1.7+PB-O	Blackhawk3.3+PB-O	-27.250	0.000	-39.842	-14.658
Blackhawk1.7+PB-O	Blackhawk3.3oz	-33.200	0.000	-45.792	-20.608
Blackhawk3.3+PB-O	Blackhawk3.3oz	-5.950	0.353	-18.542	6.642



Synthetic Pyrethroids (Warrior II): The Synthetic Pyrethroids have been used extensively against Colorado Potato Beetle in the Red River Valley. They have been relatively ineffective against CPB due to the well-established resistance seen in the local CPB populations. Adding PBO to Warrior applied at the 1.92 oz rate had no effect on either efficacy or defoliation. Plots treated with Warrior II with PBO or without PBO had similar numbers of feeding stages of CPB at all sample dates through the trial. There was no difference in the amount of defoliation seen in plots applied with either treatment. The lack of any synergism from adding PBO to Warrior II may be because the rate of resistance to this insecticide is so high in local populations that any improvement would still result in a small overall decrease in beetle numbers.

Table 11. Analysis of Variance (ANOVA) of all feeding stages of Colorado Potato Beetle in plots treated with either Warrior II or Warrior II with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Adding PBO to Warrior II had no effect on it's efficacy. Plots treated with Warrior II 1.92oz with PBO added had similar numbers of feeding stages of Colorado Potato Beetles as did plots treated with Warrior II 1.92oz without PBO.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	5.419	1	5.419	0.698	0.404
Error	1,848.431	238	7.767		

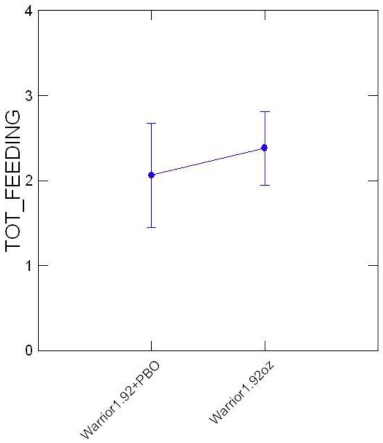
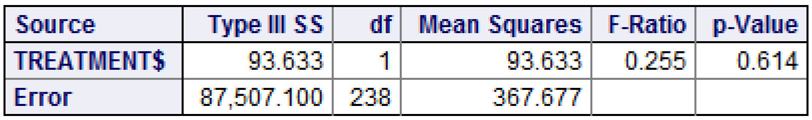
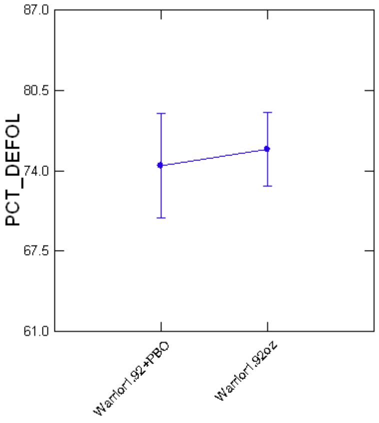


Table 12. Analysis of Variance (ANOVA) of the percentage of defoliation of plants in plots treated with either Warrior II or Warrior II with PBO added. P-values below 0.05 are considered significantly different (i.e. a real difference, no overlap of data). Plots treated with Warrior II with PBO had similar defoliation as did plots treated with Warrior II without PBO. There was no effect of adding PBO to this product in this trial.



Source	Type III SS	df	Mean Squares	F-Ratio	p-Value
TREATMENT$	93.633	1	93.633	0.255	0.614
Error	87,507.100	238	367.677		



A summary of PBO interactions can be found in the Appendix.

3) Assess role of CPB in potato disease – These trials were conducted in lab and greenhouse and had limited treatments applied in the field. Caged trials were conducted in walk-in growth rooms at the NWROC (Fig 2). Beetles were allowed to feed on PVY infected plants and then released into a cage containing uninfected plants. After allowing extensive feeding and removing beetles, plants were tested with PVY test strips (Fig. 3). Only 2 plants tested positive for PVY, both of which providing a positive signal on test strip. Tubers were collected from only one of these plants but did not sprout. Consequently, a grow out of the plant was not possible.

A cage trial was conducted in the field mirroring the methods in the lab trial. Large walk-in cages were established over planted rows in the field. Prior to installing the cage, the trial plot had been hand-planted with uninfected and 2-3 infected potatoes. A small cage was then placed over the PVY infected plants prior to emergence inside the walk-in cage. This prevented any potential infection by wild insects. After plants were established, potential vectors were placed in the PVY infected plant cage and allowed to feed on these plants prior to the inside cage being removed. At this point, the potential vectors were free to feed on the uninfected plants.

One of the replications was confounded due to the inside cage containing the PVY positive plants, being knocked off by a very strong wind front. The interior cage had not been adequately secured to the ground. At this point, we were not sure if the vetors that had been placed into the cage had fed long enough to be sufficiently viruliferous. In any case, none of the uninfected plants tested positive in the trial.

These data are preliminary at this point but seem to indicate that CPB may vector PVY in the lab, but may not in the field. We intend to repeat this trial with a larger design in 2021/22 as part of a Specialty Crop Block Grant.

Figure 2. Caged Colorado Potato Beetle trials assessing vector efficiency.

Figure 3. PVY testing strip.

Figure 4. Caged trials at the NWROC used to assess vector efficiency. Note internal cage which contains PVY infected plants upon which potential vectors are allowed to feed prior to being released into the main cage set up over non-infected plants.

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Appendix 1.

Insecticide (Mode of Action)	PBO Interaction
AgriMek (Abamectins)	No Benefit. In Red River Valley CPB populations, adding PBO did not increase efficacy of AgriMek, no additional toxicity was seen. PBO does increase toxicity to CPB populations in Central MN
Torac (METI)	Benefit. PBO significantly increased the toxicity of Torac, especially at the 21oz rate.
Coragen (Diamides)	No benefit. The addition of PBO did not increase the efficiacy of Coragen. Most publications have shown no effect of PBO on diamides.
Blackhawk (Spinosyns)	Negative effect. Adding PBO to Blackhawk had an antagonistic effect, decreasing efficacy at higher application rates.
Warrior II (Synthetic Pyrethroids)	No benefit. Adding PBO to Wrrior did not increase its efficacy. Resistance to Pyrethroids is well-established in Red River Valley CPB populations.

Managing PVY Vectors, 2020

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Executive Summary – This is a proposal to fund 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 proposal also includes refining optimum timing for vine-kill, supplementing a successful Specialty Crop Research Block from the Minnesota Dept. of Agriculture.

Rationale – The seed potato production regions of North America are 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. It has a *latency period*; the time from which the aphid acquires the virus from an infected plant to the time the aphid can then transmit the virus to a non-infected plant, is anywhere from 12 to 72 hours. Consequently, PLRV is often transmitted by aphids that colonize potato. Colonization by an aphid refers to a winged female depositing a daughter aphid which reproduces, resulting in the plant hosting a resulting population of aphids. A latency period of up to 3 days means PLRV can be controlled by well-timed applications of traditional insecticides.

On the other hand, PVY is a non-persistent virus; there is no latency period and the time from the virus can be acquired by a vector from an infected plant and transmitted to an uninfected plant is only minutes at most. Consequently, PVY is often vectored by aphid species that don’t 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 to determine of they are appropriate host plants. If a plant is not a viable host, aphids will fly (up to 1-3m) to neighboring plants to assess them as hosts. Consequently, an aphid species that does not colonize potatoes will move across a potato field, probing plants and potentially transferring inoculum. This process results in non-colonizing vector species spending short periods in each field, probing plants as they move across and eventually leaving the field. Not only does this mean that any PVY inoculum, with its negligible latency period, will be readily moved from infected to non-infected plants, but the short residence time in the field also means that traditional insecticides will not have sufficient time to prevent the transfer of inoculum by the vector. Traditional insecticides, therefore, will not control the spread of PVY. Rather, the most effective insecticides have been those that cause the insects’ feeding behavior to stop.

Currently, the main two insecticides used for this purpose have been Beleaf (FMC Corp., Philadelphia PA) and Fulfill (Syngenta, Crop Protection, Greensboro, NC). Other than these anti-feedant insecticides, the best alternative management product has, to this point, been crop oils such as Aphoil. The application of crop oils can reduce the transmission of PVY from between 40%-85% depending on the frequency of application and incorporation of other management tactics. There have been reports that these products may not be providing the length of control they previously have; this may, however, be more the result of environmental influence than the development of resistance.

Some newer products have recently gained registration for use in potatoes that may also have promise in managing the transmission of PVY (e.g. Sefina, BASF Ag Products, Research Triangle Park, NC). Additionally, other research indicates the addition of the synthetic pyrethroid Lambda Cyhalothrin (e.g.

Warrior II by Syngenta Crop Protection or Silencer by Adama) increases the length of protection crop oils provide against the transmission of PVY (Singh 2019). Interestingly, Lambda Cyhalothrin was the only insecticide shown to augment efficacy of crop oils.

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

Aphids show a preference for landing on the edge of fields. This is true for many of the aphids colonizing potato (DiFonzo et al. 1997, Suranyi et al. 2004, Carroll et al. 2004) and for non-colonizing species as well (Hodgson et al 2005). This practice facilitates the use of targeted border applications which can result in significant savings in aphid management (Carroll et al. 2009, Olson et al. 2004). However, application timing is critical and treatments must be applied prior to aphid populations dispersing across the field. 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. For example, the majority of vector flight occurs starting in late July and through August, reflecting many of the non-colonizing species moving from senescing hosts (e.g. small grains) to seek alternate food sources (Fig 1). 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. However, to be economically feasible, the timing of vine-kill would have to be optimized to balance any yield loss and disease management.

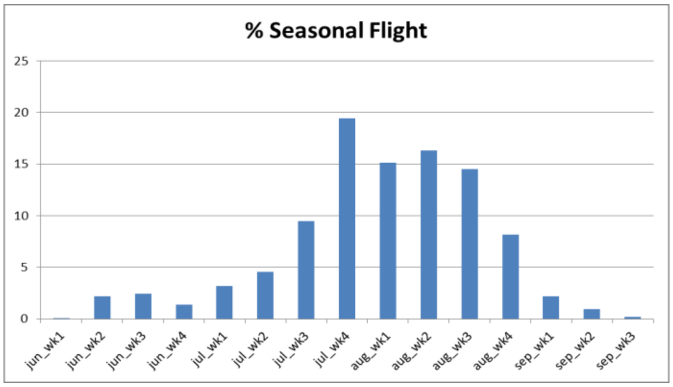

Figure 1. The average % flight of aphid vectors of potato virus disease as measured by suction trap capture through the growing season. Note peak seasonal flight occurs from the 4th week of July end of August. This is an average of data collected from 2012-2019.

The *Aphid Alert* network has developed 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 and aphid vector species identified and PVY Vector Risk Index values calculated. Results are distributed to seed producers weekly via various electronic media (NPPGA's Potato Bytes, the *Aphid Alert* blog, Twitter and email ListServs). Since 2012, the *Aphid Alert* network has provided excellent regional coverage of the Minnesota and North Dakota seed producing areas.

We propose to:

1. Continue the *Aphid Alert* network, providing potato producers with near real-time information on the regional distribution and densities of aphid vectors of virus disease and weekly assessments of PVY risk transmission at 20 trap locations.

2. Develop best recommendations for the timing of vine-kill to minimize any yield loss while providing additional disease management.
3. Compare newer products and additives that may offer additional tactics for managing the transmission of PVY.

Procedures – 1) *Aphid Alert* Trapping Network. A network of ~20 3m-tall suction traps has been established in the seed potato production areas of Minnesota and North Dakota. These traps consist of a fan drawing air down in through the trap and trapping the incoming aphids in a sample jar which is changed weekly by grower cooperators and sent to the UMN-NWROC entomology lab. Insects in the jars are sorted, aphids identified to species and aphid population dynamics at sample locations are determined. Maps are prepared weekly showing these dynamics. This information is made available to growers on two websites (aphidalert.blogspot.com and aphidalert.umn.edu), via NPPGA weekly email, linked to the NDSU Potato Extension webpage (http://www.ag.ndsu.edu/potatoextension), and posted on the AgDakota and Crops Consultants List Servs. Recommendations for beginning oil treatments or targeted edge applications can be made based on the information obtained from the regional monitoring system. Traps are established in early June and maintained until the seed field hosting the trap is vine-killed/harvested. At that point, a field is no longer attractive to aphids. We will continue 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 2014, four *Aphid Alert* suction traps were established at the MN winter grow-out location at Waialua, HI. Additional traps have been incorporated providing coverage of the grow-out site. Through the grow-out season, we identify trap contents sent to us by the cooperating grower in HI. This assures that any PVY incidence recorded in the grow-out results from planted inoculum and not from within-field transfer at the grow-out site.

2) *Vine Kill Timing* - Two separate trials will be conducted to assess the optimum timing of vine kill: effect of individual plant age in PVY transmission and the timing of desiccant application. Plant age has been reported as influencing the presentation of PVY symptoms (Schramm et al 2011), but there is little information on the influence of plant age on infection. There is some evidence that leaf age may influence susceptibility of plants to infection by virus (e.g. Takehashi, 1972). Combining this information with optimal timing of the application of desiccant should enhance management of the transmission of PVY.

A source of PVY infected potato germ plasm has been obtained from the Minnesota Dept. of Agriculture seed inspection service (no field source was been provided for this germplasm). To assess the timing of vine-kill, replicated small plots (4 plots - 2 rows x 4 plants/row each) will be established at the NWROC in Crookston. One row of 4 plants in each cage will be planted with PVY infected tubers, the other row planted with uninfected plants. All plots will be caged with 6’X6’ walk-in cages prior to emergence and maintained throughout the summer. The cages will prevent the immigration of potential vectors and movement within cages will carefully avoid mechanical contact and potential transmittance of virus. Plants will be tested several times throughout the summer to ensure their original infection status is maintained. To assess the effect of plant age on transmission, an additional plot will be established with uninfected plants which will be individually caged with small plant cages to ensure they remain uninfected.

To evaluate the timing of desiccant application, the walk-in cages will be infested with Green Peach aphids which have been fed for several days on infected PVY potatoes in the lab (i.e. to ensure they will be viruliferous). Cages will be infested in mid-August and desiccant applied to 1 cage per week until all cages have been treated. After vine-kill has been completed, all aphids in cages will be eradicated prior to the removal of the cages. All care will be exercised to prevent the escape of any viruliferous aphids.

Tubers will be collected from the uninfected plant row and grown in the greenhouse; resulting plants will be tested for PVY. Rates of PVY transmission will be compared by application dates.

To establish the effect of plant age on PVY transmission, individually caged plants will be exposed to viruliferous Green Peach aphids (prepared as above) over time. Four randomly selected caged plants will have 2 viruliferous aphids attached to their leaves using leaf-clip cages. A leaf clip cage is ¼" diam. PVC pipe cut to 1/2" length. Fine gauge netting is then glued over one end of the tube creating a tiny cage. The cage is held onto the leaf of a plant via a spring hair clip. One viruliferous Green Peach aphid will be placed into a leaf clip cage and two such cages attached to leaves of each selected potato plant. The aphids will be allowed to feed upon the potato plant for 10-15 minutes to optimize the potential for PVY transmission. Cages will then be removed and the aphids killed. Infestations will begin when plants are post-emergent and continue through the growing season to plant senescence. All plants will be assessed for PVY infection using Enzyme-Linked Immunosorbent ASSAY (ELISA) in the lab or by using ELISA sticks in the field.

3) *Product Comparison for PVY Management* - Replicated field plots will be established at the NWROC in Crookston. Replicated small plots will be treated with the management application to be tested. Treatments (Table 1) will begin prior to the arrival of aphids (as detected by the *Aphid Alert* trap onsite) and continued through the growing season as appropriately dictated by the management tactic. Starting in early July, in each plot viruliferous Green Peach aphids will be added to 10 randomly selected plants using clip cages (2 cages /plant, each cage containing one viruliferous aphid). Plants will not be re-used in subsequent re-treatments. Aphids will be allowed to feed for 10-15 minutes to optimize the potential for PVY transmission. Research by Singh (2019) recommended a schedule, based on the seasonal dynamics of aphids vectors in New Brunswick, for adding Lambda-Cyhalothrin to crop oil applications. Seasonal peaks of vector populations in Minnesota and North Dakota are significantly later in the season (Fig 1) and so application timings will be appropriately adjusted to reflect our local aphid population dynamics. Plants exposed to aphids will be assessed for PVY infection using PVY ELISA sticks in the field. Applications will be compared based on percent of plants infected with PVY.

Table 1. Foliar applications to manage transmission of PVY.

Product	Application timing	
Beleaf	1 / wk	
Beleaf	1 / 2wks	
Fulfill	1 / wk	
Fulfill	1 / 2 wks	
Sefina (Inscalis)	1/ wk	
Sefina (Inscalis)	1 / 2wks	
Aphoil	1 / wk	
Aphoil	2 / wk	
Aphoil & λ-Cyhalothrin	1 / wk with 3 λ-Cyhalothrin	
Aphoil & λ-Cyhalothrin	1 / wk with 4 λ-Cyhalothrin	
Aphoil & λ-Cyhalothrin	1 / 2 wks with 4 λ-Cyhalothrin	

Results & Discussion

COVID-19 Impacts – the University of Minnesota's COVI-19 restrictions put in place to safeguard the health and welfare of their Students, staff and faculty prevented establishing and maintaining a research effort at the Sand Plains Research Farm in Becker. All field research in 2020 was therefore conducted at the NWROC in Crookston, limiting space available for field trials. Trials focusing on responses in individual insects (e.g. disease transmission, insecticide resistance, etc), were conducted in the laboratory or greenhouse when possible.

Aphid Alert Trapping Network: in the 2020 season, the Aphid Alert Network had 20 traps in Minnesota and North Dakota and 2 in Nebraska. A total of 3 sites had trap problems preventing records from certain weeks in the season. Overall, the vector pressure was slightly less than that of 2019, but dynamics were different. Vector numbers were highly skewed to later in the season; this is not uncommon, but 2020 seemed to have a very rapid late season development of vector populations. By July 28, all traps together had captured only a total of 75 vectors. From this date until Sept 11 we saw exponential increases in vector numbers (Fig 3). Although Minnesota and North Dakota tend to have peak aphid numbers later in the growing season (Fig 4), the 2020 capture pattern lagged behind the average by approximately 2 weeks; on average, regional vector catch starts to significantly rise in mid-late July (Fig 4).

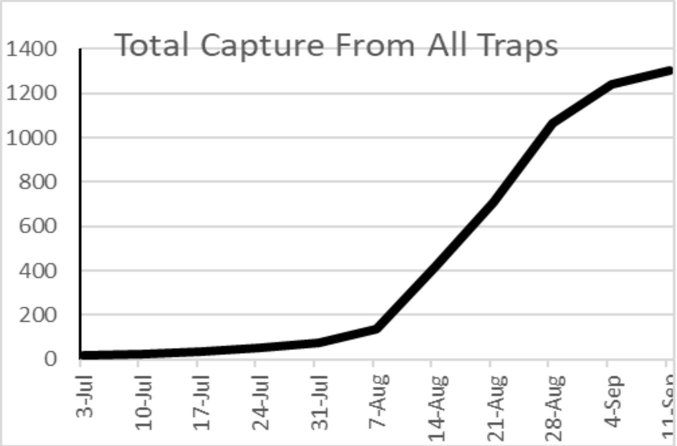

Figure 3. The cumulative capture of all vectors captured in all MN & ND Aphid Alert traps in 2020.

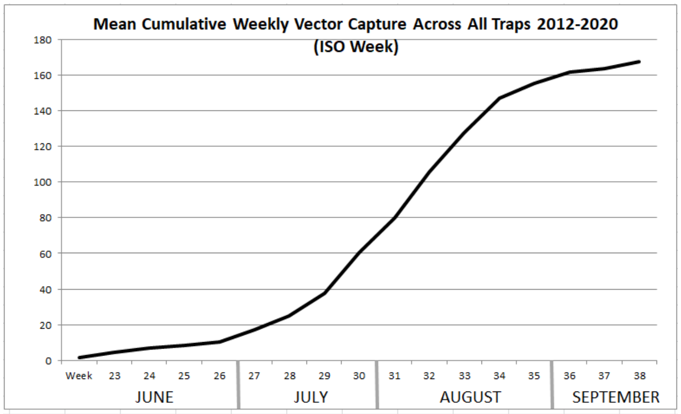

Figure 4. The summed capture by week of all vectors captured in all MN & ND Aphid Alert Traps 2012-2020 (not all site locations had data from all years, traps with more than 2 years consecutive data were included). Dates were standardized to ISO-8061 Week Number to facilitate comparison across years.

This late capture does underscore that the region's greatest chance of PVY transmission is late in the growing season and continued PVY management is necessary to avoid infection. Seed producers may want to consider vine kill by late August and continue the use of oils or antifeedant insecticides (e.g. Beleaf or Fulfill) until vines are killed or otherwise completely senesced.

The data presented in Fig. 4 provides some interesting suggestions for late season PVY management. Several growers in the region have reported already adopting the practice of 'spiking' their Aphoil applications with generic Lamda-Cyhalothrin (e.g. Silencer) to increase suppression of PVY transmission. Results reported by Singh (2019) suggest this practice, when used with one application of Aphoil per week, may be as or more efficacious that 2 applications of Aphoil per week (2 applications of Aphoil per week has long been shown to be more efficacious than a single application/week).

Singh's research, conducted in New Brunswick, reported using a schedule that included adding applications more frequently early in the season and tailing off later in the season. However, the seasonal occurrence of aphids in eastern Canada is earlier than on the Northern Plains. These data from our Aphid Alert Network would suggest that our greatest vector pressure, and therefore our greatest risk of transmission, probably doesn't start until mid-July and escalates quickly afterwards. If adopting this strategy of adding an insecticide to Aphoil, it is probably best to concentrate those applications to later in the season rather than earlier. It is also important to note that the only insecticides Singh's research reported as reducing PVY spread when added to Aphoil were Lambda-Cyhalothrin (e.g. Warrior, Silencer. Etc), Beleaf, and Fulfill. Other insecticides tested did not provide the desired synergism.

Not all Aphid Alert site locations have vector population dynamics that mirror the regional pattern (which is an average across all locations). Consequently, site specific reports have been prepared for each sample locations (e.g. Fig 5) and supplied to trap hosts. These will be used to develop more focused regional reports that will be made available on the Aphid Alert website (aphidalert.blogspot.com)

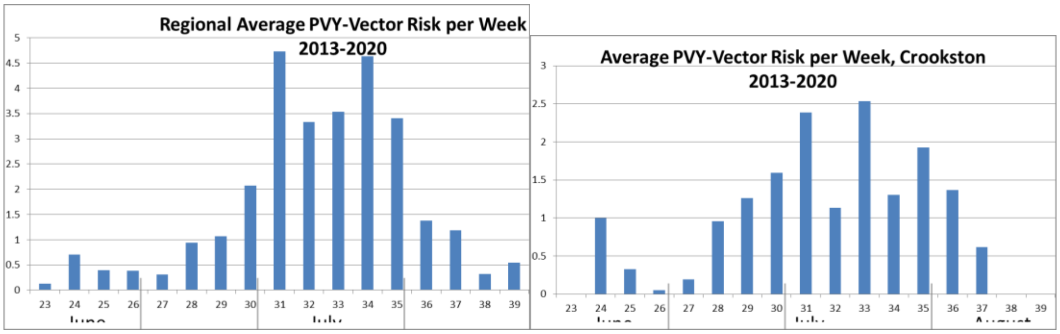

Figure 5. Mean seasonal PVY Vector Risk averaged across the region from 2012-2020 (left) vs mean seasonal PVY Vector Risk from Crookston site 2013-2020 (right).

Vine Kill Timing – Space limitations due to increased use of the NWROC, Crookston site precluded this field study. These trials will be conducted in 2021, materials have been purchased and are in place.

Product Comparison for PVY Management – These trials are being conducted in the greenhouse and environmental control rooms. Unfortunately this precludes doing all treatments at one time and requires changing treatments to allow for assessment. These trials now involve establishing winged Green Peach Aphids from our colony (Fig 6) in a small cage placed inside a larger cage (Fig 7). The small cage contains a PVY-infected plant. After being closed in the small cage and allowed to feed on the PVY positive plants for varying period of time, a non-infected plant is placed in the larger cage and the small cage opened, releasing the aphids into the larger cage with the non-infected plant. The results are now concentrating on the timing of residual activity of the combinations.

Field trials will be conducted in the summer of 2021. All equipment and supplies have been purchased.

Figure 6. Aphid colonies being maintained at the NWROC include both Green Peach Aphid (Left) and Potato Aphid (right).

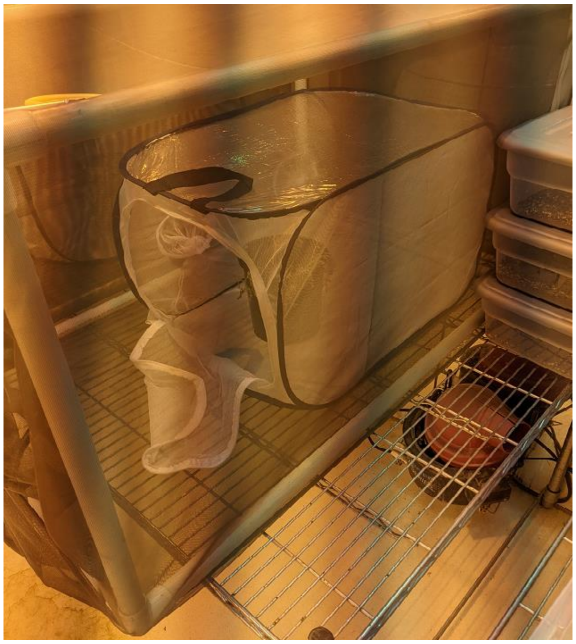

Figure 7. The cage-within-a-cage design. The small white cage holds a potted potato plant infected with PVY within which winged pahids will be placed. It sits inside a larger cage (the white PVC frame is visible in the picture).

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Developing Remote Sensing-based Yield Mapping Technologies for Potato in Minnesota

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Summary

Accurate high-resolution yield maps are imperative to identify spatial yield variability patterns, determine key factors influencing yield variability, and provide site-specific management insights in precision agriculture. However, potato yield monitors are less accessible, and existing potato yield maps generated from yield monitors show low accuracy and inconsistency, easily causing improper interpretation of on-farm yield variability. Remote sensing technologies have demonstrated a higher capability of crop health monitoring and yield prediction. Particularly, multiple temporal remote sensing monitoring at critical growth stages across the whole growing season can uniquely offer more real-time information of yield formation processes and identify the temporal limiting factors. Small plot experiments involving different cultivars and nitrogen (N) rates were conducted in 2018 and 2019, and unmanned aerial vehicle (UAV)-based remote sensing images were collected across the growing season. In 2020, two commercial fields were selected for the study, and satellite remote sensing images were obtained across the growing season. Preliminary analysis demonstrated the potential of using remote sensing images to predict potato tuber yield and generate potential yield maps. In general, remote sensing images at the early season (late June) or late season (late August or early September) were more correlated with potato tuber yield than images collected in July and early August. However, the best performing vegetation index and the best timing for potato yield prediction varied with cultivar. Using machine learning models (random forest regression (RFR) and support vector machine (SVM)) to combine different vegetation indices could significantly improve the accuracy of potato yield prediction. The potato yield map created in this study indicated that potato tuber yield varied significantly within a commercial field (from 295 cwt/ac to 940 cwt/ac). The spatial yield patterns were related to the early season or late season remote sensing images and field topography. More studies will be conducted to improve potato yield prediction using remote sensing images, soil and landscape variables, and possibly management information, as well as grower's harvested total yield data.

Background

Accurate high-resolution yield maps are imperative to identify spatial yield variability patterns within commercial fields, determine the key factors affecting yield, and finally to provide management practice insights in precision agriculture. However, currently available potato yield monitors are less accessible, and existing potato yield maps generated from yield monitors show low accuracy and inconsistency, easily causing improper interpretation of on-farm yield variability. The major influencing factors of those inaccurate potato yield maps from yield monitors include yield sensor calibration, mud or dust separation, operating errors, and data post-processing or cleaning. Therefore, yield monitor applications on potato farms are limited in Minnesota. To tackle this problem, alternative technologies need to be developed for potato yield mapping.

Remote sensing technology has been extensively applied for in-season crop health monitoring (e.g., leaf area index, biomass, diseases/pests) and yield prediction (Mulla and Miao, 2016). Generally, vegetation indices calculated from remote sensing images are used to correlate to yield variability through statistical and machine learning models. Previous studies of potato yield prediction with remote sensing have indicated that the methodology is effective for crop yield prediction and pattern analysis (Gomez et al., 2019). Particularly, multiple temporal remote sensing monitoring across the growing season can uniquely offer insights into yield formation processes and identify the limiting factors such as soil-landscape conditions, water, and nutrient management.

Recent PlanetScope imagery is a newly available commercial cube satellite platform that offers daily multispectral imagery for anywhere in the world. There are about 130 Planet Labs Dove cube satellite sensors that have been launched into sun synchronous low earth orbit. This orbit path and inclination allow for daily revisit time of any point on earth between 9:30 and 11:30 AM solar time (Planet Labs, 2018). The spatial resolution is about 3m. Little has been reported for potato yield mapping using PlanetScope satellite images.

Traditionally, simple and multiple linear regression methods have been used to develop remote sensing-based models to predict yield. The continually evolved machine learning technology in data science provides a promising tool for potato yield prediction improvement. Machine learning methods can model both linear and non-linear relationships and can also incorporate ancillary data more easily into the models to improve yield prediction (Wang et al., 2021). Hence, the integration of cutting-edge technologies on remote sensing and machine learning will significantly improve within-field yield variability assessment and provide interpretable insights for management practices.

The objective of this study was to evaluate the potential of predicting potato yield using remote sensing images.

Methods

Small-Plot N x Cultivar Study

A potato N x Cultivar study was conducted by Dr. Sanjay Gupta in 2018 and 2019. Five potato cultivars and clone (Russet Burbank, Umatilla Russet, Clearwater Russet, Lamoka, and MN13142) having a wide variation in cold-induced sweetening resistance were selected. The study was conducted at the Sand Plain Research Farm, Becker, MN, in a Hubbard loamy sand soil. A randomized complete block design with three replications was used. Each cultivar was subjected to three N rates treatments120, 240, and 360 lbs acre^{-1}. At harvest, yield and yield attributes were recorded. More detailed information about the study can be found in Dr. Sanjay Gupta's report. UAV remote sensing images were collected 4-5 times across different growth stages by Sentek. The dataset was used to evaluate the potential of using remote sensing technology for potato yield mapping.

Commercial Potato Field Study

Two commercial potato fields near Becker, MN, were selected during the growing season of 2020. A bare soil image of these two fields with soil type boundaries is shown in Figure 1. We keep the same management practices and schedules as usually adopted by growers.

Figure 1. Bare soil image showing the two commercial potato fields with soil type boundaries.

Potato growth status in two potato fields was monitored through daily satellite-based imagery data from the Planet Company (San Francisco, CA). The PlanetScope satellites provide daily data at about 3 m resolution and four spectral bands (RGB and NIR). UAV images were also collected a few times across the fields. Multidimensional datasets, including soil data, landscape, and remote sensing, were harmonized to the same spatial resolution as the PlanetScope data and extents for further processing. Vegetation indices were calculated from the PlanetScope satellite images.

To better select the most representative sites for spatial yield variability for ground sampling and validation, the conditional Latin hypercube sampling (cLHS) by integrating all features of the environment, agronomy, and remote sensing monitoring was used to determine 50 ground-truth sampling sites for yield measurement in each potato field (Figure 2). At each sampling site, 5 hills of potato were obtained by hand digging and weighed at the end of the sampling day. The yield was calculated based on 10 ft within row hill spacing and 3ft row spacing.

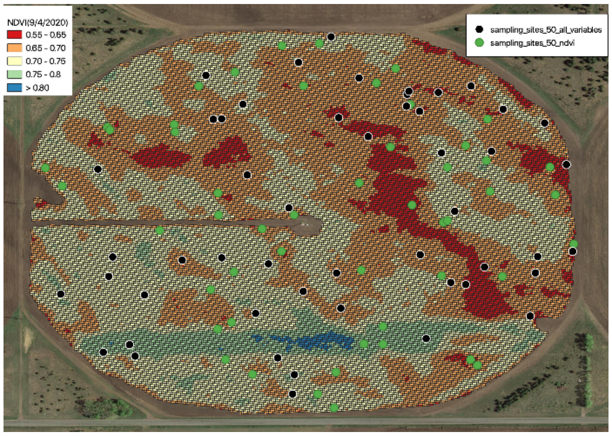

Figure 2. Ground yield sampling locations. The green dots represent possible sampling locations based only on remote sensing image data, and the black dots represent the actual sampling locations based on the consideration of soil, landscape, and remote sensing information.

Data analysis

PlanetScope images were acquired from the Planet Explorer web archive. Planet Labs offers several imagery products based on the demands of the end-user. This study used PlanetScope Analytic Ortho Scene products, which were radiometrically and geometrically calibrated to correct for any sensor artifacts. This process converted the imagery to surface reflectance and removes terrain distortion by using a digital terrain model to correct for image perspective. The final corrected 3 m spatial resolution orthomosaic was downloaded as part of a larger tile that was approximately 25 km x 16 km in dimension. To prepare the imagery for spatial analysis, the tile was clipped to the area of interest using QGIS. ArcGIS was used to further analyze the data and calculate normalize difference vegetation index (NDVI) and ratio vegetation index (RVI). The ground sampled yield and specific gravity data were used for interpolation to create a potato yield map and a specific gravity map using ArcGIS software.

In addition to separate analysis for different years, growth stages, and cultivars, the small plot data from different years were also pooled together, with 75% of the data being used for calibration and 25% for validation. Simple regression models were developed to determine the relationship (linear, power, quadratic, or exponential) between each vegetation index and potato tuber yield using SPSS 18.0 (SPSS Inc., Chicago, Illinois, USA); models with the highest R^2 indicated the best relationship. In addition to the simple regression models, two machine learning algorithms (support vector machine (SVM) and random forest regression (RFR)) were used to predict potato yield. The SVM and RFR models were developed using the scikit-learn Python ML library (Pedregosa et al., 2011; Abraham et al., 2014). The agreement between the observed and the predicted parameter was evaluated using the determination coefficient (R^2), root-mean-square error (RMSE), and relative error (REr) in prediction. The models with the largest R^2 and lowest RMSE and REr in prediction were recognized.

Results and discussion

Best timing for potato yield prediction

In general, the vegetation indices collected in late June (tuber setting stage) had the best relationship with the potato tuber yield across years (Figure 3). In 2018, the correlation between vegetation indices and potato tuber yield became weaker as potato plants developed, with the best correlation on June 26, 2018 (highest r=0.9), and worst relationships on August 2, 2018 (highest r=0.36). In 2019, the relationships were best on June 28, 2019 (highest r=0.6), followed by August 19, 2019, and August 6, 2019, with the relationships being the worst on July 23, 2019 (highest r=0.2).

In late June, the potato plant canopy was not closed yet, and most of the vegetation indices did not saturate. Potato plant growth was significantly correlated with final yield. In July, most of the potato plant canopy was closed, and most of the vegetation indices became saturated, meaning these vegetation indices could not reflect potato plant growth differences. At later growth stages with potato plant senescence, the vegetation index saturation issue became lessened and could reflect potato plant growth status, which was related to potato tuber yield. This was shown by the NDVI maps created for the commercial potato field on different dates in 2020 (Figure 4). The NDVI map on June 25 could show some plant growth patterns, while NDVI maps were relatively uniform in July 2020 due to saturation problems. From Figure 5, the spatial pattern for the NDVI map collected on August 4, 2020 was still not obvious due to canopy closure, while on Sept. 4, clear spatial patterns could be shown, possibly due to plant senescence.

Based on these results, it seems that remote sensing images collected in late June or early Sept. were better for potato yield prediction.

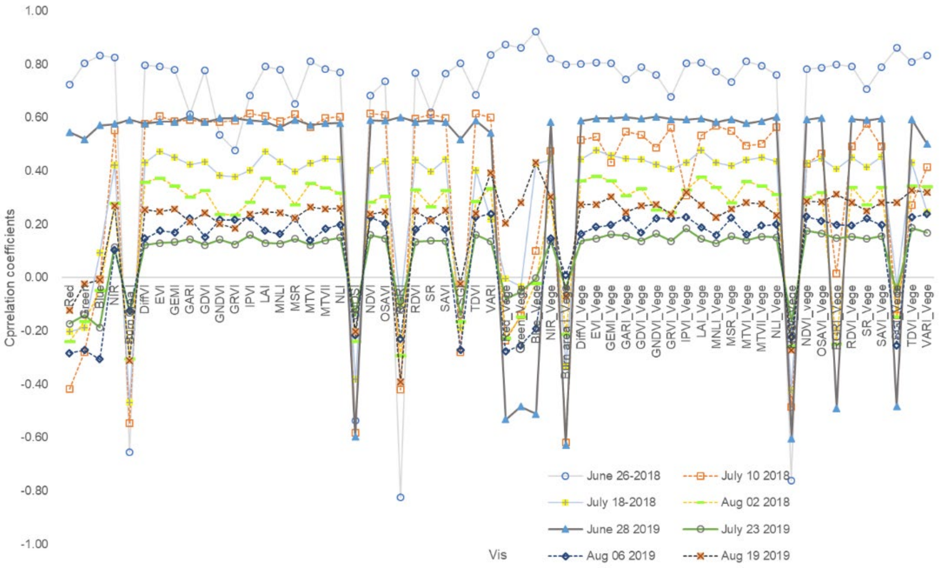

Fig. 3. Correlation coefficients for relationships between potato tuber yield and different vegetation indices were calculated from UAV remote sensing images collected on different dates in 2018 and 2019.

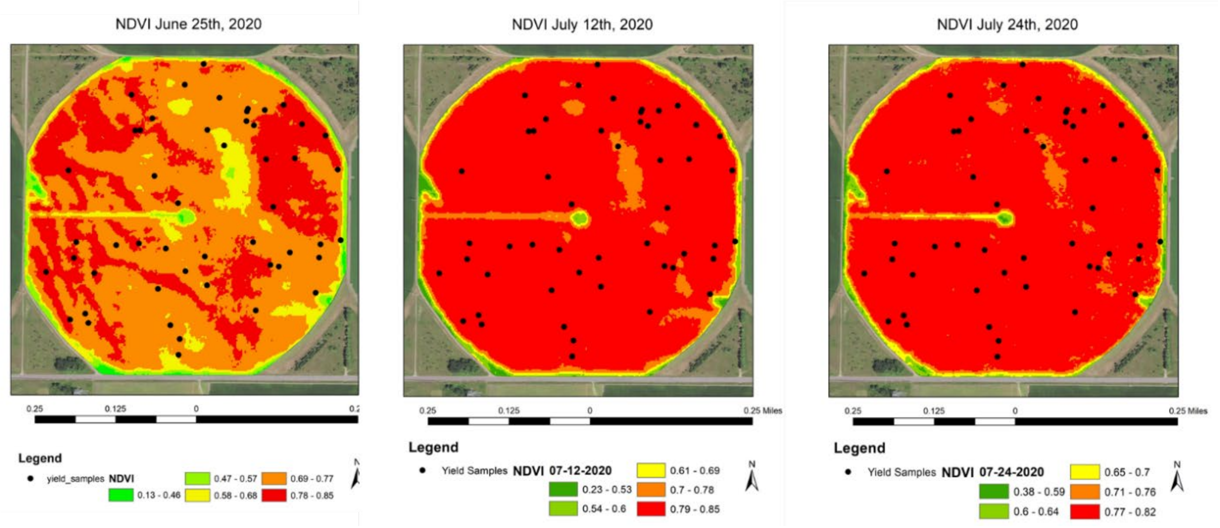

Figure 4. NDVI maps on June 25, July 12, and July 24, 2020, for the commercial potato field.

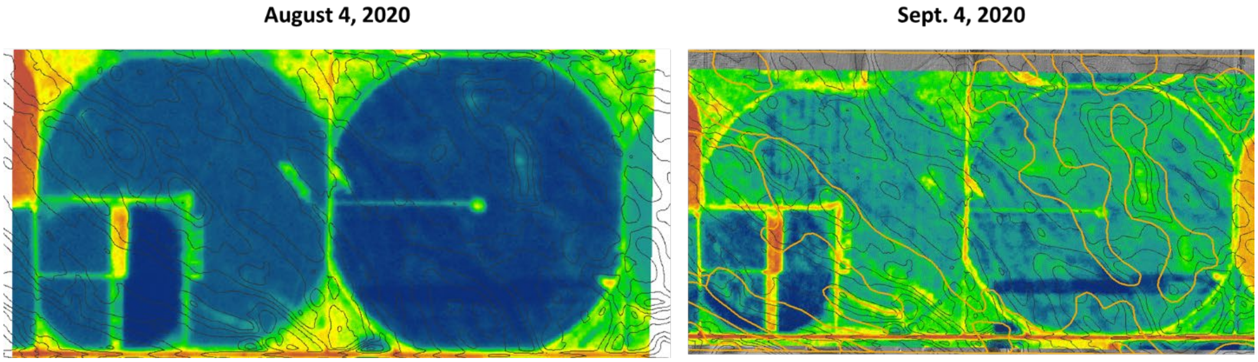

Figure 5. NDVI maps of the two commercial potato fields were calculated from PlanetScope satellite images collected on August 4, 2020 (left) and Sept. 4, 2020 (right).

Cultivar effects on potato yield prediction with remote sensing

The best performing vegetation index for predicting potato tuber yield differed with dates and cultivars (Table 1). For Clearwater Russet, the relationship between vegetation index and potato tuber yield increased as the potato crop developed, with the best relationship on August 2, 2018, but the worst relationship on June 26, 2018, at the plant vegetative growth stage. While for the Umatilla Russet cultivar, the relationships were quite stable across growth stages, although the best performing vegetation indices changed with growth stages. It should be noted that most of the relationships were not linear.

Best on this result, the best growth stage to predict potato tuber yield may be different for different cultivars, and it may also be possible to predict potato tuber yield well at later growth stages using non-linear models.

Improving potato yield prediction using machine learning models

Two machine learning methods were evaluated in this study: random forest regression (RFR) and support vector machine (SVM). These models can combine different vegetation indices and model both linear and non-linear relationships and, at the same time, consider cultivar differences. The RFR model used three vegetation indices (Visible Atmospherically Resistant Index (VARI), Non-Linear Index (NLI), and Sum Green Index (SGI)) collected on June 28, 2018, and cultivar information and performed very well, with $R^2=0.97$ for calibration $R^2=0.86$ for validation (Figure 6). The SVM model using the same vegetation indices and cultivar information also performed quite well, with $R^2=0.80$ for calibration and $R^2=0.78$ for validation (Figure 7).

Table 1. Best performing vegetation indices for predicting potato tuber yield

Cultivar	Vegetation Index	Equations	R^2	RMSE
		June 26, 2018		
CW	SGI	$Y=762.438\log(X)+123.917$	0.48	3.13
IR	VARI		0.64	2.07
UR	BAI	$Y=58.56X^2-101.16X+77.77$	0.85	2.51
RB	MTVI	$Y=5914783.29X^2-198808.45X+1722.83$	0.43	3.50
		July 10, 2018		
CW	GARI	$Y=-5380.23X^2+5915.33X-1595.63$	0.86	1.62
IR	GRVI	$Y=-27.64X^2+258.81X-569.60$	0.79	1.59
UR	EVI	$Y=-2056.92X^2+3195.77X-1189.06$	0.81	2.78
		July 18, 2018		
CW	NDVI	$Y=-181.95X^2+424.72X-189.40$	0.87	1.58
IR	TDVI	$Y=-9574.00X^2+21476.95X-12009.16$	0.77	1.63
RB	SGI	$Y=-22089.85X^2+3009.20X-42.19$	0.44	3.44
UR	GARI	$Y=3605.13X^2-4227.77X+1277.11$	0.83	2.65
		August 2, 2018		
CW	SAVI	$Y=-2042.07X^2+2430.27X-692.74$	0.88	1.49
IR	MTVI	$Y=-524.20X^2+712.17X-206.35$	0.81	1.52
RB	MTVI	$Y=-637.86X^2+996.50x-326.10$	0.61	2.89
UR	EVI	$Y=1115.85X^2-1316.90X+427.20$	0.89	2.13

Note: CW: Clearwater Russet; IR: Ivory Russet; RB: Russet Burbank; UR: Umatilla Russet; SGI: Sum Green Index; VARI: Visible Atmospherically Resistant Index; BAI: Burn Area Index (BAI); MTVI: Modified Triangular Vegetation Index; GARI: Green Atmospherically Resistant Index; GRVI: Green Ratio Vegetation Index (GRVI); EVI: Enhanced Vegetation Index; NDVI: Normalized Difference Vegetation Index; TDVI: Transformed Difference Vegetation Index; SAVI: Soil Adjusted Vegetation Index.

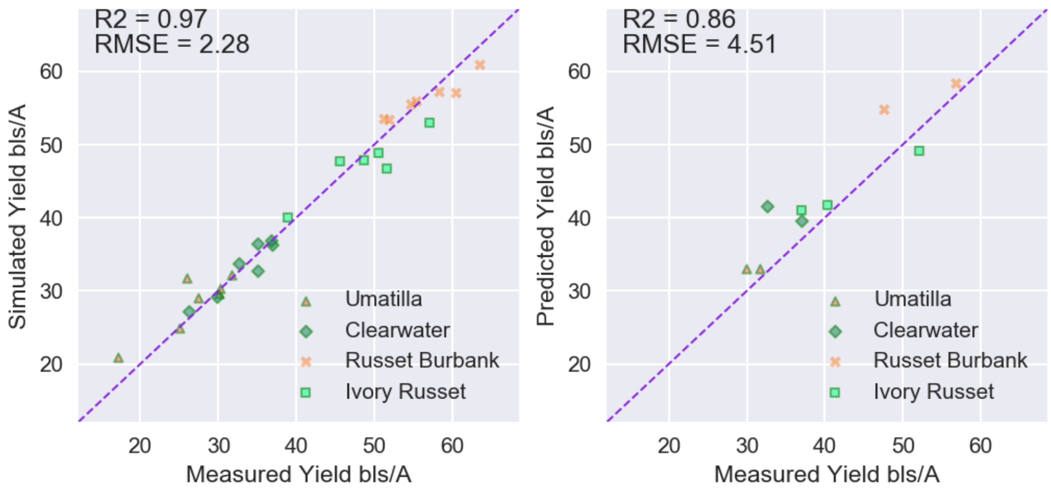

Figure 6. The calibration (left) and validation (right) results of the random forest regression (RFR) model developed using three vegetation indices (VARI, NLI, and SGI) collected on June 28, 2018, and cultivar information.

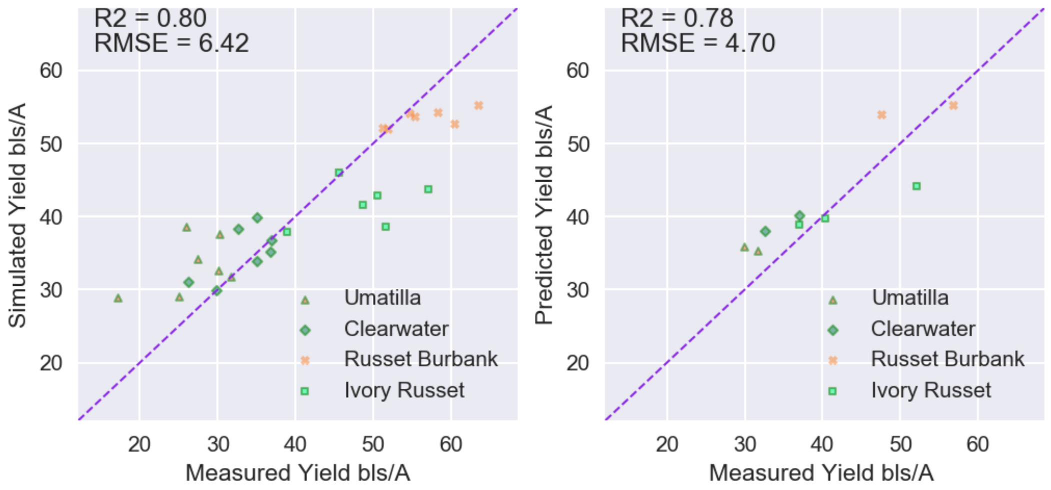

Figure 7. The calibration (left) and validation (right) results of the support vector machine (SVM) model developed using three vegetation indices (VARI, NLI, and SGI) collected on June 28, 2018, and cultivar information.

Spatial variability of potato tuber yield and specific gravity

The 50 yield samples were used for interpolation to create a yield map and specific gravity map for the whole field (Figure 8). The maps indicated that potato tuber yield varied significantly across the field, from 295 cwt/ac to 940 cwt/ac. There was a clear pattern, with the central area of the field being lower in yield. The NDVI map collected on June 25, and the yield patterns matched quite well. This was also related to the topography of the field (Figure 9). The low yielding areas had higher relative elevation. More analyses will be performed to evaluate the potential to improve potato tuber yield by combining soil-landscape information with remote sensing data.

The specific gravity varied from 1.079 to 1.092. The specific gravity map also showed clear patterns, with some areas matching the yield patterns and some areas not.

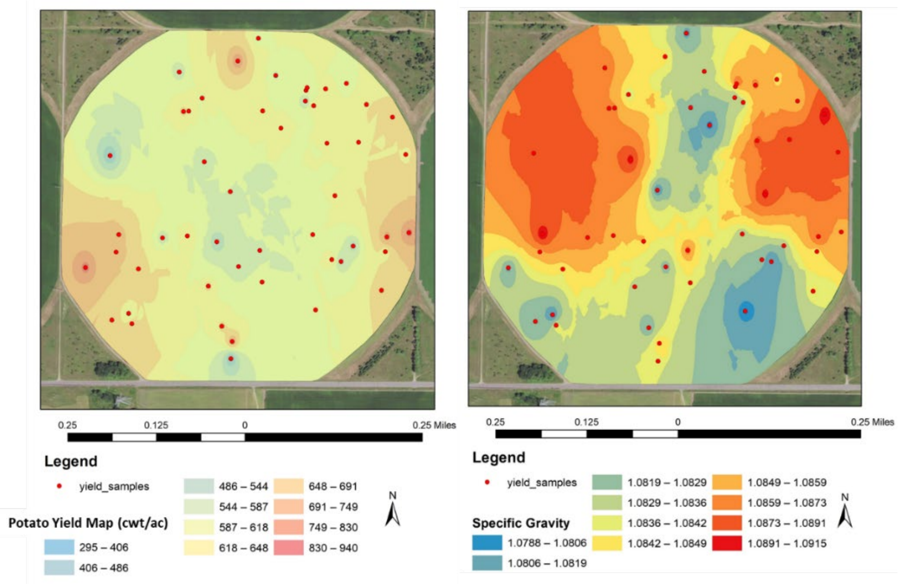

Figure 8. Potato yield map (left) and specific gravity map (right) based on spatial interpolation using 50 yield samples collected across the field.

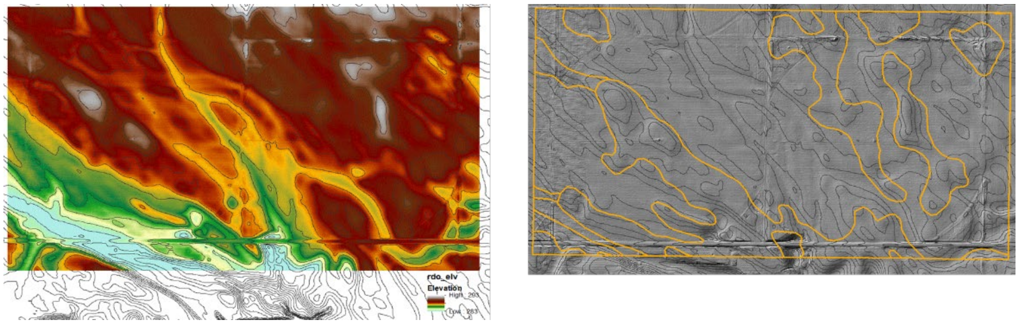

Figure 9. Topography map of the two commercial potato fields.

Implications for on-farm potato management

The results of this study indicated that potato tuber yield could be reliably predicted using remote sensing data and machine learning models. This will allow growers to adjust N application rates according to the predicted yield. The potato yield map of a commercial field will allow us to better under the yield patterns and determine the impact of soil and landscape conditions on potato yield. Since early season or late season remote sensing images can better represent potential yield patterns, it is also possible to use multi-year remote sensing images and soil-landscape properties to delineate the field into a few management zones (Miao et al., 2018). This will help potato growers to adjust fertilizer and irrigation rates in different management zones to improve nutrient and water use efficiencies. Current potato yield prediction methods will require ground yield sampling to develop and calibrate the yield prediction models. More than 5 hills need to be sampled per location in future studies, and a minimum of 10 feet will be needed. Future research will also need to evaluate the potential of using total tuber yield or an average yield of a field obtained by potato growers together with remote sensing images to generate a potato yield map.

Conclusions

This study demonstrated the potential of using remote sensing images to predict potato tuber yield and generate potential yield maps. In general, remote sensing images at early season (late June) or late season (late August or early September) were more correlated with potato tuber yield than other times of the season. However, the best performing vegetation index and the best timing for potato yield prediction varied with cultivars. Using machine learning models (RFR and SVM) to combine different vegetation indices could significantly improve the accuracy of potato yield prediction. The potato yield map created in this study indicated that potato tuber yield varied significantly within a commercial field (from 295 cwt/ac to 940 cwt/ac). The spatial yield patterns were related to the early season or late season remote sensing images and field topography. More studies will be conducted to improve potato yield prediction using remote sensing images, soil and landscape variables, and possibly management information, as well as grower's harvested total yield data.

Acknowledgements

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Report Title: Adjusting Planting Date for the Management of Verticillium Wilt
Submitted to MN Area II and Northern Plains Potato Growers Associations

Principle Investigator: Julie S. Pasche, Department of Plant Pathology, North Dakota State University, Fargo, ND 58102. Julie.Pasche@NDSU.edu

Executive Summary

Verticillium wilt arguably is the most damaging disease of potatoes when considering reduced yield and quality and the increased cost of control, and the industry is looking for sustainability in production. The availability of cultivars with Verticillium wilt resistance has been increasing, with several new options available to growers; however, susceptible cultivars like Russet Burbank are still grown across the majority of US acres. Previous research has supported management practices to reduce the effects of Verticillium wilt, but we feel there is room for additional gains in using other management practices. Seed-tubers planted into colder soils emerge more slowly when compared to a later planted crop. Our hypothesis is that a crop planted into colder soils also suffers increased losses from Verticillium wilt. This hypothesis was tested by planting three cultivars varying in susceptibility to Verticillium wilt into fumigated and non-fumigated soils at three planting dates. The trial was conducted in west-central MN under irrigated conditions. Verticillium wilt severity, total and marketable yield, tuber grade and processor return estimates were differentially affected by cultivar, planting date and fumigation. While total and market yield were reduced as planting dates were pushed later, Verticillium wilt was also reduced. In the single-year trial results reported here, the reductions in yield and adverse effects to tuber size profiles are not a good trade-off for the Verticillium wilt reductions observed. However, disease evaluations were cut short due to frost damage and disease likely advanced past the time we could accurately measure. This is supported by observed increases in total and market yield (including size profile) in response to fumigation. Stem colonization by *V. dahliae* is being evaluated to verify our hypothesis. This report includes a single year of evaluation. In the second year of this trial, planting dates will be initiated earlier to more effectively evaluate if this can be used by growers to manage Verticillium wilt in fields with high pathogen levels or where susceptible cultivars like Russet Burbank are planted.

Rationale

Verticillium dahliae increases in potato stems as the disease and season progress (Pasche et al. 2013b). Following harvest, the long-lived structures produced by the pathogen are returned to the soil where they can survive for decades. Soil fumigation is effective in reducing *Verticillium* propagules per gram of soil (Vppg) at a rate of about 41 to 78%. Therefore, a pre-fumigation level of 50 Vppg would be reduced to approximately 11 to 30 Vppg, still beyond the level of 8 Vppg suggested for growing susceptible cultivar Russet Burbank (Nicot and Rouse 1987). It is not unusual to find a pre-fumigation levels exceeding 250 Vppg in fields in Minnesota and North Dakota with a history of more than 10 potato crops. The use of susceptible cultivars, relatively short rotations and absence of vine desiccation have contributed to increasing *V. dahliae* in the soil and increasing Verticillium wilt pressure. This has led the NDSU potato pathology research group to investigate alternatives. Preliminary results indicate that vine desiccation may reduce the amount of *V. dahliae* returned to the soil without decreasing total or marketable yield

(Gudmestad MN Area II research reports). That research is continueing for two additional years with funding from the ND Dept of Ag Specialty Crop Block Program, resulting in grower recommendations for the use and timing of vine desiccation for Verticillium wilt management.

Research questions have arisen from grower observations that seed planted later, into warmer soils, emerges into more vigorous plants, possibly reducing the damage caused by *V. dahilae*. The Pasche potato pathology research project has substantial expertise in field and laboratory evaluations for Verticillium wilt developed over the past nearly 20 years (Pasche, et al. 2014; Taylor et al. 2005; Yellareddygari and Gudmestad 2017). We have already secured fumigated/non-fumigated land with a cooperator in an area where successful Verticillium wilt trials have been conducted over this timeframe. We have developed and heavily utilized molecular quantification of *V. dahilae* to determine cultivar susceptibility and the efficacy of management strategies (Pasche et a. 2013a). Many of the researchers involved in these previous studies remain in place; therefore, we do not foresee substantial hurdles in performing these studies outside of the typical obstacles of performing field research, most notably mother nature. While advances have been made in our understanding of the development and management of Verticillium wilt, additional gains are needed. Therefore, the **objectives of this research** were/are to determine the effect of planting date on the development of Verticillium wilt, the level of *V. dahliae* present in stems at harvest, total and marketable yield, tuber grade and processor returns utilizing three russet-skinned cultivars planted on three dates.

Procedures

The objectives stated above were accomplished by conducting a field trial near Park Rapids, MN in 2020 under irrigation. Grower practices, including primary tillage, standard fungicide and insecticide regimes were performed by the cooperating grower. Herbicide, side-dress fertilizer applications and cultivation were performed by NDSU. Russet Burbank (susceptible (S)), Umatilla Russet (MS) and Alturas (resistant (R)) were planted on April 30, May 17, and June 3 in fumigated and non-fumigated strips (Table 1). Seed for all treatments was obtained in March and treated in a manner similar to commercial growers to ensure high seed quality at all planting dates. Seed of all three cultivars was held at 50^{O}F until cutting approximately 6 to 7 days before anticipated planting date. Seed was then hand-cut and suberized at 55-60^{O}F with high humidity. This same procedure and timing were repeated before each planting date. 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 12 in. seed spacing and 36 in. row spacing. Soil samples were obtained during summer 2019, prior to fumigation in October 2019 and on August 21, 2020 to determine pre- and post-fumigation Verticillium propagules per gram (Vppg) of soil. Pre-fumigation, there were 20 Vppg of soil. Post-fumigation soil tests averaged 13.5 Vppg of soil in the fumigated strips and 22.5 Vppg of soil in the non-fumigated strips, which is within the range of levels we would expect. Soil temperatures were monitored starting at the first planting date using HOBO MX data loggers placed in each replicate on 4/30.

Table 1. Cultivar, planting date and metam sodium treatment evaluated for the effect on Verticillium wilt development in 2020.

Treatment	Cultivar	Planting Date	Fumigation
501	Russet Burbank	30-Apr	Yes
502	Umatilla Russet	30-Apr	Yes
503	Alturas Russet	30-Apr	Yes
504	Russet Burbank	17-May	Yes
505	Umatilla Russet	17-May	Yes
506	Alturas Russet	17-May	Yes
507	Russet Burbank	3-Jun	Yes
508	Umatilla Russet	3-Jun	Yes
509	Alturas Russet	3-Jun	Yes
510	Russet Burbank	30-Apr	No
511	Umatilla Russet	30-Apr	No
512	Alturas Russet	30-Apr	No
513	Russet Burbank	17-May	No
514	Umatilla Russet	17-May	No
515	Alturas Russet	17-May	No
516	Russet Burbank	3-Jun	No
517	Umatilla Russet	3-Jun	No
518	Alturas Russet	3-Jun	No

The number of emerged plants were counted in the center two rows of each plot starting 17 to 29 days after planting and continuing until 90% emergence was observed. Verticillium wilt was visually assessed at seven-day intervals beginning at mid-potato vegetative growth and flowering stage (from July 30 to August 27) by estimating the number of plants exhibiting symptoms. The trial sustained approximately 50% frost damage on Sept. 8 and 9, making further Verticillium wilt evaluations impossible (Fig. 1). Five stems were collected from all 72 plots (2 fumigation, 3 cultivars, 3 planting dates, 4 replicates) on September 21 and 22 and returned to the laboratory for *V. dahliae* quantification. Total yield was collected at harvest on September 26 and 28. Marketable yield, USDA grade and processor returns were also evaluated. All 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 was conducted using appropriate statistical procedures.

Preliminary Results

The mean number (across cultivars and fumigation treatments) of days to reach 90% emergence was reduced by 5 from the first to second planting dates, and 13 from the first to third planting dates (Figs. 2 and 3). However; the date of emergence was substantially delayed, with 90% emergence recorded at 6/11, 6/23 and 7/2 for the 4/30, 5/17 and 6/3 planting dates, respectively. Combining these data with soil temperatures collected from the data loggers will further clarify the associations of emergence and stem colonization by *V. dahliae*.

Figure 1. Frost damage sustained Verticillium wilt planting date trial on September 10, 2020 near Park Rapids, MN.

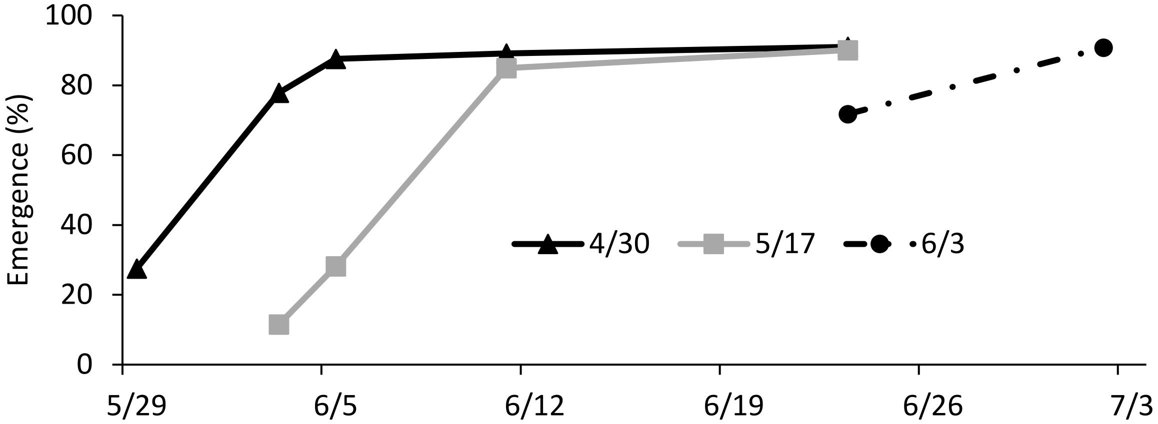

Figure 2. Days to emergence for each planting date. Values represent the means across all three cultivars, and both fumigated and non-fumigated.

Verticillium wilt incidence was very low during the time we were able to evaluate. Increased Verticillium wilt incidence would likely have been recorded had frost damage not limited our ability to rate up until harvest, three additional rating dates (weeks). The application of metam sodium did not significantly affect Verticillium wilt incidence. This is likely due to the low levels of disease observed over the shortened evaluation period. However, based on data from the final rating date, there were significant differences by planting date, cultivar and a significant planting date by cultivar interaction was observed. Across all cultivars, no difference in Verticillium wilt was observed between the 4/30 and 5/17 planting dates, but planting on 6/3 resulted in significantly lower disease incidence (data not shown). As expected, susceptible cv. Russet Burbank had significantly higher incidence of Verticillium wilt than did moderately susceptible Umatilla Russet and resistant Alturas (Fig. 4). When evaluating the cultivar by planting date data, only Russet Burbank at the 4/30 and 5/17 planting dates had higher Verticillium wilt incidence than other treatments.

Figure 3. Left-hand image - planting date 5/17 (left 4 rows) and 4/30 (right 4 rows). Right-hand image – planting date 5/17 (left 4 rows) and 6/3 (right 4 rows). Photos taken by Dean Peterson on 6/18.

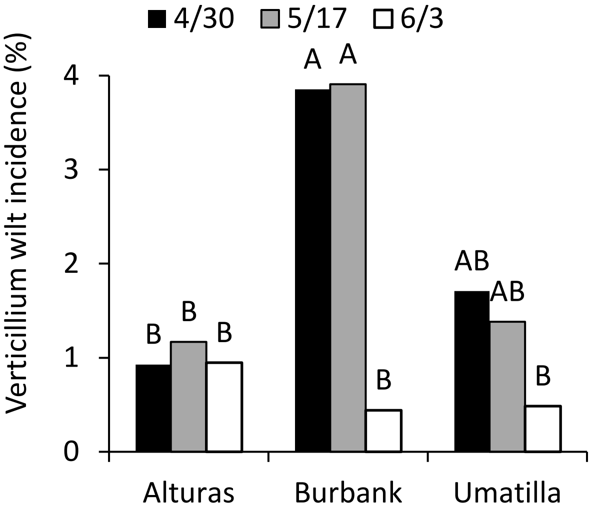

Figure 4. Verticillium wilt incidence (%) for each cultivar. Values represent the means across fumigated and non-fumigated. Within planting date, bars with the same letters are not significantly different.

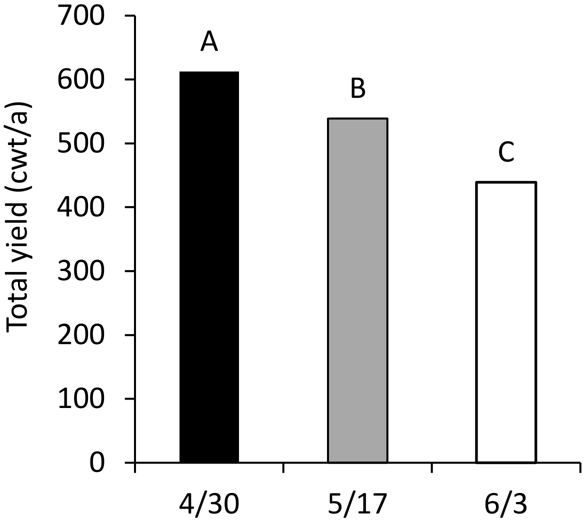

Figure 5. Total yield at each planting date. Means are calculated across cultivars and metam sodium fumigation. Bars with the same letters are not significantly different.

The delay in emergence resulted in significant differences in total yield across the three planting dates (Fig. 5). Even though no difference was observed in Verticillium wilt incidence, yields for fumigated treatments where metam sodium was applied were significantly higher than for those with no fumigation. However, there was also a significant interaction between cultivar and metam sodium treatment, meaning that yield in all three cultivars was differentially affected by metam sodium application (Table 2). Specifically, susceptible cv. Russet Burbank was the only cultivar in which a significant increase in total yield was observed from the application of metam sodium. This follows logic as Russet Burbank was the only susceptible cultivar evaluated. A reminder and note of caution, Verticillium wilt pressure was very low in these plots. We might expect to see the application of metam sodium result in differences where Verticillium pressure is higher.

A USDA grade was conducted on tubers harvested from all plots in this trial. Market yield was calculated by subtracting the weight of 'unusable' tubers (<4 oz and those with major defects) from the total yield. Analysis of market yield indicates that there was a significant interaction between cultivar and metam sodium treatment (Table 2). Similar to what was observed with total yield, the application of metam sodium significantly increased market yield only in Russet Burbank. A cultivar by planting date interaction was also observed for market yield. In both Russet Burbank and Umatilla Russet, market yield was greater with the first planting date when compared to the second and third (Table 3). In Alturas Russet, there was no difference between the first and second planting dates. This planting date by cultivar interaction was also observed for tubers in three size categories as well as unusable tubers. For the largest tuber class (>10 oz) the trend followed that of total and market yield where Russet Burbank and Umatilla Russet were more adversely affected by planting date than was Alturas Russet. This trend also held somewhat true for the other size classes. Interestingly, the application of metam sodium increased the percentage of the largest (>10 oz) tubers and decreased the percentage of the smallest (<4 oz) category across all cultivars and planting dates (Fig. 6).

Complete in-season and post-harvest grade results and processor economic analysis are included at the end of the report (Table 4). Verticillium stem colonization results are forthcoming.

Table 2. Total and market yield results averaged across planting dates, where a significant cultivar by metam sodium application interaction was observed. Values within columns with the same letter are not significantly different.

Cultivar	Fumigation	Total yield (cwt/a)		Market yield (cwt/a)	
Burbank	Yes	568.7	A	428.7	A
Burbank	No	509.6	B	347.9	BC
Alturas	Yes	534.7	AB	304.5	C
Alturas	No	520.9	B	312.4	C
Umatilla	Yes	534.0	AB	362.3	B
Umatilla	No	513.5	B	320.0	BC

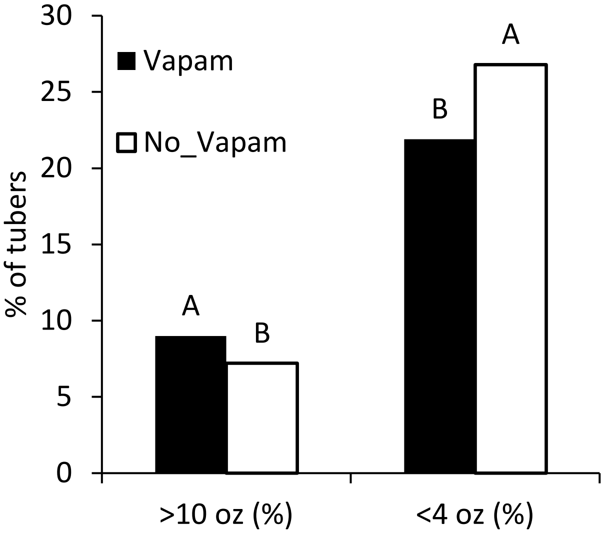

Figure 6. Percentage tubers in USDA grade categories >10 oz. and <4 oz. Means are calculated across all three cultivars and planting dates. Within size category, bars with the same letters are not significantly different.

Table 3. Market yield and grade results across fumigated and non-fumigated, where a significant cultivar by planting date interaction was observed. Values within columns and cultivar with the same letter are not significantly different.

Cultivar	Planting date	Market yield (cwt/a)		>10 oz (%)		6-9 oz (%)		4-6 oz. (%)		Unusable total (%)	
Burbank	4/30	460.8	A	11.6	A	32.4	A	30.6	B	24.5	B
Burbank	5/17	365.8	B	7.9	B	27.4	B	33.1	AB	31.9	A
Burbank	6/3	338.3	B	7.0	B	29.9	AB	35.7	A	29.9	A
Alturas	4/30	354.7	A	10.9	A	26.1	A	22.2	B	40.5	A
Alturas	5/17	350.7	A	10.0	AB	28.2	A	27.9	A	33.1	B
Alturas	6/3	220.0	B	7.6	B	26.6	A	23.5	B	46.2	A
Umatilla	4/30	422.5	A	9.4	A	27.8	A	34.4	A	28.0	B
Umatilla	5/17	295.4	B	7.4	B	19.1	B	34.3	A	41.8	A
Umatilla	6/3	305.7	B	3.8	B	26.5	A	34.6	A	30.1	B

Unusable – tubers less than 4 oz and with major defects including hollow heart.

Preliminary Conclusions

These results are preliminary, from just one year of evaluation; however, we feel that this study provided us with some interesting pieces of information to build on. Results of this trial illustrate the risks of delaying planting date. However, they also suggest that Verticillium wilt is reduced at later planting dates. In additional to total yield, we also observed some adverse trends in tuber size profiles across planting dates, particularly with Russet Burbank and Umatilla Russet. Even with the low Verticillium wilt pressure observed in this trial (again, this likely increased beyond our ability to distinguish it from frost damage), the application of metam sodium significantly increased total and market yield in susceptible cv. Russet Burbank. The percent tubers greater than 10 oz increased, and the percent tubers less than 4 oz decreased significantly across cultivars and planting dates with fumigation.

In the trial results reported here, we understand that the reductions in yield are not a good trade-off for the Verticillium reductions. However, given these results, for the 2021 trial we feel it is appropriate to move planting dates earlier to determine if there is a point at which these two factors, yield and Verticillium wilt, may balance and where that balance lies for susceptible, moderately susceptible and resistant cultivars under higher disease pressure. The location already has been selected for this trial in 2021 and will allow for an earlier start to planting. In 2021, we propose the first planting date between April 15 and 20, followed by the second and third dates 14- and 28-days following, with planting concluded by the end of May. Quantification of the colonization of stems by *V. dahliae* will be completed in the coming weeks. These data will provide a clearer picture of the effect planting date has on stem colonization and the subsequent return of inoculum to the soil.

Acknowledgments

An enormous thank you goes out to Dean Peterson, Russell Benz, Kal Larson, Binod Pandey, Rachel Selstedt, Fereshteh Shahoveisi 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, the Northern Plains Potato Growers Association and Cavendish Farms.

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Table 4. Yield, USDA grade and processor evaluation results for the trial conducted in 2020 evaluating the effect of planting date, cultivar and fumigation on the effects of Verticillium wilt caused by *V. dahliae*.

Cultivar		Plantin g Date	Treatment	Total Yield (cwt/a)	Market Yield (cwt/a)	10 oz. & over (%)			6 - 9 oz. (%)			>6 oz. (%)	4 - 6 oz (%)			Unusables (%)				Specific Gravity	Contract ($/cwt)	Gross return/acre ($)
						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	30-Apr	Vapam	657.7	507.5	11.5	2.1	13.6	31.2	2.1	33.3	46.9	28.4	2.2	30.5	22.6	15.5	3.0	4.1	1.085	$9.28	$4,709.65
502	Umatilla Russet	30-Apr	Vapam	630.7	465.9	10.6	0.5	11.1	30.5	0.4	30.9	42.0	31.6	0.4	31.9	26.1	24.8	0.4	1.0	1.093	$8.99	$4,187.16
503	Alturas Russet	30-Apr	Vapam	607.4	377.0	13.0	1.2	14.2	24.4	3.4	27.8	42.1	19.1	0.8	20.0	37.9	14.0	2.0	22.0	1.084	$9.01	$3,195.71
504	Russet Burbank	17-May	Vapam	577.3	411.2	8.5	0.0	8.5	28.5	0.6	29.1	37.6	33.5	0.3	33.8	28.7	24.8	1.5	2.4	1.084	$9.09	$3,736.98
505	Umatilla Russet	17-May	Vapam	525.7	301.0	3.3	0.0	3.3	19.9	0.3	20.2	23.5	32.8	0.7	33.5	43.0	38.2	0.0	4.9	1.092	$9.03	$2,718.21
506	Alturas Russet	17-May	Vapam	559.8	353.3	8.4	2.5	10.9	24.1	3.6	27.7	38.6	23.1	1.8	24.9	36.6	12.9	1.3	22.4	1.086	$9.06	$2,906.90
507	Russet Burbank	3-Jun	Vapam	474.2	367.3	8.9	0.2	9.1	29.9	0.4	30.3	39.4	37.3	0.6	37.9	22.7	20.4	1.8	0.5	1.086	$9.21	$3,385.81
508	Umatilla Russet	3-Jun	Vapam	445.5	319.9	7.0	2.0	8.9	26.1	1.7	27.8	36.7	34.4	0.9	35.3	28.1	22.8	0.1	5.2	1.088	$9.17	$2,932.69
509	Alturas Russet	3-Jun	Vapam	436.0	237.9	5.7	2.3	8.0	17.0	7.2	24.2	32.1	16.1	6.1	22.2	45.6	28.8	0.0	16.8	1.089	$9.11	$2,166.44
510	Russet Burbank	30-Apr	No Vapam	573.5	414.1	9.0	0.8	9.8	29.6	2.1	31.7	41.5	29.7	1.1	30.7	27.8	23.6	1.8	2.4	1.081	$8.94	$3,702.21
511	Umatilla Russet	30-Apr	No Vapam	589.5	413.0	8.3	0.5	8.8	24.0	0.7	24.7	33.5	36.0	0.7	36.7	29.9	27.7	0.6	1.5	1.094	$8.88	$3,363.67
512	Alturas Russet	30-Apr	No Vapam	614.5	354.8	7.5	1.8	9.3	22.9	3.0	25.9	35.2	20.9	1.6	22.6	42.3	21.4	2.9	18.0	1.084	$8.98	$3,186.39
513	Russet Burbank	17-May	No Vapam	524.5	329.3	5.0	0.9	5.9	23.7	2.1	25.8	31.7	29.9	1.4	31.3	37.1	33.3	2.1	1.6	1.083	$8.95	$2,864.89
514	Umatilla Russet	17-May	No Vapam	500.9	289.8	4.1	0.3	4.4	17.7	0.5	18.2	22.6	34.5	0.7	35.2	42.2	40.7	0.4	1.1	1.094	$8.91	$2,583.67
515	Alturas Russet	17-May	No Vapam	549.2	380.3	7.7	1.8	9.5	27.4	2.8	30.2	39.7	27.5	2.3	29.8	30.6	18.2	2.4	10.1	1.081	$8.99	$3,417.60
516	Russet Burbank	3-Jun	No Vapam	433.3	309.4	6.1	0.8	6.9	29.8	1.2	31.0	37.9	33.4	0.2	33.6	28.6	23.6	4.3	0.7	1.084	$8.93	$2,766.08
517	Umatilla Russet	3-Jun	No Vapam	450.0	291.4	5.6	0.6	6.2	24.7	0.7	25.4	31.6	32.7	1.3	34.0	34.4	30.6	1.1	2.7	1.095	$8.88	$2,588.62
518	Alturas Russet	3-Jun	No Vapam	393.3	220.9	7.5	0.2	7.6	22.3	1.3	23.6	31.2	24.9	0.2	25.2	43.6	30.5	5.5	7.6	1.084	$8.88	$1,802.99

Note - This trial suffered frost damage on the following dates:

September 8; 32F, slight to moderate frost damage observed (25 - 40% foliar damage)

September 9; 29F, moderate frost damage observed (40 - 50% foliar damage)

September 18; 32F, moderate frost damage observed (40 - 50% foliar damage)

Temperature was measured at Park Rapids airport, 2.25 miles away.

Processor evaluation based only on the grade categories displayed here, sugar end and fry color were not evaluated.

Report Title: 2020 Support of Irrigated Potato Research for North Dakota and Minnesota

Submitted to NPPGA & MN Area II

Principle Investigator: Julie S. Pasche, Department of Plant Pathology, North Dakota State University, Fargo, ND 58102. Julie.Pasche@NDSU.edu
Co-Principle Investigator: Gary A. Secor

Executive Summary: North Dakota State University has conducted irrigated potato research for over 30 years. Over that time, growers have become accustomed to the wealth of information generated in the areas of cultivar development, general management practices like vinekill, herbicide efficacy and damage, nutrient management, physiological defects like 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 resistance to QoI and SDHI fungicides in the early blight and brown spot pathogens in the region. We also have evaluated foliar and seed treatment fungicides in a program approach specific for the pathogens and environmental conditions in this region and conducted demonstration plots for the growers, among other things. Again, allowing us to make timely and relevant grower recommendations. Without the Inkster site, 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 likely benefitted from the work conducted in 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 production. In addition, the pressure of potato diseases, insect and weed pests, cultivar selection and use of fertilizer all differ significantly in 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 much as possible the grower experience.

The funding for the management of the Inkster irrigated research site facilitates the use of the site by all NDSU 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 also 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 and has been able to secure Vapam donations from AmVac for both the NPPGA and Hoverson to offset all expenses associated with this fumigation.

This saves the NPPGA approximately $7,500 annually. The Inkster plot coordinator also plants all cover crops and assists in planning the annual field day, in a typical year.

The total cost of managing irrigated potato research in 2020 at the NPPGA research site near Inkster, ND was approximately $63,000. We continue to make a concerted effort to re-evaluate all operations and to increase efficiencies in management of the Inkster research site. Increased costs were associated with chemicals to control pests such as disease, insects and weeds. These are typically donated, but some had to be purchased in 2020. The management team logged 56,706 vehicle miles to and from the Inkster site, 22,705 more than 2019. This increase in mileage was due to covid standards requiring only one person/vehicle and it resulted in a more than $7,000 increase in travel expense just for general management of the site. The cancelation of field days saved some management expenses (~$800) over a typical year. But as always, the crew kept the site immaculate (see images below). We look forward to working with growers and researchers in the future to tackle existing and emerging challenges faced by the industry.

Late Blight Spore Trapping Network for Minnesota

Investigators contact:

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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 2020, 40-spore traps were setup in North Dakota and Minnesota potato fields region starting the last week in June to the end of August. There were nine positives found for late blight between June 29 and August 16, 2020. This coincided with favorable weater conditions for late blight at many times throughout the growing season. Although this sentinel monitoring system is costly to operate, early detection of late blight spores can save millions of dollars in potato losses by allowing growers to adjust fungicide management plans.

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. The focus of this project is to provide real-time data on late blight spores and not just rely on a predictive weather model. Potato growing regions in Ontario, Canada and Idaho have setup similar spore trapping networks to provide early detection of late blight spores.

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 Battle Lake, Becker (2 traps), Clearlake, Gonvick, Hubbard (3 traps), Lake Bronson, Little Falls, Long Lake, Menahga, Osage, Ottertail, Park Rapids, Perham, Perham North, Pondsford, Rice, Sebeka, Staples (3 traps), Verndale, and Wadena, MN and in Cavalier, Dawson, Hoople (2 traps), Inkster, Karlsrue, Larimore, Lisbon, McCanna, Oakes, Pettibone and Tappen, ND and Kearny (2 traps), NE (Figures 1-10). On a weekly basis, starting between June 29 and July 13, cassettes were placed in the spore traps. There were some delays in getting trapping materials because of Covid-19. 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 August 30, 2020. After data was collected, ArcGIS maps were made and sent to growers by email and put on the NDSU/UMN Potato Extension webpage to let them know all reporting traps and findings. A newsletter was created, call ‘Spud Scoop’ to put all the week data for potato growers into one update. The Spud Scoop 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. Late blight DNA was found at Osage and Sebeka MN on the week ending July 5; at Lisbon, ND on the week ending on July 19; at Lake Bronson, MN on the week ending July 26; at Perham, MN and Oakes, ND on the week ending August 2; and at Little Falls, MN, Rice, MN and Cavalier, ND on the week ending August 16.

Because of this project with cooperating growers, we were able to identify late blight spore DNA allowing improved management. Thank you to all the grower who participated in this project and for the funding and support to make this happen.

What was learned? Some issues with shipping occurred in 2020 because of new rules at the USPS not allowing the shipment of envelopes greater than 0.5 inches wide to be shipped by placing letters in the mailbox. Rather, packages needed to be mailed from a post office. We will work to improve this next year. We will work on finding a location that could provide positive late blight samples as a running check.

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, Syngenta, Sipcam, Bayer Crop Science, BASF, UPL USA, Corteva, and Nufarm for supporting this effort.

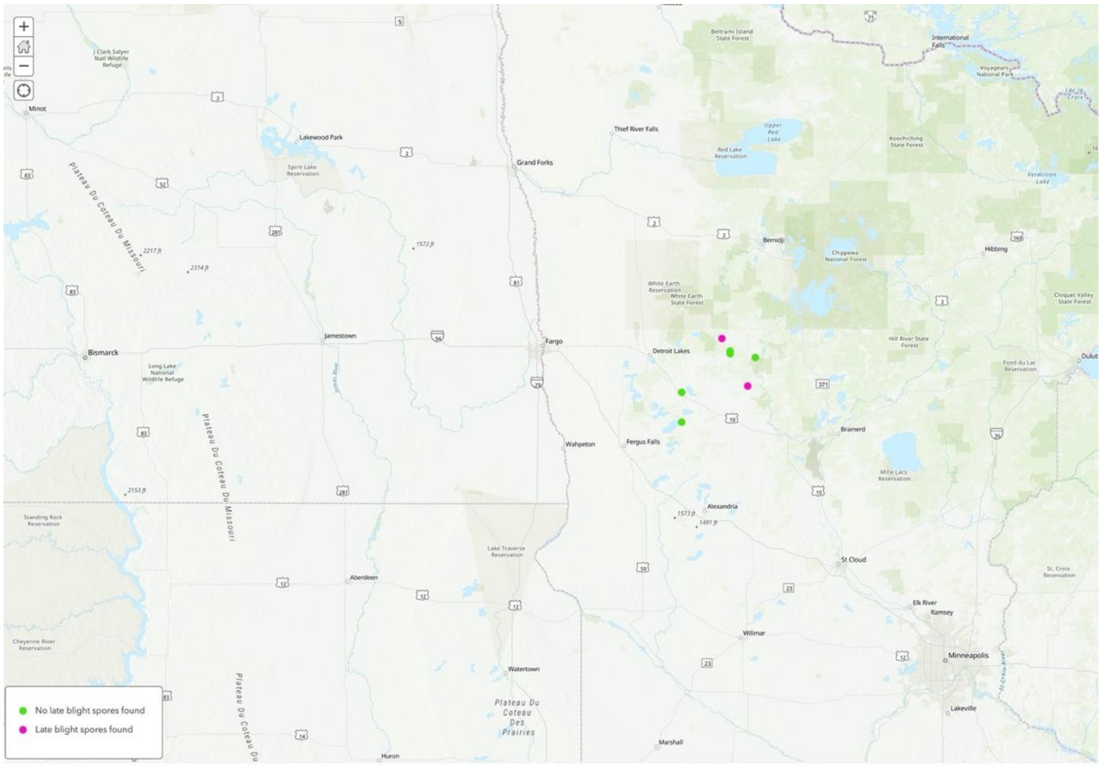

Figure 1. Results of late blight spore traps during the week of June 29 to July 6, 2020.

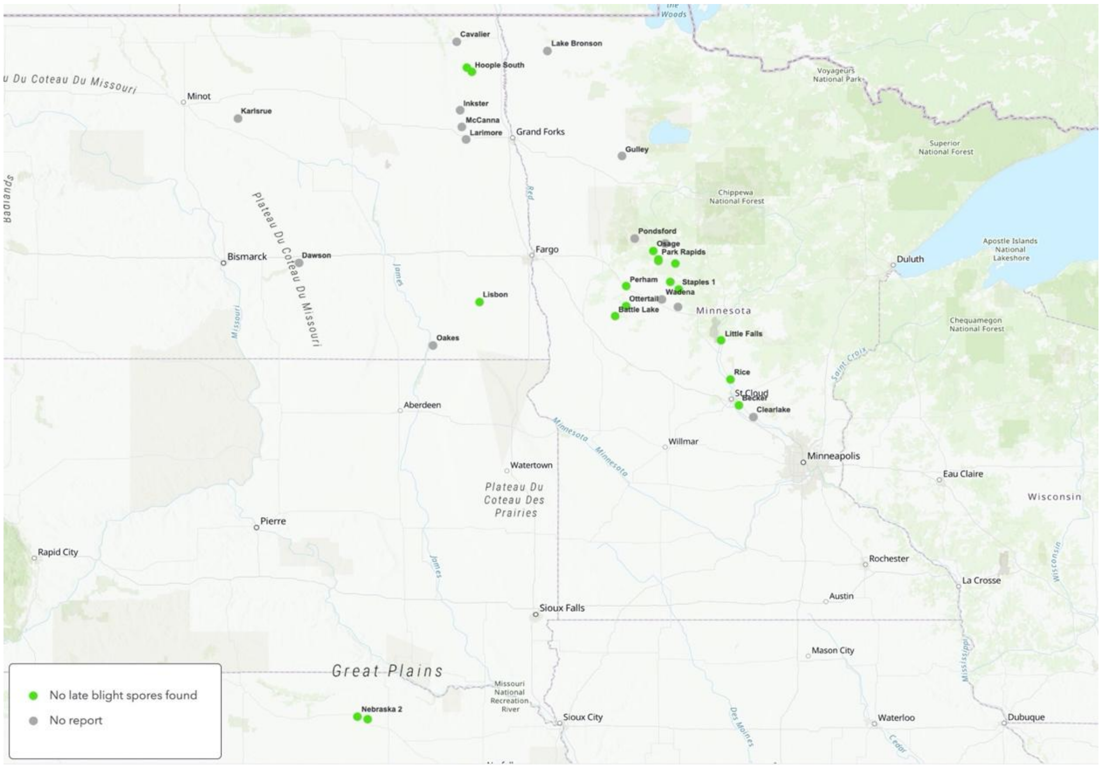

Figure 2. Results of late blight spore traps during the week of June 29 to July 6, 2020.

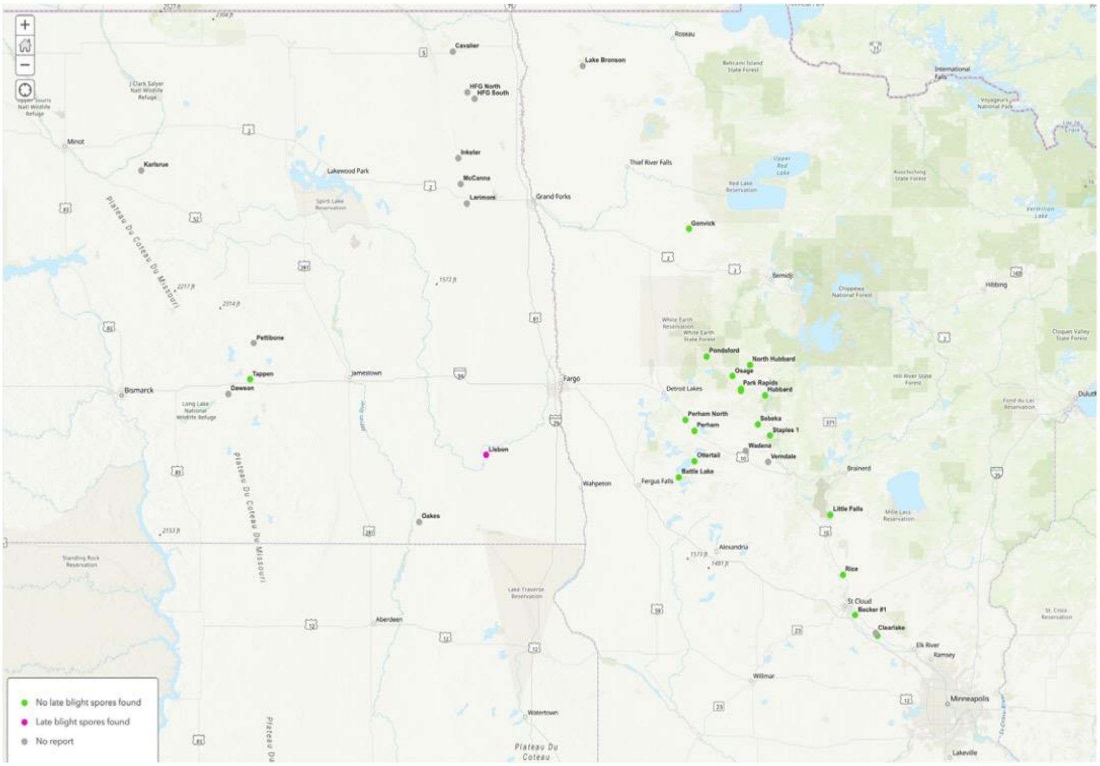

Figure 3. Results of the late blight spore traps from the week of July 6 to 13, 2020.

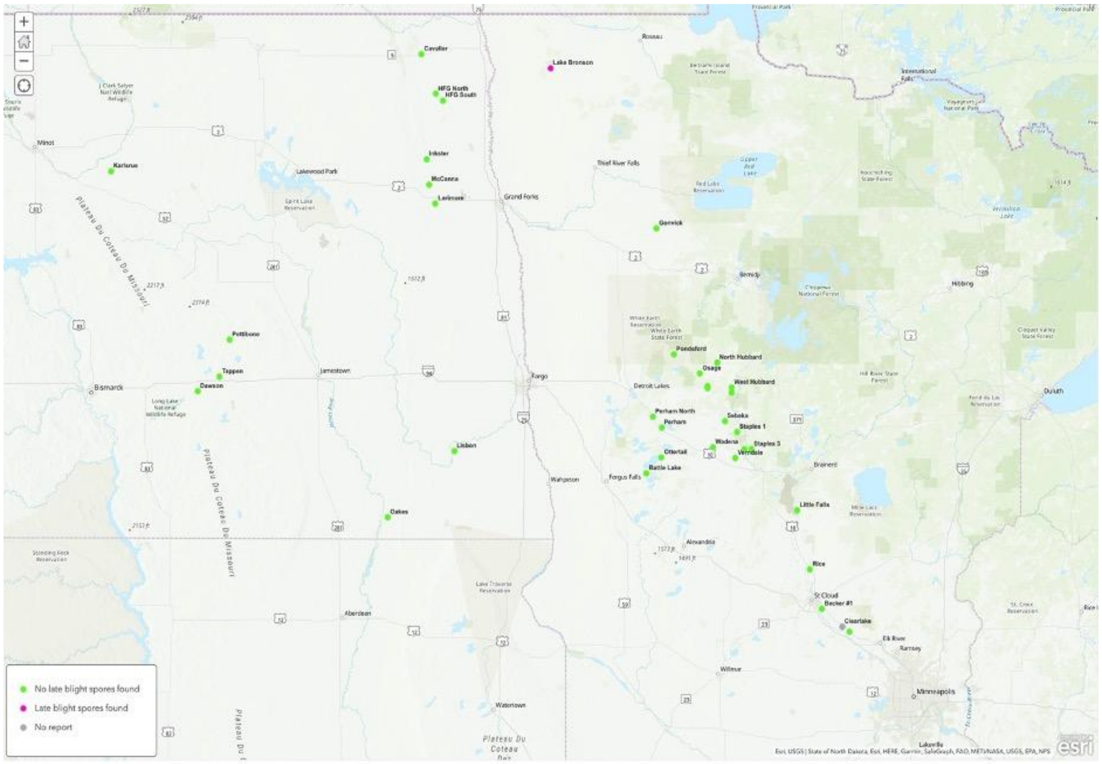

Figure 4. Results of late blight spore traps during the week of July 20 to 27, 2020.

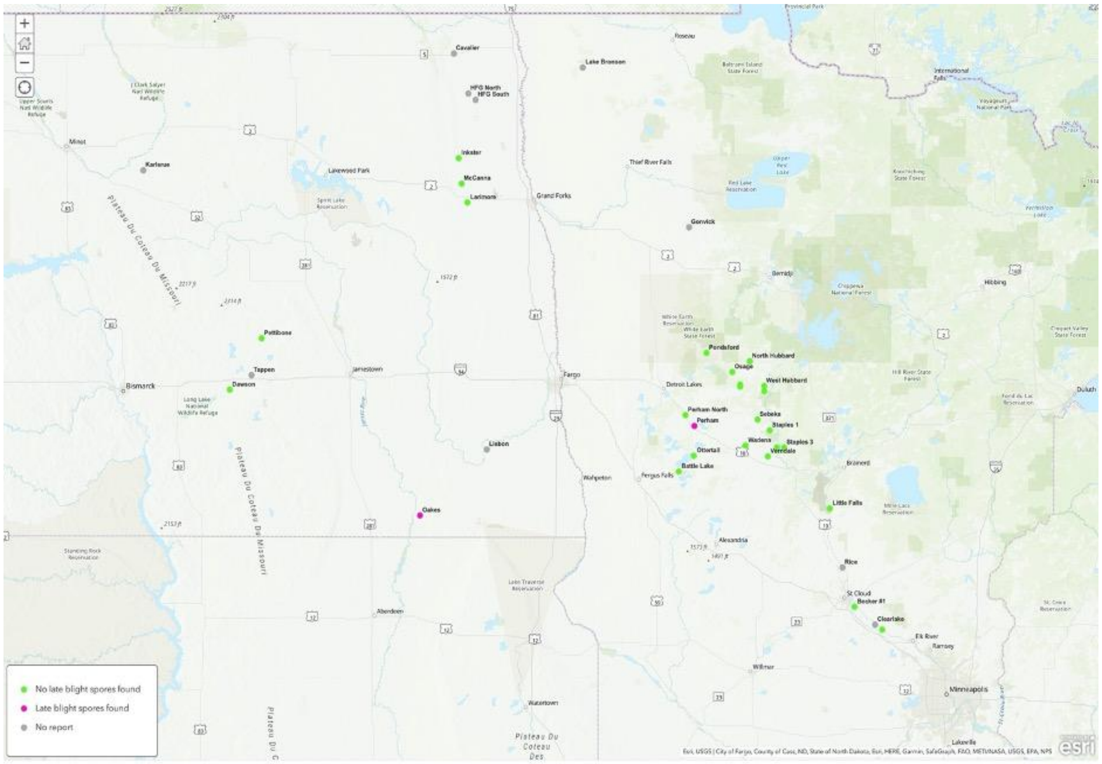

Figure 5. Results of late blight spore traps during the week of July 27 to August 3, 2020.

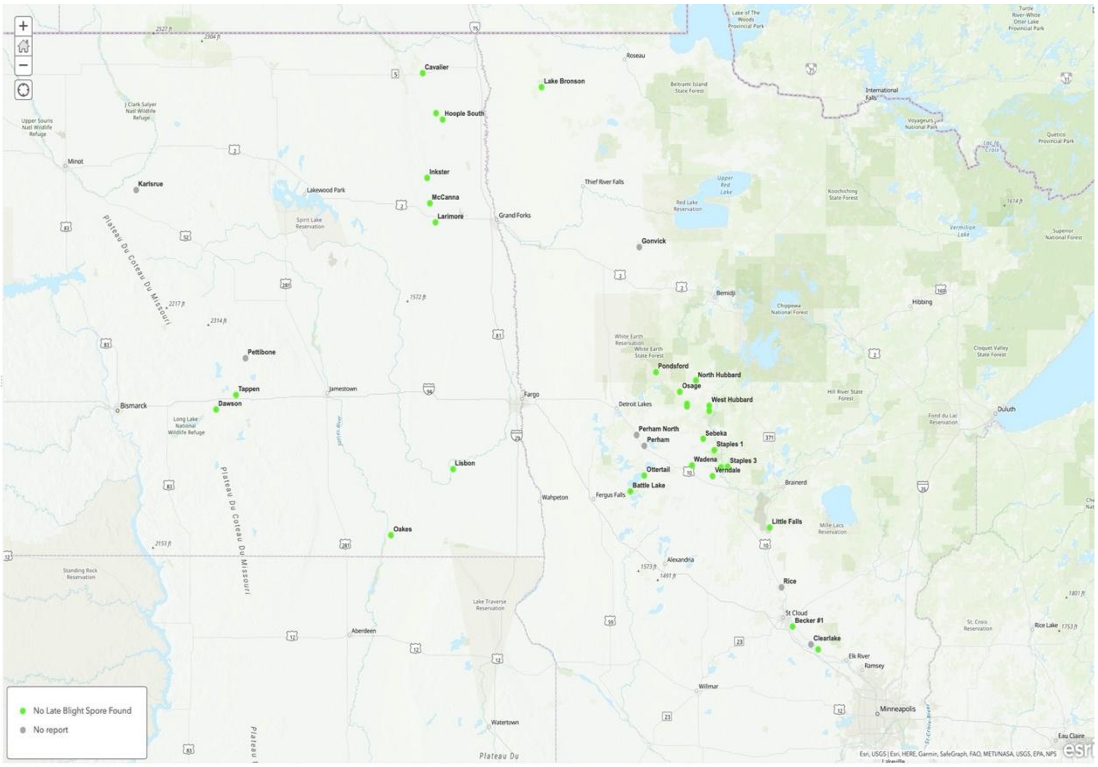

Figure 6. Results of late blight spore traps during the week of August 3 to 10, 2020.

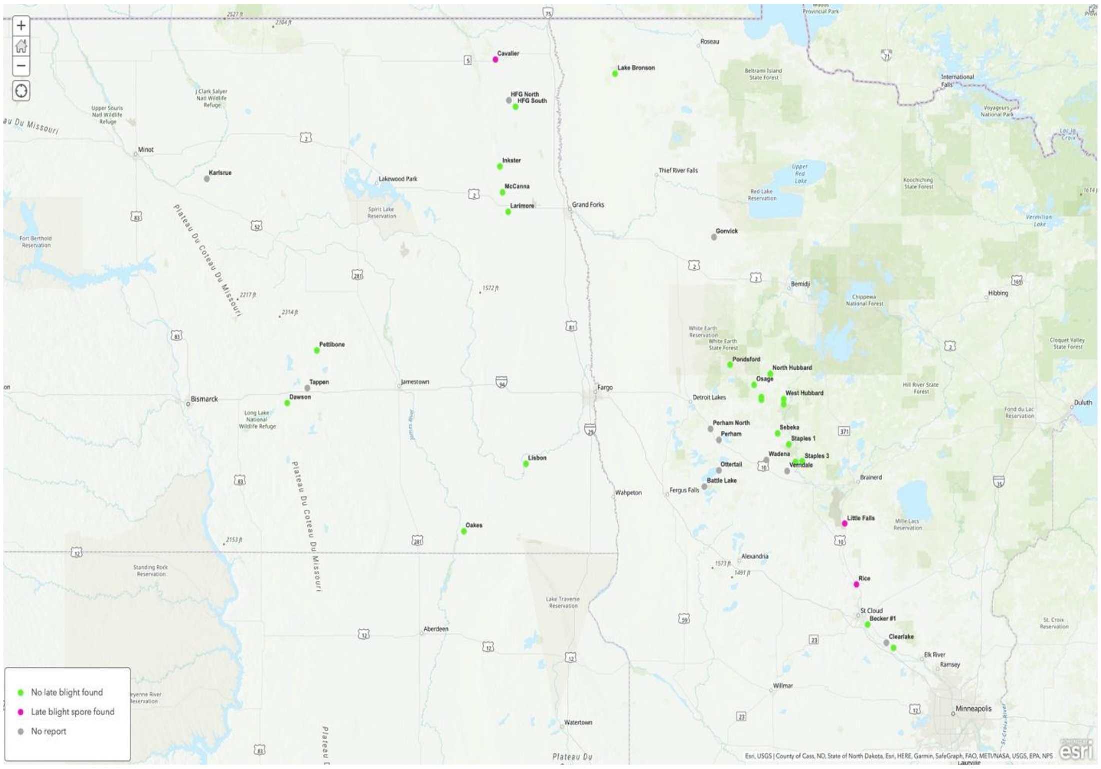

Figure 7. Results of late blight spore traps during the week of August 10 to 17, 2020.

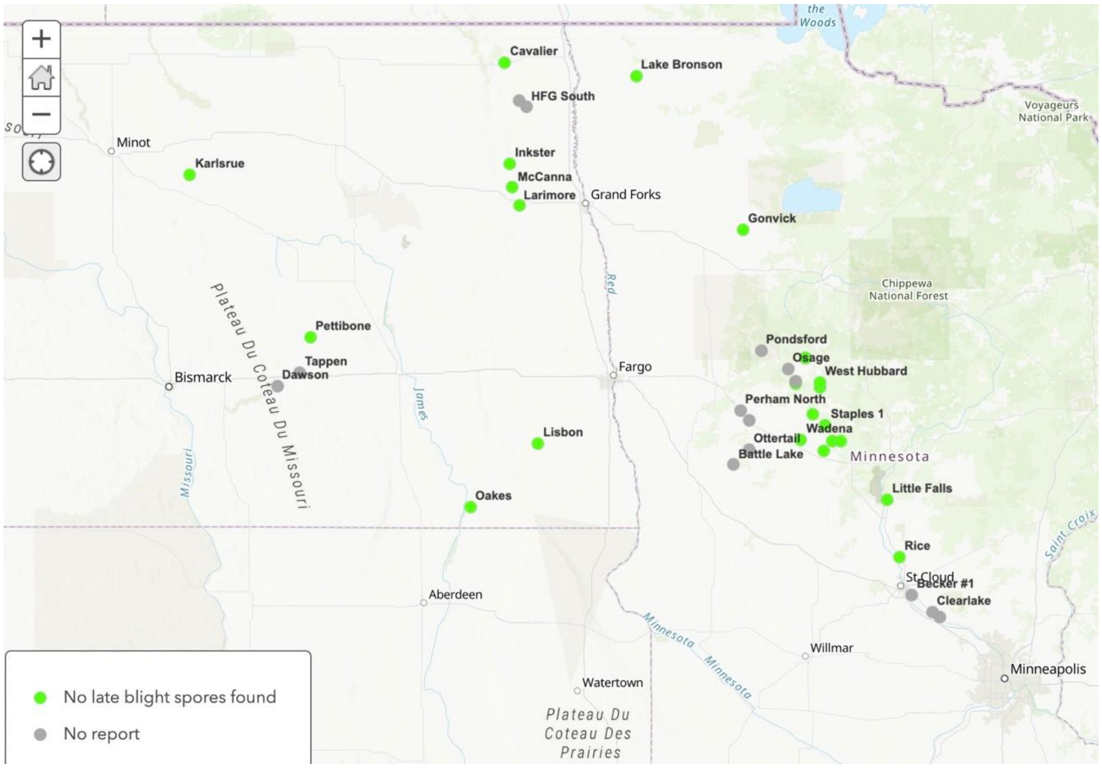

Figure 8. Results of late blight spore traps during the week of August 17 to 23, 2020.

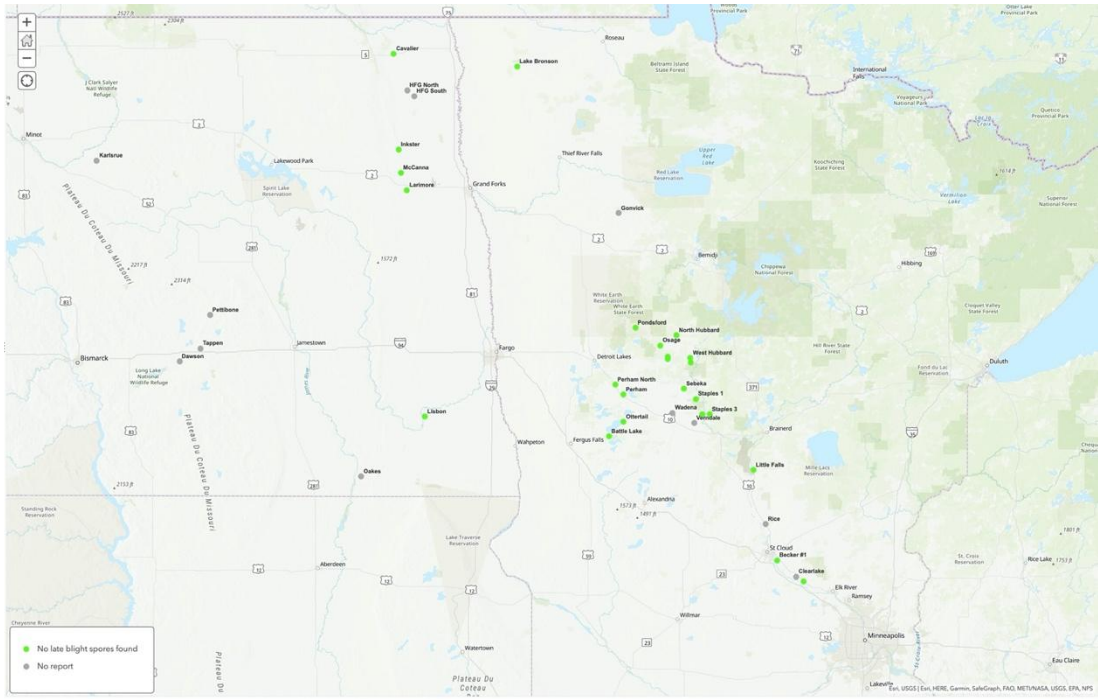

Figure 9. Results of late blight spore traps during the week of August 24-30, 2020.

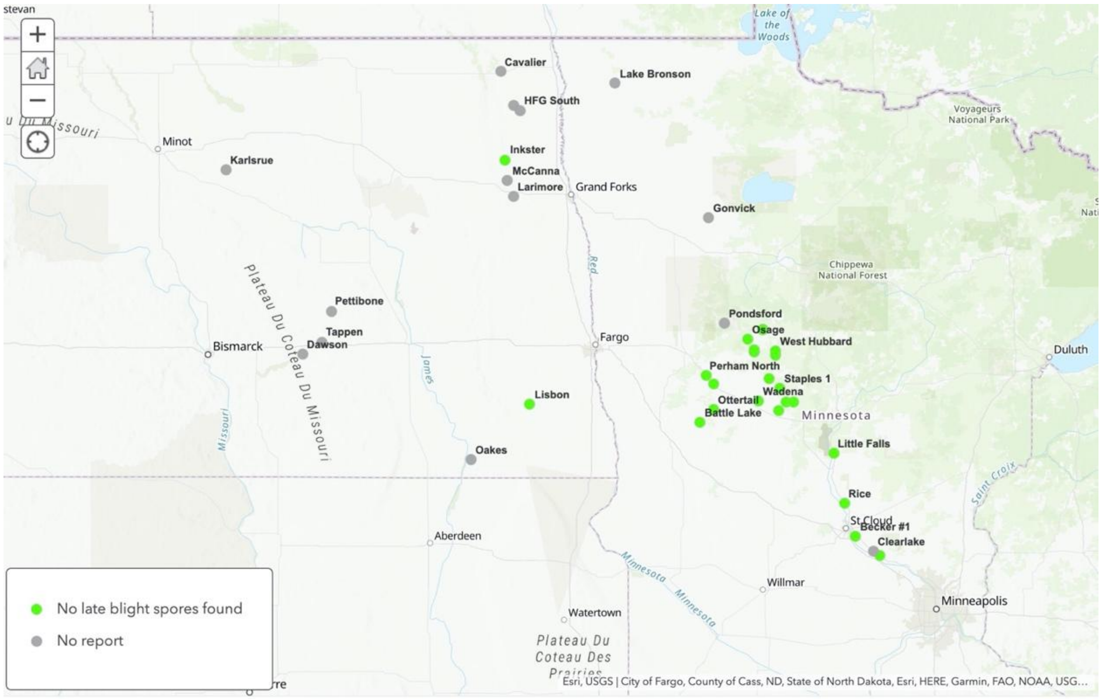

Figure 10. Results of late blight spore traps during the week of August 31-September 6, 2020.

Measuring Nitrogen Uptake in Russet Burbank

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Executive summary

Nitrogen is a highly studied nutrient because of the major effects it has in plant growth. In the United Kingdom research has found that whole plant sampling at around 50 days after emergence can give a good estimate of yield potential. It is unknown if this same model will work in the United States, but if it were to work this could eliminate the necessity of constant petiole samples or other sampling. Our objectives are to evaluate the effects of ESN, Urea and Turkey Manure to (1) determine plant uptake through the season, (2) describe differences throughout the season between soil, petiole, foliage and tuber samples, (3) define differences in tuber yield and quality.

Rationale for conducting the research

Nitrogen is stored throughout the plant and accessed when needed. Plant parts have various N concentration; for example, in leaves, the level of N can vary between 2.5% (deficient) and 7% (ample). Primarily, for monitoring the status of nutrient, the fourth leaf from the top of the potato plant is used (Stark and Westermann, 2003). In stems, this value can be from 0.5% to 6% and for tubers, between 0.5% to 3.5% (Young et al., 1993).

According to Millard and Marshall (1986), the N content of the canopy reached a maximum at around 50 days after emergence. By this time, fertilizer application had greatly increased N uptake in the foliage, but after this time leaf and stem N concentration decreased. The initiation of rapid tuber bulking after emergence (approximately 40 days), the subsequent demand for N was created. In this stage, while tuber N uptake can be 3 to 4 g N/m^2, it is 4 to 5-fold more at the end of the maturation. Uptake of N throughout the potato growing stages is essential for high-quality tubers and yield.

Our objectives are to evaluate the effects of ESN, Urea and Turkey Manure to (1) determine plant uptake through the season, (2) describe differences throughout the season between soil, petiole, foliage and tuber samples, (3) define differences in tuber yield and quality.

Procedures

A field study was conducted near Perham, MN in a commercial potato field. Russet Burbank was planted on April 29, 2020. A randomized complete block with a split-plot design and four replications was utilized. Treatments were five N sources or placements. Treatments included a non-treated check (soil test N), ESN broadcast at hilling to 265 lb N/a (grower standard practice), ESN banded at hilling 265 lb N/a, urea broadcast at hilling 265 lb N/a and turkey compost broadcast at 6.1 Mg ha^{-1} and incorporated prior to planting. Split-plots were sampling every two weeks on June 11, June 24, July 10, July 23, August 5, August 17 and August 31. Whole plant, petiole and soil samples were taken from split-plots on the previously states dates. Plots were harvested on September 8, 2020 with a single row plot harvester. After harvest tubers were graded and separated into <3, 3-6, 6-10, 10-14, and >14oz. Total yield was the summation of all tubers weighted and calculated to cwt/a. Marketable yield indicates those tubers that were >3 oz and would be saleable. Specific gravity was measured after grading potato tubers. Data were analyzed with a Tukey pair-wise comparison with a p-value of 0.05.

Results and Discussion

The 2020 growing season was interesting, in that there were no differences between treatments (Table 1). Numerical differences can be seen, but what was most surprising was the non-treated check had similar yield to the treated plots. Data from 2019 showed clearer differences between treatments, but it is unknown exactly why yield was similar in 2020. Petiole, soil, above ground whole plant, and tuber nitrogen (Figures 1-4) data also had no differences between treatments in 2020. Further work on this project is important to continue determine the value of turkey compost for potato fertility.

Table 1. Graded yield of Russet Burbank potato tubers grown near Perham, MN in 2020 with various nitrogen treatments.

Treatment	<3 oz	3-6 oz	6-10 oz	10-14 oz	>14 oz	Total yield	Marketable yield	>6 oz	>10 oz	Specific gravity
	— cwt/a						—	— % —		
Non-treated	53	228	150	39	23	493	440	43	13	1.076
ESN broadcast	37	180	209	90	39	556	519	61	23	1.080
ESN banded	44	169	181	86	13	495	451	56	20	1.075
Urea broadcast	52	192	193	73	17	527	475	54	17	1.077
Turkey compost	51	209	190	41	39	531	479	50	15	1.079

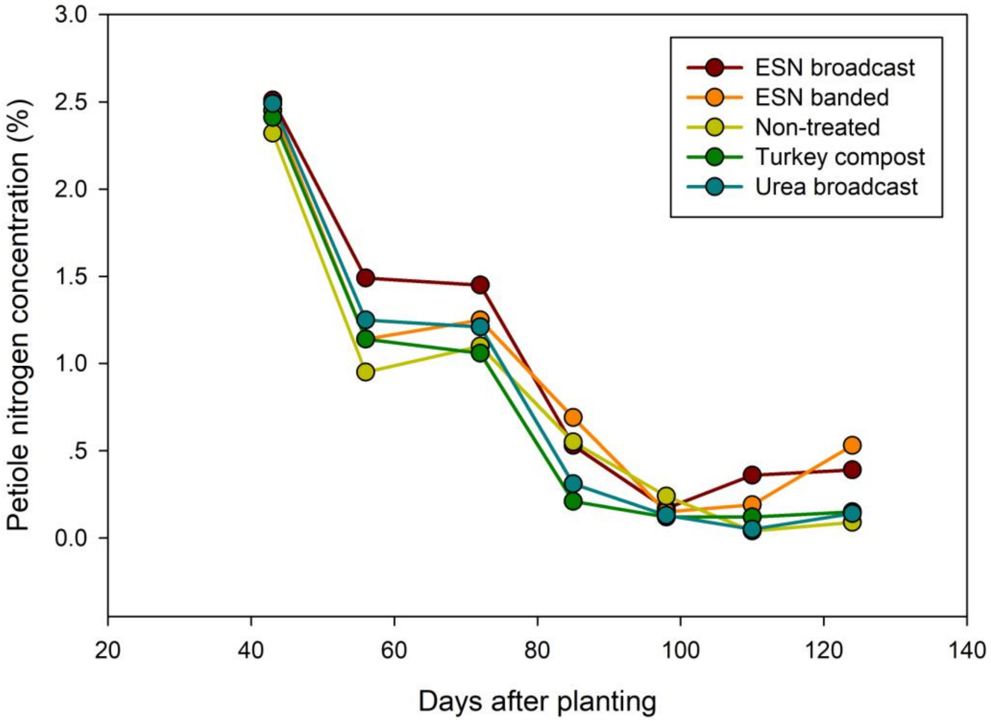

Figure 1. Petiole nitrogen (%) of Russet Burbank potato tubers grown near Perham, MN in 2020 with various nitrogen treatments.

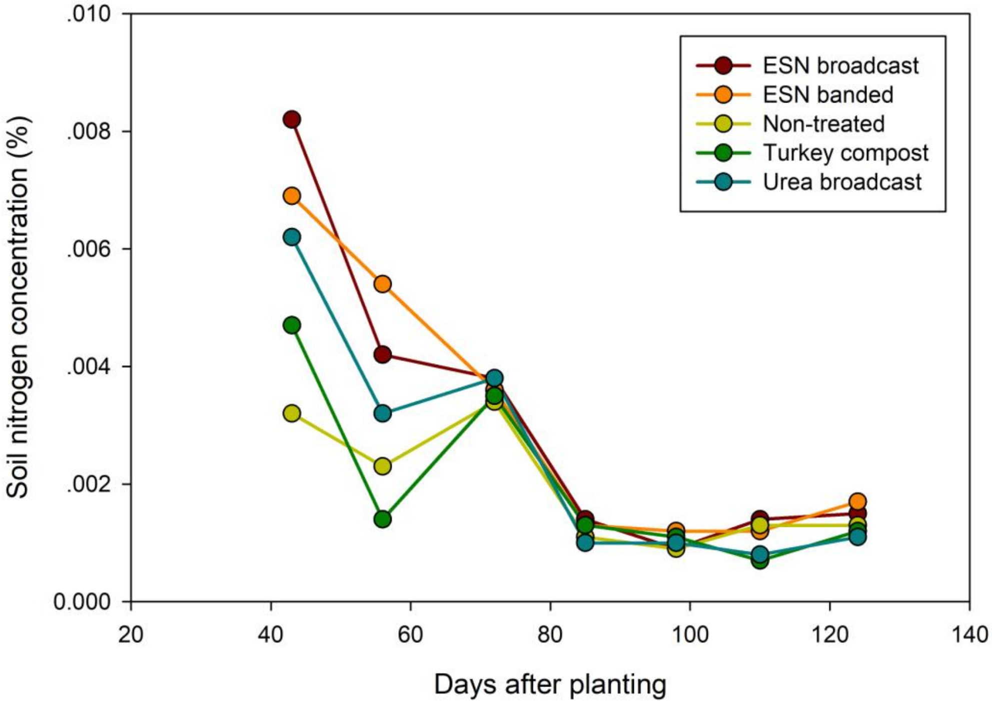

Figure 2. Soil nitrogen (%) of Russet Burbank potato tubers grown near Perham, MN in 2020 with various nitrogen treatments.

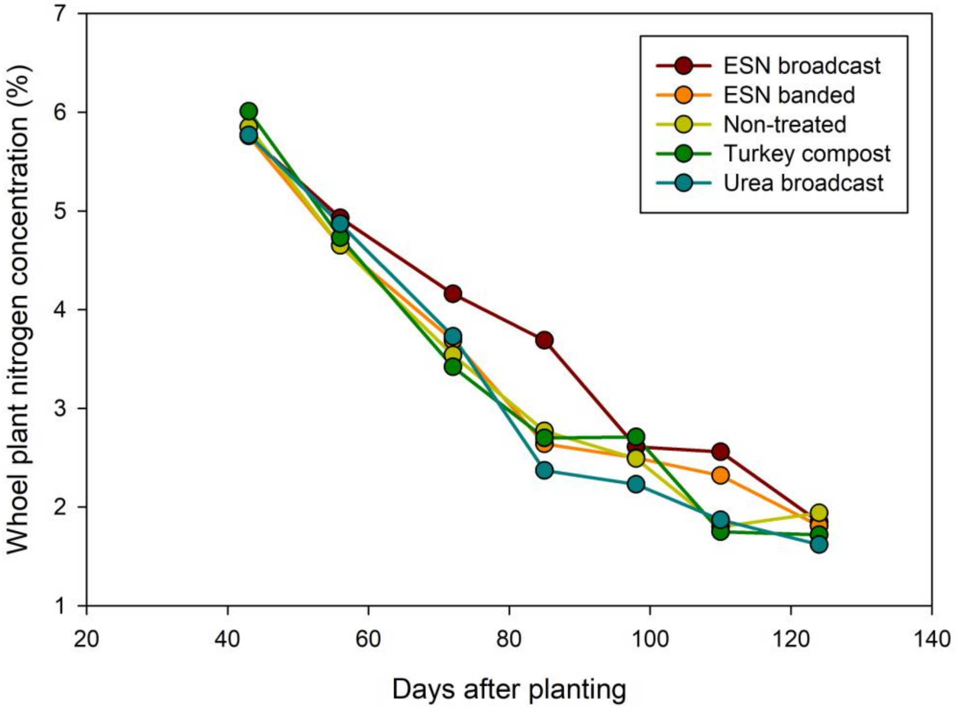

Figure 3. Whole plant (above ground) nitrogen (%) of Russet Burbank potato tubers grown near Perham, MN in 2020 with various nitrogen treatments.

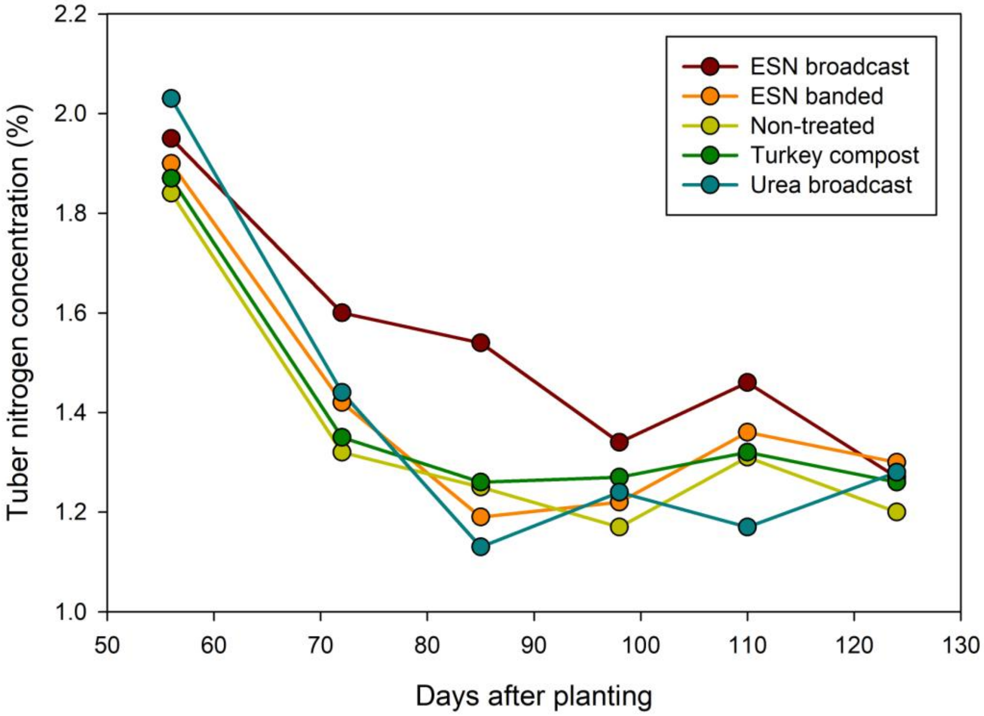

Figure 4. Tuber nitrogen (%) of Russet Burbank potato tubers grown near Perham, MN in 2020 with various nitrogen treatments.

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A1783-20

North Dakota Fresh Market Potato

Cultivar/Selection Trial Results for 2020

photo Robinson, NDSU/UMN

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Potato cultivars or selections included in this report were selected from recently released cultivars, advancing selections with release potential (numbered lines progressing through the trial process), or cultivars that are new to the U.S. Standard potato cultivars used by growers served as checks. For comparison, studies conducted in 2019 evaluated red- and yellow-skinned fresh potatoes *(https://z.umn.edu/Potato2019)*.

NDSU | EXTENSION

North Dakota State University
Fargo, North Dakota

February 2021

In 2020, two trials were conducted to identify traits of red- and yellow-skinned potato cultivars and advanced selections at Hoople, N.D. Nineteen red-skinned cultivars and 30 yellow-skinned cultivars were evaluated. Plots were established in a commercial, nonirrigated potato field utilizing common potato-production practices. The authors acknowledge J.G. Hall and Sons for hosting these trials.

Prior to planting, urea at 120 pounds of nitrogen (N) per acre was broadcast and incorporated. A randomized complete block design with four replicates was utilized. Seed tubers were hand cut to approximately 2-ounce seed pieces prior to planting; an exception was the cultivar Obama, which was planted using whole seed tubers.

Tubers were planted on May 21, 2020, in a single row with 9-inch within-row spacing. Plots were 3 feet wide and 30 feet long.

A majority of the plants emerged by June 12 in both trials. Stand and stem counts on 10 plants in a row in each plot was taken on July 9.

Vine length was measured on three plants from the base of the plant to the vine tip on Aug. 12.

Vigor evaluation was completed on Aug. 12. A rating of 1 indicated least vigor and 5 greatest vigor. Vines were desiccated on Aug. 21 and 28 with diquat. Plots were harvested on Sept. 10 and 11 with a single-row plot harvester.

After harvest, potatoes were stored at 55 F until grading. The tuber size profile distribution was determined by sorting all potatoes harvested into C size (less than 1.875 inches), B size (1.875 to 2.25 inches), A size (2.25 to 3.5 inches) and Chef size (greater than 3.5 inches). Total yield is a summation of C + B + A + Chef.

The agronomic data presented in **Tables 1 and 2** were analyzed statistically. These analyses allow the reader to ascertain, at a predetermined level of confidence, if the differences observed among cultivars/selections are reliable or if they might be due to error inherent in the experimental process.

The LSD (least significant difference) values beneath the columns apply only to the numbers in the column in which they appear. If the difference between two cultivars/selections exceeds the LSD value at 0.05 or 0.10, it means that with 95% or 90% confidence, respectively, the higher-yielding cultivar/selection has a significant yield advantage. When the difference between two cultivars/selections is less than the LSD value, no significant difference was found between the two under these growing conditions.

The CV stands for coefficient of variation and is expressed as a percentage. The CV is a measure of variability in the trial. Large CVs mean a large amount of variation that could not be attributed to differences in the cultivars/selections.

The data provided does not indicate endorsement or approval by the authors, or NDSU Extension or University of Minnesota Extension. Reproduction of the tables is permissible if presented with all the same information found in this publication (meaning no portion is deleted and the order of the data is not rearranged).

The authors acknowledge the contribution of cultivars and advanced selections for this work from the breeding programs at North Dakota State University, University of Minnesota, U.S. Department of Agriculture-Agricultural Research Service, Colorado State University, University of Wisconsin, University of Maine, Michigan State University, EBE Farms, Northern Konstar Potatoes, Parkland Seed, Real Potato, Solanum, Southern Potato and SunRain.

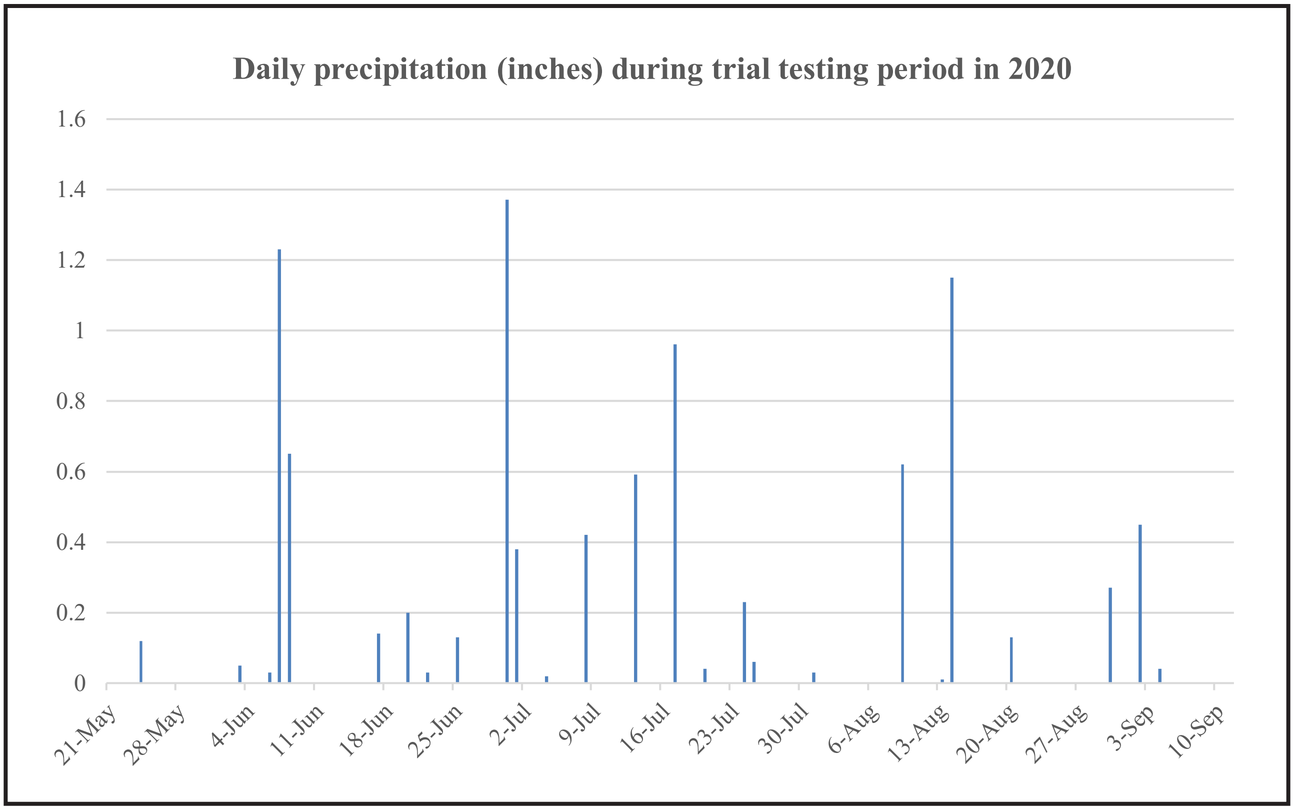

Figure 1. Daily rainfall from May 21 to Sept. 11, 2020, from the North Dakota Agricultural Weather Network weather station near Crystal, N.D.

Table 1. Agronomic performance and graded yield of red-skinned potato cultivars/selections near Hoople, N.D., 2020.

Cultivar/Selection	**Stand[1]**	**Stems/plant[2]**	**Vine length[3]**	**Vigor[4]**	**C[5]**	**B**	**A**	**Chef**	**Total yield**	**Specific gravity**
	%	**number**	**inch**		**cwt/a**					
Autumn Rose	91	3.9	26	4.0	17	155	67	1	239	1.082
Cerata	83	4.5	35	2.8	5	115	208	2	330	1.073
CO99076-6R	91	4.5	25	4.0	8	147	157	0	311	1.083
Cristina	84	3.8	26	4.0	7	167	195	3	373	1.078
Dark Red Norland	84	4.9	26	3.3	2	66	284	19	370	1.074
Dark Red Norland (Real Potato)	85	3.5	29	3.3	2	85	218	4	308	1.073
MSW 343-2R	84	2.9	26	3.8	4	101	242	8	356	1.066
ND113207-1R	84	4.2	27	3.8	16	139	128	0	283	1.068
ND13241C-6R	81	4.6	30	4.0	45	205	19	0	270	1.088
ND1431Y-2R	81	3.5	26	4.0	4	110	212	9	336	1.076
ND1455Y-1R	79	3.1	24	3.8	5	126	64	0	195	1.072
NDAF113484B-1	89	2.6	22	4.0	2	55	242	10	309	1.071
Red Norland	88	3.8	25	3.3	2	84	231	8	326	1.075
Red Pontiac	90	4.3	28	4.3	7	86	197	6	295	1.074
Red Prairie	89	3.4	27	3.8	10	209	99	0	318	1.074
Roko	82	3.6	29	4.5	5	139	183	0	327	1.080
Sangre	55	1.5	27	4.3	4	40	90	6	139	1.061
W8890-1R	92	5.4	28	3.8	14	150	133	1	299	1.075
W8893-1R	86	3.7	23	2.8	4	102	139	3	249	1.072
Column mean	84	4	27	4	9	121	164	4	298	1.075
CV %	9	17	13	13	21	25	25	126	16	0.2
LSD 0.05	11	0.9	5	0.7	6	36	59	7	68	0.004
LSD 0.10	9	0.8	4	0.6	5	30	49	6	57	0.003

[1] Stand count was taken on July 9 (seven weeks after planting) by counting every emerged plant and dividing by the number planted.

[2] Stems per plant were counted on 10 plants on July 9 (seven weeks after planting) and are shown as the average number of stems per plant.

[3] Vine length was measured on three plants from the base of the plant to the vine tip on Aug. 12.

[4] Vigor evaluation was completed on Aug. 12 (12 weeks after planting). A rating of 1 indicated least vigor and 5 greatest vigor.

[5] Potatoes were sorted on a Kerian Speed sizer as C = less than 1.875, B = 1.875-2.25, A = 2.25-3.5 and Chef = greater than 3.5 inches.

photo Robinson, NDSU/UMN

Table 2. Agronomic performance and graded yield of yellow-skinned potato cultivars/selections near Hoople, N.D., 2020.

Cultivar/Selection	Stand[1]	Stems/plant[2]	Vine length[3]	Vigor[4]	C[5]	B	A	Chef	Total yield	Specific gravity
	%	number	inch		——— cwt/a ———					
A00286-3Y	84	3.6	31	4.3	25	160	206	0	391	1.080
A06336-2Y	79	4.1	27	3.8	27	147	172	1	348	1.076
Actrice	85	3.9	29	2.8	9	96	411	17	533	1.069
Agata	89	3.7	24	3.8	18	182	284	4	489	1.071
Alegria	83	3.8	31	4.0	14	156	315	7	491	1.082
Arizona	82	4.2	29	3.5	17	186	265	19	486	1.071
Belmonda	86	4.1	33	4.0	97	191	175	0	463	1.084
CO05037-3W/Y	86	7.8	26	2.0	81	240	52	0	372	1.081
CO10064-1W/Y	83	4.7	30	4.0	75	209	77	0	360	1.101
CO11250-1W/Y	84	6.0	28	3.5	74	208	46	0	329	1.094
CO11266-1W/Y	89	4.8	32	4.5	72	196	41	0	309	1.082
Crop 56	88	4.5	34	4.8	42	236	73	1	352	1.084
Crop 58	84	3.6	28	3.5	10	123	225	25	384	1.078
Crop 80	84	4.5	31	3.8	26	146	213	0	384	1.082
Electra	81	4.1	34	5.0	22	168	280	7	476	1.072
Jelly	81	2.8	31	5.0	9	115	191	1	317	1.077
Lanorma	84	3.8	33	3.8	15	156	209	0	380	1.076
Milva	80	4.1	31	4.0	24	156	295	3	477	1.077
Montreal	85	3.9	26	3.0	26	137	296	9	468	1.077
MN04844	47	1.2	22	3.8	15	31	48	0	93	1.076
Musica	83	4.5	32	3.3	23	247	257	1	528	1.080
ND1487-1Y	84	4.7	32	4.0	57	248	126	0	431	1.078
ND1241-1Y	83	2.9	27	4.0	36	131	157	0	323	1.105
NDA081451CB-1CY	83	4.3	30	4.0	56	184	145	0	385	1.086
Melody	84	3.3	32	4.0	40	155	241	5	442	1.074
Noelle	81	5.6	31	2.0	72	231	80	0	383	1.069
Obama	85	4.9	29	3.0	24	245	268	3	541	1.072
Paroli	81	3.8	29	3.8	10	82	310	54	457	1.070
W15240-2Y	81	3.4	29	3.0	12	134	184	0	329	1.073
W9576-11Y	86	4.0	30	2.8	15	154	337	11	517	1.069
Mean	82	4.1	30	3.7	35	168	199	6	408	1.079
CV	8	22	9	13	85	19	23	180	16	0.3
LSD p=0.05	10	1.3	4	0.7	42	45	64	14	94	0.005
LSD p=0.10	8	1	3	0.6	35	38	54	12	78	0.004

[1] Stand count was taken on July 9 (seven weeks after planting) by counting every emerged plant and dividing by the number planted.

[2] Stems per plant were counted on 10 plants on July 9 (seven weeks after planting) and are shown as the average number of stems per plant.

[3] Vine length was measured on three plants from the base of the plant to the vine tip on Aug. 12.

[4] Vigor evaluation was completed on Aug. 12 (12 weeks after planting). A rating of 1 indicated least vigor and 5 greatest vigor.

[5] Potatoes were sorted on a Kerian Speed sizer as C = less than 1.875, B = 1.875-2.25, A = 2.25-3.5 and Chef = greater than 3.5 inches.

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100-12-19; web-2-20; web-1-21; web-2-21

Effects of banded versus broadcast application of ESN, turkey manure, and different approaches to measuring plant N status on tuber yield and quality in Russet Burbank potatoes

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Summary

The use of Environmentally Smart Nitrogen (ESN; Nutrien, Ltd.; 44-0-0) applied as a topdress at emergence is considered to be a best management practice in growing potatoes in Minnesota. However, this approach results in a portion of the ESN prills accumulating in the furrows between planting hills, where the N may not be accessible to plants. Banded application into the hills may prevent this N loss and improve N uptake and yield. Turkey manure is a slow-release N source that provides organic matter and stimulates microbial activity. Nitrogen management after emergence typically includes repeated applications of liquid urea and ammonium nitrate (UAN), with frequency and rates informed by petiole NO_3^--N concentrations. A more precise measure of plant N status is the N nutrient index (NNI), based on whole-plant N concentration. Both measures of N status can be estimated more cheaply and at higher resolution using remote sensing. The purposes of this study were to: (1) evaluate the potential of optimizing N uptake through banded application of ESN at emergence, (2) assess the value of turkey manure applied before planting as an organic amendment in potato production, (3) evaluate the effectiveness of NNI relative to petiole NO_3^--N concentration as a measure of crop N needs, and (4) evaluate the potential for remote-sensing-based estimates of both NNI and petiole NO_3^--N concentration to inform N management decisions. Sixteen treatments were applied in a randomized complete block design with four replicates. Total, marketable, and U.S. No. 1 yields were high in all treatments, including the control, and higher at intermediate N rates (140 to 220 $lbs \cdot ac^{-1}$ total N) than at higher rates (240 – 300 $lbs \cdot ac^{-1}$ total N), suggesting that substantial N was provided by sources other than fertilizer, such as soil organic matter and NO_3^--N in irrigation water. Banded application of ESN at emergence decreased yields, possibly due to mechanical damage during application or excessive fertilizer concentrations close to the young plants. Turkey manure increased tuber specific gravity but had no other effects on tuber yield or quality. The treatments used to compare the effectiveness of different measures of plant N status produced nearly identical regimens of UAN applications and produced very similar tuber yield and quality results. However, the treatment in which applications were based on direct measurement of NNI omitted the fourth and final application of 20 $lbs \cdot ac^{-1}$ N as UAN, and this treatment had the highest tuber specific gravity in this group of treatments. Overall, unlike the previous year, our results did not support banding ESN at emergence as a solution to prill loss from topdress application. The use of turkey manure before planting increased tuber specific gravity. It may be that regular use of turkey manure over many years would begin to have additional effects on potato yield or quality. It is likely that the effects of N management treatments would be greater in a field or year in which tuber yield is more limited by the application of N.

Introduction

Environmentally Smart Nitrogen (ESN; Nutrien Ltd.; 44-0-0) is a polymer coated urea product developed to release N over a 60-80 day period under Minnesota growing conditions. Use of ESN as an N source for potatoes is considered to be a best management practice because N release is reduced relative to uncoated urea during in the early part of the growing season, when potato root systems are small, reducing N losses.

The recommended timing and method of ESN application is at emergence and as a topdress followed by incorporation into the hill. This recommendation is based on effectiveness of crop response in previous studies and convenience of application and incorporation. However, a portion of the ESN applied in this way ends up in the furrow, which may reduce the ability of potato roots to access the N once it is released.

Turkey manure is an amendment that can supply a slow-release from of N and, at the same time, add organic matter to the soil. As long as manure is applied at least 120 days before harvest, it is considered an acceptable amendment for potato production. Because manure stimulates microbial activity in the soil, it is also considered a beneficial amendment for improving soil health.

Nitrogen applied at emergence is generally supplemented with an aqueous solution of urea and ammonium nitrate (UAN) in multiple low-rate applications in the summer, as well as a small amount of N provided at planting. The total amount of N applied in a season is based on multiple factors, including the potato cultivar, grower yield goals, the previous crop, and soil organic matter content. The frequency and size of summer UAN applications is often determined by the results of petiole NO_3^--N testing. Petiole NO_3^--N concentration is an estimate of whole-plant nitrogen status. This would be more accurately measured using whole-plant sampling to measure the nitrogen nutrition index (NNI), but the labor and analysis costs that this would entail make measuring NNI impractical in production systems. Although petiole NO_3^--N analysis is much cheaper than NNI, even this approach is too costly to provide the high-resolution information required for precision agriculture. Remote sensing has been proposed as a low-cost yet accurate method to measure crop N status.

The objectives of this study were to (1) evaluate the potential of optimizing N uptake by applying ESN closer to the growing root systems of potato plants, (2) assess the value of turkey manure applied before planting as an organic amendment in potato production, (3) evaluate the effectiveness of NNI relative to petiole NO_3^--N concentration as a measure of crop N needs, and (4) evaluate the potential for remote-sensing-based estimates of both NNI and petiole NO_3^--N concentration to inform N management in potato production.

Methods

Study design

The study was conducted in 2020 on a Hubbard loamy sand soil at the Sand Plain Research Farm in Becker, MN. The previous crop was rye. Sixteen treatments were applied in a randomized complete block design with four replicates. These treatments are summarized in Table 1.

Soil sampling

Pre-treatment soil samples to a depth of six inches were collected on April 10 and sent to the University of Minnesota Research Analytical Laboratory (St. Paul, MN) to be analyzed for Bray P; NH_4OAc-extractable K, Ca, and Mg; $Ca(H_2PO_2)_2$ / Ba-extractable SO_4-S; hot-water-extractable B; DTPA-extractable Cu, Fe, Mn, and Zn; soil water pH; and LOI soil organic matter content. NO_3^--N concentrations in two-foot soil samples collected on the same date were measured using a Wescan Nitrogen Analyzer. Results are presented in Table 2.

Planting

All plots received 200 $lbs \cdot ac^{-1}$ MOP (0-0-60) and 200 $lbs \cdot ac^{-1}$ SulPoMag (0-0-22-22S-11Mg) broadcast on April 17, supplying 164 $lbs \cdot ac^{-1}$ K_2O and 22 $lbs \cdot ac^{-1}$ S. ESN was broadcast at 318 $lbs \cdot ac^{-1}$ in plots receiving treatment 4 on April 21 to provide 140 $lbs \cdot ac^{-1}$ N. Turkey manure was applied to treatments 9 and 10 at 3 $T \cdot ac^{-1}$ on April 22, providing 18 $lbs \cdot ac^{-1}$ N.

Cut “A” Russet Burbank seed (2-3 oz) was planted in all plots on April 24, with 12” spacing within rows and 36” spacing between rows. Before row closure, a furrow was dug along either side of the furrow in each planting row of treatment 5, approximately 2 – 4 inches away from and 2 inches below the seed potatoes. ESN was banded into these furrows, and the furrows were closed back up before row closure.

Belay was applied in-furrow at planting for beetle control, along with the systemic fungicide Quadris. At row closure, a planting fertilizer blend was mechanically banded into each treatment. All treatments received 173 $lbs \cdot ac^{-1}$ DAP (18-46-0), 141 $lbs \cdot ac^{-1}$ SulPoMag, 184 $lbs \cdot ac^{-1}$ MOP, 2 $lbs \cdot ac^{-1}$ $ZnSO_4$ (17.5% S, 35.5% Zn), and 3 $lbs \cdot ac^{-1}$ Boron 15 (15% B), supplying 40 $lbs \cdot ac^{-1}$ N, 102 $lbs \cdot ac^{-1}$ P_2O_5, 181 $lbs \cdot ac^{-1}$ K_2O, 40 $lbs \cdot ac^{-1}$ S, 20 $lbs \cdot ac^{-1}$ Mg, 1 $lb \cdot ac^{-1}$ Zn, and 0.6 $lbs \cdot ac^{-1}$ B. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling.

Hilling and post-hilling fertilizer applications

Immediately prior to hilling on May 19, granular urea (treatments 2 and 3) or ESN (treatments 10-16) was applied by hand next to each hill in the appropriate treatments. In treatments 6 and 8, ESN was applied in a broad band along the top of each hill. In treatment 7, ESN was banded by hand into a furrow dug into the side of each hill, approximately 2 – 4 inches to the side of and 2 inches below the seed potatoes.

With some exceptions, each plot in treatments 2 and 4-7 received 10 $lbs \cdot ac^{-1}$ N, and each plot in treatments 12-16 received 20 $lbs \cdot ac^{-1}$ N, as 28% UAN on Jun 22 and July 2, 13, and 23. On July 2, treatment 1 received the UAN designated for treatment 2. The July 13 UAN application was delayed until July 16 in treatment 15 pending the results of tissue NO_3^--N analyses on petioles collected on July 7, which were needed to determine the application rate to be used. Finally, based on NNI results from whole-plant samples collected on July 7, it was determined that treatment 13 would receive no UAN on July 23.

ESN urea release in situ

Urea release from ESN prills installed *in situ* was monitored in three plots each of treatments 4, 5, 7, 8, and 12. At the time of ESN application for the treatment, immediately after row closure (treatments 4 and 5) or hilling (treatments 7, 8, and 12), ten flat mesh packets, each containing three grams of ESN, were buried four inches below the soil surface in the furrow between a field buffer row and each of three plots. The packets were installed in the furrow adjacent to the plots to avoid disturbing the fertilizer placement within the plots. From each plot, a packet was removed periodically and the ESN prills were separated from soil, roots, and other debris and weighed. Cumulative urea release across the season was estimated as the percent change in prill mass between burial and removal, accounting for the mass of the prill coats (taken to be 0.13 g per 3-g sample, based on previous research). Prills were installed in the treatments receiving ESN broadcast before planting or banded at planting (treatments 4 and 5) on April 24 and removed on April 27, May 1, 8, 18, and 27, June 11 and 30, July 20, August 8, and September 15 (3, 7, 14, 24, 33, 48, 67, 87, 108, and 144 days after planting, respectively). Prill were installed in the treatments receiving ESN topdressed or banded at emergence (treatments 7, 8, and 12) on May 19 and removed on May 22 and 27, June 4, 11, 18, and 30, July 13, August 3, and September 3 and 15 (3, 8, 16, 23, 30, 42, 55, 76, 107, and 119 days after emergence, respectively).

Prill collection from furrows

ESN prills were collected from the soil surface on May 27, from all treatments receiving ESN (treatments 4-8 and 10-16). In each plot, the prills were collected from 15 square feet in a separate part of the same furrow where the prill packets were installed.

Aboveground plant assessments

Plant stand was assessed in the central 18 feet of each of the central two rows of each plot (36 planted tubers in total) on May 27 (8 days after emergence fertilizer was applied). The number of stems per plant was determined on June 9 (21 days after emergence) for 10 plants in the same area where stand was assessed. On June 16 and 24, July 7 and 22, and August 4 (28, 36, 49, 64, and 77 days after emergence), terminal leaflet chlorophyll contents (leaf greenness) from the fourth mature leaf from the shoot tip were measured for 20 leaves per plot using a SPAD-502 Chlorophyll Meter (Konica Minolta). On the same dates, the petiole of the fourth mature leaf from the shoot tip was collected for 20 leaves per plot. Petioles were dried at 140°F until their weight was stable, ground, and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer.

In addition, canopy cover was evaluated using both the Canopeo application and a CropScan NIR Analyzer. Canopeo readings were taken on May 27, June 4, 8, 16, and 23, July 6, 13, 22, and 28, August 5, 11, 17, and 25, and September 3 and 8 (every 4 – 13 days from 8 to 112 days after emergence). Cropscan readings were taken on the same days, except that the readings on July 6, 22, and 28, August 5 and 11, and September 8 were instead conducted on July 7, 23, and 27, August 3 and 10, and September 11, respectively (every 4 – 14 days from 8 to 115 days after emergence).

Whole-plant samples and nitrogen nutrition index (NNI)

At four times during the season, tubers and vines were sampled from three plants per plot from treatments 1, 6, and 11 – 16. Fresh weight, dry weight, and tissue N concentration was determined for tubers and vines separately from each plot's sample. Dry weights were used to calculate dry tuber and vine biomass per acre, and these were multiplied by tuber and vine N concentration, respectively, to calculate tuber, vine, and total N uptake. Total N uptake was divided by total dry biomass per acre to calculate whole-plant N concentration. This was divided by the critical N concentration, which was calculated from the formula:

$$\text{Critical \% N} = 5.37 * \text{biomass (Mg/ha)}^{-0.45}.$$

The whole-plant N concentration divided by the critical N concentration is the nitrogen nutrition index (NNI). Values less than zero indicate N deficiency, while values greater than zero indicate that tissue N concentration exceeds plant requirements.

Whole-plant samples were collected on June 24, July 7 and 22, and August 4.

End-of-season vine and tuber harvest

Vines were sampled from 10 feet of each of the two central rows of each plot on September 15. A subsample from each vine sample was weighed, dried at 140°F until its weight was stable, and re-weighed. The N concentrations of the subsamples were determined using an Elementar CNS Element Analyzer. The data were used to estimate per-acre aboveground N uptake. Vines were chopped in all rows on September 16, 145 days after planting and 120 days after emergence.

Tubers were harvested on September 22 from the central 18 feet of the central two rows of each plot. Harvested tubers were sorted and graded on September 28-29. Twenty-five-tuber subsamples were collected for each plot, stored at 48°F, and assessed for hollow heart, brown center, and scab, and their specific gravity and dry matter content were determined. Tuber N concentrations were determined using an Elementar CNS Element Analyzer and used to estimate N uptake per acre into tubers. Vine and tuber dry biomass and N uptake were used to calculate NNI as described for whole-plant samples above.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. Data were analyzed as functions of treatment and block. Means for each treatment and each level of application timing, application method, and their interaction, were calculated and post-hoc pairwise comparisons between treatments made using the LSMEANS statement with the DIFF option. Pairwise comparisons were only evaluated where the P-value of the relevant effect in the model was less than 0.10, and pairwise comparisons with P-values less than 0.10 were considered significant. In addition to pairwise comparisons, groups of treatments were compared using ten CONTRAST statements comparing:

1. the control treatment (treatment 1) and all treatments receiving urea or ESN (treatments 2-8 and 10-16),
2. the linear contrast on total N rate, with all treatments included,
3. the quadratic contrast on total N rate, with all treatments included,
4. treatments receiving ESN at or before planting (treatments 4 and 5) and similar treatments receiving ESN at emergence (treatments 6 and 7),
5. treatments in which ESN was banded (treatments 5 and 7) versus broadcast or topdressed (treatments 4 and 6),
6. treatments receiving turkey manure before planting (treatments 9 and 10) and similar treatments not receiving manure (treatments 1 and 8),
7. treatments receiving uncoated urea at emergence (treatments 2 and 3) and treatments receiving ESN at emergence (treatments 6 and 8),
8. treatments receiving all post-planting N at emergence (treatments 3 and 8) and those receiving some N as UAN later in the season (treatments 2 and 6),
9. treatments whose N status was evaluated based on tissue N or NO_3^--N concentrations (treatments 13 and 15) and those evaluated based on remote-sensing proxies for these concentrations (treatments 14 and 16), and
10. treatments whose N status was evaluated based on NNI (treatments 13 and 14) versus petiole NO_3^--N concentration (treatments 15 and 16).

Results and discussion

Tuber yield, size, and grade

Results for tuber yield, size, and grade are presented in Table 3. Total, marketable, and U.S. No. 1 yields were high even in the control treatment (treatment 1) and the manure-only treatment (treatment 9). The highest yields were observed in treatments receiving 140 to 220 $lbs \cdot ac^{-1}$ total N, and the quadratic contrast on N rate was significant for total yield, marketable yield, and yield of U.S. No. 1 tubers as a result. High yields even in control treatments and peak yield at an N rate in the range of 140 to 220 $lbs \cdot ac^{-1}$ total N are consistent with a large amount of N being provided by means other than fertilizer applications. The two most likely sources of non-fertilizer N are soil organic matter and irrigation water. Even though soil organic matter was low in this field (1.6%; Table 2), significant N mineralization can occur given proper environmental conditions. . The field received also 13.25 inches of irrigation water with a mean NO_3^--N concentration of 9.65 ppm, providing about 27.75 lbs·ac^{-1} NO_3^--N (6.27 lbs·ac^{-1} N) throughout the season. It is plausible that mineralization from soil OM and irrigation water nitrate contributed to the relatively low response to N fertilizer this year.

The treatment in which ESN was banded at emergence (treatment 7) had the lowest total tuber yield of any treatment receiving urea or ESN. The negative effect of banded application on yield may have been a result of placing the fertilizer too close to the roots of the young plants or to mechanical damage to the roots caused by digging the trenches in which the fertilizer was placed.

At roughly equivalent N rates, yield was not significantly related to the use of turkey manure. The use of petiole NO_3^--N concentration versus NNI versus remote-sensing proxies of either of these also had no significant effect on yield. The lack of yield response to how plant N status was measured can be attributed to how similar the N treatments intended to compare these approaches (treatments 13-16) ended up being in practice. Treatment 13 did not receive the fourth application of 20 lbs·ac^{-1} N, while treatment 15 received the third application three days later than the other three treatments, but they were otherwise treated identically.

The percentage of yield represented by tubers over six or ten ounces was significantly related to treatment. The contrast comparing the control treatment (treatment 1) to the treatments fertilized with urea or ESN (treatments 2-8 and 10-16). The linear contrast on N rate for the percentage of yield in tubers over 6 or 10 ounces was significant, as was the quadratic contrast on N rate for yield in tubers over 6 ounces. Both of these effects of N rate are due to the relatively small tuber size in the control treatment (treatment 1) and the manure-only treatment (treatment 9), as N rate had a negligible effect on yield among the remaining treatments.

Tuber quality

Results for tuber quality are presented in Table 4. Treatment had no significant effects on the prevalence of hollow heart or scab. Brown center was only found in three plots, and two of these were in the treatment receiving turkey manure plus ESN (treatment 10), resulting in a marginally significant treatment effect and a significant effect of the contrast comparing the treatments receiving manure (treatments 9 and 10) and similar treatments receiving no manure (treatments 1 and 8).

Tuber specific gravity was related to treatment. It was lowest in the control treatment (treatment 1). The quadratic contrast on N rate was significant, with the highest specific gravity values found at intermediate N rates (140 – 240 lbs·ac^{-1} total N). Tuber specific gravity was higher in the treatments receiving turkey manure before planting (treatments 9 and 10) than in similar treatments that did not receive manure (treatments 1 and 8). The treatments in which plant N status was monitored based on NNI (treatments 13 and 14) had higher specific gravity than the treatments in which N status was measured based on petiole NO_3^--N concentration (treatments 15 and 16). The treatment in which NNI was measured directly from tissue tests (treatment 13) was also the one treatment in this comparison that did not receive 20 lbs·ac^{-1} N as UAN on the fourth application date (July 23), and it is therefore possible that withholding this fourth UAN application resulted in higher tuber specific gravity in this treatment.

Tuber dry matter content was also related to N treatment. The linear and quadratic contrasts on N rate were both significant, with the lowest tuber dry matter content in the manure-only treatment (treatment 9) and the highest in two treatments receiving 220 lbs·ac^{-1} total N (treatments 6 and 8, the two treatments receiving ESN topdressed at emergence).

Conclusions

Total, marketable, and U.S. No. 1 yields were high in all treatments, and the highest-yielding plots received 140 to 220 lbs·ac^{-1} total N, indicating that peak yield occurred at a relatively low N rate in this study. This suggests that N was supplied by some source other than the fertilizer treatments, such as soil organic matter and dissolved NO_3^--N in irrigation water.

Contrary to our expectations and in contrast to results from last year, banding ESN at emergence produced lower yields than any other approach to applying urea or ESN in this study. Any advantage banding produced in terms of reduced loss of prills to the furrows was much smaller than the disadvantages, which may have resulted from damage to the roots of the young plants, from either the concentrated placement of N fertilizer close to the plants or mechanical damage caused in placing that fertilizer.

At roughly equivalent N rates, the use of turkey manure had little effect on tuber yield and quality overall. However, manure application was associated with increased tuber specific gravity (but not dry matter content). It is possible that any other effects of applying turkey manure are cumulative over years of application and not evident in a single year.

For the most part, when post-hilling N rates were based on plant N status, it made little difference whether N was monitored using NNI or petiole NO_3^--N, nor whether N status was measured directly through tissue samples or by remote-sensing proxies of NNI or petiole NO_3^--N concentration, probably because the four treatments involved in these comparisons (treatments 13-16) had very similar N regimes in practice. However, the treatment in which N status was monitored through direct measurement of NNI (treatment 13) had the highest tuber specific gravity in this group. This treatment did not receive the fourth and final application of 20 lbs·ac^{-1} N as UAN, and this may explain the difference in tuber specific gravity.

It is likely that the effects of the N management strategies evaluated in this study would be greater in a field where yield was more limited by N fertilization.

Table 1. Treatments applied to evaluate the effects of banded versus topdress application of ESN, the use of turkey manure, and the use of petiole NO_3^--N concentration, NNI, or remote-sensing proxies of each to monitor plant N status.

Treatment #	Description	Application rates of N (lbs·ac^{-1})							
		Preplant N	Planting N	Emergence N	N as post-emergence 28% UAN				
		4/21 - 4/22	4/24	5/19	6/22	7/2, 7/9	7/13, 7/16	7/23	Total N
1	Control	-	40, DAP	-	-	10	-	-	50
2	Urea + UAN	-	40, DAP	140, urea	10	10 (7/9)	10	10	220
3	Urea	-	40, DAP	180, urea	-	-	-	-	220
4	ESN[1] Preplant Broad + UAN	140, ESN	40, DAP	-	10	10	10	10	220
5	ESN Plant Band + UAN	-	180, DAP + ESN	-	10	10	10	10	220
6	ESN Emerge TD[2] + UAN	-	40, DAP	140, ESN	10	10	10	10	220
7	ESN Emerge Band + UAN	-	40, DAP	140, ESN	10	10	10	10	220
8	ESN Emerge TD	-	40, DAP	180, ESN	-	-	-	-	220
9	Turkey Manure Only	18, manure	40, DAP	-	-	-	-	-	58
10	Turkey Manure + ESN	18, manure	40, DAP	162, ESN	-	-	-	-	220
11	Low N, ESN	-	40, DAP	100, ESN	-	-	-	-	140
12	High N, ESN	-	40, DAP	180, ESN	20	20	20	20	300
13	NNI[3]	-	40, DAP	140, ESN	20	20	20	-	240
14	Remote Sensing – NNI	-	40, DAP	140, ESN	20	20	20	20	260
15	Petiole	-	40, DAP	140, ESN	20	20	20 (7/16)	20	260
16	Remote Sensing – Petiole	-	40, DAP	140, ESN	20	20	20	20	260

[1] ESN: Environmentally Smart Nitrogen (44-0-0; Nutrien Ltd.)

[2] TD: topdressed

[3] NNI: nitrogen nutrition index.

Table 2. Initial soil characteristics of the study site.

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)					
1.4	58	109	655	162	6.5

0 - 6 inches						
Micronutrients					Other characteristics	
Fe	Mn	Zn	Cu	B	pH	Organic matter (%)
(mg·kg^{-1} soil)						
20	3.8	2.0	0.83	0.16	6.8	1.6

Table 3. Effects of N treatment on tuber yield, size, and grade.

Treatment #	Description	Total N rate (lbs·ac^{-1})	Yield (CWT·ac^{-1})										% yield in tubers > than:	
			Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	U.S. No. 1	U.S. No. 2	Marketable	6 oz.	10 oz
1	Control	50	6	22	148 a	173 bcde	115	49 e	506 e	452	33	485	65 d	31 e
2	Urea + UAN	220	10	23	109 cdef	175 bcde	130	145 ab	583 abc	511	49	560	77 ab	47 abc
3	Urea	220	6	23	118 cde	168 cdef	147	132 abc	588 ab	506	60	565	76 abc	47 abc
4	ESN[1] PP + UAN	220	2	15	106 def	164 cdef	137	130 abc	553 abcde	496	41	537	78 ab	48 abc
5	ESN Plant + UAN	220	9	19	109 cdef	200 ab	157	117 abc	601 a	524	58	582	78 a	45 abc
6	ESN Emerge TD[2] + UAN	220	0	19	106 def	174 bcde	149	127 abc	575 abc	503	53	556	78 ab	48 abc
7	ESN Emerge Band + UAN	220	3	17	94 f	146 ef	136	121 abc	514 de	459	38	497	78 ab	50 abc
8	ESN Emerge TD	220	7	17	112 cdef	186 abcd	135	135 abc	585 abc	514	54	568	78 ab	46 abc
9	Turkey Manure Only	58	3	23	141 ab	209 a	126	54 de	552 abcde	490	40	529	70 cd	32 de
10	Turkey Manure + ESN	220	5	23	118 cde	187 abcd	135	123 abc	587 ab	524	40	564	76 abc	44 bc
11	Low	140	5	18	126 abcd	175 bcde	193	90 cde	602 a	556	28	584	76 abc	47 abc
12	High	300	10	17	96 f	142 f	138	153 a	545 bcde	483	46	528	79 a	53 a
13	NNI[3]	240	5	15	100 ef	162 def	156	126 abc	558 abcd	500	44	544	80 a	51 ab
14	Remote Sensing – NNI	260	7	26	121 bcde	193 abc	138	97 bcd	576 abc	511	39	550	74 abc	41 cd
15	Petiole	260	4	24	114 cdef	188 abcd	118	120 abc	565 abc	506	36	541	75 abc	42 bc
16	Remote Sensing – Petiole	260	4	22	130 abc	142 f	132	110 abc	535 cde	472	42	514	72 bcd	45 abc
	Effect of treatment (P-value)		0.5622	0.9303	**0.0068**	**0.0093**	0.1823	**0.0348**	**0.0595**	0.2939	0.4267	0.1528	**0.0481**	**0.0159**
Contrasts	Check vs. N fertilized		0.8303	0.6783	**0.0004**	0.9110	**0.0638**	**0.0009**	**0.0057**	**0.0278**	0.1727	**0.0088**	**0.0002**	**0.0004**
	Linear N rate		0.4396	0.6847	**<0.0001**	**0.0169**	0.7458	**<0.0001**	0.2599	0.5531	0.1537	0.2652	**0.0005**	**<0.0001**
	Quadratic N rate		0.2748	0.6766	0.1764	0.2667	**0.0167**	0.2122	**0.0057**	**0.0192**	0.3378	**0.0089**	**0.0442**	0.1103
	ESN planting vs. emergence		0.1468	0.8861	0.4448	**0.0936**	0.7562	0.9892	0.1299	0.1995	0.6607	0.1574	0.9703	0.6419
	Banded vs. broad/TD		0.1201	0.9266	0.6016	0.7661	0.8076	0.6456	0.7532	0.7384	0.9579	0.7592	0.9026	0.9045
	Manure vs. not		0.3822	0.4472	0.9525	0.1453	0.7098	0.8842	0.2517	0.2897	0.6863	0.3760	0.6030	0.8651
	ESN vs. urea		0.1264	0.3089	0.6205	0.5147	0.8090	0.7004	0.7807	0.9973	0.9346	0.9728	0.5879	0.9667
	Emergence only vs. posthill		0.6228	0.7511	0.4135	0.8433	0.9367	0.8998	0.7332	0.8988	0.4978	0.7047	0.7829	0.8386
	Tissue vs. RS		0.8368	0.3645	**0.0539**	0.5645	0.8905	0.3394	0.7724	0.6241	0.9579	0.6463	0.1209	0.3969
	NNI vs. petioles		0.5978	0.6455	0.1986	0.3293	0.1254	0.8745	0.4183	0.4658	0.7385	0.4029	0.2101	0.5767

[1] ESN: Environmentally Smart Nitrogen (44-0-0; Nutrien Ltd.)

[2] TD: topdressed

[3] NNI: nitrogen nutrition index.

Table 4. Effects of N treatment on tuber quality.

Treatment #	Description	Total N rate (lbs·ac^{-1})	Percentage of tubers			Specific gravity	Dry matter content (%)
			Hollow heart	Brown center	Scab		
1	Control	50	6	0 b	3	1.0692 e	18.5 ef
2	Urea + UAN	220	10	0 b	3	1.0737 abcd	19.6 abcd
3	Urea	220	8	0 b	4	1.0761 a	19.3 bcde
4	ESN[1] PP + UAN	220	7	0 b	4	1.0721 bcde	18.9 bcdef
5	ESN Plant + UAN	220	8	1 b	3	1.0724 bcde	19.0 bcdef
6	ESN Emerge TD[2] + UAN	220	10	0 b	4	1.0748 ab	20.4 a
7	ESN Emerge Band + UAN	220	6	0 b	2	1.0743 abc	18.8 cdef
8	ESN Emerge TD	220	8	0 b	0	1.0712 cde	19.9 ab
9	Turkey Manure Only	58	3	0 b	8	1.0718 bcde	17.3 g
10	Turkey Manure + ESN	220	9	3 a	1	1.0748 ab	19.8 abc
11	Low	140	3	0 b	1	1.0763 a	18.9 bcdef
12	High	300	11	0 b	3	1.0712 cde	18.1 fg
13	NNI[3]	240	8	0 b	0	1.0762 a	19.4 abcde
14	Remote Sensing – NNI	260	7	0 b	0	1.0738 abcd	19.5 abcde
15	Petiole	260	5	0 b	0	1.0710 de	19.7 abc
16	Remote Sensing – Petiole	260	12	0 b	4	1.0728 bcd	18.6 def
	Effect of treatment (P-value)		0.6937	**0.0575**	0.8215	**0.0123**	**0.0021**
Contrasts	Check vs. N fertilized		0.5022	0.6191	0.7583	**0.0028**	**0.0886**
	Linear N rate		**0.0339**	0.7527	0.1730	0.1944	**0.0037**
	Quadratic N rate		0.7159	0.2313	0.5470	**0.0006**	**0.0006**
	ESN planting vs. emergence		0.8515	0.3094	0.8255	**0.0909**	0.1572
	Banded vs. broad/TD		0.7185	0.3094	0.6032	0.9474	**0.0794**
	Manure vs. not		0.7126	**0.0129**	0.2696	**0.0241**	0.1366
	ESN vs. urea		0.9565	1.0000	0.5790	0.1564	0.1147
	Emergence only vs. posthill		0.5141	1.0000	0.5790	0.6663	0.3480
	Tissue vs. RS		0.2832	1.0000	0.4417	0.8329	0.2882
	NNI vs. petioles		0.6897	1.0000	0.4417	**0.0272**	0.5455

[1] ESN: Environmentally Smart Nitrogen (44-0-0; Nutrien Ltd.)

[2] TD: topdressed

[3] NNI: nitrogen nutrition index.

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

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Summary

Potato yield responses to phosphorus (P) fertilizer are often positive even in soils with high Bray P concentrations, in excess of 50 ppm. Previous research at the Sand Plain Research Farm (SPRF) in Becker, MN, has indicated that the cultivar Ivory Russet may have a stronger yield response to P rate than Russet Burbank. Potato yield responses to P rate in high-P soils indicate that P uptake in potatoes is limited by something other than soil-test P concentration. Possibilities include the relative shallowness of potato root systems and a lack of mycorrhizal associates, especially in fumigated soils. Alternatively, Bray P concentration may not adequately measure the true availability of P in acid soils. The ratio of Mehlich-3 P concentration to Melich-3 aluminum (Al) concentration, called the P saturation index (PSI), may be a better indicator predictor of yield responses to P rate. The objectives of this study were to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying a mycorrhizal product at planting, and (4) banded versus broadcast application of P fertilizer, and (5) to evaluate PSI, Bray P, and Mehlich-3 P as predictors of potato yield response to P. The study was conducted in two sites, one at SPRF, in which the soil was not fumigated, and one at a nearby grower's field , in which the soil was fumigated with metam sodium in the previous fall. In each field, a split-plot randomized complete block design was used, with cultivar (Ivory Russet or Russet Burbank) as the whole-plot effect and P treatment as the subplot effect. Nine P treatments were tested: (1) a check treatment receiving no P fertilizer; treatments receiving triple super phosphate (TSP) at rates of (2) 75 lbs·ac^{-1} P_2O_5, (3) 150 lbs·ac^{-1} P_2O_5, (4) 300 lbs·ac^{-1} P_2O_5, and (5) 450 lbs·ac^{-1} P_2O_5 broadcast before planting; two treatments to which mycorrhizal fungal inoculum was applied in-furrow at planting after (6) no P or (7) 150 lbs·ac^{-1} P_2O_5 were broadcast before planting; and treatments receiving (8) 75 lbs·ac^{-1} P_2O_5 and (9) 150 lbs·ac^{-1} P_2O_5 as TSP banded at row opening. Ivory Russet showed a positive yield response to P rate in both sites, while Russet Burbank did not. Banded application of P had no effect on yield at SPRF and a negative effect on total and marketable Ivory Russet yield and U.S. No. 2 Russet Burbank yield at the grower field. Tuber yield response to P rate was similar between the two sites for each cultivar, indicating that fumigation did not alter P uptake. Inoculation with mycorrhizal fungi at planting had few effects on yield, and the only positive effects were observed in Russet Burbank in the non-fumigated soils of SPRF. The prevalence of hollow heart and brown center increased significantly or marginally significantly with P rate in both cultivars at SPRF and Ivory Russet at the grower field. The prevalence of scab was much higher in the non-fumigated SPRF site than the fumigated grower site. Overall, the results of this study suggest that the P use efficiency of Ivory Russet is poor compared to Russet Burbank, but the issue is not remedied by banded P application, inoculation with mycorrhizal fungi, or foregoing soil fumigation. The differences in Bray P, Mehlich-3 P, and PSI between the two sites used in this study were not large enough to substantially alter the P responses of either cultivar.

Introduction

Potato yield responses to phosphorus (P) fertilizer rare often positive even in soils with high soil-test P concentrations. For example, in soils with Bray P concentrations over 50 ppm, when yields of 400 cwt·ac^{-1} or higher are desired, the University of Minnesota Extension recommended rate of P fertilization is 75 lbs·ac^{-1} P_2O_5, and it is noted that responses in acidic, irrigated soils have been observed at application rates as high as 150 lbs·ac^{-1} P_2O_5.

Positive potato yield responses to differences in P rate even in high-P soils and at high application rates suggest that potato plants are not efficient at taking up soil P. Potatoes have relatively shallow root systems, rarely extending much below two feet into the soil, limiting the volume of soil from which they are able to acquire P. In addition, potatoes tend not to form extensive mycorrhizal associations, especially following fumigation, limiting how thoroughly they exploit P resources in the soil within the range of their root systems.

Both root system extent and success in forming mycorrhizal associations may be greatly affected by potato plant genetics. Different cultivars may therefore show different yield responses to P rate. In a P response study conducted at the Sand Plain Research Farm in Becker, MN, in 2019, the Ivory Russet showed a positive yield response at application rates between 125 and 250 $lbs\cdot ac^{-1}$ P_2O_5 in soil where Bray P concentration ranged from 64 to 78 ppm. In a separate study in the same facility in the same year, Russet Burbank showed no yield response to P rate at rates of 0 or 80 $lbs\cdot ac^{-1}$ P_2O_5 in soil with 28 to 31 ppm Bray P. As a determinate cultivar, Ivory Russet may have a less extensive root system than indeterminate Russet Burbank, and there may also be differences between the two cultivars in terms of their efficiency at forming mycorrhizal associations.

If mycorrhizal associations affect P use efficiency, it is plausible that soil fumigation, which is frequently used to control soil-borne pathogens, including fungal pathogens such as *Verticillium*, has a negative effect on potato P use efficiency. If so, this negative effect may be partially or fully compensated for by applying mycorrhizal products to potato fields at planting. Alternatively, if potato P uptake is limited more by the extensiveness of potato root systems than by their effectiveness at absorbing P within range of their root and mycorrhizal networks, P uptake efficiency might be improved by placing P closer to the plants through banded application.

Finally, it is possible that Bray P alone is not the best indicator of potato P response in acid soils. Research in Eastern Canada has found that the P saturation index (PSI), the ratio of Melich-3 extractable P to Melich-3 extractable aluminum (Al), may be a better predictor.

The objectives of this study were to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying a mycorrhizal product at planting, and (4) banded versus broadcast application of P fertilizer, and (5) to evaluate PSI, Bray P, and Mehlich-3 P as predictors of potato yield response to P.

Methods

Study design

The study was conducted at two sites in 2020, one in a non-fumigated field on the Sand Plain Research Farm (SPRF) in Becker, MN, and one in a metam-sodium-fumigated grower field approximately one mile to the east, on Hubbard loamy sand soils. Nine treatments were applied to 20-by-12-foot subplots in a split-plot randomized complete block design in each site, with whole plots defined by the potato cultivar planted: Russet Burbank or Ivory Russet. The treatments included (1) a check treatment receiving no P fertilizer; treatments receiving triple super phosphate (TSP) at rates of (2) 75 $lbs\cdot ac^{-1}$ P_2O_5, (3) 150 $lbs\cdot ac^{-1}$ P_2O_5, (4) 300 $lbs\cdot ac^{-1}$ P_2O_5, and (5) 450 $lbs\cdot ac^{-1}$ P_2O_5 broadcast before planting; (6) a check treatment receiving no P, to which the mycorrhizal product MycoGold (MycoGold LLC) was applied in-furrow at planting with a hand sprayer; (7) a treatment receiving 150 $lbs\cdot ac^{-1}$ P_2O_5 broadcast before planting plus MycoGold in-furrow at planting; and treatments receiving (8) 75 $lbs\cdot ac^{-1}$ P_2O_5 and (9) 150 $lbs\cdot ac^{-1}$ P_2O_5 as TSP banded at row opening. A summary of these treatments is presented in Table 1.

Initial soil characteristics

To measure soil characteristics before fertilizer treatments were applied, soil samples to a depth of six inches were collected from each replicate in each study site on April 17. Samples were analyzed for Bray P, Mehlich-3-extractable P, Al, Mg, Mn, Fe, Zn, and Cu, acetate-extractable K and Ca, hot-water-extractable B, SO_4^{2-}-S, pH, and loss-on-ignition organic matter content. PSI was calculated as the ratio of Mehlich-3 P to Mehlich-3 Al times 100. In addition, two-foot soil samples were collected by replicate in each site and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer. Results of these analyses are presented in Table 2. Potassium fertilizer was applied to the grower site in fall 2019, as well as gypsum in the spring, before soil samples were taken, and K and S concentrations were therefore elevated at this site.

Planting and emergence

The SPRF site received 164 $lbs \cdot ac^{-1}$ K_2O and 22 $lbs \cdot ac^{-1}$ S as 200 $lbs \cdot ac^{-1}$ MOP (0-0-60) and 200 $lbs \cdot ac^{-1}$ SulPoMag (0-0-22-22S-11Mg) on April 18. TSP was broadcast applied by hand in treatments 2 – 5 and 7 at rates indicated by treatment on April 29 at the grower site and May 5 at the SPRF site. Rows were opened and TSP mechanically banded in treatments 8 and 9 at rates indicated by treatment on April 29 at the grower site and May 6 at the SPRF site. In addition, all plots in both fields received 40 $lbs \cdot ac^{-1}$ N, 180 $lbs \cdot ac^{-1}$ K_2O, 40 $lbs \cdot ac^{-1}$ S, 21 $lbs \cdot ac^{-1}$ Mg, 1 $lb \cdot ac^{-1}$ Zn, and 0.5 $lbs \cdot ac^{-1}$ B as a combination of 87 $lbs \cdot ac^{-1}$ urea (46-0-0), 43 $lbs \cdot ac^{-1}$ MOP, 1191 $lbs \cdot ac^{-1}$ SulPoMag, 2.8 $lbs \cdot ac^{-1}$ $ZnSO_4$ (35.5% Zn, 17.5% S), and 3.3 $lbs \cdot ac^{-1}$ Boron 15 (15% B). On April 30 in the grower site and May 6 in the SPRF site, 2-3-oz. seed potatoes were planted by hand in each plot with one-foot spacing within rows and three-foot spacing between rows. Before row closure, tubers were treated with an in-furrow application of MycoGold Potato Blend, which includes mycorrhizal fungi, at a rate of 2 $oz \cdot ac^{-1}$.

At the grower site, 220 $lbs \cdot ac^{-1}$ N were applied as ESN (44-0-0; Nutrien, Ltd.) at emergence (May 13) together with 90 $lbs \cdot ac^{-1}$ N as 28% urea and ammonium nitrate (UAN). At the SPRF site, 150 $lbs \cdot ac^{-1}$ N were applied as ESN with 60 $lbs \cdot ac^{-1}$ N as urea at emergence (May 20). Plant stand was measured in the central 18 feet of the central two rows of each subplot on June 4, 11, and 22 in each site, and the number of stems per plant was determined for ten plants from the same two rows on June 15 and 22.

Petiole sampling

Petioles were collected from the grower field on June 25 and July 6 and 27 and from the SPRF field on June 25 and July 6 and 23. The petiole of the fourth mature leaf from the shoot tip was collected for 20 leaves per plot. Petioles were dried at 140°F until their weight was stable and then ground. They will be analyzed for P concentration by the University of Minnesota Research Analytical Laboratory using inductively coupled plasmolysis.

Harvest

Vines were killed with desiccant on September 4 at the grower site, 127 days after planting, and chopped on September 15. Vines were killed by chopping on September 9 at the SPRF site, 126 days after planting. Tubers were harvested from the central 18 feet of the middle two rows of each subplot on September 17 at the grower site and September 21 at the SPRF site. Tubers from the grower site were sorted on October 22-23, and those from the SPRF site were sorted on October

26-27. End-of-season soil samples were collected on September 18 at the grower site and October 7 at the SPRF site.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. Data were analyzed for each combination of site and cultivar separately, as functions of treatment and block. Means for each treatment were calculated and post-hoc pairwise comparisons between treatments made using the LSMEANS statement with the DIFF option. Pairwise comparisons were only evaluated where the P-value of the relevant effect in the model was less than 0.10, and pairwise comparisons with P-values less than 0.10 were considered significant. Four CONTRAST statements were used to evaluate particular treatment effects of interest:

1. The linear contrast on P rate, including treatments 1 – 5,
2. The quadratic contrast on P rate, including treatments 1 – 5,
3. A comparison of banded versus broadcast application, comparing treatments 2 and 3 with treatments 8 and 9, and
4. A comparison of treatments with and without added mycorrhizae, comparing treatments 1 and 3 with treatments 6 and 7.

Results and discussion

Initial soil characteristics

The initial soil characteristics of the study sites, before fertilizer treatments were applied but after MOP and gypsum were applied to the grower site, are presented in Table 2. Bray and Mehlich-3 P concentrations, Mehlich-3 Al concentration, and PSI were all higher in the SPRF site than the grower site. However, the Bray P concentration was very high (≥ 51 ppm) in both sites, and the PSI was well above the environmentally critical percentage identified in published research (15%). With a target yield of 500 $cwt\cdot ac^{-1}$, current University of Minnesota Extension recommendations would call for the application of 75 $lbs\cdot ac^{-1}$ P_2O_5 in fields with Bray P concentrations in excess of 50 ppm.

Tuber yield

Results for Ivory Russet tuber yield at the grower site are presented in Table 3. The overall effect of treatment was significant for total yield, yield of U.S. No. 2 tubers, and marketable yield. Each of these measures of yield, as well as yield in the two largest size classes (10-14 oz. and > 14 oz.), increased linearly with P rate. The yield of U.S. No. 2 tubers and the percentage of yield in tubers over 6 oz. both showed quadratic responses to P rate, each having a lower value at the highest rate (450 $lbs\cdot ac^{-1}$ P_2O_5) than at the second-highest rate (300 $lbs\cdot ac^{-1}$ P_2O_5). Total and marketable yield, the yield of U.S. No. 1 tubers, and the yield of 10- to 14-oz. tubers were lower in the treatments in which P was banded at planting (treatments 8 and 9) than in the treatments in which P was broadcast before planting at the same rates (treatments 2 and 3). The mycorrhizal product had no significant effect on yield in this cultivar and this site.

Results for Russet Burbank tuber yield at the grower site are presented in Table 4. The yield of U.S. No. 2 tubers was lower in the treatments in which P was banded at planting (treatments 8 and 9) than the treatments in which it was broadcast before planting at the same rates (treatments 2 and 3). U.S. No. 2 tuber yield also had a marginally significant negative linear relationship with the application rate of P. There were no other significant effects of treatment on yield in this cultivar and this site.

Results for Ivory Russet tuber yield at the SPRF site are presented in Table 5. As was true of Ivory Russet at the grower site, total and marketable yield were positively related to the application rate of P. The same was true of U.S. No. 1 yield and the yield of 4- to 6-oz. tubers, although yield in these categories was lowest at intermediate P rates (75 to 150 lbs·ac^{-1} P_2O_5). As was true at the grower site, the yield of U.S. No. 2 tubers was highest at the second-highest P rate (300 lbs·ac^{-1} P_2O_5), and the percentage of yield represented by tubers over 6 or 10 oz. was lower at the lowest and highest P rates (0 and 450 lbs·ac^{-1} P_2O_5, respectively) than at other P rates. However, unlike at the grower site, U.S. No. 2 yield was not positively related to P rate overall. Yields in all size classes less than 14 oz. tended to increase as the application rate of P increased. Whether P fertilizer was broadcast before planting or banded at planting did not significantly affect tuber yield. The treatments receiving mycorrhizae (treatments 6 and7) had marginally significantly lower yields of tubers over 14 oz. than the treatments receiving P at the same rates with no added mycorrhizae (treatments 1 and 3).

Results for Russet Burbank tuber yield at the SPRF site are presented in Table 6. As was true at the grower site, Russet Burbank showed few significant responses to P treatment. The yield of 6- to 10-oz. tubers was significantly related to treatment, and the percentages of yield represented by tubers over 6 or 10 oz. were marginally significantly related to treatment with no consistent relationship to P rate. The contrast comparing treatments receiving mycorrhizae (treatments 6 and 7) with otherwise similar treatments receiving no mycorrhizae (treatments 1 and 3) was marginally significant for the yield of 6- to 10-oz. tubers and the percentage of yield represented by tubers over 6 oz. In each case, the values were higher in the treatments receiving mycorrhizae (treatments 6 and 7).

Overall, the application rate of P had a much stronger effect on yield in Ivory Russet than Russet Burbank. In both fields, total and marketable yields of Ivory Russet tubers increased as P rate increased, and the percentage of yield represented by tubers over 6 oz. peaked at an intermediate P rate (75 or 300 lbs·ac^{-1} P_2O_5). That Ivory Russet responded more strongly to P rate than Russet Burbank may reflect a less extensive root system in the former cultivar, which has determinate growth, than in the latter, which is indeterminate. It is also possible that Ivory Russet is less efficient than Russet Burbank at taking up soil P within the range of its root system, whether or not one cultivar has a more extensive root system than the other. The peak in tuber size at intermediate P rates may indicate that very high P rates result in increased tuber set in Ivory Russet.

Banded P fertilizer application had a negative effect on Ivory Russet total and marketable yield at the grower site, but not at SPRF. Banded application also decreased the yield of U.S. No. 2 tubers in Russet Burbank grown at the grower site. Banded application was expected to improve plant access to P, if the extensiveness of the root system limited P uptake. The fact that the few significant effects of banded application on yield in this study were negative indicates that this approach does not increase P uptake, although it is possible that tissue P concentrations will prove to be higher in the banded-application treatments. It is not clear why banded application only affected yield at the grower site. However, excessive P fertilizer application has been found to negatively impact crops through its impacts on both the soil microbial community and Zn availability. It is possible that the microbial community at the grower site was more sensitive to P rate, perhaps as a result of soil fumigation. Petiole analysis may provide information related to the P-Zn interaction, but results for this test were not available at the time of this report.

The application of MycoGold, a product containing mycorrhizal fungi, had no effect on Ivory Russet yield beyond a marginally significant decrease in the yield of tubers over 14 oz. at SPRF. In Russet Burbank, the addition of mycorrhizae marginally significantly decreased U.S. No. 2 yield at the grower site, but it marginally significantly increased the yield of 6- to 10-oz. tubers and the percentage of yield in tubers over 6 oz. at SPRF. It was anticipated that inoculation with mycorrhizae would improve P uptake, especially at the grower site, where native populations of mycorrhizal fungi may have been suppressed by soil fumigation. However, the effects of inoculation with mycorrhizal fungi were small, and they were more positive in the non-fumigated field at SPRF than in the fumigated field.

Tuber quality

Results for tuber quality characteristics of Ivory Russet grown at the grower site are presented in Table 7. The prevalence of hollow heart and brown center were significantly or marginally significantly related to P rate. This was due to the presence of both flaws in 3% of tubers in the treatment receiving P at a rate of 450 $lbs \cdot ac^{-1}$ P_2O_5 (treatment 5). If P rate truly affects the prevalence of these internal tuber defects, the effect is small and only detectable at very high P rates. The prevalence of scab showed a marginally significant tendency to peak at intermediate P rates of 75 to 300 $lbs \cdot ac^{-1}$ P_2O_5 among the treatments receiving P broadcast before planting without mycorrhizal inoculation (treatments 1-5).

Results for tuber quality characteristics of Russet Burbank grown at the grower site are presented in Table 8. P treatment had no significant effects on tuber quality in this cultivar at this location.

Results for tuber quality characteristics of Ivory Russet grown at SPRF are presented in Table 9. As was true of this cultivar at the grower site, the prevalence of brown center and scab increased marginally significantly with P rate, and this trend largely reflects the highest prevalence occurring at 450 $lbs \cdot ac^{-1}$ P_2O_5 (treatment 5) with a lower prevalence at 300 $lbs \cdot ac^{-1}$ P_2O_5 (treatment 4). The consistency of this result between sites may indicate that very high P rates do increase the risk of hollow heart and brown center in Ivory Russet, which seems to be related to an increase in larger tubers. Specific gravity was marginally significantly related to P treatment, but it was not related to P rate, banded versus broadcast application, or inoculation with mycorrhizae.

Results for tuber quality characteristics of Russet Burbank grown at SPRF are presented in Table 10. The prevalence of hollow heart and brown center increased marginally significantly with P rate, and these increases were seen across the range of P rates tested. There were no other significant effects of treatment on tuber quality in this cultivar at this site.

Overall, a significant or marginally significant positive relationship between P rate and the prevalence of hollow heart and brown center was observed in Ivory Russet at both sites and Russet Burbank at SPRF. This effect was only seen at very high P rates in Ivory Russet, but spanned the full range of P rates tested in Russet Burbank. The prevalence of hollow heart and brown center in Russet Burbank at SPRF was very high overall, and this may explain why the effect of P rate on the prevalence of these defects could be seen at lower P rates. The fact that this effect of P rate was present in three of the four combinations of cultivar and site suggests that, although the effect was not highly significant in any case, it was biologically meaningful. The prevalence of scab was far higher at SPRF than at the grower site in both cultivars. This is probably a result of soil fumigation at the grower site, although differences in cropping history between the two sites may have contributed.

Conclusions

Previous studies at SPRF indicated that Ivory Russet may show a stronger positive yield response to P rate in soils with high test P than Russet Burbank, and this was confirmed by our results, in which total and marketable Ivory Russet yield increased linearly with P rate in both the SPRF and grower fields while total and marketable Russet Burbank yield did not respond significantly to P rate.

Banded application of P fertilizer had no effect on tuber yield at SPRF and a negative effect on total and marketable Ivory Russet yield and the yield of U.S. No. 2 Russet Burbank tubers at the grower site. This is not consistent with potato P uptake being limited by its shallow root system, since banding placed ample P close to the seed tubers.

Tuber yield was neither more nor less responsive to P rate at the grower site, in which the soil was fumigated, than at SPRF, in which it was not. Treating tubers with a product containing mycorrhizal fungi had few effects on yield, and the only positive effects were on the yield of 6- to 10-oz. Russet Burbank tubers and the percentage of yield represented by tubers over 6 oz. at SPRF, in the absence of soil fumigation. Both of these results are inconsistent with P uptake being limited by access to mycorrhizal associates in fumigated fields.

The fact that tuber yield was similarly responsive to P rate in each site also indicates that the differences in Bray P and PSI between the two sites were not consequential in this regard. Application of high rates of P caused significant or marginally significant increases in the prevalence of hollow heart and brown center in Ivory Russet at both sites, as well as Russet Burbank at SPRF. The prevalence of scab was much higher in SPRF, which was not fumigated, than in the grower site, which was fumigated with metam sodium.

Table 1. Treatments applied to both Ivory Russet and Russet Burbank potatoes at both the Sand Plain Research Farm (SPRF) and a nearby grower field.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	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] MycoGold Potato Blend applied in-furrow at planting with a hand sprayer

Table 2. Soil characteristics in the Sand Plain Research Farm (SPRF) and the grower field in spring, before P fertilizer treatments were applied. MOP and gypsum had been applied to the grower at the time soil samples were taken.

Study field	0 - 6 inches															0 - 2 feet
	Bray P (ppm)	Melich-3 P (ppm)	Melich-3 Al (ppm)	PSI (%)	pH	Organic matter (%)	NH_4OAc-K (ppm)	NH_4OAc-Ca (ppm)	Mehlich-3 Mg (ppm)	Mehlich-3 Mn (ppm)	Mehlich-3 Fe (ppm)	Mehlich-3 Zn (ppm)	Mehlich-3 Cu (ppm)	Hot water B (ppm)	SO_4^{2-}-S (ppm)	NO_3^--N (ppm)
SPRF	126	198	850	23.3	6.6	2.1	160	1201	224	54	171	6.1	2.1	0.3	4	2.6
Grower	95	136	637	21.4	6.4	1.5	432	809	108	50	161	6.1	1.2	0.2	35	4.6

Table 3. Yield, size, and grade of tubers harvested from Ivory Russet potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	4	17	90	103	68	20 d	298 bc	249	32 e	281 bc	66	32
2	75	Broadcast	No	2	16	81	120	96	37 bcd	350 ab	288	46 cde	334 a	73	39
3	150	Broadcast	No	7	13	71	126	94	57 ab	361 a	273	75 abc	348 a	78	44
4	300	Broadcast	No	2	13	64	120	105	69 a	370 a	261	95 a	357 a	79	47
5	450	Broadcast	No	6	16	75	112	112	68 a	383 a	299	68 abcd	367 a	76	47
6	0	NA	Yes	12	11	60	99	79	39 abcd	288 c	217	60 bcde	277 c	75	41
7	150	Broadcast	Yes	5	12	68	111	99	52 abc	342 ab	248	81 ab	329 ab	77	44
8	75	Banded	No	7	19	78	106	68	30 bcd	300 bc	244	38 de	282 bc	69	35
9	150	Banded	No	3	14	65	111	73	22 cd	285 c	211	60 bcd	271 c	73	34
Treatment effect (P-value)				0.7600	0.5477	0.7618	0.6291	0.1317	**0.0683**	**0.0162**	0.3565	**0.0493**	**0.0123**	0.2838	0.4422
Contrasts (P-values)	Linear P rate (treatments 1-5)			0.7324	0.5738	0.3180	0.8139	**0.0273**	**0.0060**	**0.0179**	0.4011	**0.0198**	**0.0133**	**0.0718**	**0.0539**
	Quadratic P rate (treatments 1-5)			0.8350	0.2669	0.2190	0.1167	0.4022	0.1484	0.2275	0.8732	**0.0172**	0.1704	**0.0516**	0.2783
	Banded v. broadcast (2&3 vs. 8&9)			0.9178	0.5921	0.7455	0.1467	**0.0607**	0.1099	**0.0080**	**0.0644**	0.3946	**0.0058**	0.2100	0.2419
	Mycorrhizae (1&3 vs. 6&7)			0.4399	0.1801	0.1961	0.3572	0.5214	0.5983	0.5009	0.3134	0.2202	0.6072	0.3143	0.4052

Table 4. Yield, size, and grade of tubers harvested from Russet Burbank potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	1	43	178	169	74	36	500	420	37	457	56	23
2	75	Broadcast	No	1	43	183	181	74	34	516	432	40	472	56	21
3	150	Broadcast	No	1	49	206	167	82	28	532	450	33	483	52	21
4	300	Broadcast	No	1	48	201	181	84	31	546	463	35	497	55	21
5	450	Broadcast	No	0	47	195	173	79	22	516	444	25	469	53	19
6	0	NA	Yes	0	40	200	177	68	20	505	444	21	465	52	17
7	150	Broadcast	Yes	1	53	219	189	75	25	560	477	31	508	52	18
8	75	Banded	No	2	41	178	166	92	34	511	449	21	470	57	25
9	150	Banded	No	1	53	187	155	77	25	496	416	28	444	52	21
Treatment effect (P-value)				0.5581	0.8391	0.6567	0.5804	0.8355	0.7989	0.4367	0.5557	0.1060	0.5388	0.8834	0.8265
Contrasts (P-values)	Linear P rate			0.2229	0.6036	0.3931	0.8303	0.6108	0.2123	0.4821	0.3183	**0.0621**	0.5820	0.4844	0.5723
	Quadratic P rate			0.4948	0.6337	0.3163	0.7571	0.5228	0.9178	0.1637	0.2572	0.5300	0.2041	0.7272	0.9928
	Banded v. broadcast (2&3 vs. 8&9)			0.4506	0.9067	0.4531	0.2396	0.5287	0.8539	0.3505	0.6647	**0.0232**	0.3253	0.9065	0.5670
	Mycorrhizae (1&3 vs. 6&7)			0.3309	0.9578	0.2889	0.1887	0.4886	0.2389	0.4373	0.2406	**0.0891**	0.4401	0.4630	0.1947

Table 5. Yield, size, and grade of tubers harvested from Ivory Russet potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	3	19	70 bc	72	41	32	233 c	152 bcd	62	214 c	61	31
2	75	Broadcast	No	3	13	61 bcd	71	58	35	237 c	140 cd	84	224 c	69	39
3	150	Broadcast	No	2	13	62 bcd	72	54	27	228 c	131 d	84	215 c	67	36
4	300	Broadcast	No	2	23	69 bcd	82	67	40	281 ab	160 bcd	98	258 ab	67	38
5	450	Broadcast	No	4	25	93 a	91	64	25	298 a	204 a	69	273 a	60	30
6	0	NA	Yes	2	17	57 cd	84	52	20	230 c	142 bcd	71	214 c	68	31
7	150	Broadcast	Yes	1	25	77 ab	75	52	15	245 c	171 b	49	220 c	59	28
8	75	Banded	No	6	15	52 d	79	58	28	232 c	139 cd	78	216 c	71	37
9	150	Banded	No	4	17	64 bcd	74	60	35	252 bc	168 bc	66	234 bc	67	38
Treatment effect (P-value)				0.8211	0.1964	**0.0311**	0.3962	0.5475	0.1866	**0.0039**	**0.0142**	0.1379	**0.0074**	0.2806	0.3128
Contrasts (P-values)	Linear P rate			0.6597	**0.0508**	**0.0131**	**0.0145**	**0.0511**	0.6411	**<0.0001**	**0.0015**	0.6337	**0.0002**	0.5735	0.6430
	Quadratic P rate			0.3435	0.2302	**0.0396**	0.5437	0.2879	0.3968	0.3940	**0.0171**	**0.0230**	0.5962	**0.0720**	**0.0668**
	Banded v. broadcast (2&3 vs. 8&9)			0.2270	0.3931	0.6623	0.4633	0.6917	0.8641	0.4738	0.1748	0.2792	0.6195	0.8203	0.9755
	Mycorrhizae (1&3 vs. 6&7)			0.7543	0.2114	0.8410	0.2568	0.5568	**0.0736**	0.5847	0.2570	0.2547	0.8579	0.7934	0.3250

Table 6. Yield, size, and grade of tubers harvested from Russet Burbank potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	3	59	150	80 bc	15	2	306	218	28	246	32 c	6 c
2	75	Broadcast	No	6	51	122	110 a	37	12	332	255	26	281	48 a	15 a
3	150	Broadcast	No	4	64	157	68 c	25	4	319	225	29	255	31 c	10 bc
4	300	Broadcast	No	7	54	141	88 b	29	5	317	235	28	263	39 bc	11 b
5	450	Broadcast	No	6	73	141	82 bc	29	6	330	233	24	257	35 bc	10 b
6	0	NA	Yes	5	54	124	90 b	27	7	303	225	23	248	41 ab	11 ab
7	150	Broadcast	Yes	7	62	146	85 bc	27	2	322	236	24	260	36 bc	9 bc
8	75	Banded	No	6	52	119	84 bc	32	4	291	210	29	239	41 ab	12 ab
9	150	Banded	No	7	57	144	96 ab	25	6	329	250	22	271	40 abc	10 b
Treatment effect (P-value)				0.7876	0.6137	0.3562	**0.0401**	0.1327	0.1187	0.4259	0.2613	0.6176	0.3920	**0.0910**	**0.0638**
Contrasts (P-values)	Linear P rate			0.2800	0.2106	0.9570	0.5458	0.2383	0.9956	0.4555	0.8418	0.4821	0.9901	0.7867	0.4420
	Quadratic P rate			0.5091	0.3359	0.9539	0.9633	0.1272	0.4765	0.8897	0.5399	0.5522	0.4399	0.4489	0.1089
	Banded v. broadcast (2&3 vs. 8&9)			0.5336	0.7128	0.5322	0.8886	0.6162	0.1393	0.2664	0.4086	0.5218	0.3187	0.7982	0.4938
	Mycorrhizae (1&3 vs. 6&7)			0.1456	0.6210	0.1489	**0.0672**	0.1243	0.5772	0.9985	0.4564	0.1107	0.7521	**0.0661**	0.1266

Table 7. Quality characteristics of tubers harvested from Ivory Russet potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				------------ % of tubers ------------				%
1	0	NA	No	0	0 b	8	1.0811	21.04
2	75	Broadcast	No	2	1 b	18	1.0814	21.07
3	150	Broadcast	No	0	0 b	17	1.0776	20.60
4	300	Broadcast	No	1	0 b	18	1.0805	21.02
5	450	Broadcast	No	3	3 a	9	1.0782	20.19
6	0	NA	Yes	0	0 b	17	1.0781	20.85
7	150	Broadcast	Yes	0	0 b	13	1.0787	20.15
8	75	Banded	No	0	0 b	14	1.0801	22.11
9	150	Banded	No	0	0 b	25	1.0784	20.96
			Treatment effect (P-value)	0.1713	**0.0673**	0.4683	0.2767	0.2578
Contrasts (P-values)			Linear P rate	**0.0574**	**0.0158**	0.8447	0.1506	0.2699
			Quadratic P rate	0.3704	**0.0538**	**0.0818**	0.7076	0.6743
			Banded v. broadcast (2&3 vs. 8&9)	0.2668	0.4739	0.6873	0.8719	0.1685
			Mycorrhizae (1&3 vs. 6&7)	1.0000	1.0000	0.6885	0.4617	0.5255

Table 8. Quality characteristics of tubers harvested from Russet Burbank potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				------------ % of tubers ------------				%
1	0	NA	No	4	4	1	1.0769	19.80
2	75	Broadcast	No	0	0	3	1.0792	20.45
3	150	Broadcast	No	4	1	1	1.0782	20.28
4	300	Broadcast	No	4	3	0	1.0771	20.40
5	450	Broadcast	No	3	2	1	1.0803	20.12
6	0	NA	Yes	1	1	3	1.0795	20.31
7	150	Broadcast	Yes	3	2	1	1.0785	20.12
8	75	Banded	No	3	2	1	1.0795	20.23
9	150	Banded	No	2	2	1	1.0786	20.41
			Treatment effect (P-value)	0.3666	0.5554	0.4259	0.6570	0.9860
Contrasts (P-values)			Linear P rate	0.6193	0.9842	0.3424	0.2428	0.7726
			Quadratic P rate	0.8624	0.3511	0.7598	0.5518	0.3582
			Banded v. broadcast (2&3 vs. 8&9)	0.7118	0.2466	0.3177	0.7722	0.9146
			Mycorrhizae (1&3 vs. 6&7)	0.1479	0.4363	0.3073	0.2685	0.6885

Table 9. Quality characteristics of tubers harvested from Ivory Russet potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				------------ % of tubers		-------------		%
1	0	NA	No	2	2	71	1.0712 abc	19.70
2	75	Broadcast	No	0	0	89	1.0676 cd	19.65
3	150	Broadcast	No	0	0	95	1.0682 cd	19.39
4	300	Broadcast	No	3	2	61	1.0738 ab	20.59
5	450	Broadcast	No	6	6	73	1.0714 abc	20.10
6	0	NA	Yes	0	1	71	1.0706 abcd	20.33
7	150	Broadcast	Yes	1	2	71	1.0697 bcd	20.03
8	75	Banded	No	0	0	96	1.0662 d	19.29
9	150	Banded	No	2	2	67	1.0746 a	21.26
	Treatment effect (P-value)			0.4613	0.5670	0.2443	**0.0842**	0.6993
Contrasts (P-values)	Linear P rate			**0.0542**	**0.0752**	0.3655	0.2260	0.4386
	Quadratic P rate			0.2031	0.1411	0.5216	0.7634	0.9106
	Banded v. broadcast (2&3 vs. 8&9)			0.6345	0.6388	0.3396	0.2128	0.3264
	Mycorrhizae (1&3 vs. 6&7)			0.8118	0.8142	0.2725	0.8188	0.4062

Table 10. Quality characteristics of tubers harvested from Russet Burbank potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				------------ % of tubers		-------------		%
1	0	NA	No	17	15	69	1.0617	18.36
2	75	Broadcast	No	18	17	82	1.0619	17.34
3	150	Broadcast	No	21	17	64	1.0615	17.90
4	300	Broadcast	No	22	20	89	1.0623	18.85
5	450	Broadcast	No	25	24	67	1.0605	18.32
6	0	NA	Yes	17	16	79	1.0628	17.85
7	150	Broadcast	Yes	17	11	80	1.0631	18.18
8	75	Banded	No	18	15	64	1.0626	17.37
9	150	Banded	No	16	15	77	1.0644	18.58
	Treatment effect (P-value)			0.5075	0.4662	0.4343	0.3826	0.1283
Contrasts (P-values)	Linear P rate			**0.0572**	**0.0612**	0.9552	0.4786	0.1980
	Quadratic P rate			0.9199	0.7908	0.2736	0.4203	0.9127
	Banded v. broadcast (2&3 vs. 8&9)			0.4112	0.5609	0.7663	0.1173	0.3642
	Mycorrhizae (1&3 vs. 6&7)			0.4795	0.5191	0.1501	0.1918	0.7592

Evaluation of Mosaic products as P, S, Mg, and Zn sources for Russet Burbank potatoes

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Summary

In potato production, phosphorus (P) application can improve tuber yield and quality even in soils with high soil-test P concentrations. Sulfur (S) deficiency is not as common in potato, but it can occur on sandy soils. . Evenly applying secondary macronutrients like S and magnesium (Mg) and micronutrients and zinc (Zn) can be challenging because the recommended application rates are quite low. One approach to simplifying the even application of low-application-rate nutrients is cogranulation with primary macronutrients, which are applied at much higher rates. The purpose of this study was to evaluate five products from The Mosaic Company formulated using this cogranulation approach: MicroEssentials S10 (12-40-0-10S), MicroEssentials SZ (12-40-0-10S-1Zn), and K-Mag (0-0-22-22S-11Mg), as well as two experimental products identified as EXPCRG (5-28-0-10Mg) and EXPA10S (14-24-0-10S). These products were evaluated against conventional P and S sources in an experiment with a randomized complete block design and four replicates at the Sand Plain Research Farm (SPRF) in Becker, MN. Treatment was found to have no significant effects on tuber yield, grade, size, or quality. The soil in the study site had high soil-test concentrations of P, Mg, and Zn, which may explain the lack of response to differing application rates of these nutrients. Although potatoes sometimes show positive yield responses to P fertilization even in high-P soils, other studies at the SPRF have found that Russet Burbank is not highly responsive to P application when soil-test P concentration is high. While the soil sulfate-S concentration was low, some S may have been supplied through irrigation water.

Background

Phosphorus (P) management is important in potato production because P promotes canopy growth, tuber set, and starch production, with positive implications for tuber yield and quality. Potatoes have a high soil P requirement both because P is essential to potato plant growth and tuber production and because potato plants use soil P inefficiently. As a result, potatoes may exhibit a positive yield response to P application even in soils with high soil-test P concentrations.

Sulfur (S) deficiency is not as common in potato production, but it can occur on sandy soils because sulfate leaches readily from such soils. Sulfur application rate recommendations for meeting potato crop needs in sandy soils can be based on soil sulfate-S tests, with University of Minnesota Extension recommending 10-15 lbs·ac^{-1} S as a banded application or 20-30 lbs·ac^{-1} S as a broadcast application. When sulfate-S concentration is less than 7 ppm.

The lower the desired application rate of a nutrient is, the more difficult it is to apply the nutrient evenly across the field. Uneven application may mean that micronutrient deficiencies are not corrected across areas relevant to individual plants, resulting in spatially heterogeneous micronutrient deficiencies (and possibly excesses). One approach to improving evenness of application is to cogranulate secondary macronutrients and micronutrients with primary macronutrients that are applied at much higher rates. The Mosaic Company has formulated several fertilizer products based on this approach.

The purpose of this study was to evaluate five such products as sources of P and S, as well as potassium (K), magnesium (Mg), and zinc (Zn). These include the commercially available products MicroEssentials S10 (MES10; 12-40-0-10S), MicroEssentials SZ (MESZ; 12-40-0-10S-

1Zn), and K-Mag (0-0-22-22S-11Mg), as well as two experimental products identified as EXPCRG (5-28-0-10Mg) and EXPA10S (14-24-0-10S).

Methods

Study design

The study was conducted in 2020 on a Hubbard loamy sand soil at the Sand Plain Research Farm in Becker, MN. The previous crop was rye. In a randomized complete block design with four replicates, nine fertilizer treatments were broadcast applied at planting: (1) a treatment receiving N and K as a blend of urea (46-0-0) and muriate of potash (MOP; 0-0-60) with no P; (2) a treatment receiving N, P, and K as a blend of urea, MOP, and monoammonium phosphate (MAP; 11-52-0); (3) a treatment receiving N, P, K, and S as a blend of urea, MOP, MAP, and ammonium sulfate (21-0-0-24S); (4) a treatment receiving N, P, K, and S as a blend of urea, MOP, and MES10 (12-40-0-10S); (5) a treatment receiving N, P, K, S, and Zn as a blend of urea, MOP, and MESZ (12-40-0-10S-1Zn); (6) a treatment receiving N, P, K, S, and Mg as a blend of urea, MAP, and K-Mag (0-0-22-22S-11Mg); (7) a treatment receiving N, P, K, and Mg as a blend of urea, MOP, MAP, and EXPCRG (5-28-0-10Mg), with MAP and EXPCRG each providing 50 $\text{lbs}\cdot\text{ac}^{-1}$ P_2O_5; (8) a treatment similar to treatment 7, except that 75 $\text{lbs}\cdot\text{ac}^{-1}$ P_2O_5 came from MAP and 25 $\text{lbs}\cdot\text{ac}^{-1}$ P_2O_5 came from EXPCRG; and (9) a treatment receiving N, P, K, and S as a blend of urea, MOP, MAP, and EXPA10S (14-24-0-10S). All treatments received 6.7 $\text{lbs}\cdot\text{ac}^{-1}$ Granubor (15% B), supplying 1 $\text{lb}\cdot\text{ac}^{-1}$ B. The treatments were applied to plots 20 feet long and 12 feet (four rows) wide. The treatments are summarized in Table 1.

Soil Sampling

On April 10, 2020, before fertilizers were applied, soil samples to a depth of six inches were collected, dried at 95°F until their weights were constant, and sent to the University of Minnesota Research Analytical Laboratory (UMRAL; St. Paul, MN) to be analyzed for Bray P; NH_4OAc-extractable K, Ca, and Mg; $Ca(H_2PO_2)_2$ / Ba-extractable SO_4-S; hot-water-extractable B; DTPA-extractable Cu, Fe, Mn, and Zn; soil water pH; and LOI soil organic matter content. NO_3^--N concentrations in two-foot soil samples collected on the same date were measured using a Wescan Nitrogen Analyzer. Results are presented in Table 2.

Planting and post-planting N management

On April 20, 500 $\text{lbs}\cdot\text{ac}^{-1}$ MOP (0-0-60) were broadcast to the entire field, providing 300 $\text{lbs}\cdot\text{ac}^{-1}$ K. On May 13, planting rows were opened and fertilizer was broadcast applied by hand to each plot according to treatment. A mixture of cut "A" and whole "B" Russet Burbank seed (2-3 oz.) was planted with 12" spacing within rows and 36" spacing between rows. At row closure, Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris. Throughout the season, weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling.

At hilling, on May 19, 165 $\text{lbs}\cdot\text{ac}^{-1}$ N were applied to the entire field as ESN (Nutrien, Ltd.; 44-0-0). On each of three days, July 2, 9, and 23, 20 $\text{lbs}\cdot\text{ac}^{-1}$ N was applied to all plots as 28% UAN. In total, all plots received 275 $\text{lbs}\cdot\text{ac}^{-1}$ N, 330 $\text{lbs}\cdot\text{ac}^{-1}$ K_2O, and 1 $\text{lb}\cdot\text{ac}^{-1}$ B, and all treatments except the zero-P treatment (treatment 1) received 100 $\text{lbs}\cdot\text{ac}^{-1}$ P_2O_5.

Plant stand, stems per plant, and petiole sampling

Plant stand was assessed in the central 18 feet of each of the central two rows of each plot (36 planted tubers in total) on June 4 (16 days after emergence fertilizer was applied). The number of stems per plant was determined on June 15 (27 days after emergence) for 10 plants in the same area where stand was assessed. On June 23, July 8 and 23, and August 4, the petiole of the fourth mature leaf from the shoot tip was collected for 20 leaves per plot. Petioles were dried at 140°F until their weight was stable, ground, and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer. They will also be analyzed for elemental concentrations of P, K, S, Mg, and Zn by UMRAL using inductively coupled plasmolysis.

Tuber harvest

Vines were chopped on September 14, 124 days after planting. Tubers were harvested from the central 18 feet of the middle two rows of each plot on September 25 and sorted by size and grade on October 19.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. Data were analyzed as functions of treatment and block. Petiole NO_3^--N data were analyzed for each sampling date separately. For each dependent variable, means for each treatment were calculated and post-hoc pairwise comparisons between treatments made using the LSMEANS statement with the DIFF option. Pairwise comparisons were only evaluated where the P-value of the treatment effect in the model was less than 0.10, and pairwise comparisons with P-values less than 0.10 were considered significant.

Results and discussion

Tuber harvest

Results for tuber yield, size, and grade are presented in Table 3. Treatment was not significantly related to any measure of tuber yield, size, or grade. The zero-P treatment (treatment 1) did not have low tuber yields or sizes relative to the treatments receiving 100 $\text{lbs}\cdot\text{ac}^{-1}$ P_2O_5 (treatments 2-9). Bray P tests performed on pre-fertilization soil samples indicated that soil P concentrations in this site were very high (85 ppm, on average; Table 2). Potatoes may show positive yield responses to P fertilization even on high-P soils, but results from other studies conducted at the SPRF indicate that Russet Burbank is not as highly responsive to P rate as other varieties under these conditions. While the soil sulfate-S concentration was low (4 ppm; Table 2), there was no evident tuber yield response to S rate in this study. In irrigated systems, crop S requirements are sometimes met though sulfate dissolved in irrigation water alone, and that may have been the case in this study. Concentrations of Mg and Zn at the study site (157 ppm and 3.4 ppm, respectively; Table 2) are considered sufficient to require no application of either nutrient in fertilizer.

Tuber quality

Results for tuber quality are presented in Table 4. Treatment was not significantly related to the prevalence of hollow heart, specific gravity, or dry matter content. Scab and brown center were not detected in this study. The absence of brown center was unexpected, given the high prevalence of hollow heart.

Conclusions

Tuber yield, size, grade, and quality did not respond to treatment in this study. Soil P, Mg, and Zn concentrations in the study site were all high, which may have precluded a response. Soil sulfate-S concentrations were low, but crop S requirements may have been met by sulfate dissolved in the irrigation water.

Table 1. Fertilizers and nutrients applied at planting to Russet Burbank potatoes grown at the Sand Plain Research Farm in 2020 to evaluate fertilizer products from The Mosaic Company.

Treatment #	Descripton	Fertilizers applied at planting[1] (lbs·ac^{-1})	Nutrients applied at planting (lbs/ac)						
			N	P_2O_5	K_2O	S	Mg	B	Zn
1	No P	108.7 urea; 50 MOP	50	0	30	0	0	1	0
2	MAP	62.7 urea; 50 MOP; 192.3 MAP	50	100	30	0	0	1	0
3	MAP/AmSulf	5.6 urea; 50 MOP; 192.3 MAP; 125 AmSulf	50	100	30	30	0	1	0
4	MES10	43.5 urea; 50 MOP; 250 MES10	50	100	30	25	0	1	0
5	MESZ	43.5 urea; 50 MOP; 250 MESZ	50	100	30	25	0	1	2.5
6	Map/K-Mag	62.7 urea; 192.3 MAP; 136.4 KMag	50	100	30	30	15	1	0
7	MAP:EXPCRG 1:1	66.3 urea; 50 MOP; 96.2 MAP; 178.6 EXPCRG	50	100	30	0	17.9	1	0
8	MAP:EXPCRG 3:1	64.5 urea; 50 MOP; 144.2 MAP; 89.3 EXPCRG	50	100	30	0	8.9	1	0
9	MAP/EXPA10S	4.5 urea; 50 MOP; 53.8 MAP; 300 EXPA10S	50	100	30	30	0	1	0

[1] Urea: 46-0-0; MOP: 0-0-60; MAP: 11-52-0; Ammonium sulfate: 21-0-0-24S; MES10: 12-40-0-10S; MESZ: 12-40-0-10S-1Zn; K-Mag: 0-0-22-22S-11Mg; EXPCRG: 5-28-0-10Mg; EXPA10S: 14-24-0-10S. All treatments received 6.7 lbs·ac^{-1} Granubor (15% B).

Table 2. Initial soil characteristics at the study site.

0 - 2 feet	0 - 6 inches				
Primary macronutrients			Secondary macronutrients		
(mg·kg^{-1} soil)					
NO_3^--N	Bray P	K	Ca	Mg	SO_4-S
1.4	85	143	641	157	4.0

0 - 6 inches						
Micronutrients					Other characteristics	
(mg·kg^{-1} soil)					pH	Organic matter (%)
Fe	Mn	Zn	Cu	B		
33	5.4	3.4	1.05	0.22	6.9	1.8

Table 3. Response of tuber yield, grade, and size to fertilizer treatments applied to Russet Burbank potatoes.

Treatment #	Description	Yield (CWT·ac^{-1})										% yield in tubers > than:	
		Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	U.S. No. 1	U.S. No. 2	Marketable	6 oz.	10 oz
1	No P	2	59	210	123	61	20	473	398	17	414	43	17
2	MAP	3	64	202	117	42	23	449	371	14	385	40	15
3	MAP/Ammonium sulfate	4	57	205	130	67	30	490	413	20	433	45	19
4	MES10	7	65	203	117	48	18	450	369	17	386	40	14
5	MESZ	4	72	205	111	34	20	443	356	14	370	37	12
6	Map/K-Mag	1	68	216	124	44	24	476	390	17	408	40	14
7	MAP/EXPCRG 5	2	70	200	128	44	9	451	370	11	381	40	12
8	MAP/EXPCRG 7	3	57	196	121	60	16	449	379	13	392	43	17
9	MAP/EXPA10S	3	63	207	117	41	16	444	364	17	381	38	12
Effect of treatment (P-value)		0.5620	0.8049	0.9978	0.9708	0.3634	0.5860	0.9364	0.9198	0.8560	0.9043	0.7490	0.5765

Table 4. Responses of tuber quality characteristics to fertilizer treatments applied to Russet Burbank potatoes.

Treatment #	Description	Percentage of tubers			Specific gravity	Dry matter content (%)
		Hollow heart	Brown center	Scab		
1	No P	21	0	0	1.0763	20.9
2	MAP	12	0	0	1.0729	19.9
3	MAP/Ammonium sulfate	17	0	0	1.0740	20.1
4	MES10	16	0	0	1.0717	19.7
5	MESZ	22	0	0	1.0750	21.0
6	Map/K-Mag	17	0	0	1.0776	20.4
7	MAP/EXPCRG 5	20	0	0	1.0739	20.4
8	MAP/EXPCRG 7	13	0	0	1.0722	20.4
9	MAP/EXPA10S	21	0	0	1.0739	19.8
Effect of treatment (P-value)		0.8268	-	-	0.2815	0.4802

Evaluation of NACHURS products in Russet Burbank potatoes

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Summary: Potato growers are interested in fertilizer products that can meet crop nutrient requirements at low application rates, minimizing nutrient losses. NACHURS has formulated several in-furrow and foliar fertilizer products intended to meet this demand. The purpose of this study was to evaluate the effectiveness of some of these products – K-flex, 6-24-6, Green Flag, K-fuel, Rhyzo-Link-0-0-15, and Finish Line – as nutrient sources for Russet Burbank potatoes in an irrigated system. Seven treatments were evaluated in a randomized complete block design with four replicates, receiving: (1) none of the above products, (2) 2 gal·ac^{-1} K-flex banded at planting, (3) 8 gal·ac^{-1} 6-24-6 in-furrow at planting, (4) 8 gal·ac^{-1} Green Flag in-furrow at planting, (5) 5 gal·ac^{-1} 6-24-6, 2 gal·ac^{-1} K-fuel, and 1 gal·ac^{-1} Rhyzo-Link-0-0-15 in furrow at planting, (6) 2 gal·ac^{-1} K-fuel and 1 qt·ac^{-1} Finish Line in a foliar application 49 days after emergence, and (7) 8 gal·ac^{-1} 6-24-6 in-furrow at planting plus 2 gal·ac^{-1} K-fuel and 1 qt·ac^{-1} Finish Line in a foliar application 49 days after emergence. There was no significant relationship between tuber yield, grade, size, or quality and the treatment applied. However, the number of 0-4-oz. tubers and total tubers per plant were both related to treatment. The treatment receiving K-flex in-furrow at planting (treatment 2) had the highest counts of undersized and total tubers per plant, while the treatment receiving 6-24-6, K-fuel, and Finish Line (treatment 7) had the lowest counts in each category. It is possible that K-flex promotes tuber initiation or prevents tuber reabsorption. It is not clear that any particular product used in treatment 7 accounted for the relatively low tuber counts in that treatment, since the other treatments in which each of these products was used had intermediate tuber counts.

Background:

Potato growers are interested in fertilizer products that can meet potato crop nutrient needs at low application rates to optimize yield while reducing nutrient losses. Because they place nutrients on or close to seed tubers or foliage, banded, in-furrow, and foliar applications potentially increase the efficiency of nutrient delivery. The particular nutrient salts applied may also affect how readily plants take up nutrients and how rapidly the nutrients are lost to leaching or fixation, and soil organisms may influence how accessible nutrients are to plant roots.

NACHURS has formulated several products with these concepts in mind. K-flex (0-0-19-6S), Green Flag (8-21-5), K-fuel (0-0-24), Rhyzo-Link 0-0-15 (0-0-15-5S), and Finish Line (8-4-6-0.1B-0.2Cu-1Mn-1Zn) provide K in the form of K acetate, while 6-24-6 provides most of its P as orthophosphate. These K and P sources are considered to be more readily available to plants than other P and K salts. Finish Line also provides several micronutrients in chelated form, which may prevent nutrient loss through fixation in the soil. Rhyzo-Link contains multiple species of *Bacillus* bacteria intended to improve plant access to soil nutrients through the secondary metabolites they release into the rhizosphere. The purpose of this study was to evaluate the effectiveness of these products as banded, in-furrow, and foliar nutrient sources for Russet Burbank potatoes grown under irrigation.

Methods:

Study design

The study was conducted in 2020 at the Sand Plain Research Farm in Becker, MN, on a Hubbard loamy sand soil under linear irrigation. The previous crop was rye. Seven treatments were applied in a randomized complete block design with four replicates: (1) a baseline treatment receiving standard fertilizers targeting 500-600 cwt·ac^{-1} yield, including 20 gal·ac^{-1} 10-34-0 and 1 qt·ac^{-1} NACHURS 9% Zn banded at planting; (2) a treatment receiving the baseline fertilizers plus 2 gal·ac^{-1} NACHURS K-flex banded at planting; (3) a treatment receiving the baseline fertilizers, with the rate of 10-34-0 reduced to 12 gal·ac^{-1}, plus 8 gal·ac^{-1} NACHURS 6-24-6 applied in-furrow at planting; (4) a treatment receiving the baseline fertilizers at the same rate as treatment 3 plus 8 gal·ac^{-1} NACHURS Green Flag in-furrow at planting; (5) a treatment receiving the baseline fertilizers at the same rate as treatments 3 and 4 plus 5 gal·ac^{-1} NACHURS 6-24-6, 2 gal·ac^{-1} NACHURS K-fuel, and 1 gal·ac^{-1} NACHURS Rhyzo-Link 0-0-15 in-furrow at planting; (6) a treatment receiving the same fertilizers at the same rate as treatment 1, plus a foliar application of 2 gal·ac^{-1} NACHURS K-fuel and 1 qt·ac^{-1} NACHURS Finish Line 49 days after emergence fertilizer application; and (7) a treatment receiving the same fertilizers at the same rates as treatment 3, plus the same foliar fertilizer application as treatment 6. These treatments are summarized in Table 1, and the total application rates of nutrients applied to each treatment are summarized in Table 2. The study was composed of 28 plots, each 20 feet long and 12 feet (four rows) wide.

Soil sampling

Pre-treatment soil samples to a depth of six inches were collected on April 10, 2020 and sent to the University of Minnesota's Research Analytical Laboratory (St. Paul, MN) to be analyzed for Bray P; NH_4OAc-extractable K, Ca, and Mg; $Ca(H_2PO_2)_2$ / Ba-extractable SO_4-S; hot-water-extractable B; DTPA-extractable Cu, Fe, Mn, and Zn; soil water pH; and LOI soil organic matter content. Two-foot samples were collected on the same day to be analyzed for NO_3^--N concentrations using a Wescan Nitrogen Analyzer. Results are presented in Table 3.

Planting

All plots received 300 lbs·ac^{-1} K_2O as 500 lbs·ac^{-1} MOP (0-0-60) broadcast on April 20. On May 8, N and P were applied by hand as urea (46-0-0) and diammonium phosphate (18-46-0) and worked in with a field cultivator. The amounts of urea and DAP applied to each treatment were as required to provide a total of 40 lbs·ac^{-1} N and 80.8 lbs·ac^{-1} P_2O_5 when added to rates provided by the NACHURS products in each treatment. Treatments 1 through 7 received, respectively, 34.7, 34.7, 34.6, 28.4, 32.2, 34.4, and 34.2 lbs·ac^{-1} urea and 3.5, 3.5, 26.1, 32.9, 43.3, 3.3, and 25.9 lbs·ac^{-1} DAP.

Cut "A" Russet Burbank seed was planted in all plots on May 11, with 12" spacing within rows and 36" spacing between rows. Liquid fertilizer products were applied in-furrow as specified by treatment prior to row closure. Belay was also applied in-furrow at planting for beetle control, along with the systemic fungicide Quadris. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling.

Post-planting fertilizer

At hilling, on May 19, 327 lbs·ac^{-1} ESN (44-0-0), 208 lbs·ac^{-1} ammonium sulfate (21-0-0-24S), and 167 lbs·ac^{-1} MOP were mechanically banded in all plots, providing 188 lbs·ac^{-1} N, 100 lbs·ac^{-1} K_2O, and 50 lbs·ac^{-1} S. N was applied to all plots at 12 lbs·ac^{-1} as 28% UAN on July 6. On July 7, foliar sprays were applied to treatments 6 and 7 as indicated in Table 1. On July 9, an additional 20 lbs·ac^{-1} N were applied as 28% UAN to all plots.

Plant stand and stems per plant

Plant stand was assessed in the central 18 feet of each of the central two rows of each plot (36 planted tubers in total) on June 4 and June 11 (16 days and 23 days after emergence fertilizer was applied, respectively). The number of stems per plant was determined on June 15 (27 days after emergence) for 10 plants in the same area where stand was assessed.

Petiole sampling

Petioles were collected from the fourth mature leaf from the tip of 20 shoots per plot on June 30 (7 days before foliar spray in treatments 6 and 7), July 15 (8 days after foliar spray), and August 10. Petioles were dried at 140°F until their weight was stable, ground, and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer.

Tuber harvest

On September 11, five plants were dug by hand from the central 18 feet of the two central rows in each plot. The tubers from each sample were sorted by weight and grade, and the tubers in each weight/grade category were counted on September 24. On September 14, 126 days after planting and 118 days after emergence, the vines in all plots were mechanically beaten. On September 25, the central 18 feet of the middle two rows of each plot were harvested. The tubers were sorted and graded on October 1, and the weights of tubers in each size/grade category were combined with those from the hand-counted tubers to determine yield per acre.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. Data were analyzed as functions of treatment and block. Petiole NO_3^--N data were analyzed for each sampling date separately. For each dependent variable, means for each treatment were calculated and post-hoc pairwise comparisons between treatments made using the LSMEANS statement with the DIFF option. Pairwise comparisons were only evaluated where the P-value of the treatment effect in the model was less than 0.10, and pairwise comparisons with P-values less than 0.10 were considered significant.

Results and discussion

Tuber yield, size, grade, and number

Results for tuber yield, grade, and size are presented in Table 4. Product application had no significant effect on tuber yield in any size class, yield of culled tubers, total or marketable yield, yield of U.S. No. 1 or 2 tubers, or the percentage of yield represented by tubers over 6 or 10 ounces.

Results for tuber counts are presented in Table 5. The total number of tubers per plant and the number of undersized tubers per plant were significantly related to the products applied. Both counts were highest in the treatment receiving 2 $gal \cdot ac^{-1}$ K-flex banded at planting (treatment 2) and lowest in the treatment receiving 8 $gal \cdot ac^{-1}$ 6-24-6 in-furrow at planting with a foliar application of 2 $gal \cdot ac^{-1}$ K-fuel and 1 $qt \cdot ac^{-1}$ Finish Line 49 days after emergence (treatment 7). Treatment 2 was the only treatment in which K-flex was applied, and it is possible that K-flex promoted tuber initiation or prevented tubers from being reabsorbed. None of the products used in treatment 7 was consistently associated with low tuber counts or numbers of undersized tubers across treatments.

Tuber quality

Results for tuber quality are presented in Table 6. The prevalence of hollow heart, brown center, and scab and tuber specific gravity and dry matter content were not significantly related to treatment.

Conclusions

We found no effects of treatment on tuber yield, size, grade, or quality. The number of undersized tubers and the total number of tubers per plant were related to treatment, with the most tubers per plant in the treatment receiving K-flex in-furrow at planting (treatment 2) and the fewest in the treatment receiving 6-24-6 in-furrow and K-fuel and Finish Line as a foliar application 49 days after emergence (treatment 7). It is possible that K-flex either promoted tuber initiation or prevented tuber reabsorption. It is not clear whether 6-24-6, K-fuel, or Finish Line, individually, affected tuber number.

Table 1. Products applied in each treatment and their timing and rate of application to Russet Burbank potatoes grown at the Sand Plain Research Farm.

Treatment #	Banded at planting (per acre)	In-furrow at planting (per acre)	49 DAE[1] (per acre)
1	20 gal 10-34-0, 1 qt 9% Zn	-	-
2	20 gal 10-34-0, 1 qt 9% Zn, 2 gal K-flex	-	-
3	12 gal 10-34-0, 1 qt 9% Zn	8 gal 6-24-6	-
4	12 gal 10-34-0, 1 qt 9% Zn	8 gal Green Flag	-
5	12 gal 10-34-0, 1 qt 9% Zn	5 gal 6-24-6, 2 gal K-fuel, 1 gal Rhyzo-Link 0-0-15	-
6	20 gal 10-34-0, 1 qt 9% Zn	-	2 gal K-fuel, 1 qt Finish Line
7	12 gal 10-34-0, 1 qt 9% Zn	8 gal 6-24-6	2 gal K-fuel, 1 qt Finish Line

[1] Days after emergence

Table 2. Nutrients applied to each treatment, including DAP (18-46-0) and urea (46-0-0) to maintain consistent N and P rates and 300 lbs·ac^{-1} K_2O as MOP (0-0-60) applied to all treatments before planting.

Treatment #	Products applied (with 10-34-0 and 9% Zn)	Total nutrient applied, including other fertilizers (lbs·ac^{-1})							
		N	P_2O_5	K_2O	S	Mn	Zn	B	Cu
1	-	40	80.8	300	0	0	0.24	0	0
2	K-flex	40	80.8	304	1.27	0	0.24	0	0
3	6-24-6	40	80.8	305	0	0	0.24	0	0
4	Green Flag	40	80.8	304	0	0	0.24	0	0
5	6-24-6, K-fuel, Rhyzo-Link	40	80.8	310	0.5	0	0.24	0	0
6	K-fuel, Finish Line[1]	40	80.8	305	0	0.026	0.27	0.0026	0.0051
7	6-24-6, K-fuel, Finish Line[1]	40	80.8	311	0	0.026	0.27	0.0026	0.0051

Table 3. Sits soil characteristics prior to fertilizer application.

0 - 2 feet	0 - 6 inches				
Primary macronutrients			Secondary macronutrients		
(mg·kg^{-1} soil)					
NO_3^--N	Bray P	K	Ca	Mg	SO_4-S
1.4	75	120	716	170	4.0

0 - 6 inches						
Micronutrients					Other characteristics	
(mg·kg^{-1} soil)					pH	Organic matter (%)
Fe	Mn	Zn	Cu	B		
22	3.3	2.4	0.77	0.19	7.1	1.4

Table 4. Yield, size, and grade of Russet Burbank tubers grown at the Sand Plain Research Farm.

Treatment #	Products applied (with 10-34-0 and 9% Zn)	Yield (CWT·ac^{-1})										% yield in tubers > than:	
		Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	U.S. No. 1	U.S. No. 2	Marketable	6 oz.	10 oz
1	-	0	44	190	134	64	29	460	394	22	416	49	20
2	K-flex	2	50	198	149	62	13	472	397	25	422	47	16
3	6-24-6	3	36	190	146	95	26	494	425	33	458	54	25
4	Green Flag	0	40	164	141	74	28	448	382	25	407	55	23
5	6-24-6, K-fuel, Rhyzo-Link	0	40	154	141	79	26	440	383	18	400	56	24
6	K-fuel, Finish Line	0	42	164	159	74	29	468	407	19	426	56	22
7	6-24-6, K-fuel, Finish Line	2	37	159	150	75	27	449	387	25	412	56	23
	Treatment effect (P-value)	0.4902	0.4696	0.1576	0.5246	0.3392	0.3328	0.2481	0.3474	0.2976	0.1861	0.2036	0.4163

Table 5. Counts, per plant, of Russet Burbank tubers grown at the Sand Plain Research Farm.

Treatment #	Products applied (with 10-34-0 and 9% Zn)	Tubers per plant (in 5-plant samples)										Yield per plant (lbs)	Mean tuber size (oz.)
		Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	U.S. No. 1	U.S. No. 2	Marketable		
1	-	0	4.5 abc	5.5	2.0	0.7	0.2	12.8 ab	8.0	0.3	8.3	3.2	3.9
2	K-flex	0	5.4 a	6.3	2.2	0.5	0.1	14.3 a	8.3	0.7	8.9	3.1	3.6
3	6-24-6	0	3.4 cd	5.2	2.0	0.7	0.3	11.6 bc	7.7	0.5	8.2	3.1	4.4
4	Green Flag	0	3.7 bcd	4.3	2.3	0.4	0.4	11.0 bc	6.8	0.5	7.3	2.9	4.2
5	6-24-6, K-fuel, Rhyzo-Link	0	4.7 ab	4.3	2.4	0.6	0.2	12.1 b	7.1	0.4	7.5	3.1	4.1
6	K-fuel, Finish Line	0	4.6 ab	4.7	2.4	0.4	0.1	12.2 b	7.1	0.5	7.6	2.9	3.9
7	6-24-6, K-fuel, Finish Line	0	2.9 d	4.7	1.9	0.5	0.3	10.2 c	6.9	0.4	7.3	2.7	4.3
	Treatment effect (P-value)	--	**0.0160**	0.3644	0.8162	0.6760	0.4317	**0.0327**	0.3483	0.5772	0.3474	0.5652	0.3044

Table 6. Quality characteristics of Russet Burbank tubers grown at the Sand Plain Research Farm.

Treatment #	Products applied (with 10-34-0 and 9% Zn)	Percentage of tubers			Specific gravity	Dry matter content (%)
		Hollow heart	Brown center	Scab		
1	-	9	3	12	1.0777	20.8
2	K-flex	10	4	6	1.0772	21.0
3	6-24-6	4	1	8	1.0780	20.1
4	Green Flag	9	1	10	1.0774	20.4
5	6-24-6, K-fuel, Rhyzo-Link	12	4	9	1.0780	19.9
6	K-fuel, Finish Line	13	6	12	1.0788	20.6
7	6-24-6, K-fuel, Finish Line	10	3	10	1.0783	20.7
	Treatment effect (P-value)	0.6915	0.6500	0.8051	0.9773	0.3153

Data Report for UMN Potato Breeding Program 2020

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Legacy Material

Aim: Although potato breeding has a long history at the University of Minnesota the continuity of the program was interrupted by the unexpected passing of Dr. Christian Thill, the previous breeder, in August of 2014. A team, including Dr. Asunta Thompson, Spencer Barriball, and Peter Imle, stepped in to select clones to be maintained in the program. These approximately 60 clones were maintained by the interim breeder, Dr. Thomas Michaels. Due to limitations in program resources, all clones were grown repeatedly at the Sand Plains Research Farm (SPRF) in Becker MN. In the summer of 2017, when the breeding program came under new management, all of the clones exhibited clear visual indications of multiple diseases. This disease load made evaluation of the clones impossible at that juncture.

Great effort and expertise went into the selection of these legacy clones over the previous 17 years. Presumably, these clones exhibit a range of desirable traits. Examination of four late stage clones from the Thill breeding program which were maintained by collaborators, and therefore had cleaner seed available, demonstrates the potential value of these legacy clones. For example, MN13142, which was maintained by Dr. Sanjay Gupta and Dr. Carl Rosen in the Soil Science department, is a dual purpose russet with impressive dormancy (can be stored at 50°F without CIPC for over 9 months), thick skin and a desirable shape. Peter Imle maintained 3 clones: MN12009PLWR-02R, MN12054PLWR-02R, and MN12054PLWR-03R, at Pine Lake Wild Rice. All of these clones exhibit skin color comparable to Dark Red Norland. We hypothesize that other legacy clones may exhibit similar desirable traits, which should be explored.

Even if none of the legacy clones become varieties, they should be considered as parents. Genotyping studies on the National Fry and Chip Processing Trials (NFPT and NCPT, respectively) suggest that although the US breeding programs work closely together and share material, they still maintain distinct germplasm. Our genotyping efforts confirm that UMN germplasm is distinct. It is probable that UMN clones may contain desirable haplotypes, alleles, and phenotypes, not present in other breeding programs. The pattern of genetic distinctness between programs highlights the importance of evaluating the UMN legacy material.

Between 2017 and 2019 we used anti-viral tissue culture to produce disease free plantlets of legacy clones. We eliminated 25 clones through preliminary phenotyping (pink eyes etc.), genotyping (identified duplicates), and data from regional trials prior to 2014. Our aim in 2020 was to use greenhouse mini-tubers to carry out a seed increase and evaluate phenotypes in a preliminary yield trial.

Methods: We transplanted tissue culture plantlets into the greenhouse to produce minitubers. Those minitubers were planted in 20 hill plots, with 1 ft spacing at our trial location at the Sand Plains Research Farm (SPRF) in Becker Minnesota. Vines were desiccated after 90 days and tubers were harvested two weeks later. Additionally minitubers were planted as part of our seed increase at the North Central Research and Outreach Center (NCROC) in Grand Rapids MN in 20 hill plots with 1 ft spacing. Vines were desiccated after 100 days and tubers were harvested 3 weeks later.

Results: Yield at the Sand Plains Research Farm was insufficient for grading or phenotyping. All tubers were mini tuber size or smaller and few were produced per plant. Therefore we are unable to report phenotype results.

Seed increase at the NCROC was much more successful. We produced at least 40 seed pieces per legacy clone. This will be sufficient for repeating the experiment next year. Using G1 seed harvested in the fall of 2020, will solve the dormancy and yield problems created by using greenhouse minitubers.

Conclusions: The legacy germplasm we inherited from Dr. Thill represents a considerable investment in time and expertise from both Dr. Thill and collaborators. Additionally, our genotyping efforts have demonstrated that this material represents a different population than that found in other breeding programs. Therefore, phenotyping this material and assessing it's potential for release and/or use in our crossing block is a priority for our breeding program. We attempted to by-pass a year in the process by using greenhouse minitubers for our preliminary yield trials, this approach was unsuccessful due to dormancy and seed size. We were able to produce G1 see for all 35 legacy varieties, we expect to generate phenotype data and make selections in 2022.

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. 2020 marks the third field season of the re-vamped Minnesota Potato Breeding Program. The third field year is the first one in which we have sufficient seed to perform yield trials at our trial site in Becker MN, as opposed to using visual evaluation at our seed location.

Methods:

FY1

In 2020, we planted 23,621 single hills, some of which were from our crossing block and others of which were provided to us by collaborators at North Dakota State University, University of Maine, Colorado State University, and Texas A&M. Of the single hills planted, 42% were russet, 19% were chips, 15% were yellow, 15% were specialty, and 6% were red. All single hills were planted at the NCROC and selected using visual selection.

FY2

We evaluated 621 FY2 clones this year in 12-hill plots. Of these clones, 56% were russets, 26% were chips, 13% were red, 8% were yellow, and 6% were specialty. All clones were planted at the NCROC and selected using visual selection. Additionally, post-harvest we collected quantitative measures of: specific gravity, internal defects, chip/fry color, tuber shape, tuber color, and skin set, for each of the 154 clones. This was accomplished at the USDA potato storage research facility in East Grand Forks.

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 then 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".

Additionally a different subset of 10 tubers were arranged 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[1]. Image analysis was performed in-house using the R software with the EBImage[2] package to acquire skinning, shape, and skin color data as described in Jones et al.[3] and Stefaniak et al.[4]. These tubers were cut in half and internal defects were counted.

Finally, selected individuals from FY2 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.

FY3

Our preliminary yield trials in Becker MN included 181 individuals grown in 20-hill plots. These clones were: 58% chips, 18% reds, 13% yellows and 11% russets. These were graded to obtain yield and size profile data in addition to repetition of the phenotyping for FY2. FY3 was also genotyped for PVY and Verticillium wilt resistance. Additionally 25 of the chipping clones were evaluated in 8-hills North Carolina as part of the Early Generation Southern Strategy Trial.

Results:

FY1

We selected 1.6% of the individuals over all to continue on in the program to year 2, resulting in 390 clones to be evaluated in 12 hills in 2021.

FY2

We selected 25% of the clones, resulting in 154 clones to be evaluated in preliminary yield trials in 2021. Of the selected clones 6% exhibit genetic resistance to PVY (1% resistance from stolonifera and 5% resistance from andigena) and 25% have genetic resistance to Verticillium wilt. Mean specific gravity for both chips and russets (analyzed separately) was 1.0618. See figure 1 for the distribution. Mean lightness (L*) for chips fried after no time in storage was 51.78, in the L*a*b color space where black is 0 and white is 100. See figure 2 for the distribution.

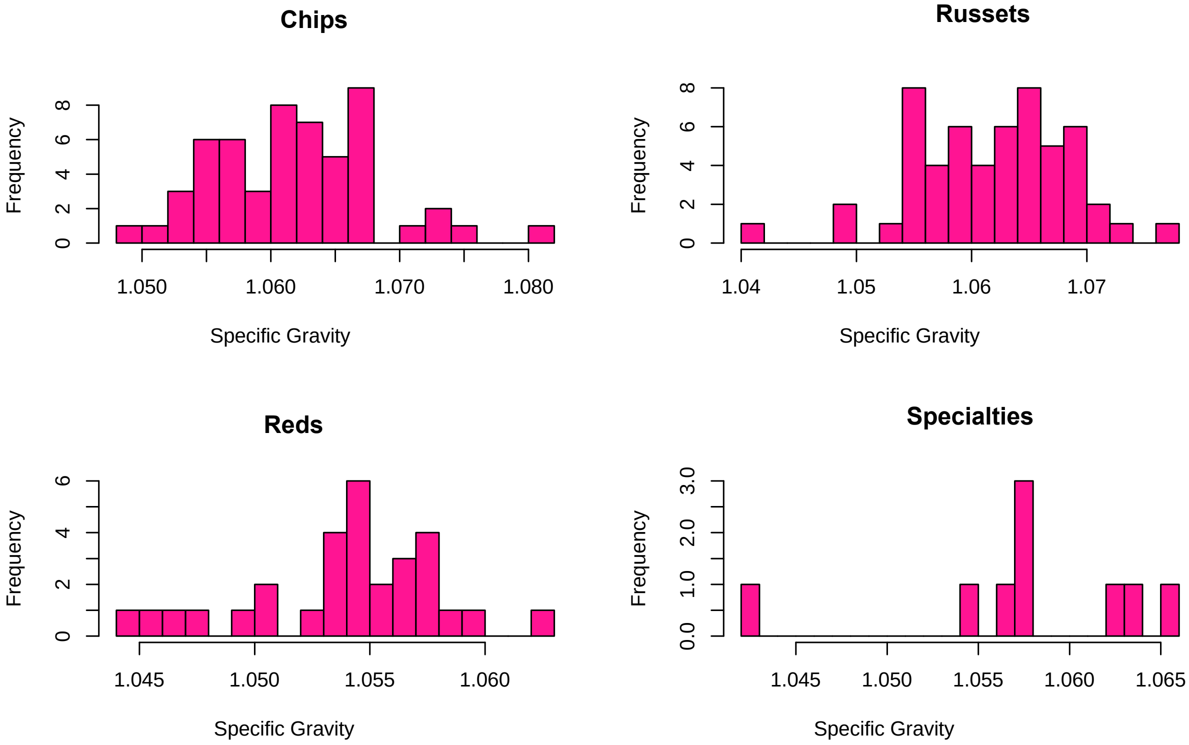

Figure 1. Specific gravity by market class for selections from FY2

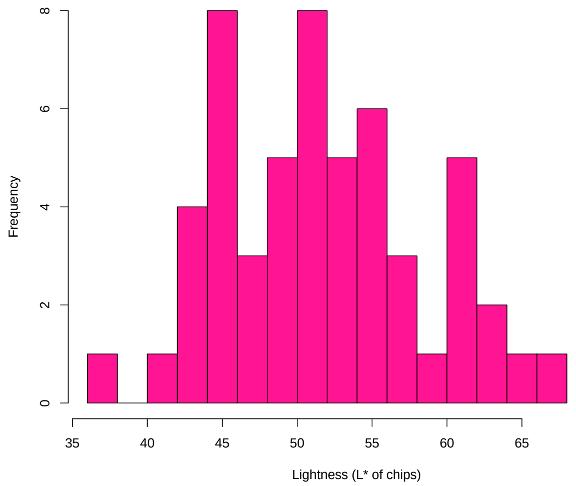

Figure 2. Lightness of chip color for FY2 chipping selections

FY3

We selected 34% of FY3 based on grading and genotype data to continue in the program, for 61 individuals which will be evaluated as FY4 in summer 2021. We selected 35 chipping potatoes (Table 1) some of which were also evaluated in North Carolina as part of the EGSS. The specific gravity for Atlantic was 1.063 and the mean specific gravity from our selections 1.066. The mean yield of our selections was 101% of Atlantic.

Table 1. 2020 FY3 Chipping Selections

Clone	Yield MN (% Atlantic)	SG MN	Yield NC (% Atlantic)	SG NC
MN18AF6643-13	93	1.0715	NA	NA
MN18AF6648-10	NA	1.061	NA	NA
MN18AF6658-5	109	1.0602	NA	NA
MN18AF6675-2	153	1.066	NA	NA
MN18AF6717-2	111	1.077	NA	NA
MN18AF6718-1	128	1.069	NA	NA
MN18AF6725-1	99	1.0697	NA	NA
MN18AF6728-7	68	1.067	NA	NA
MN18AF6730-5	146	1.0742	NA	NA
MN18AF6730-6	77	1.0645	NA	NA
MN18AF6745-4	101	1.0677	74	1.079
MN18TX17748-2	151	1.0682	NA	NA
MN18W17037-11	83	1.1037	NA	NA
MN18W17037-21	102	1.06	NA	NA
MN18W17037-26	87	1.0657	NA	NA
MN18W17037-27	90	1.0627	NA	NA

MN18W17037-33	88	1.0665	94	1.069
MN18W17037-34	77	1.064	NA	NA
MN18W17037-38	64	1.0607	89	1.069
MN18W17039-25	70	1.0602	NA	NA
MN18W17039-5	122	1.07	NA	NA
MN18W17043-12	118	1.0625	105	1.081
MN18W17043-17	133	1.0672	83	1.077
MN18W17043-2	63	1.0667	NA	NA
MN18W17043-3	90	1.0682	NA	NA
MN18W17043-6	91	1.0682	NA	NA
MN18W17052-15	124	1.0635	NA	NA
MN18W17052-4	82	1.063	NA	NA
MN18W17052-6	112	1.0745	NA	NA
MN18W17057-1	66	1.0612	NA	NA
MN18W17057-5	110	1.0615	82	1.064
MN18W17065-2	139	1.0625	87	1.075
MN18W17065-4	91	1.0612	NA	NA
MN18AF6717-6	86	1.053	96	1.081
MN18AF6724-5	103	1.0587	97	1.079

We selected eight russets (Table 2) seven of which yielded better than the check Russet Norkotah, all of which had higher specific gravity than Russet Norkotah (1.0523).

Table 2. 2020 FY3 Russet Selections

Clone	Yield (% Russet Norkotah)	SG
MN18W17091-15	140.5945939	1.0655
MN18W17076-1	119.7966019	1.0615
MN18W17079-11	193.4611677	1.061
MN18W17089-1	156.5639249	1.0602
MN18W17089-2	119.8855814	1.0575
MN18AF6758-2	169.3482381	1.0572
MN18W17091-5	205.6477999	1.0572
MN18W17091-9	79.8756269	1.054

We selected nine red skinned white flesh potatoes (Table 3). The control Red Norland exhibited 6.25% skinning, a redness score of 21.1 (higher scores are redder), and a lightness score of 35.6 (lower scores are darker). We have results from screening all the red FY3 selections for resistance to verticillium wilt and PVY. While our red varieties are all superior to Red Norland in one aspect, most of them are inferior in another. Regardless, they make promising potential parents.

Table 3. 2020 FY3 Red Selections

Clone	Yield (% Red Norland)	Redness	Lightness	Skinning (% skinned)	Vert	PVY
MN18W17009-1	65	25.4	44.4	1	No	No
MN18W17026-4	42	16.35	45.95	1.5	No	No

MN18CO15117-5	90	16.5	41.5	3	No	No
MN18W17025-4	114	26.85	38.3	3.5	No	No
MN18W17008-1	NA	12.5	43.7	4	No	No
MN18CO15117-2	82	15	38.6	6	No	No
MN18SR00011-2	127	25.75	38.95	6	No	No
MN18W17026-2	99	13.3	40.5	7	No	No
MN18W17021-2	72	20.2	29.45	14	No	No
MN18CO15083-6	64	20.6	35.7	10.5	No	Yes

We selected nine yellow skin and yellow flesh clones (Table 4) which were compared to Yukon Gold. Eight outcompeted Yukon Gold in yield. Unlike Yukon Gold none of the nine exhibited internal brown spot or brown center. Additionally two of our selections show genetic resistance to verticillium wilt.

Table 4. 2020 FY3 Yellow Selections

Clone	Yield (% Yukon Gold)	PVY	Vert
MN18AF6741-2	255	No	No
MN18CO16154-9	109	No	Yes
MN18CO16212-2	180	No	No
MN18CO16212-3	196	No	No
MN18CO16213-2	137	No	No
MN18SR00023-4	61	No	No
MN18TX17730-9	185	No	Yes
MN18TX17760-2	250	NA	NA
MN18TX17760-4	368	NA	NA

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 2021 and beyond, in order to identify promising new clones for Minnesota and North Dakota growers.

Rapid Cycling Chipping Potatoes for Genomic Selection

Aim: The potato breeding process is slow and has traditionally resulted in limited genetic gain. This is in part because the time between the first time a new clone is grown out and when it is first used as a parent is generally over five years. The North Central Breeders (Dr. Jeff Endelman at the University of Wisconsin, Dr. Dave Douches at Michigan State University, Dr. Susie Thompson at North Dakota State University, and I), are leveraging the power of genomic selection and multiple environments to speed this process. Our aim in this experiment was to test a method for choosing parents after a single year of data, using models developed by Dr. Endelman for chipping potatoes[5].

Methods: We selected nine chipping crosses which had at least one parent with PVY resistance and produced at least 800 botanical seed. For each of these crosses, 200 botanical seed were sent to each of the four participating programs. Each program used this seed to produce minitubers in the winter of 2019-2020. This resulted in each program having 200 unique individuals from each of nine families. Each clone was planted in 4 hill plots in the summer of 2020. Each program selected approximately 200 clones from a total of 1,800 individuals, half of which we expect to have PVY resistance. This winter we are genotyping all selected individuals for PVY resistance using KASP technology from Intertek.

Results: In Minnesota, we selected 144 clones based on visual appearance. We only have results back from a subset of the genotyping. Of that subset 46% has genetic resistance to PVY.

Conclusions: We will genotype 100 of our selected clones as well as 100 clones each from NDSU, MSU, and UW. Then we will use Dr. Endelman's genomic selection model[5] to select the 10 best possible combinations of parents from the genetic data. These parents will be used to generate the seed for another 10 large families which will be distributed to each participating program to repeat the process in 2022.

Additionally, we will grow our selected clones out in 12 hills in 2021. Clones which produced large numbers of seeds will be replicated across sites so that the resulting data can be used to update and improve the genomic selection model. Our aim is both to select new potential chipping varieties from these clones and to evaluate rapid cycling as a method for generating new germplasm which might be applicable to all market classes.

MN13142

Aim: MN13142 is a dual-purpose russet. It is an advanced breeding clone from Dr. Christian Thill's breeding program. We are assessing it in preparation for release in collaboration with Dr. Sanjay Gupta and Dr. Carl Rosen. In small plot evaluations in two commercial field trials it has shown desirable traits including: skin toughness, tuber shape and size, and specific gravity.

This clone is of particular interest because of its long dormancy. Specifically, it can be stored at 50°F without CIPC for over 9 months. This makes the clone of potential interest to the global market, because the practice of applying CIPC to lengthen dormancy is being challenged. The European Union has adopted lower allowable residue tolerances; and consumer pressure in the US also demands reduced CIPC use.

Methods: We planted G1 seed of MN13142 at Grand Rapids to increase our supply of breeders seed and supplemented with transplants from tissue culture plantlets grown in the greenhouse.

Additionally, The clone was submitted to the National Fry Processing Trial where it was grown in small plots (10-15 hills) in six locations: Idaho, Maine, North Dakota, Oregon, Washington and Wisconsin. Furthermore, it was included in storage trials with Dr. Darrin Haagenson and oomycete disease trials with Dr. Julie Pasche. Finally, Dr. Sanjay Gupta and Dr. Carl Rosen examined the effects of seed spacing, warming, and N rate on yield.

Results: Results from the National Fry Processing Trial were variable. In general yield was slightly low across location and it was dropped from the trial going into tier 2 (Table 5). However results from Idaho were promising.

Table 5. A summary of results from the National Fry Processing Trial. More detail is available on MediusAg

Location	SG	Yield	Yield Burbank	Yield Ranger	Rating
Idaho	1.094	493.7	578.9	621.0	Outstanding
Maine	1.092	193.7	189.1	157.2	Marginal
North Dakota	1.098	230.5	404.1	248.1	-
Oregon	1.080	665.8	776.6	913.9	Marginal
Washington	1.085	465.1	657.9	959.7	Drop
Wisconsin	1.076	409.0	530.7	491.7	Drop

Similarly, Dr. Rosen and Dr. Gupta found low yield as compared to Russet Burbank across treatments.

Table 6 Yield of MN13142 in response to warming spacing and fertility treatments. This table is from Dr. Rosen and Dr. Gupta's report at the fall meeting and is included here for comparison purposes with the National Fry Processing trial data

Treatment #	Cultivar	N rate (lbs/ac)	Seed spacing (in.)	Seed warmed?	Yield (CWT·ac^{-1})							
					Total		U.S. No. 1		U.S. No. 2		Marketable	
1	Russet Burbank	120	12	Yes	532	a	471	a	40	abc	511	a
2	MN13142	120	12	Yes	395	b	367	b	16	d	382	b
3	Russet Burbank	240	12	Yes	515	a	450	a	44	ab	494	a
4	MN13142	240	9	Yes	507	a	465	a	19	d	485	a
5	MN13142	240	12	Yes	489	a	463	a	11	d	474	a
6	MN13142	240	15	Yes	509	a	467	a	26	bcd	493	a
7	MN13142	240	12	No	526	a	484	a	28	abcd	512	a
8	Russet Burbank	360	12	Yes	511	a	447	a	44	a	492	a
9	MN13142	360	12	Yes	508	a	472	a	21	cd	493	a
Treatments 1 - 3, 5, 8 - 9		Effect of cultivar (P-value)			0.0730		0.4154		0.0034		0.0941	
		Effect of N rate (P-value)			0.3179		0.2391		0.7599		0.2969	
		Effect of cultivar*N rate (P-value)			0.1178		0.0505		0.8492		0.1101	
Treatments 4 - 6		Effect of spacing (P-value)			0.8560		0.8459		0.5739		0.7891	

Dr. Haagenson reported specific gravity higher than Prospect or Dakota Russet but lower than other comparable varieties. Additionally fries were slightly darker than most comparisons.

Table 7. Results for frying after minimal time in storage for MN13142 from Dr. Darrin Haggenson

USDA-PRW-FF 2020-2021 Planted: 05/27/2020 Harvest: 09/25/2020	11/4/2020 (0 time)				
	Suc	Gluc	SPEC	REFLECTANCE	
VARIETY	(mg/g)		GRAVITY	STEM	BUD
MN13142	1.0739	1.1798	1.0879	44.2	40.2
Russet Burbank	0.7123	0.7618	1.0904	40.2	43.6
Umatilla Russet	1.7875	0.4180	1.0986	48.2	46.7
Bannock	1.6638	0.3644	1.0947	49.1	46.5
Prospect	0.9405	0.1265	1.0744	53.7	47.7
Dakota Russet	0.8979	0.0743	1.0812	50.6	48.0
Ranger Russet	1.7600	0.3575	1.0956	44.5	49.5

Dr. Julie Pasche reported resistance to P. nicotianae, partial resistance to pink rot, and susceptibility to leak as a result of disease screening.

Conclusions: MN13142 is a promising dual-purpose russet, with impressive dormancy. However, yield is consistently slightly lower than comparisons. Considering its merits in terms of disease resistance and dormancy we are submitting it to organic trials in 2021.

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Breeding, Selection, and Development of Improved Potato Cultivars for the Northern Plains
2020 Summary

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Potato is an important horticultural crop in North Dakota (ND), Minnesota (MN), and the Northern Plains. In 2020, ND ranked third in US ha harvested at about 77,000 acres (+31,130 ha), with a value greater than $223M in 2019 (NASS 2020), ranking fifth for value among all crops in ND. Northern Plains production is ~60% processing (French fries/other frozen and chips), with the remainder fresh and certified seed. In 2020, the fresh sector dramatically increased as consumers cooked at home. Potato is management, labor, and input intensive compared to other crops. In 2020, more than 34% of acres eligible for certification by the North Dakota State Seed Department (NDSSD) were planted to cultivars (and/or selections thereof) and promising advancing selections developed by the NDSU potato breeding program; similarly, more than 32% of acres eligible in MN were developed by NDSU. ND ranks second and MN seventh for certified seed production; combined, they account for 18% of US certified seed. The NDSU potato breeding program initiated in 1930 is the core of the potato improvement team, conducting breeding, germplasm enhancement efforts, selection, evaluation, and development of improved cultivars for stakeholder adoption, focusing on incorporating durable and long-term resistance to biotic and abiotic stressors, enhanced nutritional and quality attributes, improved economic and environmental sustainability, high yield potential, and expanded marketability. Our goal is to aid in reducing input costs for producers, provide high quality raw material for the fresh market, processing and/or industrial applications, and to provide nutritious, flavorful, unique and convenient food choices for consumers. Interdisciplinary team efforts include collaborations with research and industry personnel at NDSU, UMN, and other North American programs, the North Dakota State Seed Department, the Minnesota Department of Agriculture, and with certified seed and commercial potato producers. Potato breeding is a long-term effort (more than 10 years from hybridizing to release). NDSU has released 26 cultivars; the most recent was Dakota Ruby in 2014. Following its third (2020 growing season) and final year in the national Snack Food Association Trial (SNAC), ND7519-1, a beautiful selection with cold-chipping potential will be considered for release in 2021. Dakota Crisp, Dakota Diamond, Dakota Trailblazer, Dakota Russet, and Dakota Ruby continue to find their niche in North American and global potato production; Dakota Russet is currently being evaluated and used for products including French fries, other frozen, and scrambles (a new and emerging frozen product).

Producers in the Northern Plains require early maturing cultivars across all market types due to our short growing season. Similarly, growers from other production areas across North America also look to our program for cultivars with this attribute, providing opportunities for our certified seed potato producers. Stringent quality standards exist for each market. Improved potato cultivars possessing resistance to abiotic and biotic stresses and with enhanced quality attributes, may reduce input costs for producers, provide high quality raw material for chip and frozen/French fry processing, and provide healthy and flavorful choices for consumers. To address shortcomings of industry standard cultivars, these research objectives were established for 2020:

1. Develop improved germplasm and superior potato cultivars adapted to the North Dakota, Minnesota and beyond, via traditional hybridization, emphasizing early maturity and introgressing resistance genes for biotic pests and abiotic stresses, improved quality attributes, and environmental and economic resource sustainability.
2. Identify, evaluate, and apply innovative technologies and genetics and genomics tools to increase efficiency, gain knowledge and modernize breeding efforts, including early generation selection technologies, marker assisted selection, SNP genotyping, extraction of dihaploids and development of inbred diploid lines, data mining, participatory plant breeding, and others as appropriate.
3. Conduct disease, pest and stress evaluations and agronomic production related evaluations for promising advancing selections and newly released cultivars, for development of and inclusion in cultivar specific management profiles.

Dedicated crossing blocks are used in hybridizing. From 2016 to 2020, 1,529 new families were created; in 2020, 64 parents were utilized and 283 new families resulted. Resistance traits predominating introgression included late blight, Colorado Potato Beetle, Verticillium wilt, pink rot and Pythium leak, amongst others. Dihaploid extraction of important NDSU cultivar releases was attempted during crossing in the greenhouse; however, it seems stressed pollen may have resulted in unsuccessful efforts. We are currently having success with a new pollen source and live (flowering) haploid inducer plants. Three hundred-one genotypes were submitted for SNP genotyping in 2019, and results were obtained for all in spring 2020. We are using this information, combined with phenotypic data from 2020 and prior, in a number of ways, including genome wide association studies. True potato seed resulting from the successful hybridizations is grown in the greenhouse all year in order to produce seedling tubers, which are then grown in the field in the seedling nursery.

Unselected seedling tubers were shared with the breeding programs in ID, ME, MN, and TX. The seedling nursery, clone maintenance and increase lots are grown at Baker, MN. From 2016 to 2020, more than 120,000 single hills have been evaluated in the seedling nursery representing more than 750 families. In 2020, 722 second year selections (152 retained), 235 third year (68 retained), and 265 fourth year and older (183 retained) were grown and evaluated. SNP genotyping data (DNA markers) obtained in early 2020 was used for parental selection and moving clones forward in the pipeline. Following harvest, the retained clones were subject to rapid phenotyping including imaging (in collaboration with Dr. Paulo Flores' program) and determination of specific gravity as they went into storage. Samples were retained for all chip and processing genotypes and they were chipped at harvest, and following 8 weeks storage at 38F (3.3C) and 42F (5.5C). About three acres of seed increase (advancing selections/named cultivars) was produced for our use, sharing with NDSU and other cooperators for trials, and movement to producer farms for evaluation. A genomic selection study with the north central collaborators at MSU, UMN and UW was initiated with a focus on chip processing ability and PVY resistance. About 24 Chilean selections (INIA program, Osorno, Chile) were evaluated with Drs. Secor and Kalazich; these materials offer pest, stress and quality attributes for introgression into the NDSU germplasm.

In 2020, field research trials were conducted at multiple locations; irrigated sites included Oakes, Larimore and Inkster, ND, and Park Rapids, MN (+60% of production in ND and MN is irrigated). Nine advancing red and yellow skinned genotypes compared to five standards were evaluated in a fresh market trial at Oakes; in addition, a processing trial evaluated 13 dual-purpose russet/long white selections compared to seven standards at this site. The processing trial at Larimore evaluated

14 advancing russet/long white selections. Results are reported in Tables 1 through 3. A new mini-pivot for research was built in 2020, so this was our first experience at this site. Overall, the site and trials were excellent, but yields were not as consistent as most years (for example, the LSD was 118 cwt. in 2020, where it often ranges from 35 to 50 (Table 3)). The National French Fry Processing Trial (NFPT) evaluated 50 entries, ND13213B-1Russ, ND1412Y-5Russ, ND14110B-1Russ, and ND14110B-3Russ from NDSU; seed of ND12241YB-2Russ, a promising NFPT entry in previous years was increased at Baker for 2021. ND1412Y-5Russ, ND14110B-1Russ, and ND12241YB-2Russ are advancing in the NFPT in 2021. The unreplicated preliminary processing trial included 84 genotypes and 12 industry standards providing processing and yield data to guide seed increase and movement forward in the breeding pipeline. The North Central Regional Trial had 30 fresh market entries including NDSU selections ND102663B-3R, ND102990B-2R, ND113091B-2RY, ND113338C-4R, ND1232B-1RY, ND1232B-2RY, and ND1241-1Y; growers in ND and beyond have expressed interest in five of these selections. A vine kill study conducted with Drs. Secor and Robinson and funded by ND SCBG 19-442 in response to a problem identified by ND certified seed potato growers using crop oils for deterring aphid probing was grown at Inkster; we are currently evaluating PVY movement in that trial. A processing trial with 15 entries, a common scab screening trial with 68 entries across market types, and the replicated *Verticillium* wilt resistance screening trial (25 genotypes across market types) in collaboration with Dr. Pasche were grown at Park Rapids.

Fresh market trials were grown at Crystal; the advanced trial had 30 entries, 24 advancing selections compared to six standards (Tables 4 through 6). Yields were relatively low and Red LaSoda and Red Norland led for yield and production of A sized tubers; many of our advancing selections are high setting genotypes. The preliminary fresh market trial included 90 entries (76 selections and 14 standards); many possess potential disease resistance. Chip processing trials were grown at Hoople; the chip processing trial had 14 advancing chip selections compared to seven standards summarized in Tables 7 through 9. There were limited rain showers in 2020, similar to 2019 in the northern end of the valley, reducing yields and impacting quality. The National Chip Processing Trial (NCPT) included 121 unreplicated selections (Tier 1) and 27 replicated entries (Tier 2) from US breeding programs (3 Tier 1, 1 Tier 2 from NDSU). Based on the NCPT assessments, and those in our breeding project, ND13220C-3 will be increased in 2021 for inclusion in the 2022 SNAC trial. The preliminary chip trial had 16 selections and eight industry standards. Trials at Fargo, on the NDSU campus, included an organic demonstration evaluating 20 selections and standards, and a metribuzin tolerance screening trial important for development of cultivar specific management profiles; the metribuzin tolerance trial is conducted with Dr. Harlene Hatterman-Valenti's program. Our graduate student is developing a rapid phenotyping methodology to reliably and rapidly screen germplasm for tolerance using imaging and other techniques in collaboration with Dr. Flores' group.

Superior dual-purpose russets include ND050032-4Russ, ND060735-4Russ, ND113100-1Russ, ND12241YB-2Russ, ND1412Y-5Russ, ND14110B-1Russ, and others. Promising fresh market selections include ND081571-2R, ND081571-3R, ND102663B-3R, ND102990B-2R, ND113091B-2RY, ND113207-1R, ND1232B-2RY, ND1241-1Y and ND1243-1PY. ND13106-1R is a red-skinned fingerling with some pink flesh. Outstanding chip processing selections include ND7519-1, ND7799c-1, ND102642C-2, ND113307C-3, ND1221-1, ND1241-1Y, ND12180ABC-8, ND13220C-3, ND13228AB-3 (chips from 3.3C) and others. ND12341-1Y is unique in that it is dual-purpose, a good chipper and has potential to be an exceptional fresh market offering in the yellow sector. Trial and data summaries will be submitted to the Valley Potato Grower magazine and/or made available on the potato breeding webpage (https://ag.ndsu.edu/plantsciences). The

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Table 1. Agronomic evaluations for advanced processing selections and cultivars grown at Larimore, ND, 2020. The processing trial was planted on May 27 and harvested September 23, 2020, using a single-row Grimme harvester. Entries were replicated four times; plots were twenty feet long, with a within-row spacing of 12 inches and 36 inches between rows.

Clone	Vine Size[1]	Vine Maturity[2]	Tubers per plant	Hollow Heart/ Brown Center %	Specific Gravity[3]	General Rating[4]
MN13142	3.0	1.4	6.9	0	1.0944	4.0
ND050032-4Russ	3.0	1.9	4.0	0	1.0953	3.3
ND113100-1Russ	3.8	2.3	5.1	0	1.0929	3.7
ND12162AB-1Russ	3.0	2.8	4.4	5	1.0959	2.6
ND14252B-4	3.5	2.8	6.7	3	1.0913	3/6
ND14261B-2Russ	2.0	1.9	5.1	0	1.0697	3.8
ND14265AB-3Russ	2.8	1.4	7.4	0	1.1065	3.6
ND14266AB-1Russ	2.1	1.0	7.0	0	1.0875	3.9
ND14286BC-2Russ	2.5	1.3	10.4	0	1.0740	3.0
ND14286BC-11Russ	3.8	2.3	7.3	0	1.0886	3.7
ND14318CABY-4	3.3	2.3	6.0	0	1.0817	3.9
Alturas	3.5	3.8	7.9	1	1.0992	3.5
Bannock Russet	3.5	2.8	4.7	9	1.0970	3.8
CalWhite	4.0	2.6	6.4	0	1.0932	3.0
Dakota Russet	3.3	2.1	4.6	1	1.0936	4.0
Proprietary Russet	2.5	1.3	5.9	0	1.0935	3.0
Ranger Russet	3.0	2.4	5.1	3	1.1015	3.1
Russet Burbank	3.8	2.9	7.0	4	1.0962	3.0
Russet Norkotah	3.5	1.9	4.7	14	1.0818	4.1
Shepody	3.3	2.3	4.6	0	1.0879	3.6
Umatilla Russet	3.0	2.3	10.2	0	1.1015	3.6
Mean	3.1	2.1	6.3	2	1.0918	3.5
LSD (∝=0.05)	0.9	0.9	1.9	4	0.0081	0.6

[1] Vine size – scale 1-5, 1 = small, 5 = large.
[2] Vine maturity – scale 1-5, 1 = early, 5 = late.
[3] Determined using weight-in-air, weight-in-water method.
[4] General rating based on yield, appearance, tuber size profile, shape, set, defects; scale of 1 to 5; 1 = poor, 5 = excellent (perfect).

Table 2. Yield and grade for advanced processing selections and cultivars grown at Oakes, ND, 2020. The processing trial was planted on May 27 and harvested September 23, 2020, using a single-row Grimme harvester. Entries were replicated four times; 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 %
MN13142	350	286	82	16	43	20	19	2
ND050032-4Russ	367	241	65	4	13	9	44	31
ND113100-1Russ	350	291	83	7	27	17	40	10
ND12162AB-1Russ	219	125	57	17	26	10	20	27
ND14252B-4	419	320	76	12	24	14	38	11
ND14261B-2Russ	279	240	81	19	41	19	21	0
ND14265AB-3Russ	444	361	81	11	37	19	24	9
ND14266AB-1Russ	380	317	83	16	39	19	25	2
ND14286BC-2Russ	414	278	67	27	40	15	12	7
ND14286BC-11Russ	556	497	89	6	27	16	46	5
ND14318CABY-4	290	235	81	18	42	21	18	2
Alturas	368	270	73	19	42	19	12	7
Bannock Russet	285	226	80	13	30	16	34	8
CalWhite	504	397	79	7	19	11	49	15
Dakota Russet	288	244	84	12	31	15	37	4
Proprietary Russet	307	205	67	14	32	18	17	18
Ranger Russet	318	226	72	12	28	16	28	16
Russet Burbank	309	196	60	22	33	14	13	18
Russet Norkotah	382	347	91	7	21	13	56	3
Shepody	316	236	74	10	25	12	37	16
Umatilla Russet	481	327	67	21	37	14	16	12
Mean	363	279	76	14	31	169	29	11
LSD (∝=0.05)	118	105	9	8	9	6	14	6

Table 3. French fry evaluations following grading and after 8-weeks storage at 7.7C (45F). Entries September 23, 2020, using a single-row Grimme harvester. Entries were replicated four times; plots were 20 feet long, with a within-row spacing of 12 inches and 36 inches between rows.

Clone	Fry Color[1]	Stem-end Color	% Sugar Ends[2]	Fry Color[1]	Stem-end Color	% Sugar Ends[2]
	Field Fry			Following 8 wks. at 45F (7.7C)		
MN13142	1.1	1.2	8	1.4	1.5	8
ND050032-4Russ	0.4	0.4	0	0.5	0.5	0
ND113100-1Russ	0.4	1.4	42	0.5	1.7	75
ND12162AB-1Russ	0.8	0.8	0	0.9	1.2	17
ND14252B-4	0.8	1.0	8	0.5	0.5	0
ND14261B-2Russ	0.3	1.7	42	0.8	1.0	8
ND14265AB-3Russ	1.7	1.7	0	1.0	1.0	0
ND14266AB-1Russ	0.6	1.1	29	1.1	1.8	42
ND14286BC-2Russ	0.7	0.9	29	1.8	1.8	0
ND14286BC-11Russ	0.4	0.4	0	0.5	0.8	8
ND14318CABY-4	0.3	0.3	0	0.6	0.6	0
Alturas	0.9	0.9	0	0.7	0.7	0
Bannock Russet	0.5	0.5	0	0.7	0.7	0
CalWhite	1.1	2.0	59	1.3	1.3	0
Dakota Russet	0.4	0.4	0	0.4	1.0	17
Proprietary Russet	0.9	1.6	33	0.7	1.1	67
Ranger Russet	0.8	0.8	0	0.9	1.0	8
Russet Burbank	1.0	2.1	58	1.5	1.5	8
Russet Norkotah	1.3	1.8	25	1.5	2.2	42
Shepody	1.4	1.6	8	1.4	2.0	25
Umatilla Russet	0.6	0.6	0	1.0	1.0	0
Mean	0.8	1.1	16	0.9	1.2	15
LSD (∝=0.05)	0.6	0.9	32	0.5	0.7	27

[1] 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.

[2] 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.

Table 4. Agronomic evaluations for advanced fresh market selections and cultivars, Crystal, ND, 2020. The trial was planted on May 18, vine killed on approximately August 24, and harvested with a single-row Grimme harvester on September 8. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows, replicated four times.

Clone	Vine Size[1]	Vine Maturity[2]	Tubers per Plant
1. AND00272-1R	3.8	2.5	11.0
2. ND6002-1R	3.0	3.0	5.8
3. ND7132-1R	3.5	3.5	7.5
4. ND102663B-3R	3.3	3.0	10.1
5. ND102990B-2R	3.3	2.8	12.1
6. ND113091B-2RY	3.3	2.4	18.3
7. ND113207-1R	3.3	1.6	8.6
8. ND113338C-4R	3.5	2.3	13.9
9. ND1232-1RY	3.8	2.3	12.8
10. ND1232B-2RY	3.5	2.5	11.9
11. ND14215C-4R	2.5	1.5	8.1
12. ND1241-1Y	3.5	2.5	10.1
13. ND1243-1PY	4.3	4.0	11.7
14. ND13106-1R	2.3	2.0	8.8
15. ND13109-2Y	3.1	3.0	9.0
16. ND13193B-1R	3.5	4.0	10.6
17. ND13236-2R	4.6	3.5	13.0
18. ND13241-6R	4.3	3.0	17.6
19. ND13296Y-6R	3.0	3.0	8.9
20. ND1455Y-1R	3.5	2.8	9.0
21. ND1465-1R	4.0	3.3	13.7
22. ND14151-24R	3.8	3.5	7.5
23. ND14151-25R	3.0	2.1	11.3
24. ND14151-26R	3.8	3.1	12.7
25. Dakota Ruby	3.3	2.5	11.2
26. Gala	2.5	2.0	15.6
27. Red LaSoda	4.0	3.0	6.1
28. Red Norland	2.5	2.1	6.3
29. Sangre	3.5	3.5	3.5
30. Yukon Gold	3.8	1.3	6.4
Mean	3.4	2.7	10.4
LSD (∝=0.05)	0.8	0.8	2.1

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

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

Table 5. Yield and grade for advanced fresh market selections and cultivars, Crystal, ND, 2019. The trial was planted on May 18, vine killed on approximately August 24, and harvested with a single-row Grimme harvester on September 8. The plots were 20 feet long, with a 12-inch with-in row spacing, and 36 inches between rows, replicated four times.

Clone	Total Yield Cwt./A	A Size Tubers Cwt./A	A Size %	0-4 oz. %	4-6 oz. %	6-10 oz. %	>10 oz. %	% Defects
1. AND00272-1R	314	155	49	49	39	10	1	0
2. ND6002-1R	202	109	51	42	41	10	7	0
3. ND7132-1R	262	149	57	40	43	13	3	0
4. ND102663B-3R	231	56	24	75	22	3	0	0
5. ND102990B-2R	239	39	16	83	15	1	1	0
6. ND113091B-2RY	323	43	13	86	12	1	0	0
7. ND113207-1R	278	141	50	43	38	12	6	1
8. ND113338C-4R	250	20	8	92	8	0	0	0
9. ND1232-1RY	308	84	27	73	24	3	0	0
10. ND1232B-2RY	325	126	38	61	34	5	1	0
11. ND14215C-4R	271	139	51	45	41	19	2	2
12. ND1241-1Y	203	46	19	81	17	2	0	0
13. ND1243-1PY	336	136	41	58	36	5	0	1
14. ND13106-1R	225	67	29	70	27	3	0	0
15. ND13109-2Y	242	112	43	51	34	9	2	5
16. ND13193B-1R	187	24	13	87	19	3	0	1
17. ND13236-2R	267	54	20	79	17	2	0	1
18. ND13241-6R	338	59	18	82	17	0	0	0
19. ND13296Y-6R	307	193	62	33	46	16	4	0
20. ND1455Y-1R	228	84	31	68	26	5	0	1
21. ND1465-1R	319	75	24	76	22	2	0	0
22. ND14151-24R	296	172	57	32	43	14	11	0
23. ND14151-25R	274	81	39	66	27	3	4	0
24. ND14151-26R	202	16	7	91	5	2	1	0
25. Dakota Ruby	281	90	32	66	29	3	1	1
26. Gala	320	69	20	80	18	2	0	0
27. Red LaSoda	400	179	45	9	28	17	39	7
28. Red Norland	351	201	57	12	38	20	25	5
29. Sangre	144	61	38	36	27	11	13	13
30. Yukon Gold	229	117	51	35	39	12	10	4
Mean	272	97	34	60	27	7	4	1
LSD (∝=0.05)	55	46	14	14	10	4	6	2

Table 6. Quality attributes, including shape, skin color, specific gravity, bruise potential and the general rating (breeder merit score) for advanced fresh market selections and cultivars, Crystal, ND, 2020. The trial was planted on May 18, vine killed on approximately August 24, and harvested on September 8.

Clone	Shape[1]	Color[2]	Specific Gravity[3]	Black-spot Bruise[4]	Shatter Bruise[5]	General Rating[6]
1. AND00272-1R	3.0	4.1	1.0881	2.8	2.6	3.9
2. ND6002-1R	2.1	3.5	1.0909	2.9	2.7	3.7
3. ND7132-1R	2.8	4.0	1.0825	2.0	2.5	3.9
4. ND102663B-3R	1.5	4.3	1.0874	1.8	3.1	2.2
5. ND102990B-2R	1.3	4.0	1.0883	2.1	2.4	3.9
6. ND113091B-2RY	1.0	4.0	1.0840	3.7	1.9	3.8
7. ND113207-1R	2.5	3.8	1.0702	2.1	2.8	3.5
8. ND113338C-4R	1.0	4.4	1.0872	1.4	2.7	3.3
9. ND1232-1RY	2.4	4.0	1.0919	3.0	2.1	4.0
10. ND1232B-2RY	2.5	3.8	1.0920	3.3	2.5	3.9
11. ND14215C-4R	1.3	3.2	1.0820	2.1	3.0	3.8
12. ND1241-1Y	1.0	Y	1.1049	2.2	2.3	3.7
13. ND1243-1PY	1.0	P	1.0907	2.6	2.8	3.9
14. ND13106-1R	3.8	4.1	1.0892	3.7	2.4	3.8
15. ND13109-2Y	3.8	Y	1.0798	1.7	2.4	3.0
16. ND13193B-1R	1.0	3.9	1.0831	1.9	2.6	3.2
17. ND13236-2R	1.0	3.5	1.0938	2.5	2.1	3.7
18. ND13241-6R	1.5	4.0	1.0978	2.2	2.9	3.8
19. ND13296Y-6R	3.0	4.1	1.0757	2.1	2.4	3.8
20. ND1455Y-1R	2.0	3.6	1.0865	1.7	2.5	3.3
21. ND1465-1R	2.0	3.0	1.0860	2.2	2.7	3.3
22. ND14151-24R	1.3	4.0	1.0785	2.4	2.8	3.8
23. ND14151-25R	1.8	4.1	1.0786	3.5	2.6	4.4
24. ND14151-26R	1.3	4.3	1.0708	2.4	1.5	4.0
25. Dakota Ruby	1.0	4.4	1.0918	2.1	2.9	2.8
26. Gala	1.9	Y	1.0749	1.3	1.4	3.5
27. Red LaSoda	3.0	2.8	1.0812	2.1	3.0	3.0
28. Red Norland	3.0	3.0	1.0813	2.5	2.7	3.1
29. Sangre	2.8	3.4	1.0857	1.5	2.1	2.9
30. Yukon Gold	2.8	Y	1.0885	2.8	2.4	3.9
Mean	2.0	na	1.0854	2.3	2.5	3.5
LSD ($\propto$=0.05)	0.7	0.4	0.0133	0.9	0.9	0.4

[1] Shape = 1-5; 1 = round, 2 = oval, 3 = oblong, 4 = blocky, 5 = long.

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

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

[4] Blackspot bruise potential determined by the abrasive peel method, scale 1-5, 1=none, 5=severe. As an example, Ranger Russet typically rates as a 4.0 or greater.

[5] Shatter bruise – scale 1-5, 1= none; 5 = severe.

[6] General Rating = 1-5; 1 = poor and unacceptable, 3 = fair, 4 = excellent, 5 = perfect.

na = not applicable

Table 7. Agronomic assessments, general rating and specific gravity for advancing chip processing selections and cultivars, Hoople, ND, 2019. The chip processing was planted on May 16, 2020, vine killed on August 27, and harvested on September 10 using a single-row Grimme harvester. The replicated plots were 20 feet long, with a 12-inch with-in row spacing, and 38 inches between rows.

Clone	Vine Size[1]	Vine Matur-ity[2]	Tubers per plant	General Rating[3]	Specific Gravity[4]
1. ND7519-1	3.5	2.1	7.1	3.7	1.1006
2. ND7799c-1	3.3	2.6	4.9	3.8	1.0862
3. ND092018C-2	3.0	1.6	11.0	3.1	1.1063
4. ND113307C-3	3.8	2.8	9.2	3.8	1.0980
5. ND113394CAB-7	3.5	1.6	7.9	3.7	1.10808
6. ND113508C-4	3.5	2.4	8.1	3.0	1.0983
7. ND1221-1	2.5	1.6	9.2	3.6	1.0861
8. ND12107CB-1	3.0	3.6	9.4	3.9	1.0900
9. ND13219C-3	4.3	2.6	11.6	4.0	1.1139
10. ND13219C-4	3.8	2.4	14.7	3.5	1.1080
11. ND1441Y-1	3.8	3.3	7.1	3.8	1.0944
12. ND1450CAB-3	2.8	1.5	8.6	4.0	1.0902
13. ND1451CAB-3	3.8	2.6	8.6	4.2	1.1039
14. ND1452CB-1	3.5	3.1	4.6	3.7	1.0855
15. Atlantic	3.5	2.6	6.0	3.6	1.0976
16. Dakota Crisp	3.8	4.0	13.2	3.3	1.0917
17. Dakota Pearl	2.3	2.0	6.8	4.3	1.0924
18. Lamoka	3.5	2.8	4.5	3.5	1.0980
19. Pike	2.5	2.9	6.5	3.7	1.0914
20. Snowden	3.5	2.4	7.1	3.1	1.0955
21. Waneta	3.3	3.5	5.0	3.8	1.0955
Mean	3.3	2.6	8.1	3.7	1.0967
LSD ($\propto$=0.05)	1.1	0.8	4	0.3	0.0087

[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 (perfect).

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

Table 8. Yield and grade for advancing chip processing selections and cultivars, Hoople, ND, 2020. The chip processing was planted on May 16, 2020, vine killed on August 27, and harvested on September 10 using a single-row Grimme harvester. The replicated 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 %
1. ND7519-1	247	142	57	36	42	15	6	1
2. ND7799c-1	280	122	43	15	29	15	40	2
3. ND092018C-2	287	115	39	57	33	6	1	2
4. ND113307C-3	284	151	53	45	42	11	2	1
5. ND113394CAB-7	293	162	55	32	41	14	6	7
6. ND113508C-4	302	169	56	35	41	14	6	3
7. ND1221-1	300	161	53	41	41	12	4	2
8. ND12107CB-1	379	201	52	33	36	15	16	0
9. ND13219C-3	294	104	35	63	29	6	0	1
10. ND13219C-4	341	98	24	70	25	4	1	1
11. ND1441Y-1	304	177	58	26	43	15	15	1
12. ND1450CAB-3	248	117	48	49	37	10	3	1
13. ND1451CAB-3	315	169	54	35	40	14	11	0
14. ND1452CB-1	266	122	46	14	32	14	34	6
15. Atlantic	264	147	56	24	41	15	16	5
16. Dakota Crisp	338	163	49	18	32	17	22	12
17. Dakota Pearl	268	165	60	33	44	16	6	1
18. Lamoka	244	153	62	14	40	21	24	0
19. Pike	179	76	41	58	32	9	1	0
20. Snowden	292	172	59	27	44	15	13	1
21. Waneta	264	170	64	14	43	21	22	0
Mean	285	146	51	35	38	13	12	2
LSD ($\propto$=0.05)	58	42	10	11	7	5	8	3

Table 9. Chip color (USDA chip chart and HunterLab L-value) after grading and following 8-weeks storage at 3.3C (38F) and 5.5C (42F) for advancing chip processing selections and cultivars, Hoople, ND, 2020. The chip processing was planted on May 16, 2020, vine killed on August 27, and harvested on September 10 using a single-row Grimme harvester. The replicated plots were 20 feet long, with a 12-inch with-in row spacing, and 38 inches between rows.

Clone	Field Chip		38 F (3.3C) Storage		42F (5.5C) Storage	
	Chart[1]	Hunter[2]	Chart[1]	Hunter[2]	Chart[1]	Hunter[2]
1. ND7519-1	3.3	60	8.3	44	2.0	62
2. ND7799c-1	4.0	62	8.5	47	4.5	62
3. ND092018C-2	4.0	60	10.0	34	6.0	57
4. ND113307C-3	4.0	63	9.0	44	4.8	58
5. ND113394CAB-7	5.5	59	9.1	42	7.8	50
6. ND113508C-4	4.3	60	8.5	44	3.0	60
7. ND1221-1	3.0	62	9.8	36	4.5	59
8. ND12107CB-1	5.8	59	9.8	31	9.8	44
9. ND13219C-3	3.8	63	9.0	43	6.6	55
10. ND13219C-4	2.3	65	8.5	46	4.5	58
11. ND1441Y-1	5.0	60	9.8	38	5.8	55
12. ND1450CAB-3	3.8	63	9.5	37	8.0	53
13. ND1451CAB-3	4.3	57	8.3	46	4.8	58
14. ND1452CB-1	5.3	59	10.0	28	8.8	45
15. Atlantic	3.3	63	9.8	34	7.4	52
16. Dakota Crisp	3.0	62	9.8	37	7.3	54
17. Dakota Pearl	2.3	64	8.0	47	4.5	57
18. Lamoka	3.8	62	9.8	33	4.5	60
19. Pike	5.0	60	10.0	26	9.0	45
20. Snowden	4.3	60	9.9	34	6.8	55
21. Waneta	3.5	60	9.0	39	2.3	62
Mean	4.0	61	9.2	39	5.8	55
LSD ($\propto$=0.05)	1.9	5	1.0	7	1.7	5

[1] 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.

[2] HunterLab L value – 60 minimum; 70 preferred.

Screening Cover Crops for Managing the Root-lesion Nematode, *Pratylenchus penetrans*

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Summary

Root-lesion nematode, *Pratylenchus penetrans*, is one of most important nematode pests of potato, causing significant yield loss. Additionally, the association of this nematode species with secondary pathogens causes more expanded severity to potato plants and then to the tuber yield. Chemical control strategies are costly and have a deleterious effect on soil organisms and the environment. Non-host and poor host cover crops, as well as crops with bio-fumigation properties, can be an economically effective and environmentally sound approach to manage *P. penetrans* in infested potato fields. Greenhouse experiments were conducted to screen 25 cover crops that are being used and will likely be introduced in our region to evaluate their ability to host and reduce the population of *P. penetrans*. Experiments were conducted twice using nematode infested soil in a completely randomized design with four replications for each of cover crop and control treatments. All the cover crops tested were found to maintain or increase the initial nematode population in at least one of the trials, with the exception of Alfalfa (Bullseye) which showed poor hosting ability and consistently reduced the nematode population in both trials. Annual ryegrass eliminated almost 60% of the initial nematode population in the soil while winter rye (Dylan) reduced 32% of the population in the second trial. However, both of them maintained the nematode population in the first trial. Camelina (Bison), crimson clover (Dixie), Flax (carter), foxtail millet (Siberian), winter camelina (Joelle), and control treatment wheat (Glenn) were the crops constantly maintaining the nematode population throughout the experiments with reproductive factor (Rf) < 2. Susceptible check potato (Red Norland) showed the good hosting ability for the nematode in both trials while Faba bean (Petite) was found to be an excellent host in both trials, with reproduction rate much higher than the potato susceptible check. Cover crops with poor hosting ability have the great potential to be utilized for effective management of the nematode. This research will be helpful for assisting potato farmers to select suitable cover crops for management of *P. penetrans* in the fields to reduce yield loss due to nematode infestation.

Background

Root-lesion nematodes (RLN, *Pratylenchus* spp.) are migratory endo-parasitic nematode pests of agricultural, horticultural, and industrial crops (Oliviera et al. 1999; Smiley et al. 2005) and are also the most common nematode pests in potato (Brown et al. 1980; Florini and Loria 1990). *P. penetrans* causes the most damages in potato among many species of RLN (Waeyenberge et al.

2009) and the yield losses from this nematode ranges from approximately 30% to 70% (Holgado et al. 2009; Lazarovits et al. 1991; Olthof 1989; Philis 1995). *P. penetrans* is primarily responsible for forming nematode-fungus disease complexes by interacting with *Verticillium dahlia*. (Bowers et al. 1996; Kimpinski et al. 1998). Also, the association of this nematode species with bacterium *Streptomyces scabies* (Holgado et al. 2009) has a negative impact on potato production. Different researches have reported various damage threshold of *P. penetrans* for potato, which is affected by the cultivars and environmental factors like soil texture, moisture and temperature (Orlando et al. 2020; Castillo and Vovlas 2007). It was found to be 100 nematodes/250 gram of soil for potato cultivar Saturna in Norway with 50% damage (Holgado et al. 2009). It was reported that 1-2 nematodes/g of soil caused damage to potatoes in other studies (Olthof and Potter 1973; Riedel et al. 1985; Olthof 1986).

There are several management strategies for control of *P. penetrans* which facilitate the reduction of initial nematode population and depreciate the reproduction during the growing season. Control of *P. penetrans* with chemical means by use of soil fumigants or non-fumigants still may be the best approach of management. However, their use has been globally minimized and restricted due to potential negative impact on human health, environment, and other non-target organisms (Haydock et al. 2013). Several biological control measures for *P. penetrans* have been tested, but their use in agriculture is limited. Various environment-friendly approaches have been introduced for control of the root-lesion nematode such as the introduction of resistant cultivars, but moderate resistance is only limited to a few crops (Davis and MacGuidwin 2014). Crop rotation is also difficult to employ for management of the nematode because of its wide host range (Orlando et al. 2020).

An alternative means of management of *P. penetrans* can be the use of cover crops which may reduce the nematode population through different mechanisms. Biofumigation by cover crops of the Brassicaceae family can be applied to limit the reproduction of plant-parasitic nematodes. Several varieties of *Brassica napus*, *B. rapa*, *B. nigra*, and *B. juncea* were found to cause 56%-95% mortality of *P. neglectus* under laboratory conditions (Potter et al. 1998). Non-host and poor host cover crops of *P. penetrans* can be utilized to reduce the reproduction of nematodes in the growing season. Some cover crops can also provide an alternative means of nematode management by trapping the nematodes, stimulating the nematode eggs to hatch, but not allowing them to reproduce within the cover crop plants. Reproduction of *P. penetrans* was found to be effectively suppressed by marigolds (Pudasaini et al. 2006) and potato followed by marigold resulted in significantly higher average potato yield (Kimpinski et al. 2000). However, the hosting ability and population reduction capability of cover crops in our region is not well studied.

The objectives of this project were to screen 25 cover crop species and cultivars to 1) determine their hosting ability and 2) to evaluate their population reduction capability to the root-lesion nematode, *P. penetrans*.

Materials and Methods

Selection of cover crop species and cultivars

A total of 25 cover crops that are commonly used or will likely be introduced to our region of North Dakota and Minnesota were selected for the experiments under controlled greenhouse conditions with the goals of determining their hosting and population reduction abilities of *P. penetrans* (Table 1). Unplanted infested soil (fallow), potato (cv. Red Norland), and wheat (Glenn) were used as control treatments for comparison. The cover crop seeds were acquired from Forage and Biomass Crop Production Program (North Dakota State University, Fargo, ND), Allied Seed (Nampa, ID), and Great Northern AG (Plaza, ND).

Inoculum preparation, soil processing, and nematode extraction

P. penetrans population collected from an infested potato field located in central Minnesota and susceptible host, potato cultivar Red Norland were used to increase the nematode population in the greenhouse. Potatoes were spread in plastic trays with moist paper towels in the bottom and kept at room temperature of 22^{o}C for 15 days for pre-sprouting. This helps potatoes to sprout and develop some root structures before planting and provides early food for nematode infection. Those sprouted potatoes were cut into 2 to 3 pieces 3-4 days before planting to provide adequate time for healing of cut sections.

Potatoes were planted in plastic pots of 20 cm x 15 cm (1.5 kg soil capacity) and kept in the greenhouse with 16-hours of daylight and an average temperature of 22°C for 10 weeks. A single sprouted piece of potato was used per pot and covered with an appropriate amount of soil. The potatoes were harvested after 10 weeks and roots were separated from the soil which were then rinsed with tap water. The roots were then cut into 1-cm small pieces and nematodes were extracted from root tissue using Whitehead tray method (Whitehead and Hemming 1965) for population maintenance and increase. Soil from all pots was compiled and mixed thoroughly and three soil subsamples were taken to extract nematodes by using sugar centrifugal floatation method (Jenkins 1964). Nematodes from soil subsamples were quantified under an inverted light microscope (Zeiss Axiovert 25, Carl Zeiss Microscopy, NY, USA). Then, the infested soil was mixed with pasteurized sandy soil to obtain enough soil for testing cover crops. Three subsamples were again taken after mixing to determine the initial nematode population in the soil. Mixed soil was kept in a cold room at 4^{o}C to avoid changes in the nematode population until planting.

Cover crop greenhouse experiments

Two greenhouse trials were conducted to evaluate the hosting and population reduction ability of 25 cover crops to *P. penetrans*. The initial nematode populations were 1,590/kg of soil and 1,670/kg of soil for the first and second trial, respectively. Trial 1 and 2 were set up in February and September of 2020, respectively. Before planting, slow-release fertilizer (14-14-16 NPK) was mixed with soil at a rate of 5 g per kg of soil. Each pot was filled with 1 kg of the soil before planting and were arranged in a completely randomized design (CRD). All treatments were replicated four times.

All crops were directly seeded into the soil at 1-3 cm depth depending upon their seed size, except potato, which was pre-sprouted before planting as described above. Seedlings were thinned out to an appropriate number of plants per pot for each treatment (Table 1) after their establishment. Both trials were conducted in the Agriculture Experiment Station, NDSU greenhouse with 16-hours of daylight at an average temperature of 22^{o}C for 12 weeks. Plants' height was taken before termination of the trials. During termination, plant tops were removed, roots were separated from soil, and they were stored in a cold room at 4^{o}C in separate individual plastic bags until they were processed and nematodes were extracted within a month.

Processing of soil and root samples, identification and quantification of nematodes

After termination of the trial, the soil and roots from pots were processed differently. The Whitehead tray method was used to extract nematodes from the roots of plants (Whitehead and Hemming 1965). All the roots from each pot were cut into 1-cm long pieces and incubated for 48 hours with tap water. Nematodes from soil samples were extracted using the sugar centrifugal floatation method (Jenkin 1964). A subsample of 200 g of soil was taken from the soil sample in each pot for nematode extraction. Extracted nematodes were kept in 50 ml suspension tubes, identified, and counted using an inverted light microscope (Zeiss Axiovert 25, Carl Zeiss Microscopy, NY, USA). Nematodes population extracted from 200 g of soil were converted to the total number of *P. penetrans* in 1 kg of soil and nematode numbers obtained from roots of each plant were added to the corresponding nematode number from soil to get the final nematode population for each pot.

Reproductive factor and host ability ratings

The nematode reproductive factor (Rf) on each of the experimental units (individual pot with crop plants) was calculated by dividing the final nematode population on the tested crop by the initial nematode population. The average Rf of nematodes on a treatment was calculated as an average of Rf from four replicates of each treatment. In order to determine the hosting ability of cover crops, five 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) were designated base on the average Rf as described in previous studies (Mbiro and Wesemael 2016; Schomaker et al. 2013). Hosting ability ranking was assigned to each crop in each of the trials.

Data analysis

The SAS software (SAS 9.4; SAS Institute Inc., Cary, NC) was used to analyze the reproductive factors and population reduction percentage (PRP) of *P. penetrans* on cover crops in two trials. PRP was calculated using the formula [(initial nematode population on the tested crop – final nematode population on the tested crop)/initial nematode population 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 reproductive factor (Rf) and population reduction percentage (PRP) for the tested cover crops.

Results and Discussion

Alfalfa (Bullseye) had the highest nematode population reduction (37.18%) in the first trial and the second-highest (52.84%) in the second trial, with the Rf values less than 1 in both trials suggesting its poor hosting ability for *P. penetrans* (Table 2, Table 3). Other cover crops from the Fabaceae family used in this experiment had Rf >1. Faba bean (Petite) was found to be an excellent host in both trials with the greatest values of reproductive factor (Rf = 16.56 for trial 1, Rf = 14.59 for trial 2). Its Rf values were much higher than the susceptible check, potato cultivar Red Norland (Rf = 2.97 for trial 1, Rf = 3.33 for trial 2). Crimson clover (Dixie) served as a maintenance host in both trials (Rf = 1.45 for trial 1, Rf = 1.81 for trial 2) while forage pea (Arvika)) was a suitable host to the nematode (Rf = 5.61 for trial 1, Rf = 3.78 for trial 2). Sunn hemp showed only maintenance hosting ability in trial 1 (Rf = 1.86) but it served as an excellent host for *P. penetrans* in trial 2 (Rf = 7.73) (Table 2, Fig. 1). Miller (1978) observed the highest number of this nematode per total root mass of alfalfa cultivar Saranac, and Mbiro and Wesemael (2016) found alfalfa cultivar Alpha to be a good host suggesting variable reactions in different cultivars of the same crop to the nematode species when compared to our results. More Alfalfa cultivars need to be tested in future experiments.

Wheat (Glenn), used as a control treatment in our experiment displayed maintenance host ranking for *P. penetrans* in both trials (Table 2, Fig. 1). Annual ryegrass showed the highest reduction of nematodes (58.68%) in the second trial but it maintained the initial nematode population in the first trial (Tables 2 and 3). Similarly, winter rye reduced nematode population in the second trial but maintained the nematode population in the first trial. Marks and Townshend (1973) found winter rye to be a good host while it appeared a poor host for *P. penetrans* in another study (Mbiro and Wesemael 2016). Winter rye is the cover crop that consistently survives the winters in North Dakota, and it is one of the best cover crops to provide soil cover in the spring. More Winter rye cultivars need to be evaluated in future experiments.

In addition, other cover crops from the Poaceae family showed varied reactions in two trials except for foxtail millet (Siberian) and Japanese millet which consistently appeared to be maintenance (Rf = 1.31-1.45) and good host (Rf = 2.31-2.71), respectively, in both trials (Table 1). Bélair et al. (2002) also found Japanese millet to be very efficient in multiplying *P. penetrans* supporting our result. Forage oat supported nematode reproduction in our study (Table 1) and the similar reaction of forage oat has been reported in previous studies (Bélair et al. 2002; Rudolf et al. 2017; Thies et al. 1995; Vrain et al. 1996).

All the cover crops belonging to the Brassicaceae family tested had Rf greater than 1 at least in one of the trials (Table 2). Camelina (Bison) and winter camelina (Joelle) both consistently maintained nematode population throughout the experiments while carinata and crambe (Belann) showed good and excellent hosting ability for *P. penetrans*, respectively, in both trials. On the other hand, three cultivars of oilseed radish (Concorde, Control, and Image) all supported the nematode reproduction by more than two folds in the first trial but in the second trial Control and Image maintained the nematode population and Concorde reduced the initial nematode population by almost 7% (Tables 2 and 3). The cultivars with distinct reactions in two trials need to be tested in further experiments. Only one crop in the Linaceae family tested, flax cv. Carter consistently exhibited maintenance hosting ability for the nematode in both trials.

P. penetrans reproduced very well in the susceptible check potato cultivar Red Norland with around 200% population increase compared to the initial nematode population (Table 3), which suggests a conducive greenhouse environment and suitable soil conditions for the nematode reproduction. As a control, 56% and 66% of the initial nematode were recovered from the unplanted infested soil (fallow) at the end of the first and second trial, respectively (Table 2).

Conclusions

Several studies have reported effective management of root-lesion nematodes by using cover crops depending upon their hosting ability to the nematode species along with added benefits to the soil health. Twenty-five cover crops along with three control treatments were tested under controlled greenhouse conditions for management of the root lesion nematode *P. penetrans*. Only alfalfa (Bullseye) consistently showed poor hosting ability throughout the experiments with reducing the highest percentage of nematode population among the cover crops in the first trial. However, we also found the lowest nematode population recovered from annual ryegrass among all the cover crops in the second trial followed by alfalfa (Bullseye) and winter rye (Dylan). In addition, white proso millet and oilseed radish (Concorde) reduced nematode populations in one of the trials. The cultivars with distinct reactions to the nematode in two trials need to be tested in further experiments. Cover crops with poor hosting ability can be potentially utilized for management of *P. penetrans*. Additionally, cover crops with maintenance hosting ability may be tested under field conditions to determine their potential use to manage this nematode.

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Table 1. List of cover crops and controls tested for the root-lesion nematode, *P. penetrans* under controlled greenhouse conditions.

Crop (Cultivar or Cultivar Not Stated = CNS)	Scientific Name	Family	No. of Plants Per Pot
Alfalfa (Bullseye)	*Medicago sativa* L.	Fabaceae	4
Annual ryegrass (CNS)	*Lolium multiflorum* L.	Poaceae	2
Camelina (Bison)	*Camelina sativa* (L.) Crantz	Brassicaceae	2
Carinata (CNS)	*Brassica carinata* L.	Brassicaceae	1
Crambe (Belann)	*Crambe abyssinica*	Brassicaceae	1
Crimson clover (Dixie)	*Trifolium incarnatum* L.	Fabaceae	3
Daikon radish (Eco-till)	*Raphanus sativus* L.	Brassicaceae	1
Ethiopian cabbage (CNS)	*Brassica carinata* L.	Brassicaceae	1
Faba bean (Petite)	*Vicia faba* Roth	Fabaceae	2
Flax (Carter)	*Linum usitatissimum* L.	Linaceae	1
Forage oat (CNS)	*Avena sativa* L.	Poaceae	2
Forage Pea (Arvika)	*Pisum sativum*	Fabaceae	2
Foxtail millet (Siberian)	*Setaria italica* subspp. R*ubofructa* (L.) P. Beauv.	Poaceae	2
Japanese millet (CNS)	*Echinochloa esculenta* L.	Poaceae	2
Mighty Mustard brown mustard (Kodiak)	*Brassica juncea* L.	Brassicaceae	1
Oilseed radish (Concorde)	*Raphanus sativus* L.	Brassicaceae	1
Oilseed radish (Control)	*Raphanus sativus* L.	Brassicaceae	1
Oilseed radish (Image)	*Raphanus sativus* L.	Brassicaceae	1
Potato (Red Norland)	*Solanum tuberosum*	Solanaceae	1
Sunn hemp (CNS)	*Crotolara juncea* L.	Fabaceae	1
Turnip (Pointer)	*Brassica rapa subsp. rapa* L.	Brassicaceae	1

Crop (Cultivar or Cultivar Not Stated = CNS)	Scientific Name	Family	No. of Plants Per Pot
Turnip (Purple top)	*Brassica rapa subsp. rapa* L.	Brassicaceae	1
Wheat (Glenn)	*Triticum aestivum* L.	Poaceae	2
White mustard (Master)	*Sinapis alba* L.	Brassicaceae	1
White proso millet (CNS)	*Panicum miliaceum L*	Poaceae	2
Winter camelina (Joelle)	*Camelina sativa* (L.) Crantz	Brassicaceae	2
Winter rye (Dylan)	*Secale cereale* L.	Poaceae	2
Unplanted infested soil	-	-	-

Table 2. Host ranking of cover crops and control treatments to the root lesion nematode, *Pratylenchus penetrans* in two greenhouse trials.

Cover crop/cultivar	Trial 1[v]			Trial 2		
	Final Population[w]	Rf[x]	Host ranking[y]	Final Population	Rf	Host ranking
Alfalfa (Bullseye)	999	0.63	P	788	0.47	P
Annual ryegrass (CNS[z])	1,819	1.14	M	690	0.41	P
Camelina (Bison)	2,140	1.35	M	1,979	1.19	M
Carinata (CNS)	5,799	3.65	G	5,686	3.41	G
Crambe (Belann)	13,337	8.39	E	7,746	4.64	E
Crimson clover (Dixie)	2,313	1.45	M	3,031	1.81	M
Daikon radish (Eco-till)	6,955	4.38	E	3,340	2.00	G
Ethiopian cabbage (CNS)	8,024	5.05	E	4,970	2.98	G
Faba bean (Petite)	26,325	16.56	E	24,360	14.59	E
Flax (Carter)	2,145	1.35	M	2,108	1.26	M
Forage oat (CNS)	2,182	1.37	M	3,936	2.36	G
Forage pea (Arvika)	8,916	5.61	E	6,300	3.78	G
Foxtail millet (Siberian)	2,078	1.31	M	2,414	1.45	M
Japanese millet (CNS)	4,303	2.71	G	3,850	2.31	G
Mighty mustard (Kodiak)	9,474	5.96	E	3,448	2.07	G
Oilseed radish (Concorde)	4,141	2.61	G	1,554	0.93	P
Oilseed radish (Control)	4,440	2.79	G	3,095	1.85	M
Oilseed radish (Image)	3,309	2.08	G	2,421	1.51	M

	Trial 1[v]			Trial 2		
Cover crop/cultivar	Final Population[w]	Rf[x]	Host ranking[y]	Final Population	Rf	Host ranking
Potato (Red norland)	4,720	2.97	G	5,555	3.33	G
Sunnhemp (CNS)	2,958	1.86	M	12,906	7.73	E
Turnip (Pointer)	5,535	3.48	G	1,840	1.10	M
Turnip (Purple top)	6,340	3.99	G	4,518	2.70	G
Wheat (Glenn)	1,937	1.22	M	1,900	1.14	M
White mustard (Master)	6,825	4.29	E	3,591	2.15	G
White proso millet (CNS)	1,374	0.86	P	3,469	2.08	G
Winter Camelina (Joelle)	2,873	1.81	M	2,823	1.69	M
Winter rye (Dylan)	2,525	1.59	M	1,134	0.68	P
Non-planted infected soil	885	0.56	-	1,100	0.66	-

[v] Trial 1 was initiated in February 2020 with initial nematode density of 1,590 *P. penetrans/*1 kg of soil and trial 2 was initiated in September 2020 with the initial nematode density of 1,670 *P. penetrans/*1 kg soil.

[w] Final population is the average final population of nematodes from four 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 experiment unit (pot).

[x] Rf (Reproductive factor) is the mean reproductive factor of four replications for each treatment and was calculated by dividing the final population of target nematode by the initial population of the nematode.

[y] Host ranking was based on the categorization of reproductive factors 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 et al. 2016; Schomaker et al. 2013).

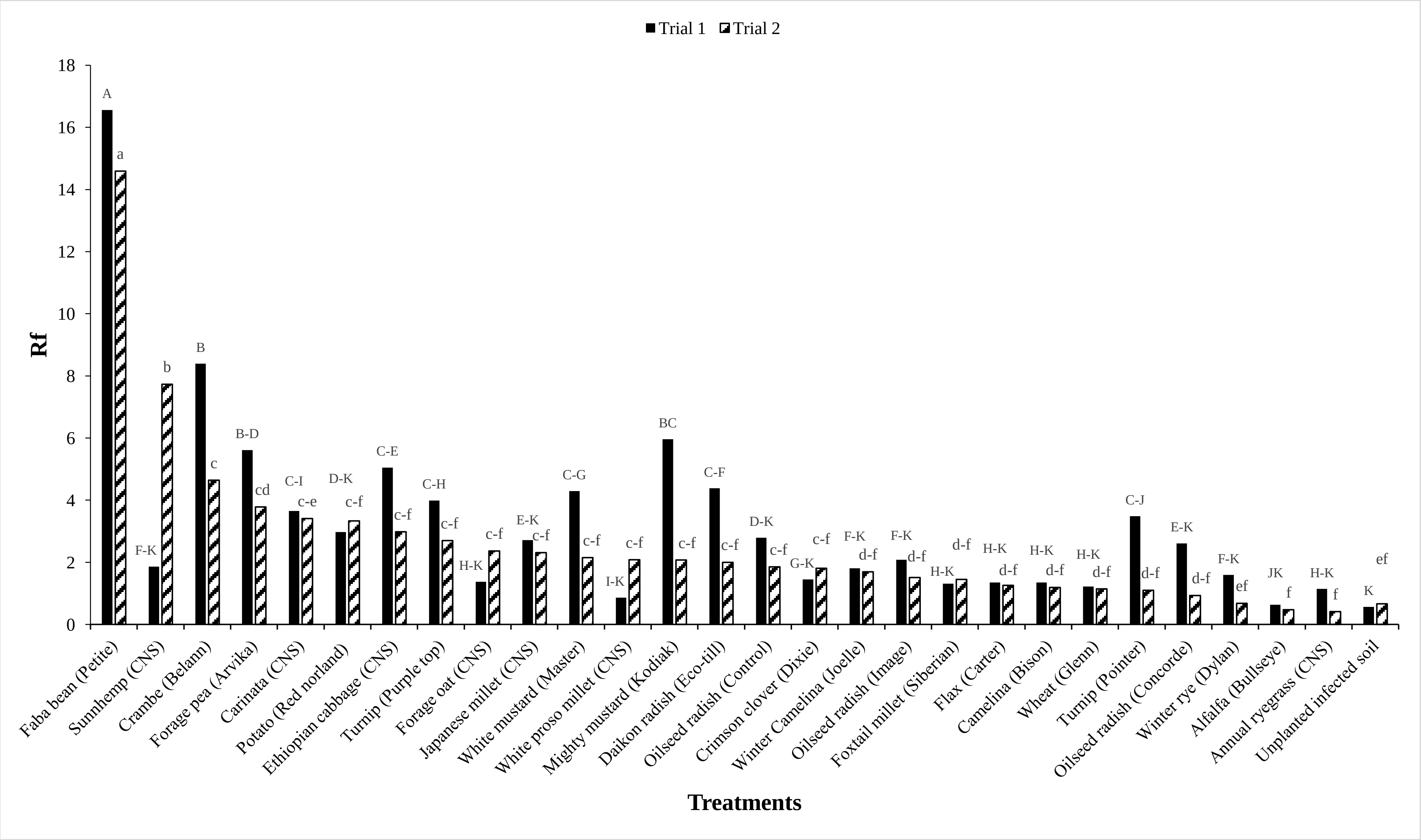
[Z] CNS - cultivar not stated.

Table 3: Population reduction percentage of *P. penetrans* by 25 cover crops and control treatments in greenhouse experiments.

Cover crop/cultivar	Population reduction percentage (PRP)^v	
	Trial 1	Trial 2
Alfalfa (Bullseye)	37.18 *a*	52.84 *AB*
Annual ryegrass (CNS)	-14.39 *a-c*	58.68 *A*
Camelina (Bison)	-34.59 *a-d*	-18.49 *A-C*
Carinata (CNS)	-264.69 *c-i*	-240.49 *B-D*
Crambe (Belann)	-732.49 *j*	-363.85 *D*
Crimson clover (Dixie)	-45.44 *a-e*	-81.51 *A-D*
Daikon radish (Eco-till)	-343.71 *f-i*	-100 *A-D*
Ethiopian cabbage (CNS)	-420.35 *g-i*	-197.6 *A-D*
Faba bean (Petite)	-1555.7 *k*	-1358.7 *F*
Flax (Carter)	-34.91 *a-d*	-26.2 *A-C*
Forage oat (CNS)	-37.23 *a-d*	-135.7 *A-D*
Forage pea (Arvika)	-467.02 *h-j*	-277.25 *CD*
Foxtail millet (Siberian)	-30.66 *a-d*	-44.54 *A-C*
Japanese millet (CNS)	-170.63 *a-g*	-130.54 *A-D*
Mighty mustard (Kodiak)	-495.82 *ij*	-106.44 *A-D*
Oilseed radish (Concorde)	-160.41 *a-g*	6.96 *A-C*
Oilseed radish (Control)	-163.54 *a-g*	-85.33 *A-D*
Oilseed radish (Image)	-108.08 *a-f*	-50.97 *A-C*
Potato (Red norland)	-196.86 *a-h*	-232.64 *A-D*

Cover crop/cultivar	Population reduction percentage (PRP)[v]	
	Trial 1	Trial 2
Sunn hemp (CNS)	-93.87 *a-f*	-672.83 *E*
Turnip (Pointer)	-248.1 *b-i*	10.18 *A-C*
Turnip (Purple top)	-298.74 *d-i*	-170.51 *A-D*
Wheat (Glenn)	-21.83 *a-c*	-13.77 *A-C*
White mustard (Master)	-315.1 *e-i*	-115.05 *A-D*
White proso millet (CNS)	13.6 *ab*	-107.71 *A-D*
Winter Camelina (Joelle)	-80.69 *a-f*	-69.01 *A-C*
Winter rye (Dylan)	-58.8 *a-e*	32.11 *AB*
Non-planted infected soil	44.34 *a*	34.13 *AB*

[v] Population reduction percentage (PRP) is the average of % reduction in nematode populations from four replications for each treatment. Nematode population reduction (%) = (initial population on the tested crop - final population on the tested crop)/initial population on the tested crop x 100. PRP with the same letters are not significantly different according to Tukey's honestly significant difference (HSD) ($P < 0.05$). Negative (-) PRP indicates nematode population increase in treatments.


■ Trial 1 ▨ Trial 2
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Faba bean (Petite)
Sunnhemp (CNS)
Crambe (Belann)
Forage pea (Arvika)
Carinata (CNS)
Potato (Red norland)
Ethiopian cabbage (CNS)
Turnip (Purple top)
Forage oat (CNS)
Japanese millet (CNS)
White mustard (Master)
White proso millet (CNS)
Mighty mustard (Kodiak)
Daikon radish (Eco-till)
Oilseed radish (Control)
Crimson clover (Dixie)
Winter Camelina (Joelle)
Oilseed radish (Image)
Foxtail millet (Siberian)
Flax (Carter)
Camelina (Bison)
Wheat (Glenn)
Turnip (Pointer)
Oilseed radish (Concorde)
Winter rye (Dylan)
Alfalfa (Bullseye)
Annual ryegrass (CNS)
Unplanted infected soil
Treatments

Fig. 1. Reproductive factor (Rf) of *P. penetrans* on 25 cover crops species and cultivars in greenhouse experiments, with initial nematode population of 1,590 and 1,670 per kg of soil for the first and second trial, respectively. Rf is the average reproductive factor of four replications of each treatment. Rf values with the same letters are not significantly different according to Tukey's honestly significant difference (HSD) ($P < 0.05$).