MHPEC Sulphur Study Report 2019-2021

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Introduction

The Field Variability Study (FVS) was conducted from 2015 to the present day with the overall goal of identifying and remediating factors responsible for variable processing potato yield. Fifty-five soil, plant, and environmental factors were identified in 23 grower fields and each factor was ranked according to impact on potato yield in a new partial least squares model generated in 2020. Soil sulphur availability has been identified as the fourth most influential variable responsible for differences in total yield at row closure, which is approximately late June to Early July. Soil sulphur availability at all sampled soil depths throughout the growing season swept the top nine most influential variables responsible for variation in the 6-to-10-oz, 10-to-12-oz, and 12-oz and greater yields. The assumed ideal soil sulphur test is 40-lb in potato (as published by the University of Manitoba in Agvise's soil sulphur guidelines at https://www.agvise.com/wp-content/uploads/2017/03/Sulphur-Magnesium-and-Chloride-guidelines.pdf).

The FVS also offered insight into the amount of soil sulphur typically seen in grower fields, which ranged from 0-to-120-lb, regardless of sampling date. In a cursory examination of the data set, 40-to-60-lb of sulphur appeared to be the beneficial amount of available soil sulphur, where compromised yields were observed outside of this range. The lowest yields appeared to be associated with sampling sites with virtually no soil sulphur, which was especially prevalent in sandy soils. This cursory examination was done by hand did not have the benefit of any statistical test or association. **The goal of this study was to identify the exact range of soil sulphur needed by row closure and possible products and rates needed to accomplish the task in order to achieve desired benefits to total yield and larger tuber size categories (greater than 6-oz). Outcomes of this study were set in the context of small, controlled research plots to demonstrate the importance of a unique sulphur fertilizer regime to potato growers in order to justify field-scale validation studies that are necessary for industry adoption.**

Methods

A factorial randomized complete block design was enacted with four-blocks in 2019, 2020, and 2021. The soil at the site was a Halboro series Orthic Black Chernozem with a loamy sand texture. The site has a typical crop rotation of potato-wheat-canola and is irrigated. All of these factors were a reasonable representation of lighter soils that potatoes are grown on in Manitoba, except the black chernozem exhibits greater organic matter content typical of lighter soils. Regardless of the organic content, the crop rotation resulted in low preseason soil sulphur tests with approximately 4-to-14-lbs of soil sulphur available (data not shown), and all plots would be considered sulphur deficient without additional treatment.

Experimental plots were individually fertilized on May 2nd 2019, April 30th 2020, and April 27th 2021. Fertilizers were applied with a custom-modified R-tech Terra Meter fertilizer applicator that was set up to apply up to three different fertilizers in a single pass. Two sets of three-Gandy Boxes were arranged in horizontal rows, and a single box of amazon cups was set up at the front in order to accommodate the three different types of fertilizer at possible rates of 6 lbs/acre (A) to 584 lbs/A (rates varied depending on fertilizer pellet size, vehicle speed, and gear combinations selected). The machine was set to broadcast all fertilizers over four potato rows at 36 inches between the rows. Each row of fertilizer applicators was calibrated for each pelleted formulation of fertilizer employed in the experiment and for every fertilizer rate in the treatment structure. Pre-plant fertilizer was immediately mixed into soil post-application with a Lely Roterra 350-33 (Lely, Maassluis, Netherlands) to a depth of up to 10-inches. Russet Burbank seed (2-to-3-oz, average 2.5-oz (data not shown)) was planted on May 6th 2019, May 5th 2020, May 4th 2021 with no gaps between plots, 36-inches between rows, 13-inches between seed pieces within row, and 6-inches deep (from top of hill). The seed treatment, pesticide applications and irrigation schedule were typical for the potato growing region in Carberry, Manitoba (data not shown). Hills were created as plants emerged on June 7th 2019, June 2nd 2020 and 2021 using a power hiller attached to a tractor. Row closure was observed on July 15th 2019, June 30th 2020 and July 7th 2021 and five 0-6 in. and 6-12 in. soil and 30-petiole samples per plot were collected on the same day. Thirty petioles were collected weekly on every Friday in July from four ammonium sulphate treatments to determine if a fertigation event was required the following week. Finally, five 0-6 in. and 6-12 in. soil samples were taken from every plot for late bulking soil sulphur assessment on the August 20th 2019, August 18th 2020, and August 19th 2021. The pounds of sulphur available in soils and the percentage of sulphur in petioles were determined by Agvise Inc (Northwood, North Dakota, USA).

Fertigation events were to be conducted in July as determined by low petiole percentage sulphur in the ammonium sulphate treatment only, regardless ammonium sulphate of rate applied to the plot preplant. Low petiole percentage sulphur was observed once in each year on July 15th 2019, July 23rd 2020, and July 9th 2021. Fertigation was conducted through a Hardi (Davenport, Iowa, USA) NL 80-26' SB PT sprayer with three inline filters, triple nozzle bodies, and three boom controls using a minidrift 03-blue nozzle at approximately 41 PSI at 2-3 miles per hour. Applications were done in the early morning and diluted as quickly as possible to limit fertilizer burn. One-gallon of ammonium thiosulphate was mixed with 10-imperial gallons of water and applied only to the ammonium sulphate treatment. This application was immediately diluted with ¼-inch of water from a linear irrigator (see Fig. 1 below). There was a frost on September 8th

2020 where the temperature reached -2 ºC at night, which was not anticipated to significantly impact any yield results and resulted in moderate foliar damage right before harvest.

Fig 1. An example fertigation event demonstrating concentrate is applied directly to foliage and then immediately diluted to the correct ratio by a linear irrigator on a cloudy morning to prevent fertilizer burn.

The entire experiment was 2,282.34-m^2 (approximately 0.57-acre). Each plot was 3.6-m wide and 12-m long, or 43.2-m^2 (approximate 0.011-acre). Harvest calculations were based upon a 10-m harvest row, which was left undisturbed in each plot throughout the season until harvest. The experiment was constructed with five fertilizer treatments: Tiger XP (Tiger-Sul Inc, Shelton, Connecticut, USA), Tiger Combo (Tiger-Sul Inc), no sulphur amendment (negative control), magnesium sulphate ($MgSO_4$, Redfern Farm Services, Brandon, Manitoba), ammonium sulphate ($(NH_4)_2SO_4$) as a soil amendment with ammonium thiosulphate ($(NH_4)_2S_2O_3$, Redfern Farm Services, Brandon, Manitoba, the treatment will henceforth be abbreviated ATS) through fertigation. Each fertilizer treatment, except the negative control, was applied at the equivalent of 20,-60,-and 100-lb of sulphur expected in the soil by row closure (approximately early July). The total amount of each fertilizer needed to achieve the goal by row closure varied based on sulphur content along with exact application rates displayed in Table 1 below:

Formulation (NPKS)	Fertilizer	Goal lb by row closure	lb/A of product required to achieve goal	lb product applied preplant per replicate(Per 4 plots)	Fertigation Fertilizer and Formulation	Sulphur Fertigation rate (lb)
0-0-0-85	Tiger XP	20	24	1.2	None	None
0-0-0-85	Tiger XP	60	71	4	None	None
0-0-0-85	Tiger XP	100	118	6	None	None
12-0-0-50	Tiger Combo	20	40	2	None	None
12-0-0-50	Tiger Combo	60	120	6	None	None
12-0-0-50	Tiger Combo	100	200	10	None	None
0-0-0-16	Magnesium Sulphate	20	125	7	None	None
0-0-0-16	Magnesium Sulphate	60	375	19	None	None
0-0-0-16	Magnesium Sulphate	100	625	32	None	None
21-0-0-24	Ammonium Sulphate	20	68	4	Ammonium Thiosulphate 12-0-0-26	3
21-0-0-24	Ammonium Sulphate	60	188	10	Ammonium Thiosulphate 12-0-0-26	3
21-0-0-24	Ammonium Sulphate	100	313	16	Ammonium Thiosulphate 12-0-0-26	3
Negative Control (no additional sulphur)			0	0	None	None

Table 1. Sulphur fertilizer products employed in the study are listed by sulphur content to display the amount of each product necessary to achieve the goal lb of sulphur available at row closure, as determined at a soil test conducted by Agvise, Inc. (Northwood, North Dakota). The fertigation rate assumes three-lb sulphur is in approximately one-gallon of ammonium thiosulphate (ATS) per fertigation event. One fertigation event was required in 2019, as determined by petiole testing from Agvise Inc. All plots received 115 lb/acre (A) of mono-ammonium phosphate (MAP, 11-52-0-0), 42.24 lb/A of Kmag blend (0-0-60-0), and 466.6 lb/A of ESN (polymer coated urea named Environmentally Smart Nitrogen, 44-0-0) from Redfern Farm Services, Brandon, Manitoba.

Harvest occurred on September 17th 2019, September 14th 2020, and September 13th 2021 and was completed using a 1-row digger on a 10-m section of a designated harvest row that was unsampled and untrampled during the season. This harvest row was the innermost part of each plot to buffer it as much as possible from edge effects. The total yield of each plot was recorded as lb harvested, as well as the lb of each tuber size category (less than 3-oz, 3-to-5.9-oz, 6-to-9.9-oz, 10-to-11.9-oz, 12-oz and greater) and quality metrics were recorded (weight of rotted tubers, green tubers, and hollow heart tubers in grams, as well as specific gravity). The size profile used to calculate an approximate Canadian dollar value to determine bonuses and deductions for a mid-season shipment of Burbank potatoes from a demonstration processor contract (data not shown).

Statistical tests were conducted with SAS v9.4 (SAS, Cary, NC). More specifically, the mixed procedure (proc mixed) was employed to construct a linear regression model to compare the variables of fertilizer treatment, year, and desired soil test (lb/acre) by row closure to a yield parameter (for example: the fertilizer Tiger XP at 60-lb by row closure impact on the 6-to-10-oz yield category). This analysis was completed for each yield parameter separately (e.g. 6-to-10-oz yield was run separately from total yield). In each case a Satterthwaite approximation is used to delineate limits for all variables that had a lower boundary constraint of zero. The blocking factor was used as a random effect as a vector for the mixed model. Because assumptions for the normal distribution of errors and homogeneity of variances were not met (data not shown), the repeated statement was used to model the variance of the fertilizer used. Finally, the lsmeans statement was used to determine significance of pairwise comparisons of a yield parameter between two fertilizer treatments (provided the type III test of fixed effects from the mixed model was significant with $P \leq 0.05$). Familywise type I error was controlled for the multiple comparisons in the lsmeans statement using a Tukey adjustment, with all subsequent reported *P*-values between specific treatments referring to this Tukey-adjusted *P*-value.

Sulphur Fertilizer Conversions and Cost Estimate Analysis

All of the following conversions and calculations are taken from Manitoba Soil Fertility Guide. (https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/calculating-fertilizer-rates.html)

Fertilizer Product Applied to Actual Nutrient Applied Conversion Process

To convert lb of fertilizer product per acre to lb of actual nutrient per acre, the total lb of product was multiplied by the percentage of the plant nutrient content that is within the product. This percentage was found within the chemical breakdown of each product. For example: Tiger Combo is 12-0-0-50 (Nitrogen-Phosphorous-Potassium-Sulphur). This means there is 12% nitrogen and 50% sulphur within the product. Multiplying the total weight of the fertilizer product by the percentage of each nutrient within the product produces the total nutrient value in lb within that fertilizer product. This calculates the rate of actual nutrient that is being applied per acre. If the conversion is opposite and the product amount is needing to be found the actual nutrient needs to be divided by the percentage. This is shown below.
Tiger Combo (TC) (12-0-0-50)

$$\left(\frac{\text{x lb S}}{\text{ac}}\right)\left(\frac{\text{100 lb TC}}{\text{50 lb S}}\right)=\frac{\text{x lb TC}}{\text{ac}} \qquad \left(\frac{\text{x lb TC}}{\text{ac}}\right)\left(\frac{\text{50 lb S}}{\text{100 lb TC}}\right)=\frac{\text{x lb S}}{\text{ac}}$$

$$\left(\frac{\text{x lb N}}{\text{ac}}\right)\left(\frac{\text{100 lb TC}}{\text{12 lb N}}\right)=\frac{\text{x lb TC}}{\text{ac}} \qquad \left(\frac{\text{x lb TC}}{\text{ac}}\right)\left(\frac{\text{12 lb N}}{\text{100 lb TC}}\right)=\frac{\text{x lb N}}{\text{ac}}$$

Converting Fertilizer Prices into Price per Unit of Nutrient

Example 1. Single Nutrient Fertilizers

There was just one set of calculations for single nutrient containing products which is shown the in the Urea section. The first step is converting the price per tonne to price per lb. The cost per tonne of urea was $1,295.00 as of December 2021 and there are 2204-lb per tonne. Therefore, dividing $1,295.00 per tonne of urea by 2204-lb of urea equaled $0.588 per lb. This total was then divided by the percent of actual plant nutrient that is within the fertilizer for urea, or 46%. These calculations yielded a price per lb of actual nitrogen that is being applied and, in this case, was $1.28 per lb. This method was used for all single nutrient fertilizers by interchanging the product with the appropriate amount of nutrient within that fertilizer amendment.

$$\left(\frac{\$1{,}295.00}{tonne\ urea}\right)\left(\frac{tonne\ urea}{2204\ lb\ urea}\right)\left(\frac{100\ lb\ urea}{46\ lb\ N}\right)=\frac{\$1.28}{\text{lb N}}$$

Example 2. Multiple Nutrient Fertilizers

When there were two nutrients within a fertilizer product, the most common nutrient or the nutrient that is not being compared the total value of that nutrient was subtracted. In the case of ammonium sulphate (AS) (21-0-0-24), there was nitrogen (21%) and sulphur (24%) within the fertilizer product so the total value of nitrogen must first be subtracted. One tonne of AS is converted to lb AS using 2204-lb/tonne. Then this is converted to the lb of actual nitrogen that is within the fertilizer product by multiplying 21%. This yields 462.84-lb within that 1-tonne is actual nitrogen. To find the total N value this is multiplied by the price per pound of nitrogen that was calculated in the urea calculation which is $1.28/lb N. The total value of the nitrogen within AS is $591.20. The total value of AS is $835.00 as of December 2021 therefore $591.20 needs to be subtracted from $835.00 which equals $243.80 per tonne AS without the N value. This is then converted to cost per lb by dividing it by 2204-lb per tonne which equals $0.11 per lb. To yield the cost per actual sulphur this divided by the 24% which is the actual plant nutrient amount. This makes the cost of sulphur in ammonium sulphate $0.46 per lb sulphur. This method can be used for all multiple nutrient fertilizers just interchanging the products with the appropriate amount of each nutrient within that fertilizer amendment.

$$1\text{ tonne AS}\left(\frac{2204\ lb\ AS}{1\ tonne\ AS}\right)\left(\frac{21\ lb\ N}{100\ lb\ AS}\right)\left(\frac{\$1.28}{lb\ N}\right)=\$591.20\ N\ value$$

$$\frac{\$835.00}{tonne\ AS}-\frac{\$591.20\ N\ value}{tonne\ AS}=\frac{\$243.80}{tonne\ of\ S\ in\ AS}$$

$$\left(\frac{\$243.80}{tonne\ AS}\right)\left(\frac{tonne\ AS}{2204\ lb\ AS}\right)\left(\frac{100\ lb\ AS}{24\ lb\ S}\right)=\frac{\$0.46}{\text{lb S}}$$

Nitrogen value of multi-nutrient fertilizers

Urea and ESN are two very common granular nitrogen fertilizers used by Manitoba processing potato growers. Urea is the baseline nitrogen amendment used in the Manitoba community and this is why it was selected for deciding base value of nitrogen within the multi-nutrient fertilizers. ESN has become part of growing practice on many farms, but since it has properties that make it a slow-release product, it has extra value when compared to urea and was not chosen as the baseline for these reasons.

Liquid urea-ammonium nitrate (UAN) is commonly used as a liquid nitrogen fertilizer to help top up nutrients throughout the growing season. Due to the addition of water, the concentration of nutrients is lower, mimicking what happens with the ATS fertilizer treatment, which is why this treatment has a different value of nitrogen within the cost breakdown.

The magnesium sulphate treatment ($MgSO_4$) became unavailable in the spring of 2021. Due to the most common magnesium amendments being foliar standalone products and micronutrient combination products, the costs of magnesium use could be skewed when determining a baseline. The method chosen to determine actual nutrient amounts for the sake of fertilizer cost comparisons was the same as other multi nutrient fertilizer breakdowns previously outlined. This will show the sulphur amount being the same amount as ammonium sulphate and using that as the value subtracted to find the magnesium value to know how much that micronutrient was within that fertilizer.

Calculate Cost of Fertilizer Product Applied

The first step is converting the price per tonne of fertilizer to price per lb of fertilizer. The cost per tonne of Tiger XP is $745.00 as of December 2021 and there are 2204-lb per tonne. For example to reach the goal of 60-lb sulphur per acre 71-lb of product will need to be applied per acre. That means that 71-lb XP will have to be divided by 2204 lb to convert into tonne of XP product which is 0.032 tonne XP per ac applied. This is then multiplied by the price per tonne which is $745.00. This means that the value of the 71-lb XP applied would be $24.00 per acre. This method doesn’t change with multi-nutrient fertilizers just interchange the lb of product applied and the value of that product.

$$\left(\frac{71\ lb\ XP}{ac}\right)\left(\frac{1\ tonne\ XP}{2204\ lb\ XP}\right)\left(\frac{\$745.00}{tonne\ XP}\right)=\frac{\$24.00}{ac}$$

Results

Nutrient results for 2019-2021:

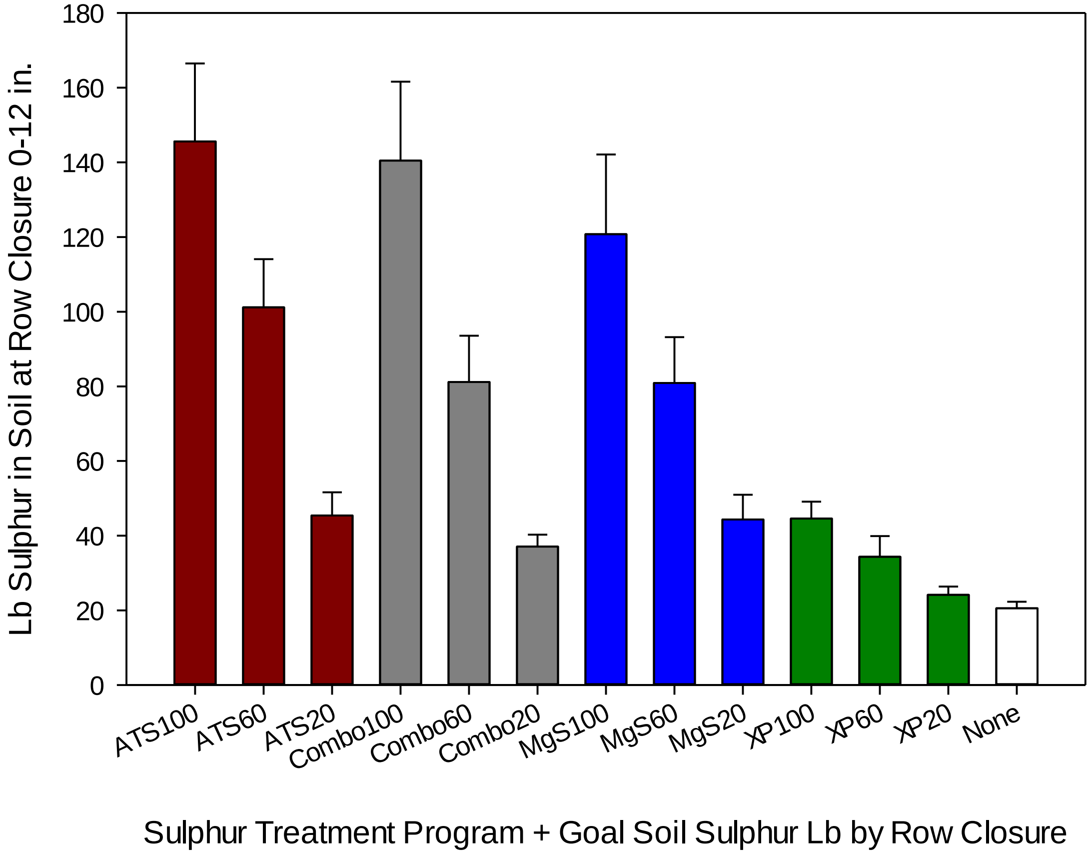

Figure 1 (above): The effect of sulphur treatment program (x-axis) on the availability of soil sulphur (y-axis) at row closure. Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure (i.e. all 60 treatments target 60-lb on the Y-axis of this figure). All fertilizer rates for each treatment can be found in Table 1.

In general, across three years of small plot experiments, increasing amount of fertilizer (such as targeting 100-lb soil sulphur by row closure compared to 20-lb) resulting in increasingly variable responses in levels of soil sulphur, as indicated by increasing whisker length on the highest rates of all treatments. Bearing in mind that the assumed ideal soil sulphur test is 40-lb in potato (as published by the University of Manitoba in Agvise's soil sulphur guidelines at https://www.agvise.com/wp-content/uploads/2017/03/Sulphur-Magnesium-and-Chloride-guidelines.pdf), each 100-lb rate for every fertilizer treatment was well above the 40-lb goal. Each 60-lb rate for every fertilizer treatment was at or above the 40-lb goal, albeit with a much smaller margin for error in specific cases such as Tiger XP and the ammonium sulphate 60-lb. An unexpected result was observed where the 20-lb rates of magnesium sulphate and ammonium sulphate actually achieved a result over the 40-lb threshold by row closure, whereas Tiger XP and Combo 20-lb did not.

There was a significant effect of soil sulphur treatment on the amount of available soil sulphur at row closure ($P < 0.0001$). In general, all 100-lb fertilizer treatments provided significantly more soil sulphur than the negative controls ($P \leq 0.05$, Table 2). Similarly, all 60-lb and 20-lb fertilizer treatments provided more soil sulphur than negative controls except Tiger Combo, which trended towards significance ($P = 0.1142$), and Tiger XP, which was nonsignificant ($P \geq 0.05$, Table 2). In the cases of ammonium sulfate and Tiger Combo treatments their respective 100-lb treatments provided significantly more soil sulphur than 60-lb treatments, and 60-lb treatments provided significantly more soil sulphur than 20-lb treatments. An unexpected observation with the magnesium sulphate treatment was that 100-lb treatments did not have significantly more soil sulphur than the 60-lb treatments, but the 60-lb treatments did have significantly more soil sulphur. Tiger XP treatments did not differ from one-another significantly other than the 100-lb treatment providing more soil sulphur than the 20-lb treatment.

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Ammonium sulphate 100-lb	Ammonium sulphate 20-lb	$P < 0.0001$
Ammonium sulphate 100-lb	Ammonium sulphate 60-lb	$P = 0.0239$
Ammonium sulphate 100-lb	None	$P < 0.0001$
Ammonium sulphate 60-lb	Ammonium sulphate 20-lb	$P = 0.0054$
Ammonium sulphate 60-lb	None	$P < 0.0001$
Ammonium sulphate 20-lb	None	$P = 0.0039$
Tiger Combo 100-lb	Tiger Combo 60-lb	$P < 0.0001$
Tiger Combo 100-lb	Tiger Combo 20-lb	$P < 0.0001$
Tiger Combo 100-lb	None	$P < 0.0001$
Tiger Combo 60-lb	Tiger Combo 20-lb	$P < 0.0001$
Tiger Combo 60-lb	None	$P < 0.0001$
Tiger Combo 20-lb	None	$P < 0.0001$
Magnesium sulphate 100-lb	Magnesium sulphate 60-lb	$P = 0.4178$ *NS
Magnesium sulphate 100-lb	Magnesium sulphate 20-lb	$P = 0.0002$
Magnesium sulphate 100-lb	None	$P < 0.0001$
Magnesium sulphate 60-lb	Magnesium sulphate 20-lb	$P = 0.9889$ *NS
Magnesium sulphate 60-lb	None	$P < 0.0001$
Magnesium sulphate 20-lb	None	$P = 0.1142$ *NS
Tiger XP 100-lb	Tiger XP 60-lb	$P = 0.9618$ *NS
Tiger XP 100-lb	Tiger XP 20-lb	$P = 0.0005$
Tiger XP 100-lb	None	$P < 0.0001$
Tiger XP 60-lb	Tiger XP 20-lb	$P = 0.8008$ *NS

Tiger XP 60-lb	None	*P* = 0.5928 *NS
Tiger XP 20-lb	None	*P* = 0.9999 *NS

Table 2 (above): Specific pairwise comparisons of sulphur treatments on available soil sulphur at row closure are listed with the numerically greatest treatment on the left and lesser column on the right. Combinations of fertilizers that are not present were either not significant ($P \leq 0.05$) or not of experimental interest. *P*-values above the 0.05 threshold on the Tukey test are denoted with *NS as nonsignificant in the *P*-value column and were included for completeness.

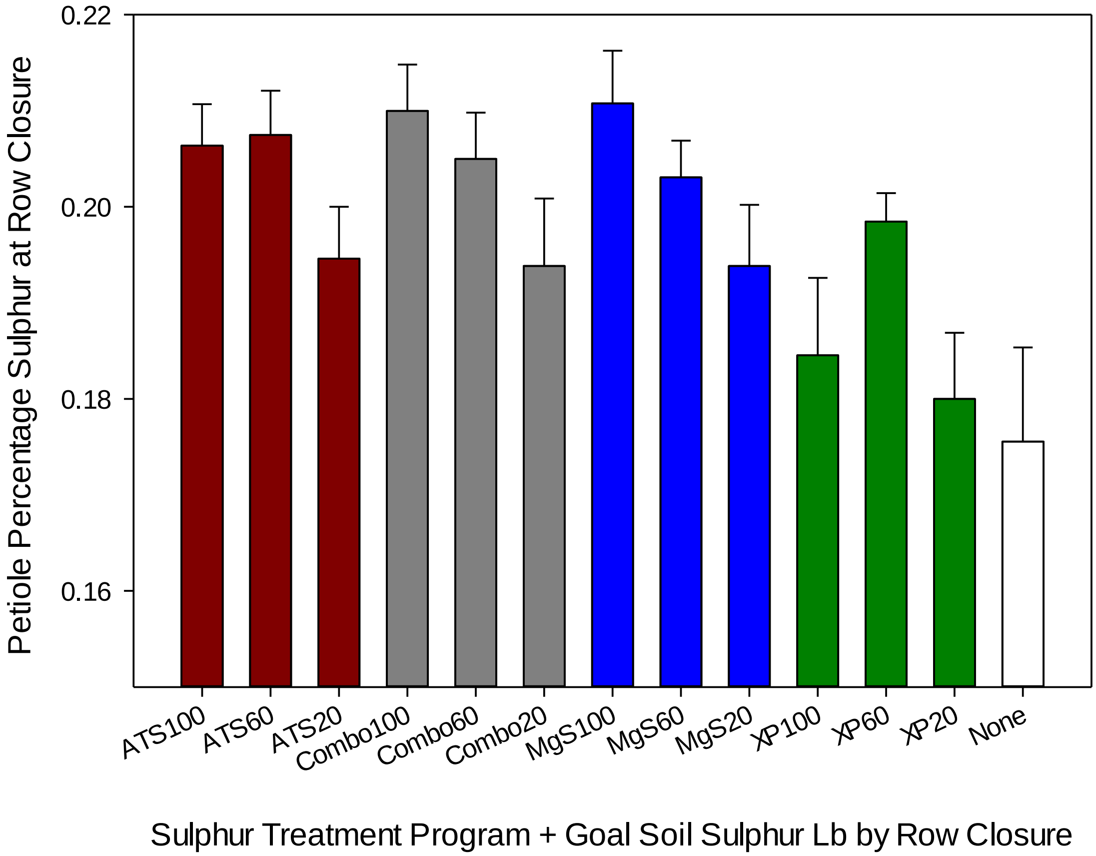

Figure 2 (above): The effect of sulphur treatment program (x-axis) on the availability of petiole sulphur (y-axis) at row closure. Bars indicate mean percent of sulphur, and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure. All fertilizer rates for each treatment can be found in Table 1.

Agvise Inc specifies that row closure petiole sulphur sufficiency is 0.2% to 0.5%, whereas petioles low in sulphur are 0.01% to 0.19% and high sulphur 0.51% to 0.99% (data not shown). The petioles for every fertilizer's 60-lb treatment were at or above the 0.2% threshold for sufficiency. In general, the petioles for every 100-lb treatment were above the 0.2% threshold and the 20-lb treatment was at or just below the same threshold. However, Tiger XP 100-and-20-lb treatments were generally low and below the 0.2% threshold.

There was a significant effect of soil sulphur treatment on the amount of available petiole sulphur at row closure ($P < 0.0001$). Generally, petiole sulphur levels within the same fertilizer but different rates (20, 60, 100) were statistically indistinguishable ($P \geq 0.05$, data not shown), but all fertilizer 100 and 60 rates provided significantly more petiole sulphur than the negative control ($P \leq 0.05$, Table 3) with the only exception of Tiger XP. The only fertilizer treatment where fertilizer rates had significantly different petiole sulphur was Tiger XP 60-lb vs 20-lb ($P = 0.0017$, Table 3).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Ammonium sulphate 100-lb	None	$P = 0.0350$
Ammonium sulphate 60-lb	None	$P = 0.0509$
Tiger Combo 100-lb	None	$P = 0.0020$
Tiger Combo 60-lb	None	$P = 0.0063$
Magnesium sulphate 100-lb	None	$P = 0.0001$
Magnesium sulphate 60-lb	None	$P = 0.0450$
Tiger XP 100-lb	None	$P = 0.9999$*NS
Tiger XP 60-lb	None	$P = 0.8994$*NS
Tiger XP 60-lb	Tiger XP 20-lb	$P = 0.0017$

Table 3 (above): Specific pairwise comparisons of sulphur treatments on available petiole sulphur at row closure are listed with the numerically greatest treatment on the left and lesser column on the right. Combinations of fertilizers that are not present were either not significant ($P \leq 0.05$) or not of experimental interest. *P*-values above the 0.05 threshold on the Tukey test are denoted with *NS as nonsignificant in the *P*-value column and were included for completeness.

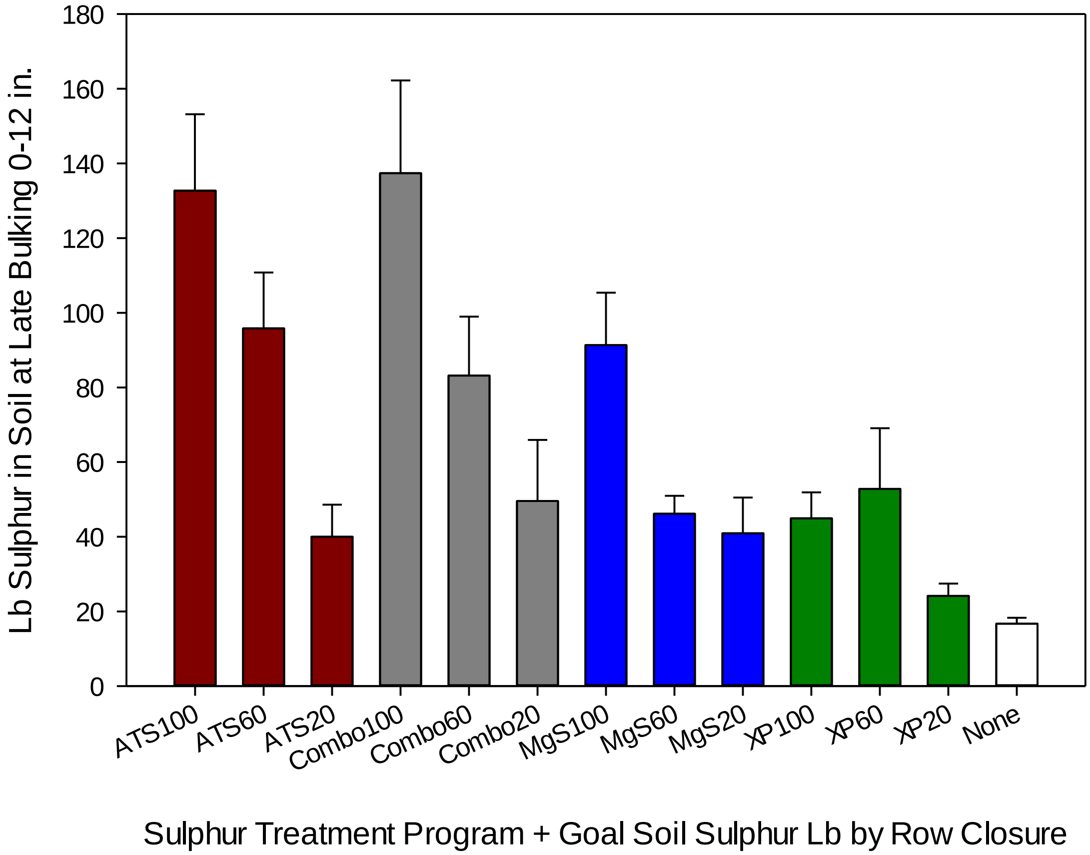

Figure 3 (above): The effect of sulphur treatment program (x-axis) on the availability of soil sulphur (y-axis) at late bulking. Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure, **NOT** the targets for late bulking. All fertilizer rates for each treatment can be found in Table 1.

Statistical analysis for late bulking soil sulphur availability was not possible using the same methods as the other soil, plant, and yield parameters because the convergence criteria wasn't being met and infinite likelihoods were being created by mixed models. Despite this setback, observations can be made about the persistence of sulphur products throughout the season with this data in Fig. 3. In general, ammonium sulfate and Tiger Combo levels soil sulphur were maintained between row closure (Fig. 1) and late bulking (Fig. 2) with numerically similar means regardless of fertilizer rate. Magnesium sulfate levels decreased between row closure (Fig. 1) and late bulking (Fig. 2) by approximately 40-lb of soil sulphur on average for higher 100-and-60-lb treatments. The magnesium sulfate 20-lb treatments did not appreciably decrease between row closure and late bulking (decrease by 3-lb on average). The Tiger XP 60 treatment increased in soil sulphur levels between row closure (Fig. 1) and late bulking (Fig. 2) by an average of 18-lb, whereas the 20-and-100-lb treatments did not appreciably change in the lb of soil sulphur available (average of 0.5-lb increase). An additional observation of note with Tiger XP is that virtually all fertilizer rates had the standard error on soil sulphur measurements double between row closure and late bulking, which stands out compared to the standard error on the other fertilizers remaining consistent between the sampling dates. Both the observations with the increase in total soil sulphur and the variability from plot-to-plot could be explained by the slow-release nature of Tiger XP as it is being converted to plant-available sulphates that can be used or leached.

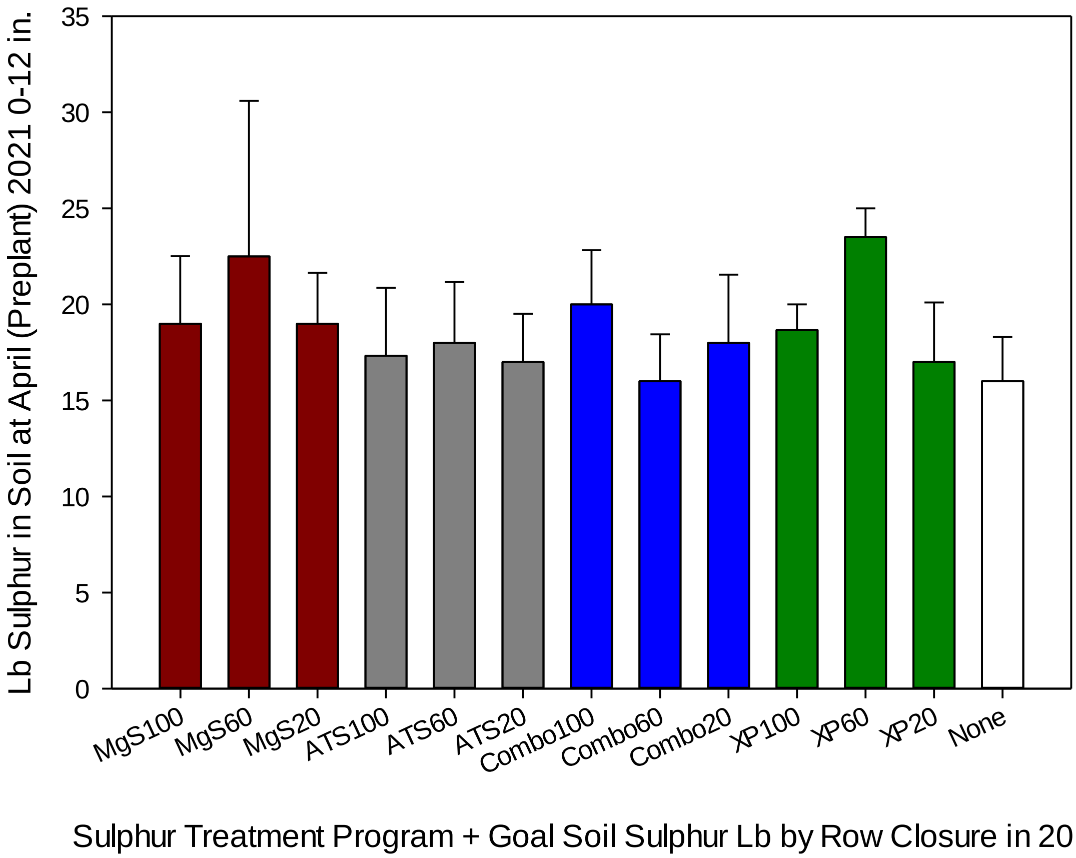

Figure 4 (above): The effect of sulphur treatment program (x-axis) **from 2019** on the availability of soil sulphur (y-axis) in **April 2021**. Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure **in 2019, NOT the targets for 2021**. All fertilizer rates for each treatment can be found in Table 1.

Because of the leaching potential associated with sulphur fertilizers and the sandy soil of the site, questions arose on the long-term potential of slow-release products to persist in plots years after the experiment was complete. The crop rotation on this site is typically potato-wheat-canola, which is typical of the Carberry growing area. Tillage typically precedes the potato year and occurs with plant and digging potatoes, which means the potential for soil movement between plots is low, but not impossible, in the years between 2019 research and 2021 sampling. In general, most fertilizers, regardless of rate, only had 15-to-25-lb of residual soil sulphur (Fig. 4). What is notable is that two years after Tiger XP was applied to soil, overall levels had moved from being below the other fertilizers to more-or-less equivalent. Another unusual observation was that the numerically greatest residual sulphur in soil observed with the magnesium sulfate and Tiger XP treatments at the 60-lb rate.

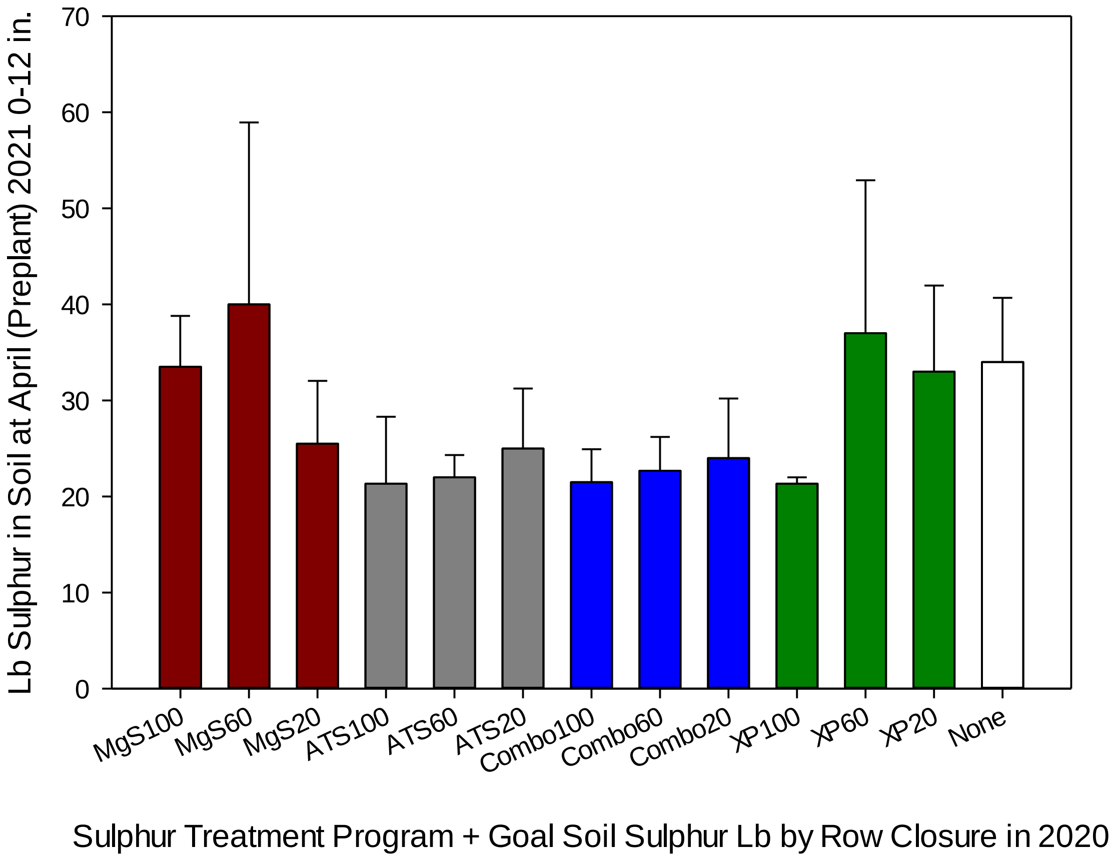

Figure 5 (above): The effect of sulphur treatment program (x-axis) **from 2020** on the availability of soil sulphur (y-axis) in **April 2021**. Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure **in 2020, NOT the targets for 2021** (although field variability study data suggests more soil sulphur throughout season is a positive yield attribute). All fertilizer rates for each treatment can be found in Table 1.

A similar interest extended in studying in the residual sulphur after only one year of experimentation. In the year after potato experimentation, wheat was grown on the site with a similarly limited potential for plot-to-plot soil transfer. The concern for plot-to-plot transfer should be noted as the negative control was found to have more soil sulphur than some of the other fertilizer treatments (Fig. 5). However, magnesium sulfate and Tiger XP plots appeared to have closer to 30-lb of soil sulphur, and again the 60-lb treatments had the most residual sulphur any fertilizer and rate evaluated (numerically). Ammonium sulfate and Tiger Combo treatments appeared to have an average of approximately 20-lb of soil sulphur one (Fig. 6) and two years (Fig. 5) after application, which displays a remarkable consistency across different sets of plots over time.

Yield Results for 2019-2021:

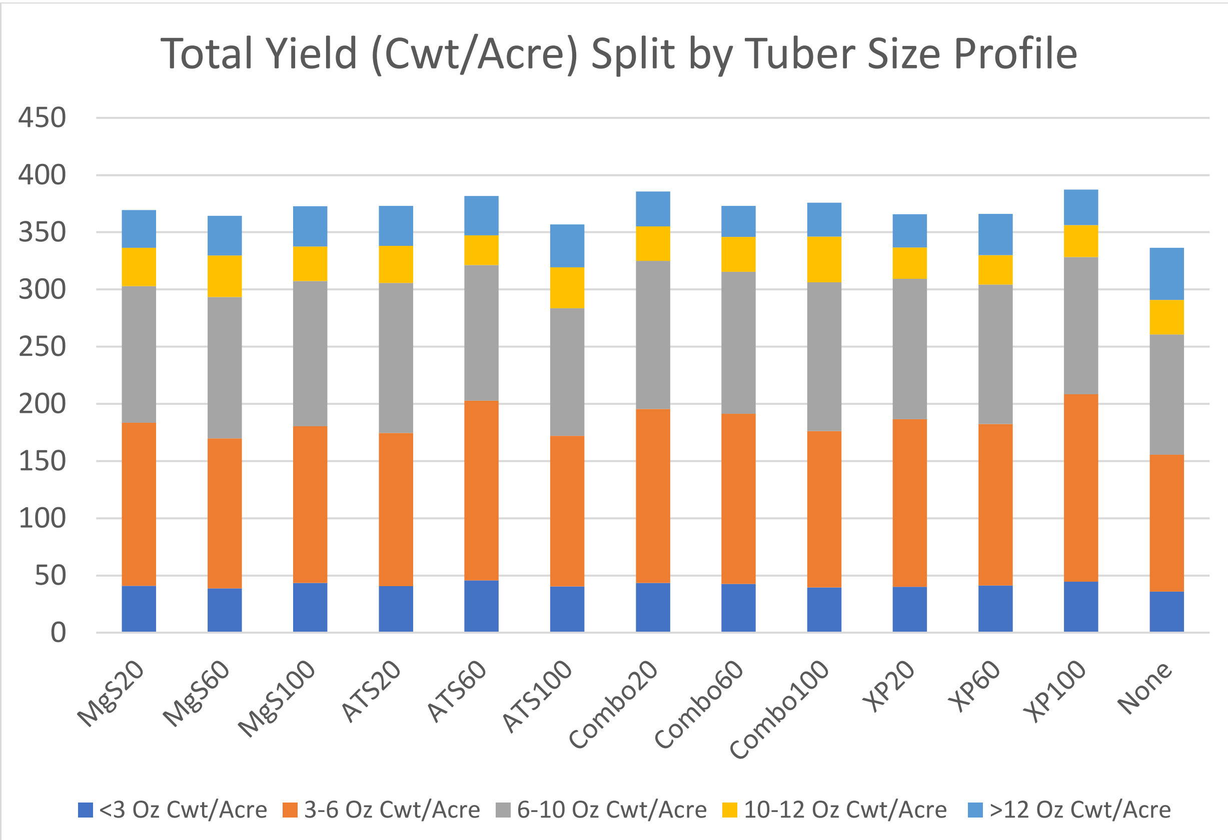

Fig. 6: The total yield (cwt/acre) of each fertilizer treatment and rate with each column separated by the tuber size profile (cwt/acre) average across 2019-2021. Bars indicate mean yield and standard errors were not shown to reduce the load of data in the figure. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure in each year.

There was a significant impact of sulphur fertilizer and rate on total yield (P = 0.0272). None of the total yields from ammonium sulphate treatments were statistically distinguishable from each other or the negative control ($P \geq 0.05$, data not shown). None of the yields from plots subjected to Tiger Combo treatment, regardless of rate, were statistically distinguishable from one-another

($P \geq 0.05$), but plots from each treatment produced significantly more yield than the negative control (Table 4). Similarly, plots with magnesium sulphate treatment were not statistically distinguishable all treatments but trended ($P < 0.11$) towards significantly more yield than the negative control. Tiger XP treatments were also not statistically discernable from each other ($P \geq 0.05$), but the 100-lb rate generated significantly more yield than the negative control ($P = 0.0068$) and the 60-and-20-lb rates trended ($P < 0.11$) very closely towards significance compared to the negative control (Table 4).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Tiger Combo 100-lb	Tiger Combo 60-lb	*P* = 0.9880*NS
Tiger Combo 100-lb	Tiger Combo 20-lb	*P* = 1.0000*NS
Tiger Combo 100-lb	None	*P* = 0.0055
Tiger Combo 60-lb	Tiger Combo 20-lb	*P* =0.9947*NS
Tiger Combo 60-lb	None	*P* = 0.0085
Tiger Combo 20-lb	None	*P* = 0.0124
Magnesium sulphate 100-lb	Magnesium sulphate 60-lb	*P* = 1.0000*NS
Magnesium sulphate 100-lb	Magnesium sulphate 20-lb	*P* = 1.0000*NS
Magnesium sulphate 100-lb	None	*P* = 0.1043*NS
Magnesium sulphate 60-lb	Magnesium sulphate 20-lb	*P* = 1.0000*NS
Magnesium sulphate 60-lb	None	*P* = 0.1070*NS
Magnesium sulphate 20-lb	None	*P* = 0.0752*NS
Tiger XP 100-lb	Tiger XP 60-lb	*P* = 0.9987*NS
Tiger XP 100-lb	Tiger XP 20-lb	*P* = 0.8993*NS
Tiger XP 100-lb	None	*P* = 0.0068
Tiger XP 60-lb	Tiger XP 20-lb	*P* = 1.0000*NS
Tiger XP 60-lb	None	*P* = 0.0537*NS
Tiger XP 20-lb	None	*P* = 0.0729*NS

Table 4 (above): Specific pairwise comparisons of sulphur treatments on total yield are listed with the numerically greatest treatment on the left and lesser column on the right. Combinations of fertilizers that are not present were either not significant ($P \leq 0.05$) or not of experimental interest. *P*-values above the 0.05 threshold on the Tukey test are denoted with *NS as nonsignificant in the *P*-value column and were included for completeness.

There was a nonsignificant impact of sulphur fertilizer and rate on the cwt/acre of tubers that were less than three ounces in weight ($P = 0.6231$, data not shown), three-to-six ounces in weight ($P = 0.1867$, data not shown), six-to-ten-ounce tubers ($P = 0.8021$, data not shown), and tubers over 12-ounces ($P = 0.7265$, data not shown).

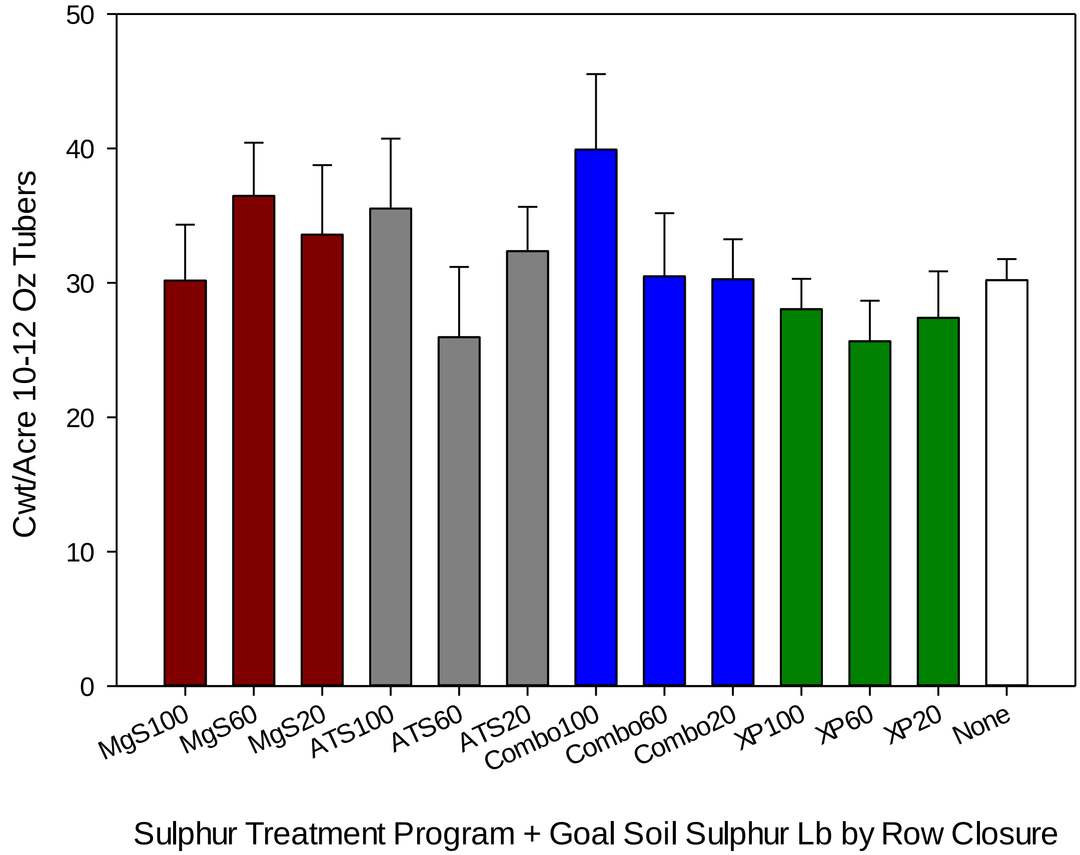

Fig. 7: The effect of sulphur treatment program (x-axis) on the 10-to-12-oz tuber yield (y-axis). Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure. All fertilizers and rates can be found in Table 1.

There was a significant impact on sulphur fertilizer treatment and rate on the cwt/acre of yield that was 10-to-12-oz in size ($P = 0.0422$). None of the total yields from ammonium sulphate, magnesium sulphate, or Tiger XP treatments were statistically distinguishable from each other or the negative control ($P \geq 0.05$, data not shown). However, the Tiger Combo 10-lb treatment produced more 10/12 oz tubers than the 20-lb treatment ($P = 0.0334$) and negative control ($P = 0.0105$, Table 5).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Tiger Combo 100-lb	Tiger Combo 60-lb	*P* = 0.1807*NS
Tiger Combo 100-lb	Tiger Combo 20-lb	*P* = 0.0334
Tiger Combo 100-lb	None	*P* = 0.0105
Tiger Combo 60-lb	Tiger Combo 20-lb	*P* = 0.6192*NS

Tiger Combo 60-lb	None	*P* = 0.4610*NS
Tiger Combo 20-lb	None	*P* = 0.7617*NS

Table 5 (above): Specific pairwise comparisons of sulphur treatments on 10 to 12-oz yield are listed with the numerically greatest treatment on the left and lesser column on the right. Combinations of fertilizers that are not present were either not significant ($P \leq 0.05$) or not of experimental interest. *P*-values above the 0.05 threshold on the Tukey test are denoted with *NS as nonsignificant in the *P*-value column and were included for completeness.

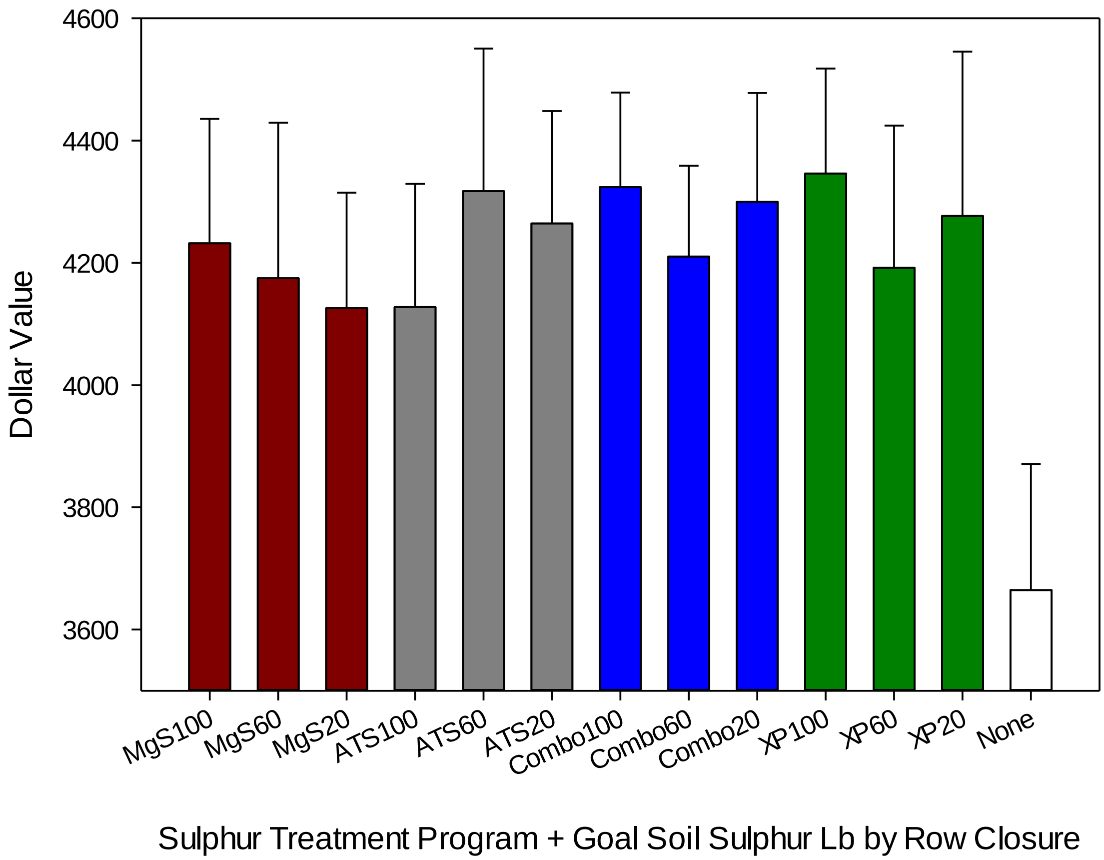

Fig. 8: The effect of sulphur treatment program (x-axis) on the estimated dollar value of plots scaled up to cwt/acre (y-axis). Bars indicate mean lb of sulphur and the standard error is above each bar. MgS signifies magnesium sulphate, while ATS stands for ammonium sulphate + ammonium thiosulfate fertigation. Combo represents Tiger-Sul's Combo product, as XP stands for Tiger-Sul's XP product. None represents the negative control, where no additional sulphur fertilizers/fertigation events were added. The number 20, 60, and 100 refer to the fertilizer targets for row closure. All fertilizers and rates can be found in Table 1.

There was a significant ($P = 0.0440$) impact of sulphur fertilizer and rate on the estimated dollar value of plots (when scaled up to cwt/acre). None of the total yields from ammonium sulphate or magnesium sulphate treatments were statistically significant when compared to each other or the negative control ($P \geq 0.05$, data not shown). Both treatments of Tiger Combo and Tiger XP, regardless of rate, generally netted significantly more value than the negative control with the exception of Tiger XP 60-and-20-lb rates, which only trended ($P < 0.11$) towards significance (Table 6). There were no differences ($P \geq 0.05$) between the value of any rate of Tiger Combo or XP, but there was the beginning of a possible trend ($P = 0.1386$) with Tiger Combo 100-lb rate being more valuable than the Tiger Combo 20-lb rate (Table 6).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	P-value
Tiger Combo 100-lb	Tiger Combo 60-lb	$P = 0.7631$*NS
Tiger Combo 100-lb	Tiger Combo 20-lb	$P = 0.1386$*NS
Tiger Combo 100-lb	None	$P = 0.0140$
Tiger Combo 20-lb	Tiger Combo 60-lb	$P = 0.2495$*NS
Tiger Combo 60-lb	None	$P = 0.0319$
Tiger Combo 20-lb	None	$P = 0.0009$
Tiger XP 100-lb	Tiger XP 60-lb	$P = 1.0000$*NS
Tiger XP 100-lb	Tiger XP 20-lb	$P = 1.0000$*NS
Tiger XP 100-lb	None	$P = 0.0026$
Tiger XP 60-lb	Tiger XP 20-lb	$P = 1.0000$*NS
Tiger XP 60-lb	None	$P = 0.0991$*NS
Tiger XP 20-lb	None	$P = 0.0519$*NS

Table 6 (above): Specific pairwise comparisons of sulphur treatments on estimated dollar value are listed with the numerically greatest treatment on the left and lesser column on the right. Combinations of fertilizers that are not present were either not significant ($P \leq 0.05$) or not of experimental interest. P-values above the 0.05 threshold on the Tukey test are denoted with *NS as nonsignificant in the P-value column and were included for completeness.

Sulphur Fertilizer Cost Estimates

Fertilizer	**Nitrogen value #1**			**Nitrogen value #2**		
	$/lb N	**$/lb S**	**$/lb Mg**	**$/lb N**	**$/lb S**	**$/lb Mg**
Nitrogen						
Urea	$0.52	-	-	$0.63	-	-
UAN	$0.55	-	-	$0.55	-	-
Sulphur						
Ammonium Sulphate	$0.52	$0.37	-	$0.28	$0.28	-
Ammonium Thiosulphate	$0.55	$0.61	-		$0.61	-
Tiger Combo	$0.52	$0.42	-		$0.40	-
Tiger XP	-	$0.26	-		$0.26	-
Magnesium Sulphate	-	$0.37	$2.47	-	$0.37	$2.47

Table 7 (above): Sulphur fertilizer cost estimates for December 2020 are broken down by $/lb nitrogen (N), $/lb sulphur (S), and $/lb magnesium (Mg). No statistical analysis was completed on this table. Liquid urea-ammonium nitrate (UAN) and ammonium thiosulphate (ATS) are estimated amounts based on granular percent increase between 2020 and 2021. Urea increased 244% and ammonium sulphate increased 189%. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Fertilizer	**Nitrogen value #1**			**Nitrogen value #2**		
	$/lb N	**$/lb S**	**$/lb Mg**	**$/lb N**	**$/lb S**	**$/lb Mg**
Nitrogen						
Urea	$0.52	-	-	$0.63	-	-
UAN	$0.55	-	-	$0.55	-	-
Sulphur						
Ammonium Sulphate	$0.52	$0.37	-	$0.28	$0.28	-
Ammonium Thiosulphate	$0.55	$0.61	-		$0.61	-
Tiger Combo	$0.52	$0.42	-		$0.40	-
Tiger XP	-	$0.26	-		$0.26	-
Magnesium Sulphate	-	$0.37	$2.47	-	$0.37	$2.47

Table 8 (above): Sulphur fertilizer cost estimates for December 2021 are broken down by $/lb nitrogen (N), $/lb sulphur (S), and $/lb magnesium (Mg). Magnesium Sulphate is unavailable for purchase this year. No statistical analysis was completed on this table. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Pre-Plant Fertilizer	Fertigation Fertilizer	Actual Sulphur Pre-Plant Applied (lb/ac)	Actual Sulphur Fertigation (lb/ac)	Cost of Pre-Plant Application ($/lb S/ac)	Cost of Fertigation Application ($/lb S/ac)	Total cost of Sulphur Application ($/lb S/ac)
Negative Control (no additional sulphur)		0	0	$0.00	$0.00	$0.00
Tiger XP 0-0-0-85	None	20	0	$5.25	$0.00	$5.25
Tiger Combo 12-0-0-50	None	20	0	$7.97-8.47	$0.00	$7.97-8.47
Magnesium Sulphate 0-0-0-16-8Mg	None	20	0	$7.49	$0.00	$7.49
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	20	0.6	$5.68-7.49	$0.36	$6.04-7.85
Tiger XP 0-0-0-85	None	60	0	$15.76	$0.00	$15.76
Tiger Combo 12-0-0-50	None	60	0	$23.92-25.41	$0.00	$23.92-25.41
Magnesium Sulphate 0-0-0-16-8Mg	None	60	0	$22.46	$0.00	$22.46
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	60	0.6	$17.03-22.46	$0.36	$17.39-22.83
Tiger XP 0-0-0-85	None	100	0	$26.26	$0.00	$26.26
Tiger Combo 12-0-0-50	None	100	0	$39.87-42.35	$0.00	$39.87-42.35
Magnesium Sulphate 0-0-0-16-8Mg	None	100	0	$37.44	$0.00	$37.44
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	100	0.6	$28.38-37.44	$0.36	$28.74-37.80

Table 9 (above): The breakdown per acre on sulphur fertilizer costs on a per lb sulphur/ac basis for December 2020. The range is created by using the two nitrogen values within table 7 affecting the sulphur base costs from table 7. Magnesium Sulphate has the same S cost as ammonium sulphate due to using ammonium sulphate as the base S price since there were no base Mg prices. No statistical analysis was completed on this table. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Pre-Plant Fertilizer	Fertigation Fertilizer	Actual Sulphur Pre-Plant Applied (lb/ac)	Actual Sulphur Rate Fertigation (lb/ac)	Cost of Pre-Plant Application ($/lb S/ac)	Cost of Fertigation Application ($/lb S/ac)	Total cost of Sulphur Application ($/lb S/ac)
Negative Control (no additional sulphur)		0	0	$0.00	$0.00	$0.00
Tiger XP 0-0-0-85	None	20	0	$7.95	$0.00	$7.95
Tiger Combo 12-0-0-50	None	20	0	$11.07-11.56	$0.00	$11.56
Magnesium Sulphate 0-0-0-16-8Mg	None	20	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	20	0.6	$7.41-9.22	$0.42-0.55	$8.02-9.77
Tiger XP 0-0-0-85	None	60	0	$23.86	$0.00	$23.86
Tiger Combo 12-0-0-50	None	60	0	$33.20-34.69	$0.00	$33.20-34.69
Magnesium Sulphate 0-0-0-16-8Mg	None	60	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	60	0.6	$22.22-27.65	$0.42-0.55	$22.83-28.20
Tiger XP 0-0-0-85	None	100	0	$39.77	$0.00	$39.77
Tiger Combo 12-0-0-50	None	100	0	$55.33-57.82	$0.00	$55.3357.82
Magnesium Sulphate 0-0-0-16-8Mg	None	100	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	100	0.6	$37.03-46.09	$0.42-0.55	$37.64-46.64

Table 10 (above): The breakdown per acre on sulphur fertilizer costs on a per lb sulphur/ac basis for December 2021. The range is created by using the two nitrogen values within table 8 affecting the sulphur base costs from table 8. Magnesium Sulphate was unavailable for purchase this year. No statistical analysis was completed on this table. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Pre-Plant Fertilizer	Fertigation Fertilizer	Product Rate Pre-Plant Applied (lb/ac)	Product Rate Fertigation Applied (lb/ac)	Cost of Pre-Plant Application ($/lb product/ac)	Cost of Fertigation Application ($/lb product/ac)	Total cost of Sulphur Application ($/lb product/ac)
Negative Control (no additional sulphur)		0	0	$0.00	$0.00	$0.00
Tiger XP 0-0-0-85	None	24	0	$5.36	$0.00	$5.36
Tiger Combo 12-0-0-50	None	40	0	$10.98	$0.00	$10.98
Magnesium Sulphate 0-0-0-16-8Mg	None	125	0	$32.21	$0.00	$32.21
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	68	3	$13.58	$0.61	$14.19
Tiger XP 0-0-0-85	None	71	0	$15.85	$0.00	$15.85
Tiger Combo 12-0-0-50	None	120	0	$32.94	$0.00	$32.94
Magnesium Sulphate 0-0-0-16-8Mg	None	375	0	$96.64	$0.00	$96.64
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	188	3	$37.53	$0.61	$38.14
Tiger XP 0-0-0-85	None	118	0	$26.34	$0.00	$26.34
Tiger Combo 12-0-0-50	None	200	0	$54.90	$0.00	$54.90
Magnesium Sulphate 0-0-0-16-8Mg	None	625	0	$161.07	$0.00	$161.07
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	313	3	$62.49	$0.61	$63.10

Table 11 (above): The breakdown per acre on sulphur fertilizer costs on a per lb product/ac basis for December 2020. The range is created by using the two nitrogen values within table 7 affecting the sulphur base costs from table 7. No statistical analysis was completed on this table. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Pre-Plant Fertilizer	Fertigation Fertilizer	Product Rate Pre-Plant Applied (lb/ac)	Product Rate Fertigation Applied (lb/ac)	Cost of Pre-Plant Application ($/lb product/ac)	Cost of Fertigation Application ($/lb product/ac)	Total cost of Sulphur Application ($/lb product/ac)
Negative Control (no additional sulphur)		0	0	$0.00	$0.00	$0.00
Tiger XP 0-0-0-85	None	24	0	$8.11	$0.00	$8.11
Tiger Combo 12-0-0-50	None	40	0	$17.70	$0.00	$17.70
Magnesium Sulphate 0-0-0-16-8Mg	None	125	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	68	3	$25.76	$1.16	$26.92
Tiger XP 0-0-0-85	None	71	0	$24.00	$0.00	$24.00
Tiger Combo 12-0-0-50	None	120	0	$53.09	$0.00	$53.09
Magnesium Sulphate 0-0-0-16-8Mg	None	375	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	188	3	$71.23	$1.16	$72.38
Tiger XP 0-0-0-85	None	118	0	$39.89	$0.00	$39.89
Tiger Combo 12-0-0-50	None	200	0	$88.48	$0.00	$88.48
Magnesium Sulphate 0-0-0-16-8Mg	None	625	0	Unavailable		
Ammonium Sulphate 21-0-0-24	Ammonium Thiosulphate 12-0-0-26	313	3	$118.58	$1.16	$119.74

Table 12 (above): The breakdown per acre on sulphur fertilizer costs on a per lb product/ac basis for December 2021. The range is created by using the two nitrogen values within table 8 affecting the sulphur base costs from table 8. Magnesium Sulphate is unavailable for purchase this year. No statistical analysis was completed on this table. Prices are estimates in Canadian dollars provided courtesy of the companies that provided the fertilizer products, and prices are subject to change in subsequent years after the study.

Discussion

The present study was based upon statistical associations created from the larger field variability study that encompassed observations from 23 grower fields over five years. The goal of this study was to identify the exact range of lb of soil sulphur needed by row closure and possible products and rates needed to accomplish the task to improve yield and quality of processing potatoes.

One resource of regional significance (as published by the University of Manitoba in Agvise's soil sulphur guidelines at https://www.agvise.com/wp-content/uploads/2017/03/Sulphur-Magnesium-and-Chloride-guidelines.pdf) has pointed to a preplant target 40-lb of soil sulphur, and the variability study suggested that recommendation should be extended to row closure to improve the size and value of tuber yield. An unexpected result was observed where the 20-lb rates of magnesium sulphate and ammonium sulphate actually achieved a result over the 40-lb threshold by row closure, whereas Tiger XP and Combo 20 did not (Fig. 1). An astute observer will note that the negative control plots still tested as having some soil sulphur despite the absence of treatment (Figs. 1 and 3). It is possible that residual sulphur pushed some of the 20-lb rates over the 40-lb target. Based on the evidence in this study, negative control plots that tested with an average of 20-lb by row closure did not improve the total yield (Fig. 6, Table 4), 10-to-12-oz yield (Fig. 7, Table 5), and estimated dollar value (Fig. 8, Table 6) - suggesting that 20-lb in the soil by row closure is insufficient soil sulphur and supporting the original target of at least 40-lb. In addition, assuming approximately 20-lb residual on average per plot prior to fertilization, and additional 20-lb of sulphur (totaling 40-lb) was often statistically indistinguishable from fertilizer treatments targeting 60-lb by row closure – which provides additional evidence that 40-lb of sulphur by row closure is a reliable target. Lastly, the only reliable tuber size increase within a fertilizer treatment occurred in 10-to-12-oz yield with Tiger Combo 100 when compared to Tiger Combo 20 (P = 0.0334, Table 5). This did not increase the total yield (P = 1.000, Table 4), but did net a better bonus on the estimated dollar value that large enough to trend towards significance (P = 0.1386, estimated average $60/cwt, Table 6). These three pieces of evidence support keeping the row closure soil sulphur target at 40-lb.

The observation that Tiger Combo at the 100-lb rate results in more 10-to-12-oz tubers and trends towards increased value provides more solid corroboration of the variability study results and that some sulphur products may require increased rates to manifest yield improvements. In the case of two of the other products evaluated (Tiger XP and magnesium sulfate), any rate provided yield and quality and value improvements over the negative control and low rates didn't present any advantage over higher rates (Figs 6, 7, 8; Tables 4, 5, 6). This result could indicate that in many cases, the lowest rates of sulphur are sufficient to reap the most benefit. Experimentation with each specific product would probably be required to discern which case prevails with which fertilizer product, as there are or will be sulphur products that could be used as fertilizer in potato production systems that were not part of the present study.

At row closure, each 100-lb rate for every fertilizer treatment was well above the 40-lb overall goal from the variability study. Each 60-lb rate for every fertilizer treatment was at or above the 40-lb goal, albeit with a much smaller margin for error in specific cases such as Tiger XP 60-lb and the ammonium sulphate 60-lb. In general, Tiger XP's slow-release nature and elemental sulphur ingredient are probably causes for why release was lower than expected targets by row closure (Fig. 1) and why the treatment appears to catch up with other fertilizer regimens in later years (Figs. 4 and 5).

In general, across three years of small plot experiments, increasing amount of fertilizer (such as targeting 100-lb soil sulfur by row closure compared to 20-lb) resulted in increasingly variable responses in levels of soil sulphur (Fig. 1). Part of this observation can be explained by increasing fertilizer levels, but there most likely is an interaction with leaching potential. The site that was selected was lighter, sandier soil with a propensity for leaching. When combined with large precipitation events in May or June, it is possible that the higher rates of sulphur fertilizers had more leaching potential.

A major part of grower acceptance of new products and practices is an understanding of the costs associated with the changes. A challenge in setting cost estimates between 2020-2021 is the approximately 180-250% change in price over a 12-month period (depending on product, Tables 7-8). In 2020 (Table 7), the estimated costs per lb of sulphur were $0.26 for Tiger XP, $0.37 for ammonium sulphate, $0.37 for magnesium sulphate, $0.42 for Tiger Combo, and $0.61 for ammonium thiosulphate. The estimate costs for sulphur per 20-lb rate of actual sulphur applied were $5.25 for Tiger XP, $7.97-8.47 for Tiger Combo, $7.49 for magnesium sulphate, and $6.04-7.85 for the mixture of ammonium sulphate and ammonium thiosulphate (table 9). The estimate costs for fertilizer product per 20-lb rate were $5.36 for Tiger XP, $10.98 for Tiger Combo, $32.21 for magnesium sulphate, and $14.19 for the mixture of ammonium sulphate and ammonium thiosulphate (Table 11). There is a large assumption that the 20-lb rate provides no statistical advantage in total yield, value, or tuber size profile only when there are an average 20-lb sulphur in the soil at the start of season, otherwise a higher rate of sulphur is needed to achieve the 40-lb minimum by row closure. The assumption that comparing prices on the basis of the actual nutrient the mixture is the normal practice in Manitoba when comparing fertilizer products (https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/calculating-fertilizer-rates.html). Employing this practice, the mixture of ammonium sulphate and ammonium thiosulphate and magnesium sulphate product are the most cost effective. Due to the varied nitrogen and magnesium content in these products, which is more expensive, it sways the cost comparison in their favour. Due to the excess costs of magnesium as a micronutrient it increases the total cost of the product. This is also seen with the increased amount of nitrogen in ammonium sulphate compared to the other products. Given this assumption and the cost estimates, Tiger XP and Combo provide the most cost-effective means of achieving the row closure targets and net increased yields and tuber size profiles in soils that are deficient in soil sulphur at the start of season when looking at the cost of total product per acre being applied. The combined use of ammonium sulphate and thiosulphate has been employed in Manitoba processing potato industry, and the present study supports that this treatment effectively covers row closure soil sulphur products, but at a cost higher than the Tiger Combo and XP treatments. The use of magnesium sulphate is not widely employed in Manitoba and was the most expensive treatment. These trends carried over across the higher fertilizer rates for the same products.

The final piece of the puzzle to change sulphur recommendations and practices in potato production systems is to take the results of this plot scale study up to the field scale and verify the practice works on the large scale, is practical, and generates tangible profits for growers. If successful, these experiments should pave the way to changes in the blend of fertilizer that growers broadcast preplant in Manitoba in order to manage sulphur deficiency in the most cost-effective manner possible. If successful, this method can also provide a successful blueprint for nutrient research for consultants, agronomists, and researchers to conduct applied work on farm and in controlled plots to establish best, profitable practices.

Acknowledgements

The authors would like to thank Alan Manns for his time and skill in applying the fertigation treatment to specific plots with the meticulousness and repeatability demanded by the principal investigator. The authors also appreciate the efforts of Lindsey Andronak, Brian Baron, and Eric Claeys for their contributions to plot setup and maintenance as members of the Agriculture and Agri-Food Canada (AAFC) partner at the Canada Manitoba Crop Diversification Centre (CMCDC) in Carberry, Manitoba, where this study was conducted in 2019. Similarly, the efforts of Alex Christison, Matthias Schira, Jane Giesbrecht, Garth Christison, Andrea Hamilton, Nicole Buurma, and Whitley McDonald are appreciated and were necessary for successful plot establishment and maintenance in 2020 and 2021 at CMCDC. The authors would be remiss to not thank Jack and Dave Adriaansen for donating the 'Russet Burbank' seed used in the study in 2019-2021. This study was conducted with sulphur fertilizers and guidance on fertilizer pricing from Tiger-Sul Inc and Redfern Farm Services.

This study was funded in part by the Canadian Agricultural Partnership through the province of Manitoba's Ag Action Program (Project #1000210208). Research staff salaries were funded by a Province of Manitoba Strategic Initiative (#1000219435) and student wages were partially subsidized by the Canada Summer Jobs Program (#0-18636969). This study was also funded by the three partners of the Manitoba Horticulture Productivity Enhancement Centre (MHPEC) Inc: The Keystone Potato Producers Association, McCain Foods, and Simplot Canada II.