MHPEC Sulphur Study Report 2019-2020

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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 6-10, 10-12, and 12+ oz yields. The assumed ideal soil sulphur test is 40 lbs 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 0-120 lbs, regardless of sampling date. In a cursory examination of the data set, 40-60 lbs 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 (6+ ozs). 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. 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 4-14 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 and April 30th 2020. 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 (2-3 oz, average 2.5 oz (data not shown)) was planted on May 6th 2019 and May 5th 2020 with no gaps between plots, 36 inches between rows, 13 inches between seed pieces within row, and 6 inches deep (from top of hill). Seed was treated with Titan Emesto (Bayer, Leverkusen, Germany) at a rate of 20.8 mL per 100 kg of seed. The 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 and June 2nd 2020 using a power hiller attached to a tractor. Row closure was observed on July 15th 2019 and June 30th 2020, 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 and August 18th 2020. The lbs of sulphur available in soils and the percentage of sulphur in petioles were determined by Agvise Inc (Northwood, North Dakota).
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 and July 23rd 2020. Fertigation was conducted through a Hardi (Davenport, IA, 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 2-4 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 3.6m 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, Irricana, Alberta), Tiger Combo (Tiger-Sul Inc, Irricana, Alberta), 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 ($(NH_4)_2S_2O_3$ ATS) through fertigation (Redfern Farm Services, Brandon, Manitoba). Each fertilizer treatment, except the negative control, was applied at the equivalent of 20, 60, and 100 lbs 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, with exact application rates displayed in Table 1 below:

Formulation (NPKS)	Fertilizer	Goal lbs by row closure	Lbs/A of product required to achieve goal	Lbs product applied preplant per replicate (4 plots)	Fertigation Fertilizer and Formulation	Sulphur Fertigation rate (lbs)
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 lbs of sulphur available at row closure, as determined at a soil test conducted by Agvise, Inc. (Northwood, North Dakota). The fertigation rate assumes three lbs 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 lbs/acre (A) of mono-ammonium phosphate (MAP, 11-52-0-0), 42.24 lbs/A of Kmag blend (0-0-60-0), and 466.6 lbs/A of ESN (polymer coated urea named Environmentally Smart Nitrogen, 44-0-0) from Redfern Farm Services, Brandon, Manitoba.

Harvest occurred on September 17^{th} 2019 and September 14^{th} 2020 and was completed using 1-row digger on a 10m 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 lbs harvested, as well as the lbs of each tuber size category (less than 3 oz, 3-5.9 oz, 6-9.9 oz, 10-11.9 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 (lbs/acre) by row closure to a yield parameter (for example: the fertilizer Tiger XP at 60 lbs by row closure impact on the 6-10 oz yield category). This analysis was completed for each yield parameter separately (e.g. 6-10 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. In 2020, when year became a significant interaction term, the slice statement was used to study simple effects in the dataset that combined both years of study.

Results

The growing seasons in 2019 and 2020 were so different that the data could not be combined across years for analysis. The mixed procedure identified the year variable as highly significant ($P < 0.0001$) for each yield category, indicating that combining any yield data from the same treatment across years would incur such extreme variability that no statistical test could identify any differences between treatments. The following results will be presented with each year analyzed separately.

Yield Results for 2020:

There was no significant sulphur treatment effect on total yield ($P = 0.1164$), value ($P = 0.1303$), specific gravity ($P = 0.1499$) or any size profile in 2020 (Fig. 2). More specifically, observed differences in the 3-6 oz yield ($P = 0.6253$), 6-10 oz yield ($P = 0.5394$), 10-12 oz yield ($P = 0.1163$), and greater than 12 oz yield ($P = 0.5133$). There was also no significant sulphur treatment effect on the percentage of any tuber size profile in 2020. More specifically, observed differences in the 3-6 oz percent yield ($P = 1$), 6-10 oz percent yield ($P = 0.8817$), 10-12 oz percent yield ($P = 0.2545$), and greater than 12 oz percent yield ($P = 0.2520$).

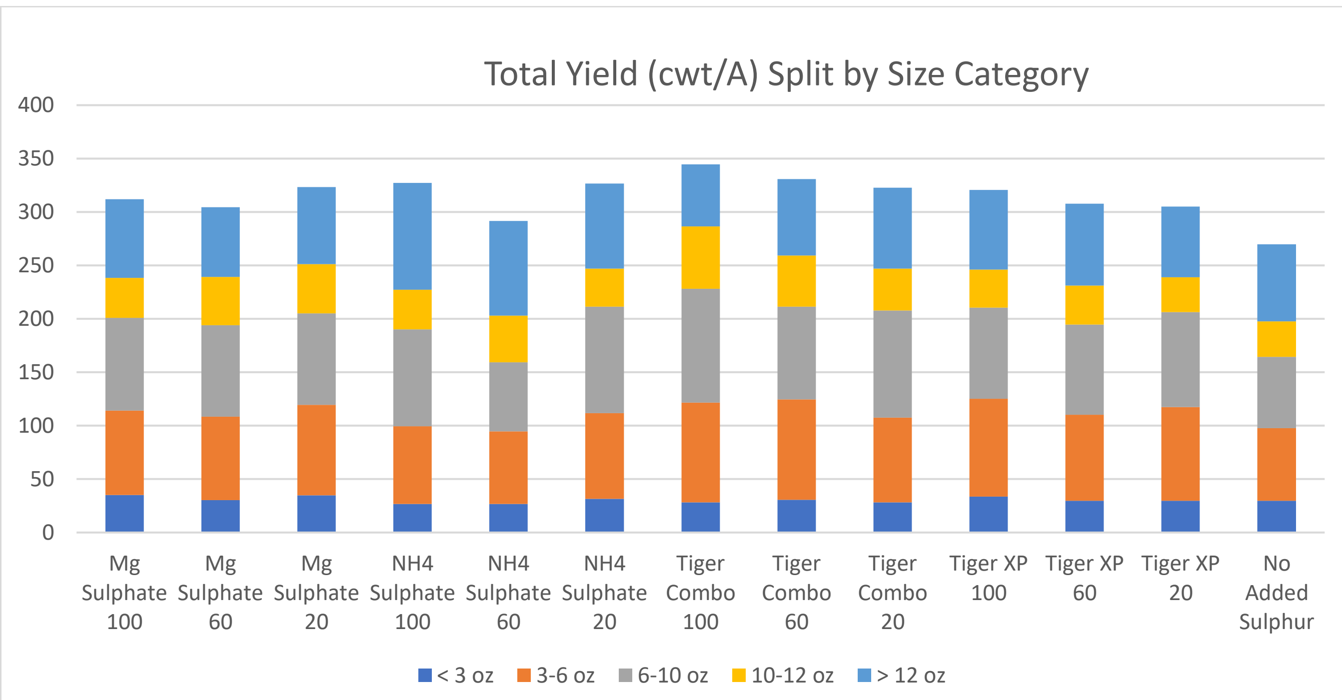

Fig. 2 The total yield consisting of the average of the four replicates of each fertilizer treatment with each column separated by the tuber size profile in 2020. The tuber size profile also consists of the average of the four replicates within a given treatment. There was no significant sulphur treatment effect on total yield or any size category.

There was a significant effect ($P = 0.0164$) of fertilizer product use on total yield when the rates of each fertilizer were combined in the 2020 analysis. All fertilizers improved total yield when compared to the negative control. There were no significant total yield differences between the fertilizer products. Tiger Combo trended towards significance vs Magnesium Sulphate (Mg

Sulphate in Fig. 3, P = 0.0989) and Tiger XP trended towards significance vs Magnesium Sulphate (Mg Sulphate in Fig. 3, P = 0.9089), with Tiger Combo treatments having the numerically greatest yield.

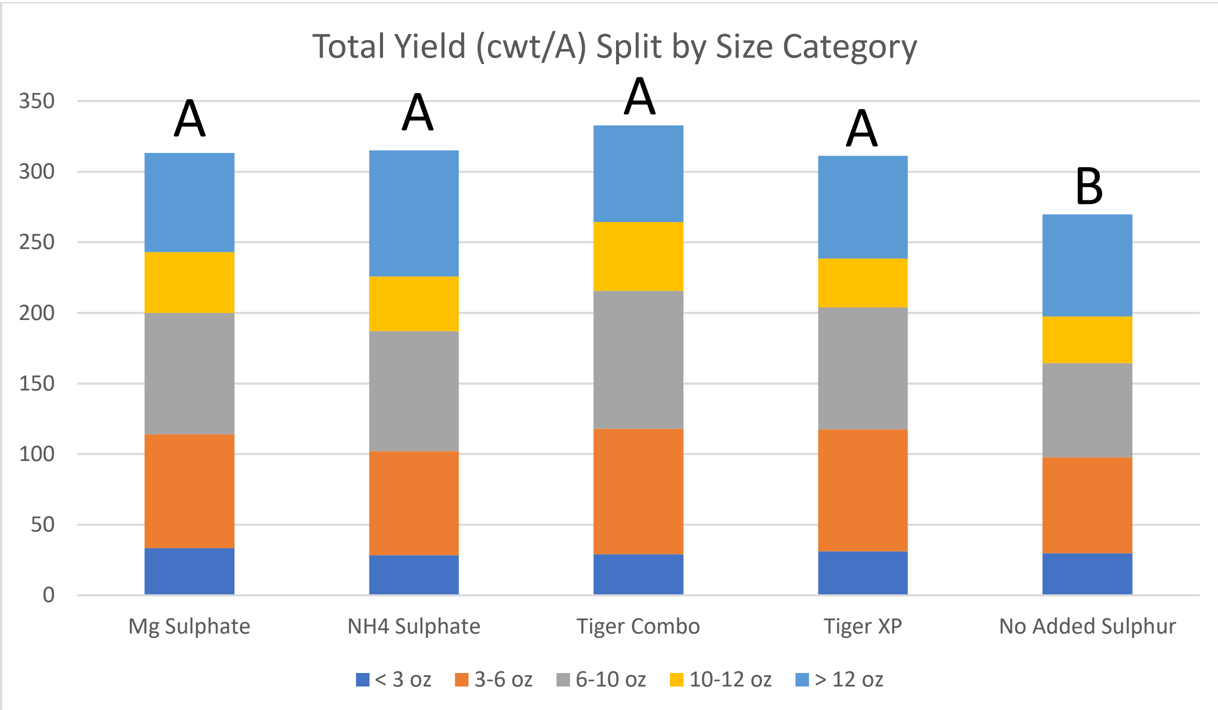

Fig. 3 The total yield by each fertilizer product consisted of the average of the twelve replicates of each fertilizer product (treatment rates combined) with each column separated by the tuber size profile. Letters denote statistical differences as determined by the mixed procedure with Tukey post-hoc tests with significance determined at $P \leq 0.05$. There was a significant effect (P = 0.0164) of fertilizer product use on total yield when the rates of each fertilizer were combined in the 2020 analysis. All fertilizers improved total yield when compared to the negative control. There were no significant total yield differences between the fertilizer products.

There was also a significant effect (P = 0.0211) of fertilizer use on the dollars per cwt when the rates of each fertilizer were combined in the 2020 analysis. All fertilizers improved total yield when compared to the negative control, which received no sulphur fertilizer. There were no significant dollar value differences between the fertilizer products. Tiger Combo trended towards significance vs Magnesium Sulphate (Mg Sulphate in Fig. 4, P = 0.1006).

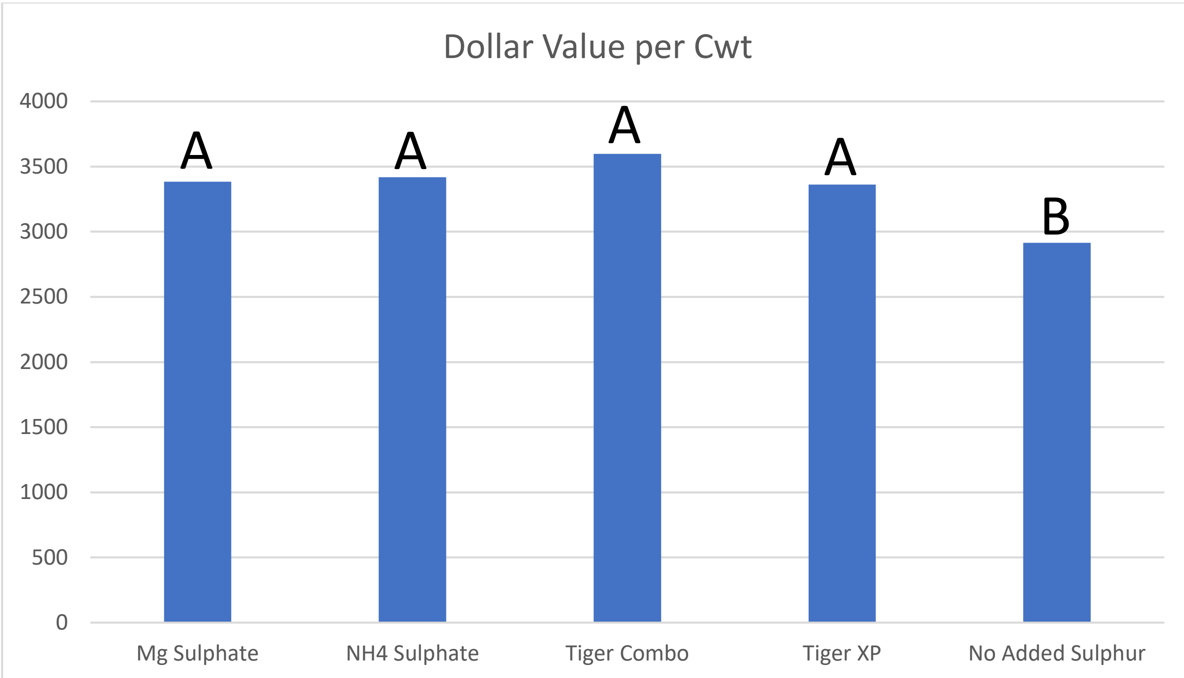

Fig. 4 The dollar values per cwt for each fertilizer product that consisted of the average of the twelve replicates of each fertilizer product (treatment rates combined). Letters denote statistical differences as determined by the mixed procedure with Tukey post-hoc tests with significance determined at $P \leq 0.05$. There was a significant effect ($P = 0.0164$) of fertilizer product use on total yield when the rates of each fertilizer were combined in the 2020 analysis. All fertilizers improved the value when compared to the negative control. There were no significant total yield differences between the fertilizer products.

There was also one final significant effect ($P = 0.0094$) of fertilizer use on the 10-12 oz yield when the rates of each fertilizer were combined in the 2020 analysis. All fertilizers improved total yield when compared to the negative control except the Tiger XP ($P = 0.8950$) and Ammonium Sulphate treatments ($P = 0.9750$). There were no significant total yield differences between the fertilizer products. Tiger Combo trended towards significance vs Tiger XP (Fig. 5, $P = 0.1070$), and Tiger Combo was the treatment with numerically greater 10-12 oz yield.

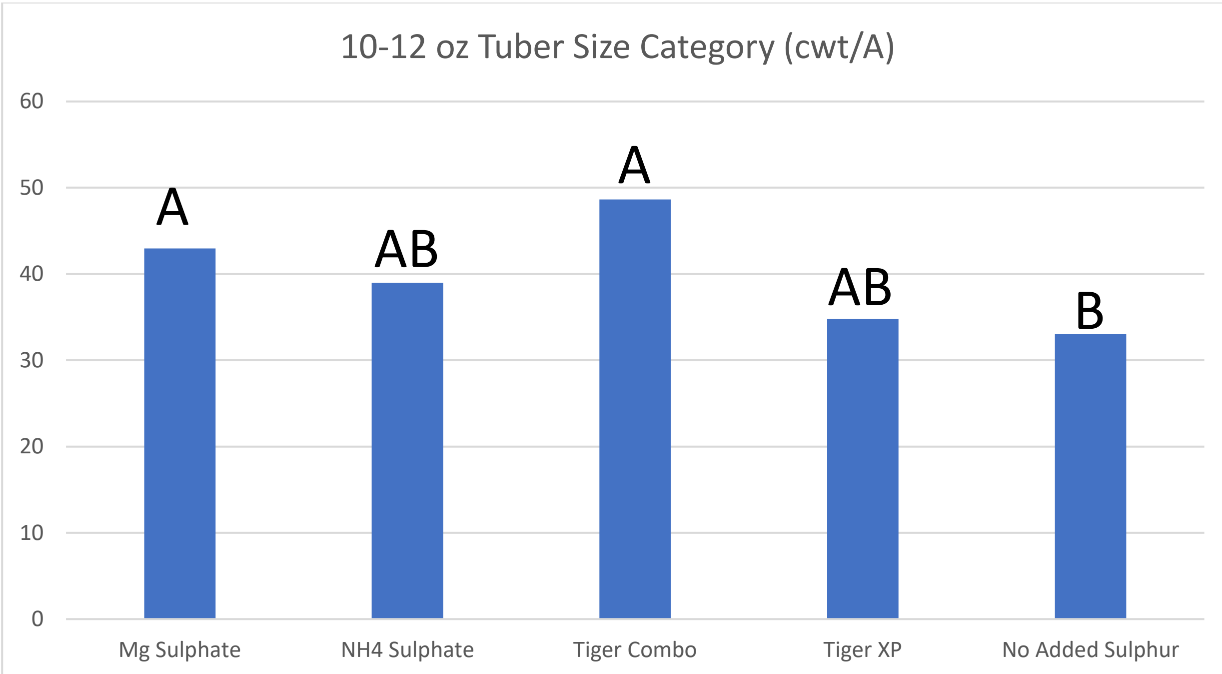

Fig. 5 The 10-12 oz yield for each fertilizer product that consisted of the average of the twelve replicates of each fertilizer product (treatment rates combined). Letters denote statistical differences as determined by the mixed procedure with Tukey post-hoc tests with significance determined at $P \leq 0.05$. All fertilizers improved total yield when compared to the negative control except the Tiger XP ($P = 0.8950$) and Ammonium Sulphate treatments ($P = 0.9750$). There were no significant total yield differences between the fertilizer products.

Because of the significant interaction of year, any combined analysis and interpretation of main effects with fertilizer use on yield for 2020 and 2019 data would be null and void. However, it is legitimate to test the simple effects of fertilizer rate on total yield (Table 2), dollars per cwt (Table 3) and 10-12 oz yield (Table 4). Particular fertilizer rates that had a significant impact on the dependent variable (total yield, dollar value, or 10-12 oz yield) are highlighted in green, and the test does not indicate whether the trend is positive or negative (i.e. a significant result in the none, or no additional sulphur fertilizer added, doesn't necessarily mean that the experiment failed. It could mean that the "none" treatment had lower yield than other treatment, but that can not be verified until a main effects test can be done without an interaction.)

Tests of Effect Slices for Total Yield				
Effect	**Fertilizer**	**Rate**	**F Value**	**Pr > F**
Year*Fertilizer*Rate	**NH4 Sulphate**	**20**	4.36	0.0527
Year*Fertilizer*Rate	**NH4 Sulphate**	**60**	10.27	0.0053
Year*Fertilizer*Rate	**NH4 Sulphate**	**100**	0.29	0.5990
Year*Fertilizer*Rate	**Tiger Combo**	**20**	39.38	<.0001
Year*Fertilizer*Rate	**Tiger Combo**	**60**	14.46	0.0015

Tests of Effect Slices for Total Yield				
Effect	**Fertilizer**	**Rate**	**F Value**	**Pr > F**
Year*Fertilizer*Rate	**Tiger Combo**	**100**	13.55	0.0019
Year*Fertilizer*Rate	**Mg Sulphate**	**20**	6.12	0.0236
Year*Fertilizer*Rate	**Mg Sulphate**	**60**	9.24	0.0071
Year*Fertilizer*Rate	**Mg Sulphate**	**100**	7.99	0.0112
Year*Fertilizer*Rate	**None**	**0**	74.47	0.0002
Year*Fertilizer*Rate	**Tiger XP**	**20**	4.26	0.0538
Year*Fertilizer*Rate	**Tiger XP**	**60**	4.70	0.0437
Year*Fertilizer*Rate	**Tiger XP**	**100**	0.46	0.5056

Table 2 Test of simple effects of fertilizer and rate on total yield using the slice feature in proc mixed. Particular fertilizer rates that had a significant impact on the dependent variable (total yield, dollar value, or 10-12 oz yield) are highlighted in green ($P \leq 0.05$)

Tests of Effect Slices Dollars/cwt				
Effect	**Fertilizer**	**Rate**	**F Value**	**Pr > F**
Year*Fertilizer*Rate	**NH4 Sulphate**	**20**	4.25	0.0555
Year*Fertilizer*Rate	**NH4 Sulphate**	**60**	9.08	0.0081
Year*Fertilizer*Rate	**NH4 Sulphate**	**100**	0.20	0.6617
Year*Fertilizer*Rate	**Tiger Combo**	**20**	36.87	<.0001
Year*Fertilizer*Rate	**Tiger Combo**	**60**	10.93	0.0042
Year*Fertilizer*Rate	**Tiger Combo**	**100**	10.36	0.0052
Year*Fertilizer*Rate	**Mg Sulphate**	**20**	5.16	0.0358
Year*Fertilizer*Rate	**Mg Sulphate**	**60**	7.41	0.0140
Year*Fertilizer*Rate	**Mg Sulphate**	**100**	7.42	0.0140
Year*Fertilizer*Rate	**None**	**0**	60.68	0.0004
Year*Fertilizer*Rate	**Tiger XP**	**20**	3.76	0.0683
Year*Fertilizer*Rate	**Tiger XP**	**60**	3.88	0.0644
Year*Fertilizer*Rate	**Tiger XP**	**100**	0.27	0.6127

Table 3 Test of simple effects of fertilizer and rate on dollars per cwt using the slice feature in proc mixed. Particular fertilizer rates that had a significant impact on the dependent variable (total yield, dollar value, or 10-12 oz yield) are highlighted in green ($P \leq 0.05$)

Tests of Effect Slices 10-12 oz yield (cwt/acre)				
Effect	**Fertilizer**	**Rate**	**F Value**	**Pr > F**
Year*Fertilizer*Rate	**NH4 Sulphate**	**20**	0.67	0.4255
Year*Fertilizer*Rate	**NH4 Sulphate**	**60**	10.40	0.0051
Year*Fertilizer*Rate	**NH4 Sulphate**	**100**	3.00	0.1020
Year*Fertilizer*Rate	**Tiger Combo**	**20**	3.44	0.0822
Year*Fertilizer*Rate	**Tiger Combo**	**60**	9.10	0.0082
Year*Fertilizer*Rate	**Tiger Combo**	**100**	18.45	0.0006
Year*Fertilizer*Rate	**Mg Sulphate**	**20**	12.70	0.0023
Year*Fertilizer*Rate	**Mg Sulphate**	**60**	7.17	0.0155
Year*Fertilizer*Rate	**Mg Sulphate**	**100**	9.30	0.0070
Year*Fertilizer*Rate	**None**	**0**	0.94	0.3750
Year*Fertilizer*Rate	**Tiger XP**	**20**	1.78	0.2013
Year*Fertilizer*Rate	**Tiger XP**	**60**	9.86	0.0064
Year*Fertilizer*Rate	**Tiger XP**	**100**	6.84	0.0188

Table 4 Test of simple effects of fertilizer and rate on dollars per cwt using the slice feature in proc mixed. Particular fertilizer rates that had a significant impact on the dependent variable (total yield, dollar value, or 10-12 oz yield) are highlighted in green ($P \leq 0.05$)

Yield Results for 2019:

There was no significant sulphur treatment effect on total yield (P = 0.2184), value (P = 0.3564), or any size profile in 2019. More specifically, observed differences in the 3-6 oz yield (P = 0.4908), 6-10 oz yield (P = 0.7179), 10-12 oz yield (P = 0.3162), and greater than 12 oz yield (P = 0.8958) were all not significant (Fig 6). The effect of sulphur treatment on specific gravity trended towards significance (P = 0.1060, Fig. 6), which is a notable outcome for a single year of study.

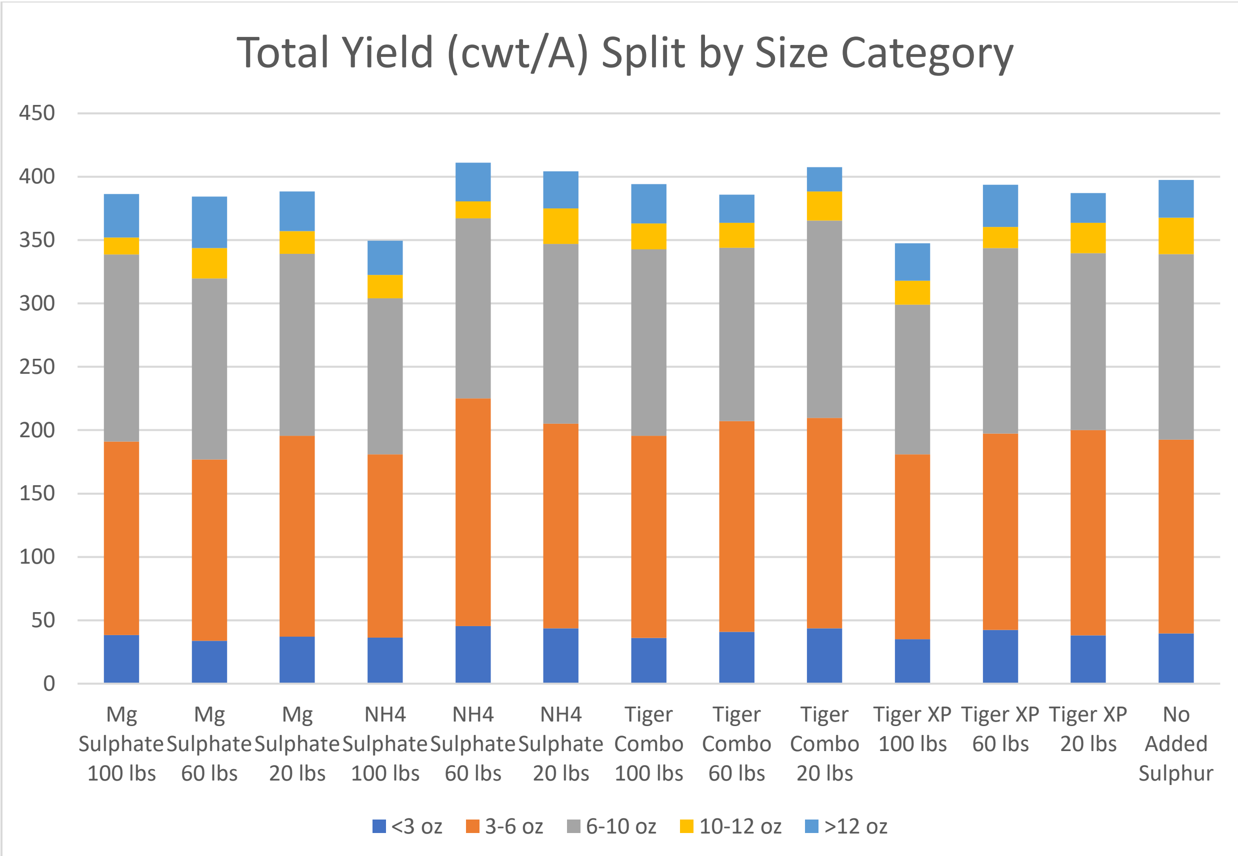

Fig 7. The total yield consisting of the average of the four replicates of each fertilizer treatment with each column separated by the tuber size profile. The tuber size profile also consists of the average of the four replicates within a given treatment. There was no significant sulphur treatment effect on total yield or any size category.

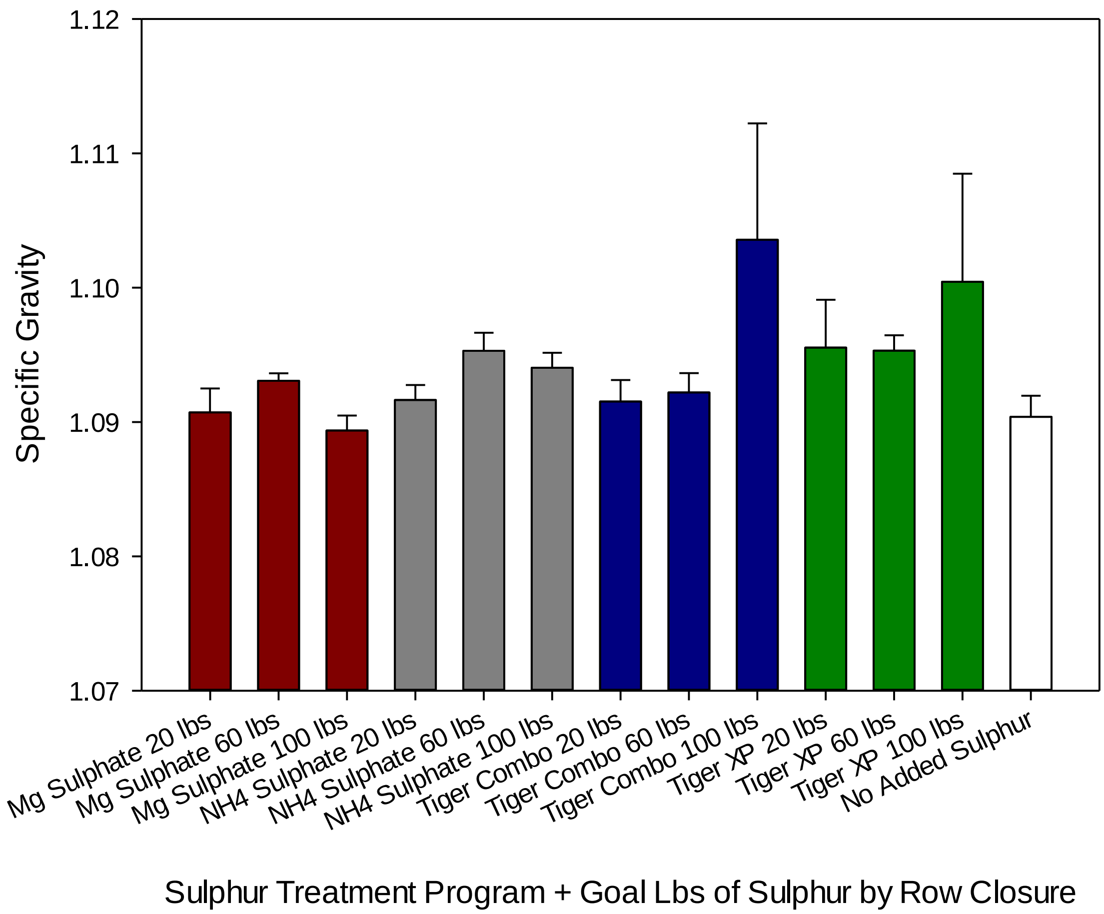

Fig. 7. The effect of sulphur treatment program on potato specific gravity. There was a nearly significant effect (*P* = 0.1060) of sulphur treatment program on specific gravity.

2020 Soil and Petiole Sulphur results

The pounds of soil sulphur at row closure from 0-6 inches in depth did not differ between treatments (*P* = 0.1868, data not shown), nor did the soil sulphur levels at the same depth at late bulking (*P* = 0.3776, data not shown). The amount of petiole sulphur did not differ between treatments at row closure (*P* = 0.7639, data not shown). The observed pounds of soil sulphur at row closure from 6-12 inches were significantly different between treatments (*P* <.0001).

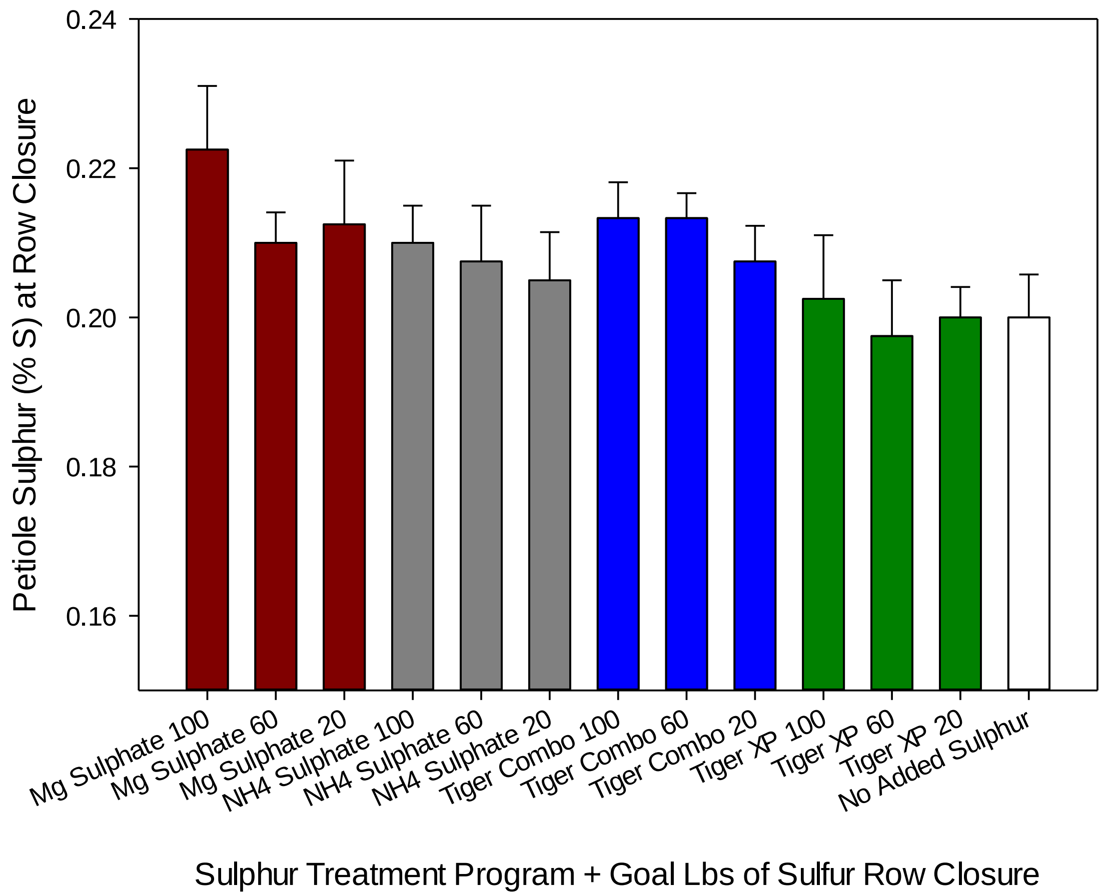

Fig. 8 The effect of sulphur treatment program (x-axis) on the availability of soil sulphur (y-axis) at row closure. Bars indicate mean lbs of sulphur and the standard error is above each bar. Mg sulphate signifies magnesium sulphate, while NH4 sulphate stand for ammonium sulphate. All fertilizer rates for each treatment can be found in Table 1.

Specific pairwise comparisons of sulphur treatments on available petiole sulphur is as follows in Table 5. The greater column refers to the treatment with the greatest lbs of sulphur in soil, whereas the lesser has the smaller amount of petiole sulphur. Combinations of fertilizers that are not present were not significant ($P \geq 0.05$). This list does include comparisons that trended towards significance ($P = 0.05 \leq 0.1$).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
NH4 Sulphate 100	No Added Sulphur	<.0001
NH4 Sulphate 100	Tiger XP 20	<.0001
Tiger Combo 100	Tiger Combo 20	<.0001
Tiger Combo 100	Tiger Combo 60	<.0001
Tiger Combo 60	No Added Sulphur	<.0001

Tiger Combo 60	Tiger XP 20	<.0001
Tiger Combo 100	No Added Sulphur	<.0001
Tiger Combo 100	Tiger XP 20	<.0001
Tiger Combo 100	Tiger XP 60	<.0001
Tiger Combo 100	Tiger XP 100	<.0001
Mg Sulphate 100	No Added Sulphur	<.0001
Mg Sulphate 100	Tiger XP 20	<.0001
NH4 Sulphate 100	Tiger Combo 20	0.0002
NH4 Sulphate 100	Tiger XP 60	0.0002
Tiger Combo 100	NH4 Sulphate 20	0.0003
NH4 Sulphate 100	Tiger XP 100	0.0003
Mg Sulphate 100	Tiger Combo 20	0.0004
Mg Sulphate 100	Tiger XP 60	0.0004
Mg Sulphate 100	Tiger XP 100	0.0007
Tiger Combo 100	Mg Sulphate 20	0.001
Tiger Combo 60	Tiger XP 60	0.001
Tiger Combo 60	Tiger Combo 20	0.002
Tiger Combo 60	Tiger XP 100	0.005
Tiger Combo 100	Mg Sulphate 60	0.006
NH4 Sulphate 60	No Added Sulphur	0.011
NH4 Sulphate 60	Tiger XP 20	0.015
Tiger Combo 100	NH4 Sulphate 60	0.026
NH4 Sulphate 100	Mg Sulphate 20	0.051
NH4 Sulphate 100	NH4 Sulphate 20	0.055
Mg Sulphate 100	Mg Sulphate 20	0.062
NH4 Sulphate 20	Mg Sulphate 100	0.071
NH4 Sulphate 60	Tiger Combo 20	0.082
NH4 Sulphate 60	Tiger XP 60	0.087

In general, all fertilizers met or exceeded their target amount of soil sulphur on average with the exception of Tiger XP (Fig. 8). All of the fertilizer treatments that targeted 100 lbs of soil sulphur by row closure were observed with significantly more soil sulphur than the treatment with no added sulphur, with the exception of Tiger XP 100 lbs. Considerable variability was observed for all fertilizers with the 60 lbs soil sulphur target, and the only fertilizer treatment with this target that varied from the treatment that received no additional soil sulphur was the ammonium sulphate 60 lbs treatment (Table 5). Tiger Combo 100 lbs was observed with significantly more soil sulphur than Tiger Combo 60 and 20 lbs treatments. Ammonium sulphate (NH4 sulphate, Tables 1, 5) at 100 lbs was observed with significantly more soil nitrogen than the Ammonium sulphate 20 treatment, but not when compared with the Ammonium sulphate 60 treatment. Magnesium sulphate (Mg sulphate, Tables 1, 5) at

100 lbs was observed with significantly more soil nitrogen than the magnesium sulphate 20 treatment, but not when compared with the magnesium sulphate 60 treatment. Tiger XP treatments did not differ from one-another in terms of available soil sulphur at row closure, and most fertilizer treatments had significantly more soil sulphur than any of the Tiger XP treatments (table 5).

2019 Soil and Petiole Sulphur results

The first year of study in 2019 indicated that sulphur treatments had a significant effect on the amount of available soil sulphur, in lbs, at row closure (P = 0.0277) and late bulking (P = 0.0079).

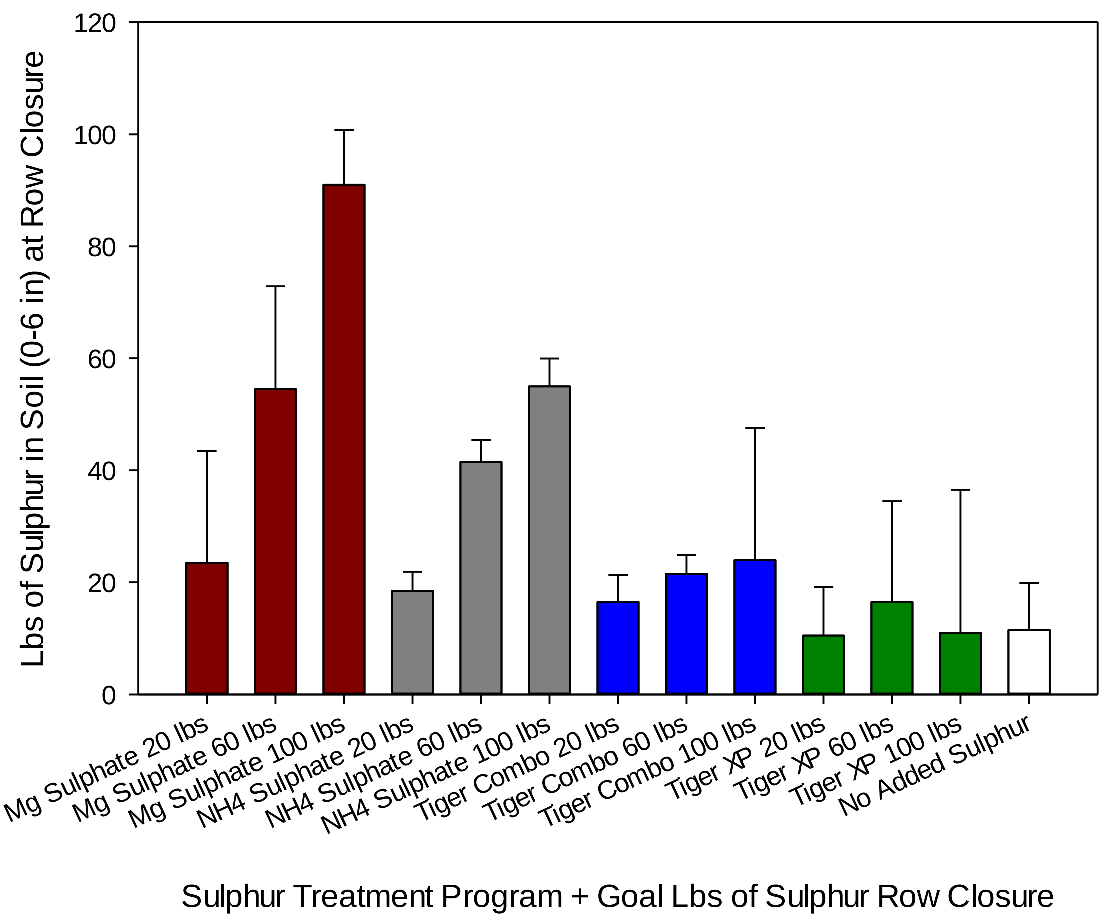

Fig 9. The effect of sulphur treatment program (x-axis) on the availability of soil sulphur (y-axis) at row closure. Bars indicate mean lbs of sulphur and the standard error is above each bar. Mg sulphate signifies magnesium sulphate, while NH4 sulphate stand for ammonium sulphate. All fertilizer rates for each treatment can be found in Table 1.

The goal of each treatment, whether 20, 60, or 100 lbs, was to have a standardized amount of sulphur available by row closure in order to evaluate the impact on final yield parameters and compare between fertilizer products. Treatments where 20 lbs of sulphur was intended to be available in the soil were generally very close to the target because the means in Fig 9 are generally close to 20 lbs. However, 60 and 100 lbs of soil sulphur were harder to achieve with the same precision. The 60 and 100 lb targets for ammonium (NH4) sulphate, Tiger combo, and Tiger XP were less than expected by approximately 20-60 lbs of sulphur at row closure. The exception was observed with the magnesium (Mg) sulphate treatment, where the amount of available sulphur was within 10 lbs of the target by row closure (Fig 9).

Specific pairwise comparisons of sulphur treatments on available soil sulphur at row closure is as follows in Table 6. The greater column refers to the treatment with the largest amount of soil sulphur, whereas the lesser has the smaller amount of soil sulphur. Combinations of fertilizers that are not present were not significant ($P \leq 0.05$). This list does not include comparisons that trended towards significance ($P \leq 0.1$).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Ammonium sulphate 100 lbs	Tiger combo 20 lbs	$P = 0.0478$
Ammonium sulphate 100 lbs	None	$P = 0.0189$
Ammonium sulphate 100 lbs	Tiger combo 60 lbs	$P = 0.0269$
Magnesium sulphate 100 lbs	Ammonium sulphate 20 lbs	$P = 0.0381$
Magnesium sulphate 100 lbs	Tiger combo 100 lbs	$P = 0.0418$
Magnesium sulphate 100 lbs	Tiger combo 20 lbs	$P = 0.0376$
Magnesium sulphate 100 lbs	Tiger combo 60 lbs	$P = 0.0287$
Magnesium sulphate 100 lbs	Magnesium sulphate 20 lbs	$P = 0.0417$
Magnesium sulphate 100 lbs	None	$P = 0.0293$
Magnesium sulphate 100 lbs	Tiger Xp 100 lbs	$P = 0.0363$
Magnesium sulphate 100 lbs	Tiger Xp 20 lbs	$P = 0.0338$
Magnesium sulphate 100 lbs	Tiger Xp 60 lbs	$P = 0.0326$
Magnesium sulphate 60 lbs	Ammonium sulphate 20 lbs	$P = 0.0410$
Magnesium sulphate 60 lbs	Tiger combo 100 lbs	$P = 0.0493$
Magnesium sulphate 60 lbs	Tiger combo 20 lbs	$P = 0.0403$
Magnesium sulphate 60 lbs	Tiger combo 60 lbs	$P = 0.0385$
Magnesium sulphate 60 lbs	None	$P = 0.0295$
Magnesium sulphate 60 lbs	Tiger Xp 100 lbs	$P = 0.0387$
Magnesium sulphate 60 lbs	Tiger Xp 20 lbs	$P = 0.0353$
Magnesium sulphate 60 lbs	Tiger Xp 60 lbs	$P = 0.0338$
Tiger combo 20 lbs	None	$P = 0.0287$

In general, all magnesium sulphate and the 100-lb treatment of ammonium sulphate increased soil sulphur at row closure compared to the negative control; no sulphur was supplied in any negative control plot. Ammonium sulphate and magnesium sulphate generally provided more soil sulphur than comparable rates of Tiger Xp. Magnesium sulphate was the only sulphur fertilizer where the comparison between 100 and 20 lbs treatments produced statistically distinguishable soil sulphur tests.

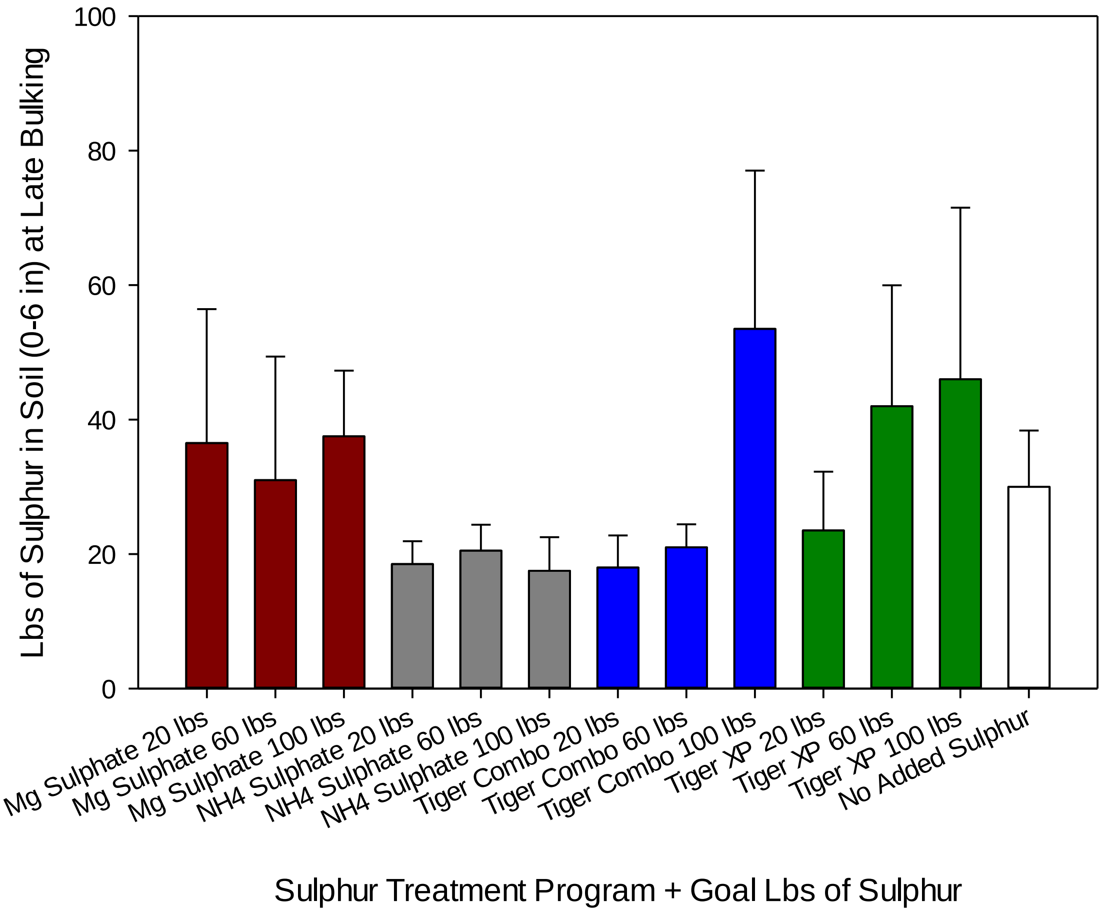

Fig 10. The effect of sulphur treatment program (x-axis) on the availability of soil sulphur (y-axis) at late bulking. Bars indicate mean lbs of sulphur and the standard error is above each bar. Mg sulphate signifies magnesium sulphate, while NH4 Sulphate stand for ammonium sulphate. All fertilizer rates for each treatment can be found in Table 1.

Specific pairwise comparisons of sulphur treatments on available soil sulphur at late bulking is as follows in Table 7. The greater column refers to the treatment with the largest amount of soil sulphur, whereas the lesser has the smaller amount of soil sulphur. Combinations of fertilizers that are not present were not significant ($P \leq 0.05$). This list does not include comparisons that trended towards significance ($P \leq 0.1$).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
None	Ammonium sulphate 60 lbs	$P = 0.0293$
Tiger Xp 20 lbs	Ammonium sulphate 60 lbs	$P = 0.0261$
Tiger Xp 60 lbs	None	$P = 0.0279$
Tiger Xp 60 lbs	Tiger Xp 20 lbs	$P = 0.0145$
Tiger Xp 100 lbs	Ammonium sulphate 60 lbs	$P = 0.0453$

Fewer comparisons between rates within or between treatment programs were statistically significant at late bulking (Table 3) than at row closure (Table 2). A likely explanation for these observations exists in two general observations when contrasting Figs 2 and 3: first, the standard errors generally appear to be larger at late bulking than at row closure (indicating greater variability of soil sulphur in the late season). Second, the general availability of soil sulphur was less in the later season than the early season for treatments with magnesium sulphate, but the opposite was true for Tiger Xp. An additional noteworthy observation was that lower rates of Tiger Xp had more available soil sulphur than the ammonium sulphate treatment. Finally, Tiger Xp was the only treatment again to have statistically significant differences between the lowest rate (20 lbs) and the moderate rate (60 lbs).

The availability of petiole sulphur at row closure, expressed in the percentage of dry plant matter composed of sulphur, was also significantly impacted by sulphur treatment (*P* = 0.0002).

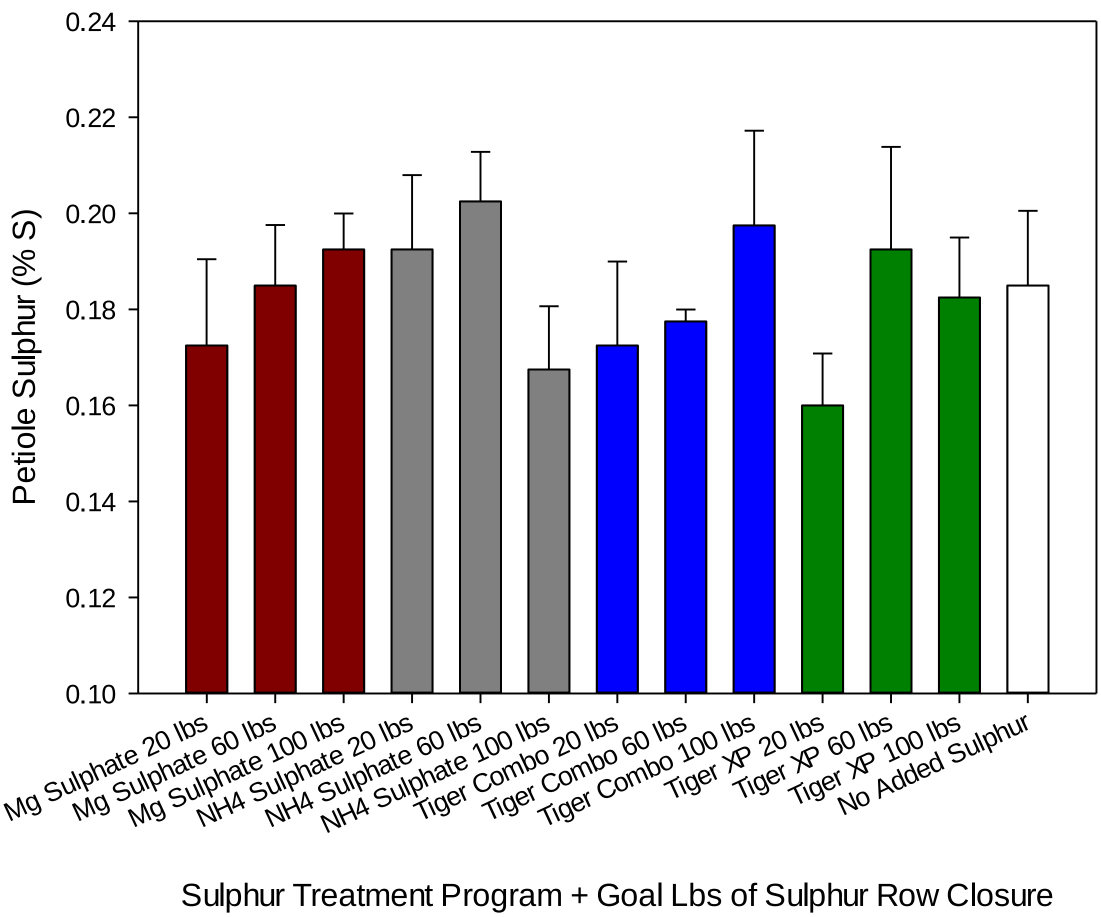

Fig 11. The effect of sulphur treatment program (x-axis) on the availability of petiole sulphur (y-axis) at row closure. Bars indicate mean lbs of sulphur and the standard error is above each bar. Mg sulphate signifies magnesium sulphate, while NH4 Sulphate stand for ammonium sulphate. All fertilizer rates for each treatment can be found in Table 1.

Specific pairwise comparisons of sulphur treatments on available petiole sulphur is as follows in Table 8. The greater column refers to the treatment with the largest amount of petiole sulphur, whereas the lesser has the smaller amount of petiole sulphur. Combinations of fertilizers that are not present were not significant ($P \leq 0.05$). This list does not include comparisons that trended towards significance ($P \leq 0.1$).

Greater Fertilizer Treatment	Lesser Fertilizer Treatment	*P*-value
Ammonium sulphate 100 lbs	None	$P = 0.0035$
Ammonium sulphate 100 lbs	Tiger Xp 20 lbs	$P = 0.0038$
Ammonium sulphate 100 lbs	Tiger Xp 100 lbs	$P = 0.0077$
Ammonium sulphate 60 lbs	Tiger Xp 20 lbs	$P = 0.0012$
Ammonium sulphate 60 lbs	Tiger Xp 100 lbs	$P = 0.0032$
Ammonium sulphate 60 lbs	None	$P = 0.0014$
Magnesium sulphate 100 lbs	Tiger combo 60 lbs	$P = 0.0379$
Magnesium sulphate 100 lbs	Tiger Xp 20 lbs	$P = 0.0263$
Magnesium sulphate 100 lbs	None	$P = 0.0004$
Magnesium sulphate 100 lbs	Tiger Xp 100 lbs	$P = 0.0008$
Magnesium sulphate 100 lbs	Tiger Xp 20 lbs	$P = 0.0002$
Magnesium sulphate 60 lbs	None	$P = 0.0020$
Magnesium sulphate 60 lbs	Tiger Xp 20 lbs	$P = 0.0018$
Tiger combo 60 lbs	None	$P = 0.0121$
Tiger combo 60 lbs	Tiger Xp 100 lbs	$P = 0.0379$
Tiger combo 60 lbs	Tiger Xp 20 lbs	$P = 0.0149$
Tiger Xp 100 lbs	Tiger Xp 60 lbs	$P = 0.0294$
Tiger Xp 100 lbs	Tiger Xp 60 lbs	$P = 0.0037$
Tiger Xp 60 lbs	None	$P = 0.0013$
Tiger Xp 60 lbs	Tiger Xp 20 lbs	$P = 0.0006$

In general, all sulphur amendments increased soil sulphur at row closure compared to the negative control, where no sulphur was supplied. Ammonium sulphate and magnesium sulphate generally provided more soil sulphur than comparable rates of Tiger Xp. Tiger Xp was the only sulphur fertilizer where the 100, 60, and 20 lbs rates actually produced statistically distinguishable soil sulphur tests.

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 lbs 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.

The results contained in this report are from two years of study that were analyzed separately, indicating all results and trends are still preliminary at best. At least two combined years of study are required for conclusive results. In addition, these results are from small plot studies. Field scale studies with grower partners are required to identify if trends carry over into larger scales and are economically feasible for processing growers to enact on their farms.

Because of the significant interaction of year, any combined analysis and interpretation of main effects with fertilizer use on yield for 2020 and 2019 data would be null and void. For example, this would mean that one cannot analyze the combined data set to determine if sulphur fertilizer and rate had greater impact than another on total yield. There are a few possible explanations for why lower yields were observed in plots receiving the same treatment in 2020 compared to 2019. Dan Sawatzky told Spud Smart Magazine in their fall 2020 issue (page 54) that the 2020 growing season was "less than ideal with a later planting date and drier, hotter weather following which resulted in some heat stress expression through heat runners, especially in the Russet Burbank crop." Infrequent and heavy rain events (up to 4 inches at a time, data not shown) over the course of July and August also contributed to that heat stress by decreasing the water available for evaporative cooling during the bulking season.

The significant interaction of year makes it reasonable to compare simple effects such as asking the question: in both 2019 and 2020, did a particular sulphur fertilizer rate have an impact on total yield? The simple effects in the results from tables 2, 3 and 4 indicate all three rates of Tiger Combo and magnesium sulphate have significant impacts on total yield, dollar value per cwt, and 10-12 oz yield. There is a problem in that these simple effects do not translate well into comparisons that Tiger Combo or magnesium sulfate at 100 lbs by row closure significantly improved total yield.

The procedure employed to analyze the simple effects was the slice procedure in proc mixed. The slice procedure is generally not used unless a study have significant interactions. Even if there wasn't a significant interaction, the use of the slice procedure comes with a power (and likely accuracy) advantage over the separate standard t-tests, because t-tests use only half of the observations to compute the error term and significance is only based on half the degrees of freedom. Using simple effects tests (like planned contrasts) will use the within-cell variation for all the cases in the data set and generally will result in a smaller and more reliable error term, thus leading to higher power. **The reason why the statistical theory is important here is that even though there were no significant comparisons of fertilizer and rate on yield or size profile (Fig. 2), which would normally constitute experimental failure, the significant simple effects slices with higher power show that there are significant trends underlying in the dataset. It is entirely possible that the results that trended towards significance, total yield (P = 0.1164), value (P = 0.1303), specific gravity (P = 0.1499), 10-12 oz yield (P = 0.1163), are actually important variables impacted by sulfur fertilizer but we lack the statistical power to identify them**. It is possible that magnesium sulfate and Tiger Combo fertilizers have the most meaningful impact of the four fertilizers tested. The remedy for the lack of statistical power is another year of study with a balanced design and a year that allows the data from 2021 to be combined with 2020 or 2019 data.

The results from 2020 support that using virtually any of the four sulfur fertilizers, regardless of rate, provides improvements to total yield, dollar value, and 10-12 oz yield when compared to the treatment that received no additional sulfur (Figs. 2, 3, 4). Of the four fertilizers, magnesium sulfate and Tiger Combo were the most consistent in producing significantly greater total yield, dollar value, and 10-12 oz yield when compared to the treatment that received no additional sulfur (Figs. 2, 3, 4). It could be possible that the use of any small amount of sulfur fertilizer on sandier soils, such as the one the present experiment was planted on, can provide basic improvements to yield and dollar value, specifically in the 10-12 oz tuber size category and the bonuses that come with having more tubers that are larger.

The present study was set up with the assumption that the ideal soil sulphur test is 40 lbs 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). At least one additional year of study is needed to ensure that a target of 60 lbs of soil sulfur by row closure ensures that at least 40 lbs remains in sandy soils approximately two months after fertilization (row closure) and that this target provides the desired improvements to yield and value. 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 sulfur deficiency in the most cost-effective manner possible.

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