

Variable Rate Starter Fertilization Based on Soil Attributes

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Introduction

Starter fertilizers containing phosphorus (P) have been found to enhance early growth and yield of corn, especially on poorly drained soils of the northern Corn Belt (Randall and Hoeft, 1988; Vetsch and Randall, 2002). The largest yield responses to starter P are often found where soil test P is less than optimum (Bermudez and Mallarino, 2004) and on P fixing soils (Rehm et al., 1988). Phosphorus fixation is usually associated with calcareous soils with pH values greater than 7.4. A significant proportion of soils in South Dakota, Minnesota and Iowa, which developed from glacial deposits from Des Moines Lobe till, are P fixing soils. The location and extent of P fixing soils varies significantly by geographic region within these states and more importantly it varies across the landscape within a given farm field. Identifying or mapping the extent of P fixing soils in a given field can be aided by several soil attributes. Soil test P, pH, calcium carbonates (CaCO_3) and soil, topographic and yield maps could all aid in identifying these areas in fields. Generally, grid soil samples, analyzed for pH and soil test P, are the first step toward identifying and mapping low P and potential P fixing areas of fields.

On P fixing soils a fluid starter fertilizer, like ammonium polyphosphate (APP), applied in-furrow may be an efficient and economic way to manage P compared with a traditional broadcast application. Especially, on farmland in short-term rental contracts, where the farmer is not necessarily interested in building soil test levels. Instead their primary goal is to maximize yield and profit while minimizing risk. Previous research has answered many questions on starter fertilizer sources, placements and rates. However, widespread adoption of variable rate fertilization and availability of variable rate controllers has led to two new questions. 1) Does the optimum rate of starter fertilizer vary enough within a field to require variable rates of starter? 2) What soil attributes or landscape parameters can be used to make variable starter rate application recommendations? The goal of this study is to address these questions by measuring the response of corn to multiple rates of APP applied in-furrow to a field containing soil variability (pH, soil test P, etc.) typical of the region. The starter rates will be applied within blocks of with and without broadcast P fertilizer. The with and without broadcast P blocks will allow us to compare the efficiency of starter P to broadcast P across the landscape.

The objectives of this study are: 1) to measure the effect of rate of application of APP on early growth of corn, grain yield, P removal in grain and fertilizer use efficiency; 2) to determine if the optimum rate of APP varies within a field; 3) to develop and calibrate an algorithm for making variable rate starter applications based on soil attributes; and 4) to compare and contrast the effects of broadcast P addition on the response(s) observed in objectives 1, 2 and 3.

Methods

This field research study was performed using a modified strip trial design. This unique design uses traditional small plot methodology, which includes small plot equipment (planter and combine), experimental design, and appropriate statistical analysis. However, each two-three acre experiment was arranged like a traditional strip trial with strips running the length of the field. The primary difference was each strip was subdivided in 65 ft long segments with each treatment (rate of P fertilizer) randomly applied within each strip and replication using variable rate controllers and GPS guidance. This design allows for treatment randomization and replication, like typical small plot studies. Except, each research location had 16 replications; whereas, traditional small plot studies have 4 replications. The advantage of this design over multiple traditional small plots was it allowed for comparisons across the landscape within the same experimental unit while it maintained independence between samples. Sample independence is an issue when statistically analyzing traditional strip trials where a single treatment is applied to a strip the length of the experiment. This design also allowed differences in soil type, soil test P, pH and other soil attributes to be tested as main effects in the statistical model. Individual replications were pooled together based on soil attributes prior to statistical analysis.

Research locations (Gaylord and Stewart in 2012; New Richland, Willmar, and Janesville in 2013; Waseca, New Richland and St. Charles in 2014 and New Richland and Clarkfield in 2015) were established in the spring. Seven locations were in south-central Minnesota, two (Willmar and Clarkfield) were in west-central Minnesota and one (St. Charles) in southeast Minnesota. Prior to fertilizer application, one composite soil sample (0-6 inch depth) was taken from two neighboring plots or an area about 20 ft. wide by 45 ft long. A total of 4 samples were taken from each of the 16 replications at each location. Each sample was analyzed for soil test P (both Bray P₁ and Olsen), pH, CaCO₃ and exchangeable K. One composite (6-12 inch) soil sample for soil test P (both Bray P₁ and Olsen) was taken from each of the 16 replications to characterize the subsoil at each site. Fertilizer treatments (eight) were a factorial combination of broadcast and starter applied P fertilizer at multiple rates. Two rates (0 and 120 lb P₂O₅/ac) of triple super phosphate were broadcast-applied preplant and incorporated with tillage. Then four rates [0, 2.5, 5 and 7.5 gal/ac (0, 9.9, 19.7 and 29.6 lb P₂O₅/ac)] of APP were applied in-furrow at planting. Broadcast P rates were the main plots and starter rates were sub-plots in a split plot arrangement of a randomized complete block design. Other essential crop nutrients (nitrogen, potassium, sulfur and zinc) were applied prior to spring tillage at rates to optimize corn production. The majority of these experimental sites were corn following soybean; therefore, the authors feel the effect of nitrogen in the starter treatments would be minimal.

Extraordinary cool and wet conditions occurred during the spring of 2013 and 2014, which delayed field operations and planting at some locations. Corn was planted on May 15 at New Richland and June 2 at Willmar and Janesville in 2013. At the V5 growth stage of corn, eight whole corn plants were harvested from each plot, dried at 150° F., weighed to determine dry matter yield, ground, and analyzed for total P. Stand counts and NDVI readings were also taken at V5. Corn grain yields were measured by combine harvesting the center two rows of each four-row plot. Grain yields are reported at 15.5% moisture. A grain sample was collected from each plot, dried at 150° F., ground, and then analyzed for total P. Phosphorus removal in the grain was calculated from the yield and grain P concentration data.

Results and Discussion

A summary of soil test data from initial soil samples taken at each location is presented in Table 1. Soil test P as measured by the Bray P1 test (0-6 inch samples) averaged in the High (16-20 ppm) to Very High (21+ ppm) categories/levels at the Gaylord, Stewart, New Richland-13 (2013) and Janesville locations (Kaiser et al., 2011). Bray P was considerably lower at other locations, especially Waseca, New Richland-15 and Clarkfield. Mean Bray P was greatly influenced by the extent of high pH soils at each location; moreover, it would be expected that the Olsen P test would be a better predictor of crop response. Soil test K (ammonium acetate) levels in the 0-6 inch depth averaged in the High and Very High categories at all locations except St. Charles and New Richland-15, which received fertilizer K prior to planting. The location average pH was near neutral at Gaylord, New Richland (2013 and 2014), Willmar, St. Charles and Waseca; calcareous at Stewart, New Richland-15 and Clarkfield; and acid at Janesville. Similar to pH, calcium carbonate (CaCO_3) concentration varied significantly among locations. Calcium carbonate concentrations were low at Gaylord, Janesville, New Richland-13 and St Charles; intermediate at Stewart, Willmar and New Richland-14 and high at Waseca, New Richland-15 and Clarkfield. There were significant ranges in pH and CaCO_3 concentration across most locations; therefore, for much of the analyses and discussion we will focus on the Olsen P test, which better represents the high pH (calcareous) soils. Average (0-6 inch depth) Olsen P levels were High (12-15 ppm) to Very High (16+ ppm) at Gaylord, Stewart and Janesville; Medium (8-11 ppm) at New Richland (all), Clarkfield and St. Charles; and Low (4-7 ppm) at Willmar and Waseca. Olsen P ranged from Low to Very High at all locations except St. Charles and Waseca. Locations differed in their extent of low P testing areas. At the Willmar, St. Charles, Waseca and New Richland-15 locations, most of the field tested Low to Medium in Olsen P (Figures C, G, H and I); whereas, at Janesville most of the field tested High or Very High (Figure D). The New Richland-13 and 14 and Clarkfield locations had nearly equal sizes of Low, Medium and High/Very High P testing areas (Figures E, F and J). This type of variability allowed us to look not only at the response to broadcast and starter phosphorus across the field, but within soil test P levels. Generally, fields were selected that had considerable variability in soil test P and potential for response to fertilizer P.

Daily precipitation and average air and soil temperatures are presented in the Appendix (Figures A1-3 and B1-3). Early growing season conditions in 2012 were very warm and relatively wet; whereas, very cool and wet conditions occurred in 2013 and 2014 which delayed planting. April and May of 2015 were dry with normal temperatures, which was ideal for early planting. The rest of the 2015 season had ample and well distributed rainfall. Starter fertilizer is generally used to increase early season plant growth in cool and wet soils. Therefore, the weather in 2012 and 2015 was less conducive for promotion of early plant growth by starter fertilizer than the weather in 2013 and 2014. Research has shown early growth differences are still possible even in warm springs. Excessive rainfall in June of 2014 resulted in drown out areas at New Richland and Waseca. Unfortunately, data from these areas had to be discarded. Many locations had a period during the growing season with less than ideal rainfall, especially in 2012. These dry periods increased variability but did not dramatically reduce yields.

		Table 1. Summary of soil test values for samples collected, prior to treatment application, from the starter studies in 2012 through 2015.										
Location	Depth			pH			CaCO ₃		SOM	Olsen-P		
		Inch	-----ppm-----	Min	Avg.	Max	Avg, Max	Min		Min	Avg.	Max
Gaylord-12	0-6	25	209	5.9	6.8	7.8	0.3, 2.2	5.8	4	14	27	
Stewart-12	0-6	19	208	6.4	7.6	8.0	3.4, 12.0	5.0	4	13	28	
New Rich.-13	0-6	16	251	6.2	7.3	7.8	1.2, 5.1	5.7	5	10	29	
	6-12	6	165	7.2	7.6	7.7		4.5	5	8	11	
Willmar-13	0-6	12	176	6.1	7.2	8.0	1.5, 13.6	3.3	4	7	36	
	6-12	4	138	6.0	7.3	7.9		2.8	2	4	6	
Janesville-13	0-6	27	171	5.3	5.8	6.5	0.0, 0.3	5.8	6	19	38	
	6-12	24	164	5.3	5.8	6.9		5.4	6	17	36	
New Richl.-14	0-6	13	135	5.8	7.0	8.0	1.9, 13.4	4.7	3	8	24	
	6-12	4	92	6.4	7.4	8.1		3.6	2	4	7	
St. Charles-14	0-6	11	98	6.3	6.8	7.3	0.1, 0.4	2.6	5	8	11	
	6-12	11	91	6.3	6.7	7.1		2.1	5	8	12	
Waseca-14	0-6	6	184	5.7	6.6	7.8	2.6, 38.2	4.8	2	5	10	
	6-12	5	116	5.7	6.9	7.9		4.0	2	4	6	
New Richl.-15	0-6	5	129	7.0	7.6	7.9	11.4, 41.1	5.6	3	9	17	
	6-12	3	82	6.7	7.0	8.0		4.7	1	3	9	
Clarkfield-15	0-6	7	263	6.8	7.8	8.0	8.4, 39.2	4.2	4	9	20	
	6-12	2	171	7.6	7.9	8.1		4.0	2	3	5	
	†Minimum (Min), Average (Avg.), and Maximum (Max) Olsen phosphorus values for the soil samples collected at each location.											

Statistical analysis of these data was difficult due to adverse environmental conditions that affected response at some locations. Early season flooding of plot areas at several locations was the primary concern and late season drought stress at Stewart was also a factor. Of the 16 replications at each site, data from six replications were discarded at Gaylord, seven at Stewart, two at New Richland in both 2013 and 2014, four at Willmar, five at Janesville and two at Waseca. Unfortunately, much of the high carbonate area at Waseca drowned out and no yield data were collected from these areas. All 2015 data were used in statistical analyses.

Plant populations were generally not affected by broadcast and/or starter fertilizer P rates except for New Richland-14 (2014) where populations were slightly greater (800 plants/ac) when broadcast P was not applied (Table 2). Final populations varied somewhat among locations partly because two different planters were used in this study and they had slightly different seeding rates. At Gaylord, Stewart, Willmar, and St. Charles approximately 34,500 seeds/ac were planted to achieve a final stand of 32-34,000 plants/ac; whereas, at New Richland (all), Janesville, Waseca and Clarkfield 35-36,000 seeds/ac were planted to obtain a final population of 34-35,000 plants/ac. Final populations were greater than desired (36,200 plants/ac) at Stewart but near ideal at other locations. The Waseca population data was lost due to a computer failure.

Table 2. Corn plant populations at V5 as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
-lb P ₂ O ₅ /ac-		-----plants per acre-----				
Gaylord-12	0	33150	33850	33290	34430	33680
	120	33900	33250	32370	35130	33660
	Average†	33520	33550	32830	34780	
Stewart-12	0	36640	36900	36100	35650	36320
	120	36750	36265	35480	36140	36160
	Average	36700	36580	35790	35890	
New Rich.-13	0	35730	35650	36150	35650	35790
	120	36190	35660	35490	35790	35780
	Average	35960	35650	35820	35720	
Willmar-13	0	34380	35200	34910	35060	34890
	120	34140	34580	35580	34860	34790
	Average	34260	34890	35240	34960	
Janesville-13	0	35190	35510	36300	35330	35580
	120	36240	35870	35390	34830	35580
	Average	35720	35690	35840	35080	
New Rich.-14	0	33030	32690	32930	33420	33020a
	120	31940	32540	32090	32300	32220b
	Average	32490	32610	32510	32860	
St. Charles-14	0	33610	33390	34090	33120	33550
	120	33780	33610	33460	33340	33550
	Average	33700	33500	33770	33230	
Waseca-14	0	no data	no data	no data	no data	--
	120	no data	no data	no data	no data	--
	Average	--	--	--	--	
New Rich.-15	0	34410	34750	34560	34220	34480
	120	34600	35010	34440	34840	34720
	Average	34500	34880	34500	34530	
Clarkfield-15	0	35170	34350	34970	34190	34670
	120	35250	35030	35100	34490	34970
	Average	35210	34690	35040	34340	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different.

Treatment effects on total dry weight (mass) of whole corn plants at the V5 stage are presented in Table 3. The main effect of broadcast P application increased V5 plant mass at Willmar and Janesville in 2013 and at all locations in 2014 but did not affect plant mass in 2015. When averaged across broadcast P rates, plant mass was greater with starter P application at all locations in 2013 and 2014 (cool and/or wet springs) and in 2015, a cool dry spring. In 2013 and 2015, the greatest mass generally occurred with 5 and 7.5 gal/ac rates, the 0 gal/ac control had the least mass and the 2.5 gal/ac rate was intermediate. In 2014, plant mass was greater than the control (0 gal/ac rate) with 2.5, 5.0 and 7.5

gal/ac rates but no differences among the 2.5, 5.0 and 7.5 gal/ac rates were observed. Starter fertilizer application did not affect plant mass at either location in 2012 (a very warm spring). Considerable variability in V5 plant mass was observed at Gaylord. One treatment, 120 lbs of broadcast P plus 7.5 gal/ac of starter, had unusually lower mass. A few plots at this location were affected by flooding or by water running across the plots early in the growing season which may have contributed to variability.

Table 3. Mass of V5 corn plants as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
	-lb P ₂ O ₅ /ac-	-----grams per plant-----				
Gaylord-12	0	7.96	8.54	7.54	7.89	7.98
	120	8.30	7.99	8.00	6.97	7.81
	Average†	8.13	8.26	7.77	7.43	
Stewart-12	0	5.73	6.05	5.23	6.14	5.79
	120	5.98	5.88	6.17	5.88	5.98
	Average†	5.85	5.96	5.70	6.01	
New Rich.-13	0	5.94	7.50	8.58	7.72	7.43
	120	6.63	7.60	8.08	8.58	7.72
	Average†	6.28c	7.55b	8.32a	8.15ab	
Willmar-13	0	4.49	5.08	5.29	5.09	4.99b
	120	5.02	5.23	5.52	5.47	5.31a
	Average†	4.76b	5.15ab	5.40a	5.28a	
Janesville-13	0	5.39	6.37	7.29	7.70	6.69b
	120	7.22	7.90	8.29	8.19	7.90a
	Average†	6.31c	7.13b	7.79a	7.94a	
New Rich.-14	0	8.09	9.18	8.91	9.34	8.88b
	120	9.24	9.69	9.44	10.10	9.62a
	Average	8.66b	9.43a	9.17b	9.72a	
St. Charles-14	0	7.44	8.36	8.20	8.60	8.15b
	120	8.53	8.73	8.84	9.00	8.78a
	Average	7.99b	8.55a	8.52a	8.80a	
Waseca-14	0	4.73	6.70	6.71	6.93	6.27b
	120	5.45	7.96	8.18	8.91	7.62a
	Average	5.09b	7.33a	7.45a	7.92a	
New Rich.-15	0	2.89	3.24	3.16	3.29	3.14
	120	3.39	3.54	3.67	3.85	3.61
	Average	3.14b	3.39ab	3.41ab	3.57a	
Clarkfield-15	0	5.90	6.82	6.73	6.69	6.53
	120	6.28	6.44	6.92	6.45	6.52
	Average	6.09b	6.63a	6.82a	6.57ab	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different.

We hypothesized that because the broadcast rate of 120 lb P₂O₅/ac was so much greater than the needs of corn early in the growing season, it may diminish the early growth effects of starter fertilizer P.

However, no significant broadcast P \times starter P interactions were found in these data. The lack of significant interactions suggests that both P application methods contribute to greater mass of small corn plants; furthermore, their contributions are an additive effect and one application method did not substitute for the other in these data.

Phosphorus concentrations in V5 plants were increased significantly by broadcast P application at six of ten locations [New Richland (all three), Willmar, St. Charles and Waseca] and concentrations were numerically greater at the Stewart and Janesville locations (Table 4). The greatest increase in plant P concentration with broadcast P application occurred at the New Richland (all three) and Waseca locations which had some of the lowest Olsen P levels. The differences in P concentration along with increased plant mass contributed to increased P uptake with broadcast P application at six of ten locations (Table 5). Phosphorus concentration in V5 corn plants was increased significantly ($P<0.05$) by starter P application only at Stewart in 2012 (Table 4). The lack of significant and consistent differences in P concentration is likely due to greater plant mass with these treatments, which results in dilution of P concentration in the plant. Another factor to consider is the rates of P applied in the starter (10, 20 and 30 lb P₂O₅/ac) were much less than the broadcast rate (120 lb P₂O₅/ac). At these rates starter P was effective at increasing plant mass but did not significantly increase P concentration like broadcast P did. Starter application did increase P uptake at all 2013 and 2014 locations which were dominated by cool and wet conditions. However, starter application did not increase P uptake in 2012 or 2015. These data showed both broadcast and in-furrow placed starter P fertilizer generally enhanced early growth of corn and increased P uptake, especially in cool and wet springs.

Treatment effects on corn grain yield for each individual location are summarized in Table 6. When averaged across starter P rates, broadcast P application increased corn yields 7, 9, 25, 12, 24 and 13 bu/ac at the Stewart, New Richland-13, Willmar, New Richland-14, Waseca and Clarkfield locations, respectively (Figure K). Starter P increased corn yields at only two of ten locations (New Richland-13 and Waseca), when averaged across the main effect of broadcast P rate. A significant broadcast P \times starter P interaction at Gaylord and New Richland-14 showed starter fertilizer increased yields only when no broadcast P was applied. At responsive locations, starter rate had minimal affect on corn yields. This finding contradicts our experimental hypotheses that yield response would be affected by starter rate and starter rates should be varied based on soil attributes. At Willmar the observed yield differences, a large (25 bu/ac) response to broadcast P but no response to starter, were concerning; therefore, Willmar data were excluded from the across location analyses.

Relative yield as affected by treatment main effects and soil test (Olsen P) levels across locations (Willmar excluded) are presented in Table 7 and Figures L, M and N. For this analysis the plot areas were divided into zones based on soil test levels or categories. Five levels (Very Low, Low, Medium, High and Very High) are used in the University of Minnesota fertilizer recommendations bulletin. In figure N, we reduced the number of levels from five to three (Low Medium and High) to better balance the amount of data in each group.

Table 4. Corn plant (V5) phosphorus concentration as affected by broadcast and starter fertilizer P rates.

Location	Broadcast P Rate	10-34-0 Starter Rate (gallons per acre)				Average†
		0	2.5	5.0	7.5	
	-lb P ₂ O ₅ /ac-	-----%				
Gaylord-12	0	0.45	0.45	0.44	0.47	0.45
	120	0.46	0.46	0.46	0.47	0.46
	Average†	0.46	0.46	0.45	0.47	
Stewart-12	0	0.51	0.49	0.48	0.50	0.50
	120	0.50	0.51	0.50	0.54	0.51
	Average†	0.51ab	0.50b	0.49b	0.52a	
New Rich.-13	0	0.42	0.43	0.42	0.41	0.42b
	120	0.48	0.46	0.47	0.45	0.47a
	Average†	0.45	0.45	0.45	0.43	
Willmar-13	0	0.38	0.39	0.37	0.40	0.39b
	120	0.40	0.40	0.41	0.42	0.41a
	Average†	0.39	0.40	0.39	0.41	
Janesville-13	0	0.47	0.45	0.42	0.45	0.45
	120	0.46	0.46	0.46	0.48	0.46
	Average†	0.47	0.45	0.44	0.46	
New Rich.-14	0	0.30	0.30	0.31	0.31	0.30b
	120	0.34	0.36	0.34	0.36	0.35a
	Average	0.32	0.33	0.32	0.34	
St. Charles-14	0	0.38	0.40	0.39	0.40	0.39b
	120	0.42	0.42	0.44	0.44	0.43a
	Average	0.40	0.41	0.41	0.42	
Waseca-14	0	0.28	0.28	0.28	0.28	0.28b
	120	0.33	0.33	0.33	0.34	0.33a
	Average	0.31	0.30	0.31	0.31	
New Rich.-15	0	0.49	0.47	0.47	0.50	0.48b
	120	0.54	0.52	0.52	0.52	0.52a
	Average	0.52	0.49	0.49	0.51	
Clarkfield-15	0	0.43	0.42	0.43	0.43	0.43
	120	0.43	0.41	0.43	0.45	0.43
	Average	0.43	0.42	0.43	0.44	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different.

Relative yields were least when the Olsen P level was Very Low (0-3 ppm), intermediate when Olsen P was Low (4-7 ppm) and greatest when Olsen P was Medium, High and Very High, when averaged across the main effects of broadcast P and starter P rate (Table 7). When averaged across soil test level and starter P, broadcast P application increased relative yields 6.6 percentage points. The main effect of starter application rate increased relative yields about 4-4.5 percentage points with the 5 and 7.5 gal/ac rates of starter fertilizer compared with the control (0 gal/ac rate), when averaged across the main effects of soil test P levels and broadcast P application. A significant broadcast P × Olsen soil test P level interaction (Figure L) showed a yield response to broadcast P occurred at all Olsen P levels

except the Very High (≥ 16 ppm) level. This finding is consistent with many other studies that show the greatest probability and magnitude of a yield response occurs at low soil test values and both probability and magnitude of response diminish as soil test P increases. A significant broadcast P \times starter P interaction showed starter fertilizer application increased relative corn yields only when broadcast P was not applied (Figure M). This response to starter fertilizer occurred regardless of soil test P level (Figure N). Furthermore, the rate of starter did not significantly affect yield response. This finding is contrary to our initial hypothesis that Low P and/or high pH (calcareous) areas of the field would require a greater starter rate.

Table 5. Whole plant phosphorus uptake at V5 as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
	-lb P ₂ O ₅ /ac-	milligrams/plant-----				
Gaylord-12	0	35.8	39.8	36.3	37.6	37.4
	120	38.0	36.7	38.3	32.7	36.4
	Average†	36.9	38.3	37.3	35.2	
Stewart-12	0	29.0	29.7	25.2	30.8	28.7
	120	30.1	29.4	30.9	31.6	30.5
	Average†	29.5	29.5	28.0	31.2	
New Rich.-13	0	24.6	31.7	35.9	31.4	30.9b
	120	32.0	34.9	38.4	38.9	36.0a
	Average†	28.3c	33.3b	37.1a	35.2ab	
Willmar-13	0	17.4	20.1	19.9	20.3	19.4b
	120	20.0	21.0	22.8	23.1	21.7a
	Average†	18.7b	20.6ab	21.3a	21.7a	
Janesville-13	0	25.5	28.8	30.5	34.4	29.8b
	120	33.7	35.8	38.0	39.1	36.7a
	Average†	29.6c	32.3bc	34.2ab	36.8a	
New Rich.-14	0	25.0	28.0	28.5	30.0	27.9b
	120	32.2	36.1	33.9	37.4	34.9a
	Average	28.6b	32.1a	31.2ab	33.7a	
St. Charles-14	0	28.4	33.2	31.7	34.7	32.0b
	120	36.2	36.9	38.7	39.5	37.8a
	Average	32.3c	35.1b	35.2ab	37.1a	
Waseca-14	0	14.0	19.3	19.6	20.0	18.2b
	120	18.4	26.7	27.6	30.3	25.8a
	Average	16.2b	23.0a	23.6a	25.2a	
New Rich.-15	0	14.5	15.3	14.8	16.7	15.3
	120	18.9	18.8	19.6	20.8	19.5
	Average	16.7	17.0	17.2	18.8	
Clarkfield-15	0	25.3	29.3	29.1	28.9	28.1
	120	27.3	27.0	29.4	28.8	28.1
	Average	26.3	28.1	29.2	28.9	

†Within each row or column, small letters following numbers indicate treatment significance at $P < 0.05$. Numbers followed by different letters are significantly different.

Table 6. Corn grain yield as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
	-lb P ₂ O ₅ /ac-	bushels per acre				
Gaylord-12	0	180*	187*	189*	190*	187
	120	191	188	190	189	189
	Average†	186	188	190	189	
Stewart-12	0	222	229	226	227	226b
	120	231	233	235	234	233a
	Average†	227	231	230	230	
New Rich.-13	0	206	216	220	217	215b
	120	222	222	227	222	224a
	Average†	214b	219ab	224a	220ab	
Willmar-13	0	139	147	144	150	145b
	120	173	172	169	167	170a
	Average†	156	160	156	158	
Janesville-13	0	190	191	193	198	193
	120	198	192	194	194	195
	Average†	194	191	194	196	
New Rich.-14	0	149*	158*	160*	159*	156b
	120	164	167	163	167	165a
	Average	157	162	161	163	
St. Charles-14	0	175	173	172	178	175
	120	176	180	180	173	177
	Average	175	177	176	175	
Waseca-14	0	109	138	138	137	131b
	120	147	152	164	156	155a
	Average	128b	145a	151a	146a	
New Rich.-15	0	218	219	222	216	219
	120	218	222	225	219	221
	Average	218	221	223	214	
Clarkfield-15	0	191	194	195	199	195b
	120	208	211	204	209	208a
	Average	200	203	199	204	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different. * Notes significant interaction, starter yields different only without broadcast P.

Grain moisture at harvest varied among locations because of planting and harvesting date differences and was considerably drier in 2012 than other years (Table 8). No significant differences in grain moisture were observed in 2012 partly due to an early spring and dry summer which resulted in very dry grain at harvest. In 2013, grain moisture was reduced slightly with both broadcast and starter P application at Janesville. However, a significant broadcast P × starter rate interaction at Janesville showed starter fertilizer application reduced grain moisture only when broadcast P was not applied and had no effect when broadcast P was applied. Starter fertilization reduced grain moisture at New

Richland-13 and Waseca. The 5 and 7.5 gal/ac rates of starter P reduced grain moisture about one percentage point compared with the 0 gal/ac control at New Richland-13. These data showed fertilizer application occasionally reduced grain moisture at harvest thereby saving farmers money in grain drying costs which increases the likelihood of getting a positive economic return from the cost of the fertilizer.

Table 7. Relative corn yield as affected by treatment main effects including soil test P levels, when analyzed across locations (Willmar location excluded).

Treatment Effects		Relative yield
Main Effects		%
Olsen P Level		
Very Low		83.2 c
Low		96.6 b
Medium		99.0 a
High		100.9 a
Very High		100.1 a
<i>P > F:</i>		<0.001
Broadcast Rate		
0 lb P ₂ O ₅ /ac		92.7 b
120 lb		99.3 a
<i>P > F:</i>		<0.001
Starter (10-34-0) Rate		
0 gal/ac		93.5 b
2.5 gal		94.8 b
5.0 gal		98.0 a
7.5 gal		97.6 a
<i>P > F:</i>		0.001
Interactions, (P > F)		
Level*Broadcast Rate		<0.001
Level*Starter Rate		0.103
Broadcast Rate*Starter Rate		0.001
Level*Broadcast*Starter		0.124

Treatment effects on grain P concentration and removal are presented in Tables 9 and 10, respectively. When averaged across starter P rates, broadcast P application increased grain P concentration only at New Richland (2013 and 2014) and Willmar; whereas, broadcast P application increased grain P removal at five of ten locations. Starter P rate had little effect on grain P concentration and removal and there were no significant interactions.

Summary

Research on the effects of ammonium poly phosphate (APP) rate with and without broadcast P application on corn production in Minnesota was conducted from 2012 through 2015. Some key findings from this four-year, ten location study include: 1) plant populations were rarely affected by

fertilizer P treatments (broadcast or starter); 2) generally, broadcast and starter fertilizer enhanced early growth of corn (V5 whole plant mass) in cool and wet springs (2013 and 2014), but had less or no effect in warm and dry springs (2012 and 2015); and 3) corn grain yields were increased by broadcast P application at six of ten locations, while starter application increased yields at only two of ten locations. At two additional locations starter fertilizer increased yields in the absence of broadcast P application.

Table 8. Corn grain moisture at harvest as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate -lb P ₂ O ₅ /ac-	0	2.5	5.0	7.5	
Gaylord-12	0	16.8	16.5	17.0	17.1	16.9
	120	17.0	16.1	16.5	16.9	16.6
	Average†	16.9	16.3	16.8	17.0	
Stewart-12	0	14.7	14.4	14.5	14.6	14.6
	120	14.2	14.7	14.5	14.5	14.5
	Average†	14.5	14.5	14.5	14.6	
New Rich.-13	0	26.9	26.5	26.1	25.9	26.4
	120	26.6	26.1	25.7	25.9	26.1
	Average†	26.8a	26.3ab	25.9b	25.9b	
Willmar-13	0	22.4	23.3	22.2	23.0	22.7
	120	24.0	24.8	24.2	24.5	24.4
	Average†	23.2	24.0	23.2	23.7	
Janesville-13	0	25.5*	24.6*	24.6*	24.3*	24.7a
	120	24.3	24.3	24.0	24.1	24.2b
	Average†	24.9a	24.4b	24.3b	24.2b	
New Rich.-14	0	16.9	16.6	16.6	16.9	16.8
	120	17.0	17.1	17.1	16.7	17.0
	Average	16.9	16.8	16.9	16.8	
St. Charles-14	0	17.2	17.0	16.7	17.2	17.0
	120	16.9	16.5	16.6	17.4	16.8
	Average	17.1	16.7	16.6	17.3	
Waseca-14	0	23.1	22.2	22.0	21.4	22.2
	120	22.0	21.5	21.8	21.7	21.8
	Average	22.5a	21.9b	21.9b	21.5b	
New Rich.-15	0	19.2	19.2	19.2	19.1	19.2
	120	19.0	19.1	19.1	19.2	19.1
	Average	19.1	19.2	19.1	19.2	
Clarkfield-15	0	14.4	14.6	14.4	14.8	14.6
	120	14.6	14.6	14.3	14.3	14.4
	Average	14.5	14.6	14.4	14.5	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different. * Significant broadcast P rate*starter P rate interaction.

When averaged across locations, a significant broadcast P \times soil test P level interaction showed relative yields were increased by broadcast P application only at Very Low, Low, Medium and High soil test P levels, but not at the Very High level. Furthermore, the magnitude of the yield response or increase was greatest at the Very Low soil test level (0-3 ppm Olsen P) and was considerably less at other Olsen P levels. A significant broadcast P \times starter P interaction showed starter fertilizer increased relative corn yields only when broadcast P was not applied; interestingly, this response to starter fertilizer occurred regardless of soil test P level and the rate of starter did not significantly affect yield response.

Table 9. Corn grain phosphorus concentration as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
	-lb P ₂ O ₅ /ac-	-----%				
Gaylord-12	0	0.28	0.27	0.28	0.27	0.27
	120	0.28	0.29	0.31	0.29	0.29
	Average†	0.28	0.28	0.29	0.28	
Stewart-12	0	0.32	0.32	0.30	0.32	0.32
	120	0.33	0.31	0.35	0.32	0.33
	Average†	0.32	0.32	0.32	0.32	
New Rich.-13	0	0.21	0.20	0.21	0.21	0.21b
	120	0.24	0.26	0.24	0.24	0.25a
	Average†	0.22	0.23	0.23	0.23	
Willmar-13	0	0.19	0.22	0.20	0.19	0.20b
	120	0.24	0.23	0.24	0.25	0.24a
	Average†	0.22	0.23	0.22	0.22	
Janesville-13	0	0.27	0.28	0.28	0.28	0.28
	120	0.27	0.28	0.28	0.28	0.28
	Average†	0.27	0.28	0.28	0.28	
New Rich.-14	0	0.20	0.22	0.24	0.21	0.22b
	120	0.24	0.24	0.26	0.22	0.24a
	Average	0.22b	0.23ab	0.25a	0.22b	
St. Charles-14	0	0.27	0.27	0.27	0.28	0.27
	120	0.27	0.27	0.28	0.27	0.27
	Average	0.27	0.27	0.28	0.27	
Waseca-14	0	0.20	0.20	0.20	0.20	0.20
	120	0.21	0.21	0.21	0.20	0.21
	Average	0.20	0.21	0.20	0.20	
New Rich.-15	0	0.41	0.40	0.40	0.43	0.41
	120	0.39	0.38	0.38	0.38	0.38
	Average	0.40	0.39	0.39	0.41	
Clarkfield-15	0	0.34	0.31	0.30	0.32	0.32
	120	0.32	0.33	0.32	0.30	0.32
	Average	0.33	0.32	0.30	0.31	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different.

These findings contradict our experimental hypothesis that corn grain yield response would be affected by starter rate and starter rates should be varied based on soil attributes. Even though these data were not completely clear on the optimum rate of APP for Minnesota. The data suggest APP rates should not exceed five gal/ac.

Table 10. Phosphorus removal in corn grain as affected by broadcast and starter fertilizer P rates.

Location	Broadcast	10-34-0 Starter Rate (gallons per acre)				Average†
	P Rate	0	2.5	5.0	7.5	
-lb P ₂ O ₅ /ac-		-----lb P ₂ O ₅ /ac-----				
Gaylord-12	0	54.5	55.6	56.8	56.5	55.8
	120	58.5	58.3	62.9	59.0	59.7
	Average†	56.5	57.0	59.8	57.8	
Stewart-12	0	77.2	79.1	71.1	80.0	76.7b
	120	82.4	79.1	88.4	82.1	83.0a
	Average†	79.8	79.1	79.8	80.9	
New Rich.-13	0	47.0	47.8	50.8	49.6	48.8b
	120	57.4	62.3	59.8	59.1	59.7a
	Average†	52.2	55.1	55.3	54.4	
Willmar-13	0	30.2	35.3	31.6	32.2	32.3b
	120	44.2	43.7	43.8	44.2	44.0a
	Average†	37.2	39.5	37.7	38.2	
Janesville-13	0	55.7	58.8	58.8	59.3	58.2
	120	57.6	58.2	59.7	59.6	58.8
	Average†	56.7	58.5	59.2	59.5	
New Rich.-14	0	33.1	36.8	41.2	36.8	37.0b
	120	43.7	44.7	45.7	40.1	43.6a
	Average	38.4b	40.8ab	43.5a	38.5b	
St. Charles-14	0	50.4	50.2	51.3	53.0	51.2
	120	51.8	52.8	55.0	51.1	52.7
	Average	51.1	51.5	53.1	52.0	
Waseca-14	0	23.0	30.2	30.1	29.1	28.1b
	120	33.0	35.1	37.6	33.9	34.9a
	Average	28.0b	32.7a	33.8a	31.5ab	
New Rich.-15	0	97.6	95.0	96.2	101.0	97.5
	120	91.6	91.7	91.1	91.0	91.3
	Average	94.6	93.4	93.7	96.0	
Clarkfield-15	0	69.5	65.6	62.1	68.9	66.5
	120	72.2	74.5	69.5	67.9	71.0
	Average	70.8	70.1	65.8	68.4	

†Within each row or column, small letters following numbers indicate treatment significance at P<0.05. Numbers followed by different letters are significantly different.

Conclusions

In conclusion these data do not support the use of variable rates of P as ammonium poly phosphate (APP) in Minnesota. When a high rate of P (120 lb P₂O₅/ac) was broadcast prior to planting corn, the benefit of APP was negligible. However, in the absence of broadcast P, corn yield responses to APP were observed in four of ten (40%) of these trials.

Acknowledgements

The authors thank the Minnesota Corn Growers, Corn Research and Promotion Council and the Fluid Fertilizer Foundation for the funding this project and the FFF partnering labs for “in-kind” support. We also thank the field research crews at the Department of Soil, Water, and Climate and Southern Research and Outreach Center for their assistance with the project. We also thank our farmer cooperators for their assistance and the use of land for this research project.

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Appendix: Additional Tables and Figures

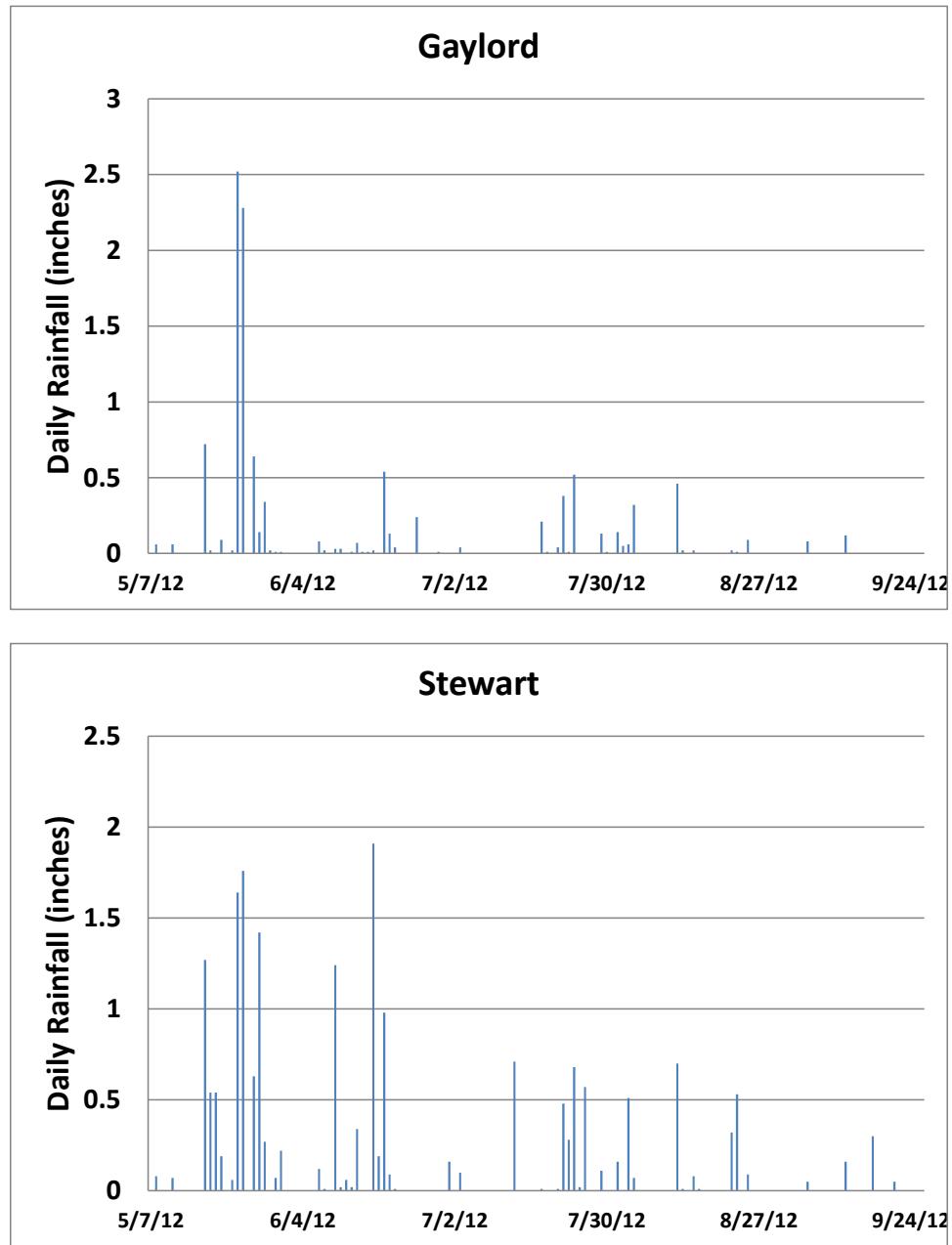


Figure A1. Summary of daily total precipitation data from Gaylord and Stewart beginning May 7 and ending at harvest in 2012. Total precipitation was 10.91 inches at Gaylord and 19.92 inches at Stewart. Data does not include all precipitation following fertilizer application.

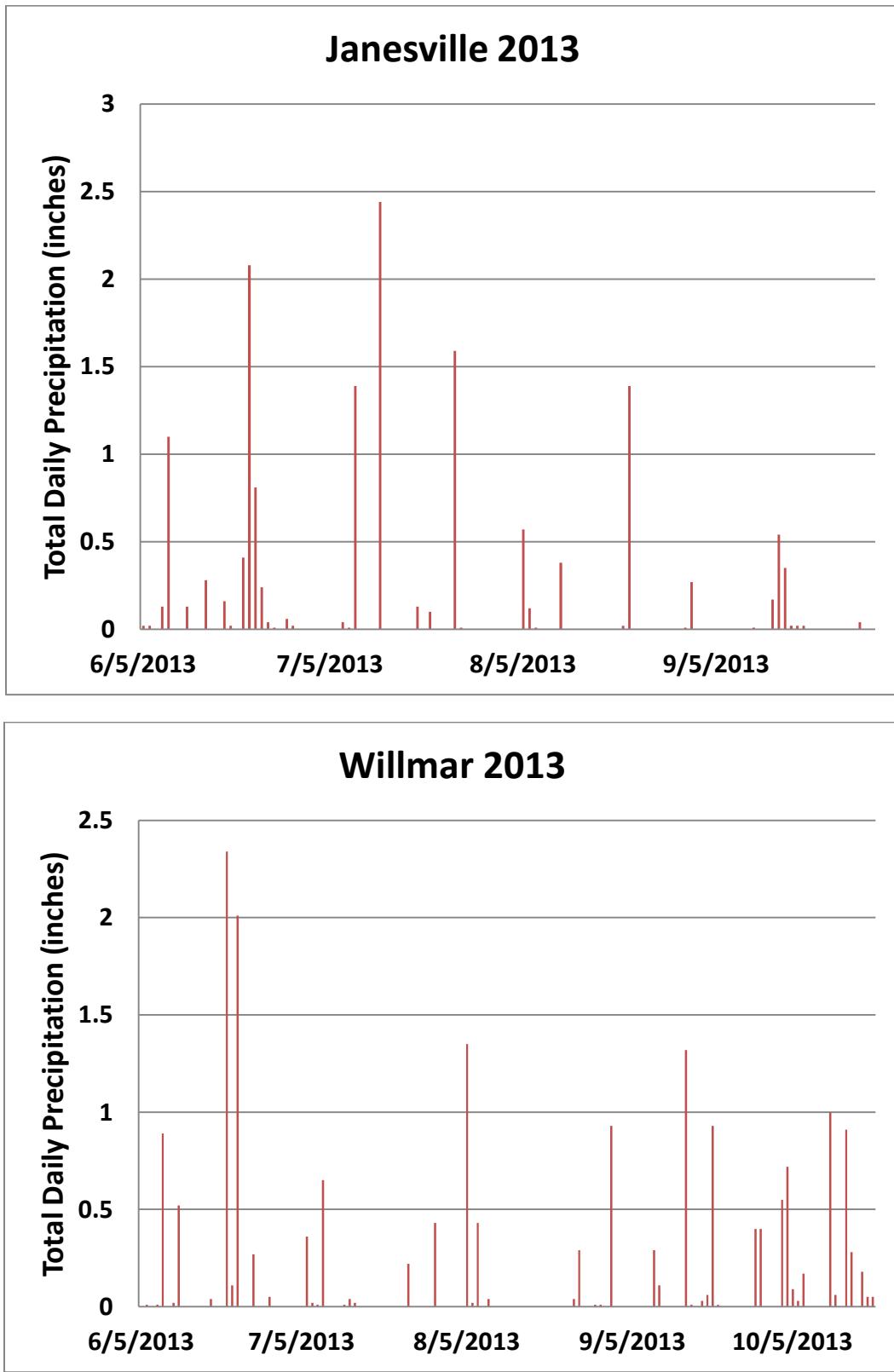


Figure A2. Summary of daily total precipitation data from Janesville and Willmar beginning June 6 and ending at harvest in 2013. Total precipitation was 17.60 inches at Janesville and 18.81 inches at Willmar. Data does not include all precipitation following fertilizer application.

New Richland 2013

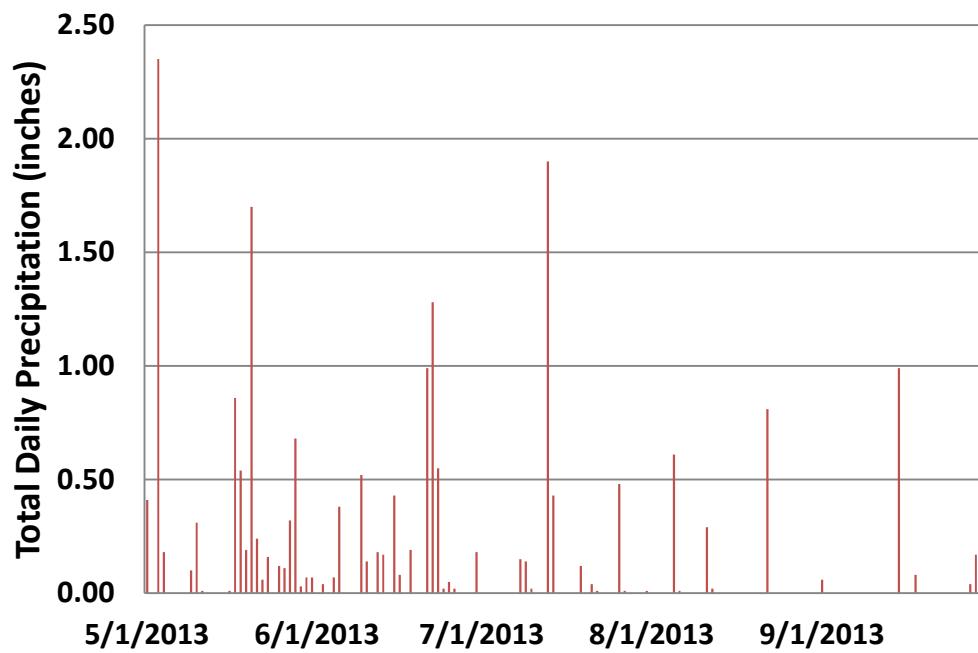


Figure A3. Summary of daily precipitation data from New Richland for the period from May 1 to September 30, 2013. Total precipitation was 20.20 inches.

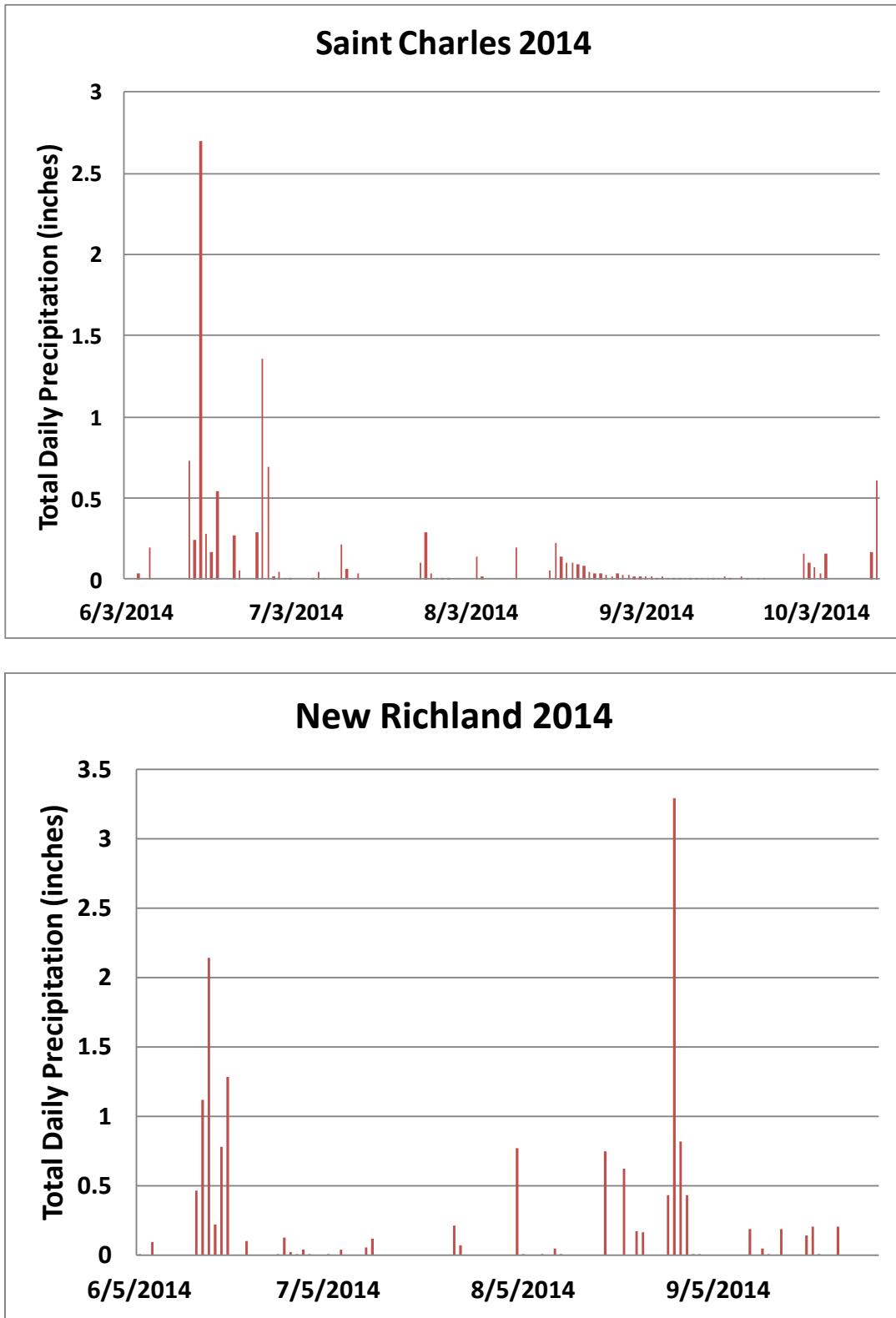


Figure A4. Summary of daily total precipitation data from New Richland and St. Charles beginning June 4 and ending at harvest in 2014. Total precipitation was 11.31 inches at St. Charles and 18.82 inches at New Richland.

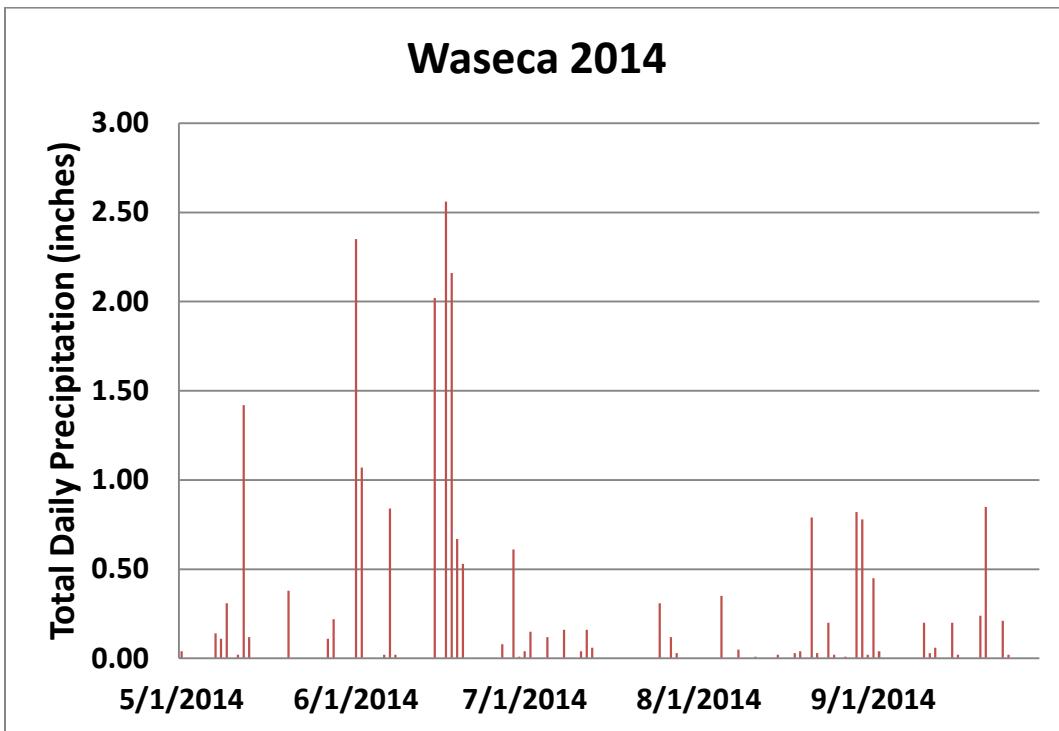
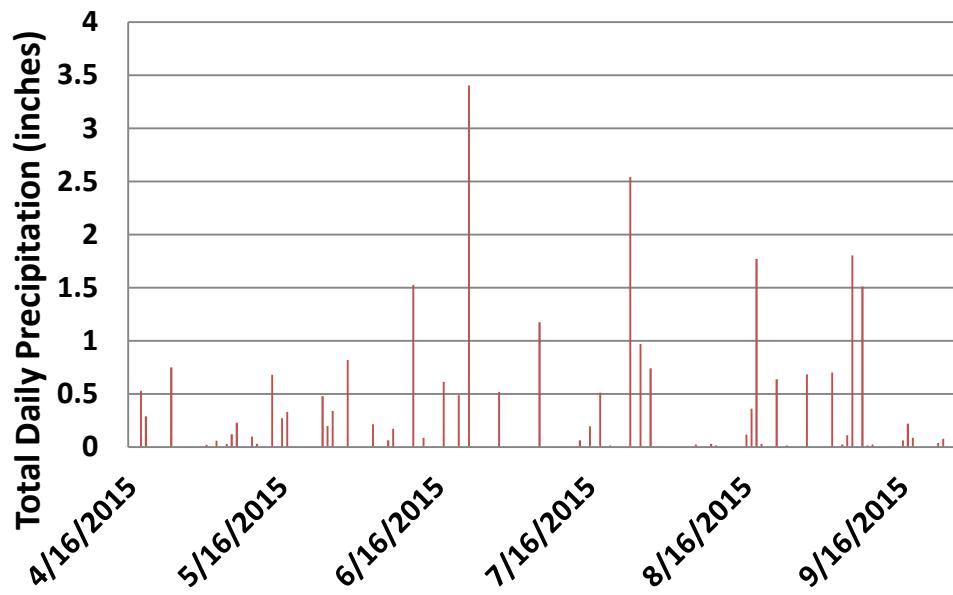


Figure A5. Summary of daily precipitation data from Waseca for the period from May 1 to September 30, 2014. Total precipitation was 22.49 inches.

New Richland 2015



Clarkfield 2015

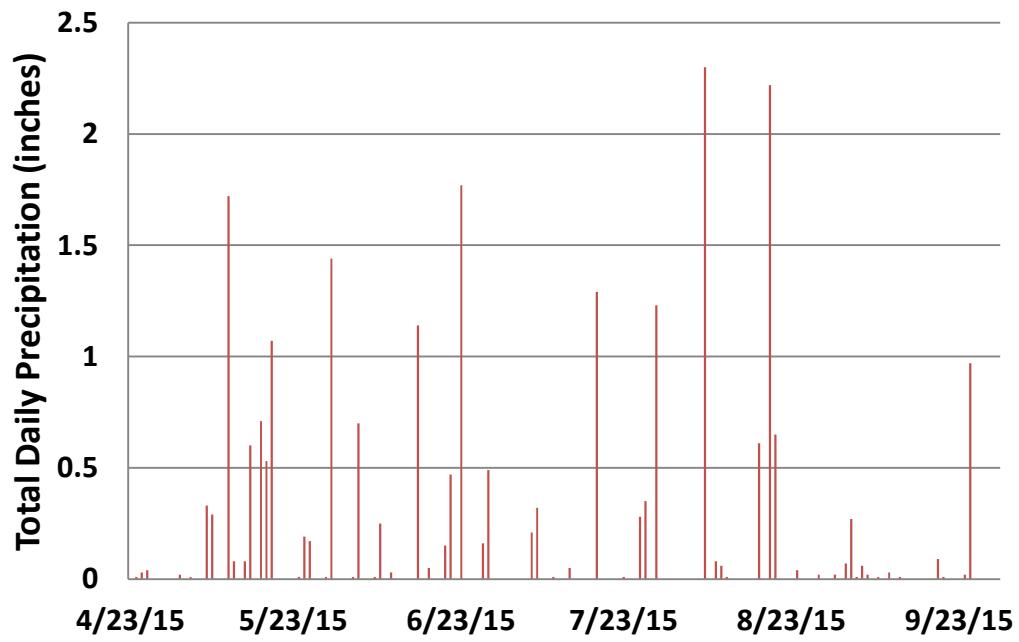


Figure A6. Summary of daily total precipitation data from New Richland beginning April 16 and Clarkfield beginning April 23 and ending on September 30 in 2015. Total precipitation was 27.00 inches at New Richland and 23.90 inches at Clarkfield.

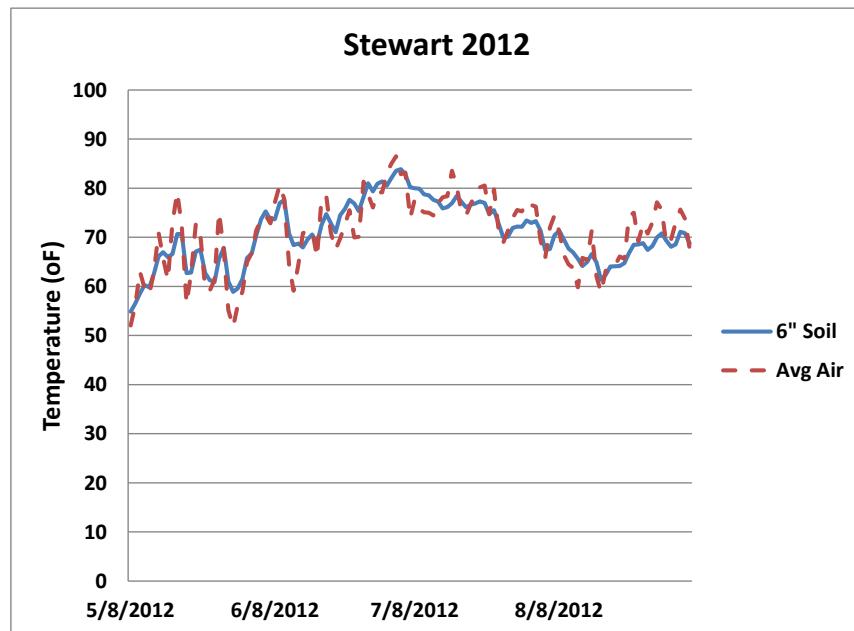
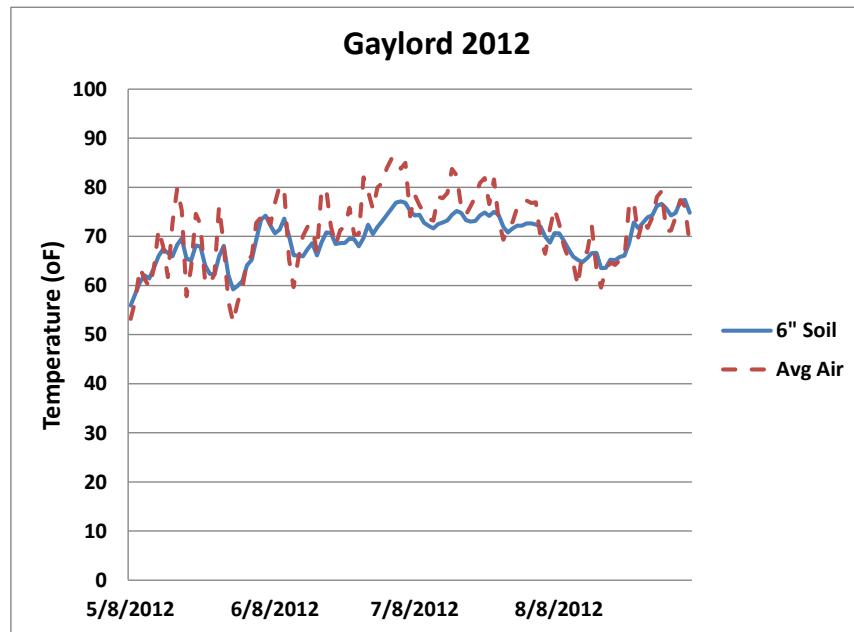


Figure B1. Summary of daily average 6" soil and air temperature from two field locations studied in 2012.

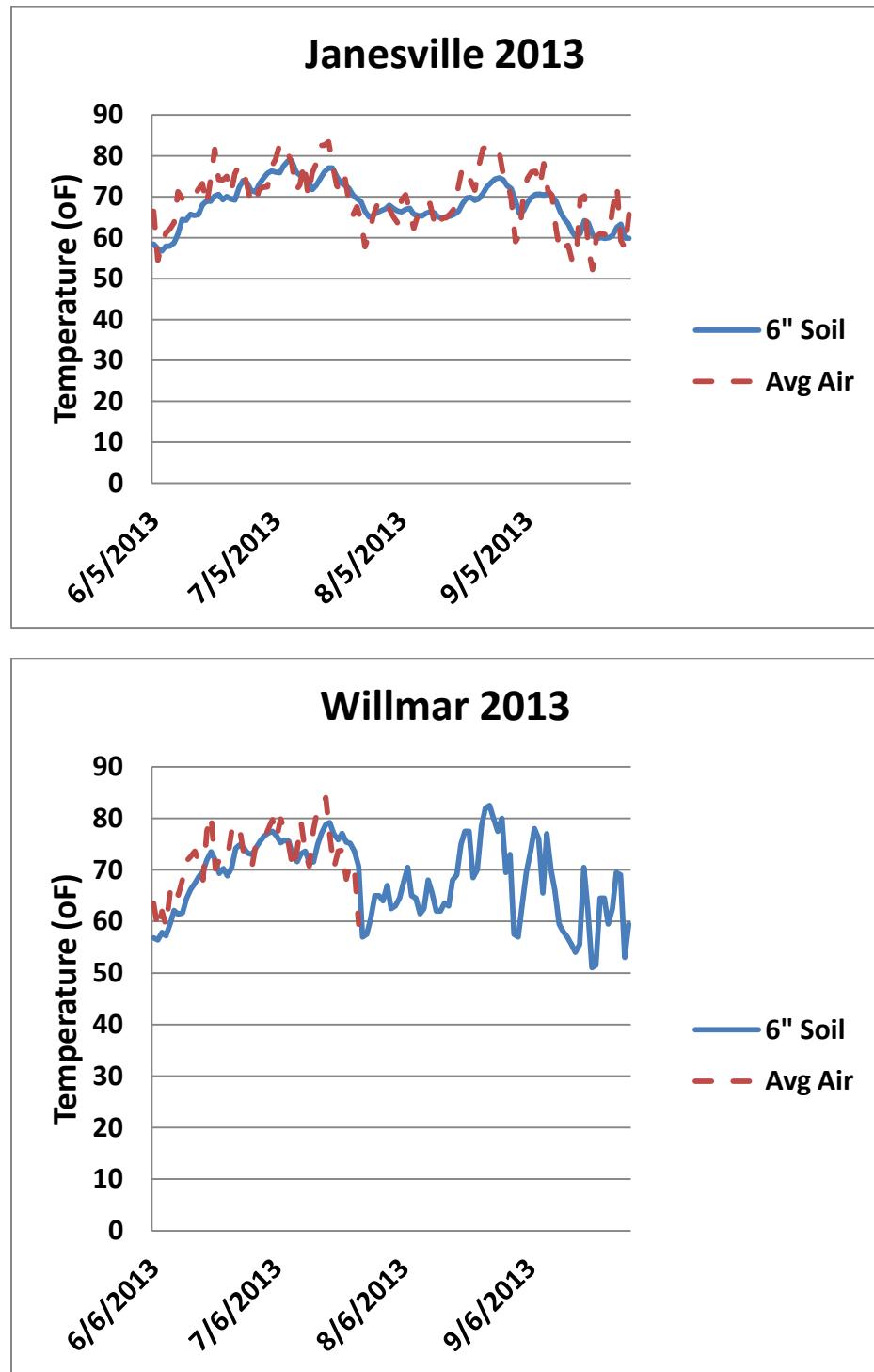


Figure B2. Summary of daily average 6" soil and air temperature at Janesville and Willmar in 2013.

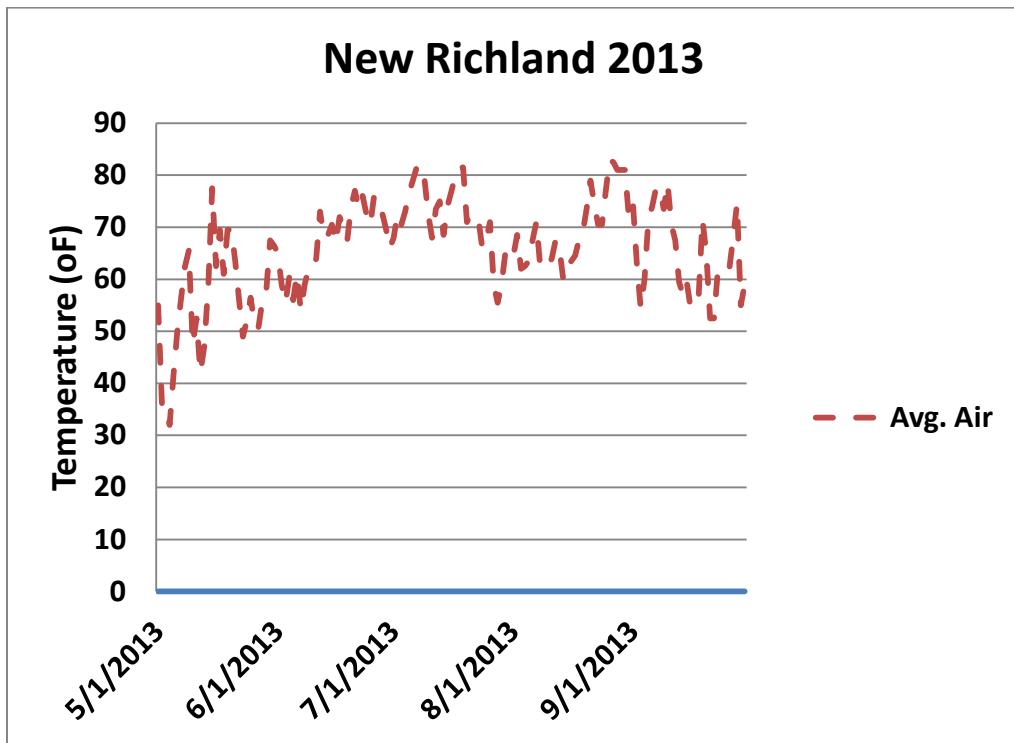
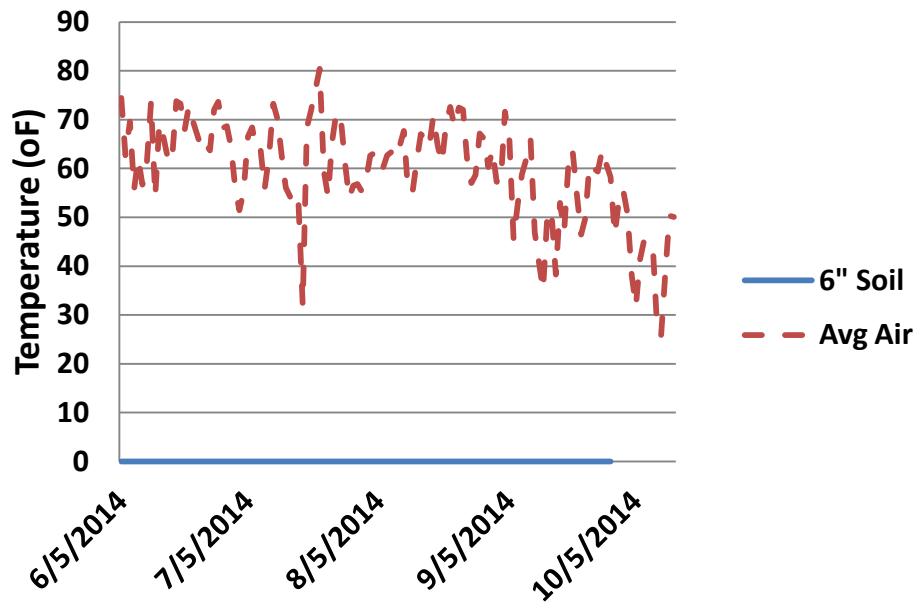


Figure B3. Summary of growing season (May – September) daily average air temperature at New Richland in 2013.

New Richland 2014



Saint Charles 2014

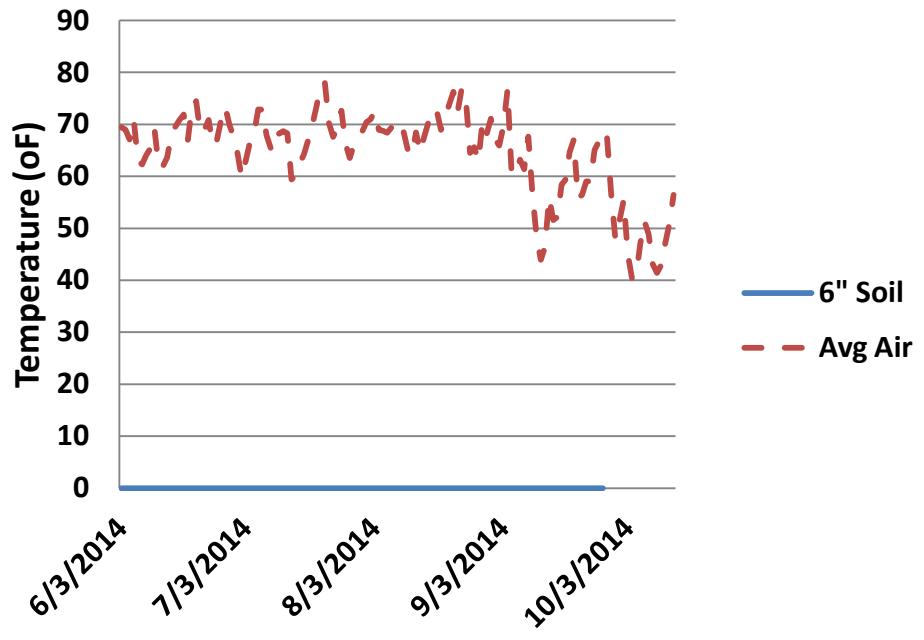


Figure B4. Summary of daily average 6" soil and air temperature at New Richland and St. Charles in 2014.

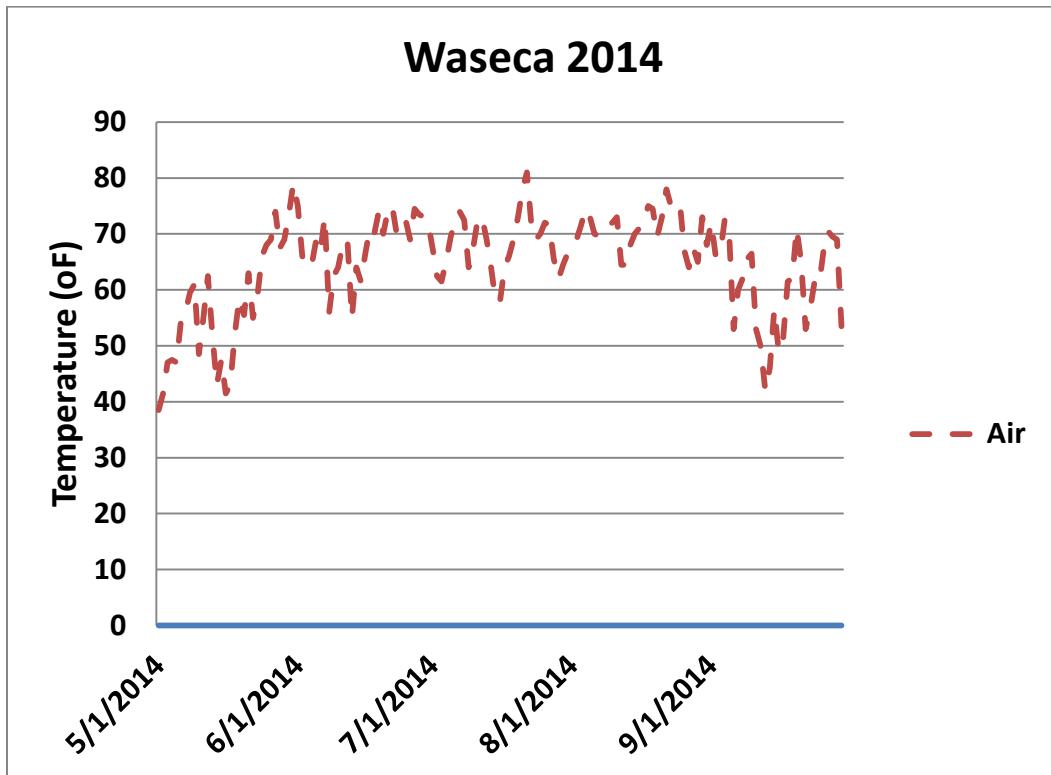


Figure B5. Summary of growing season (May – September) daily average air temperature at Waseca in 2014.

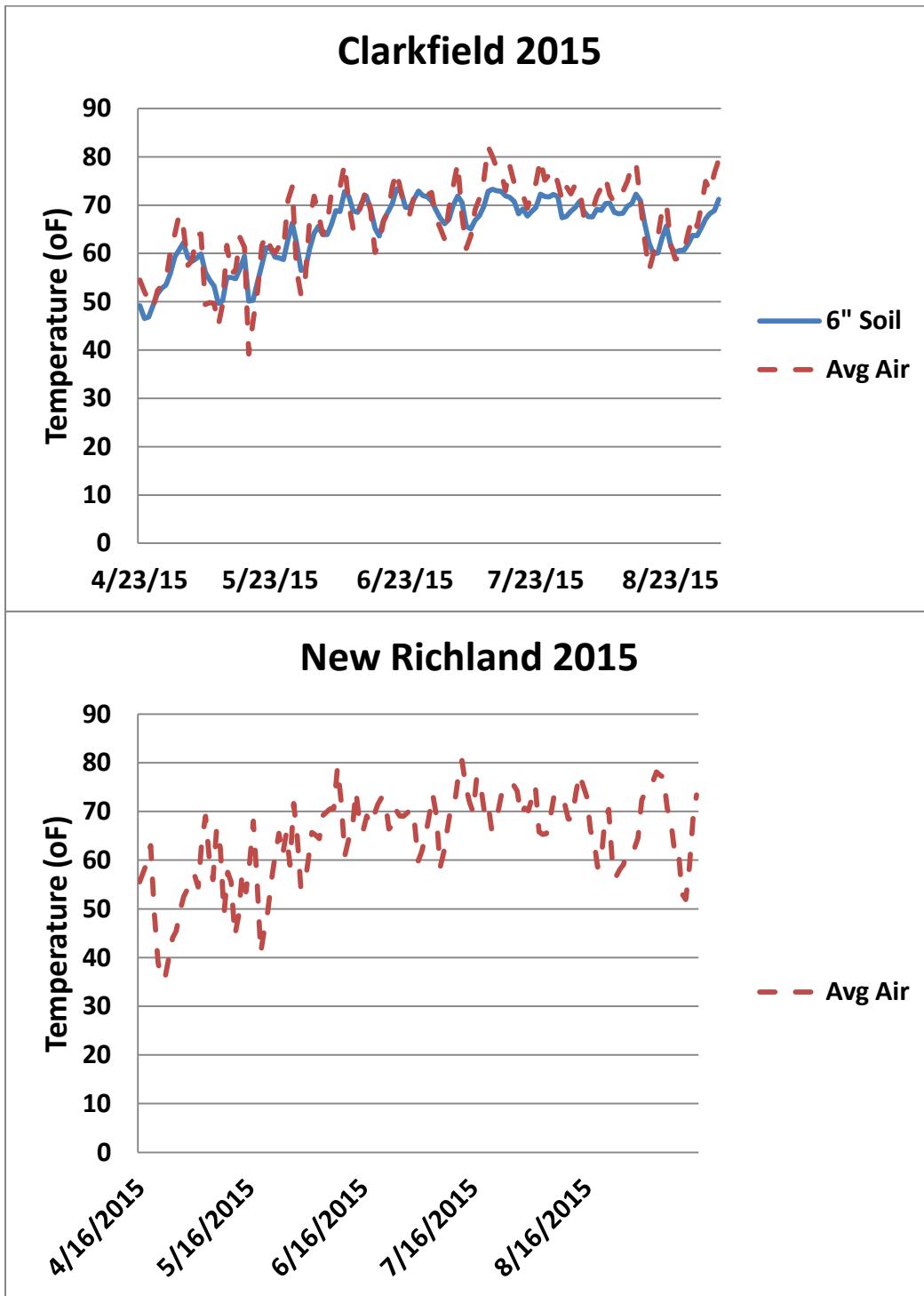


Figure B6. Summary of growing season (May – September) daily average air temperature at Clarkfield in 2015.

VR Starter Willmar 2013

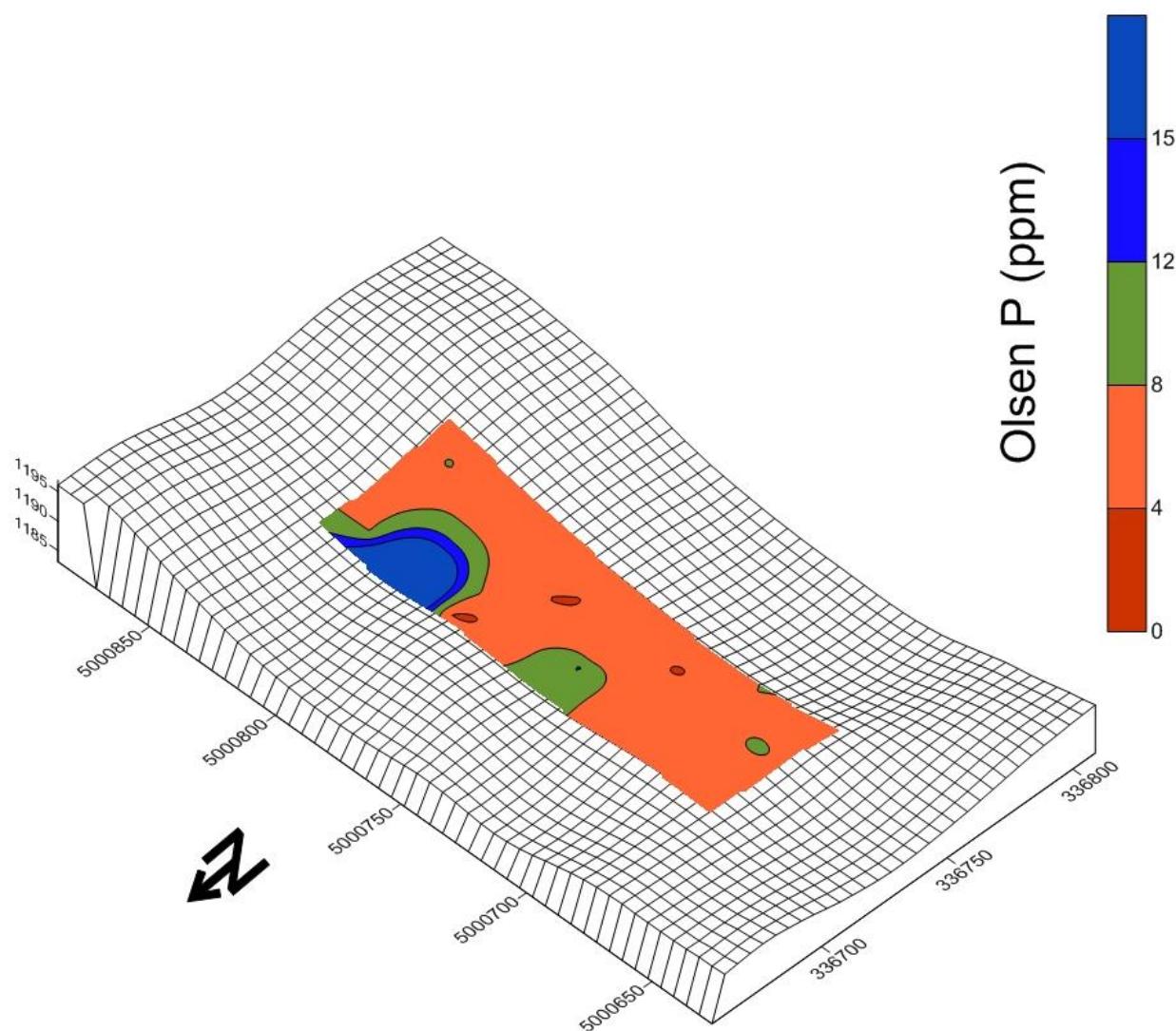


Figure C. Inherent variability in soil test phosphorus (Olsen P) at Willmar in 2013.

VR Starter Janesville 2013

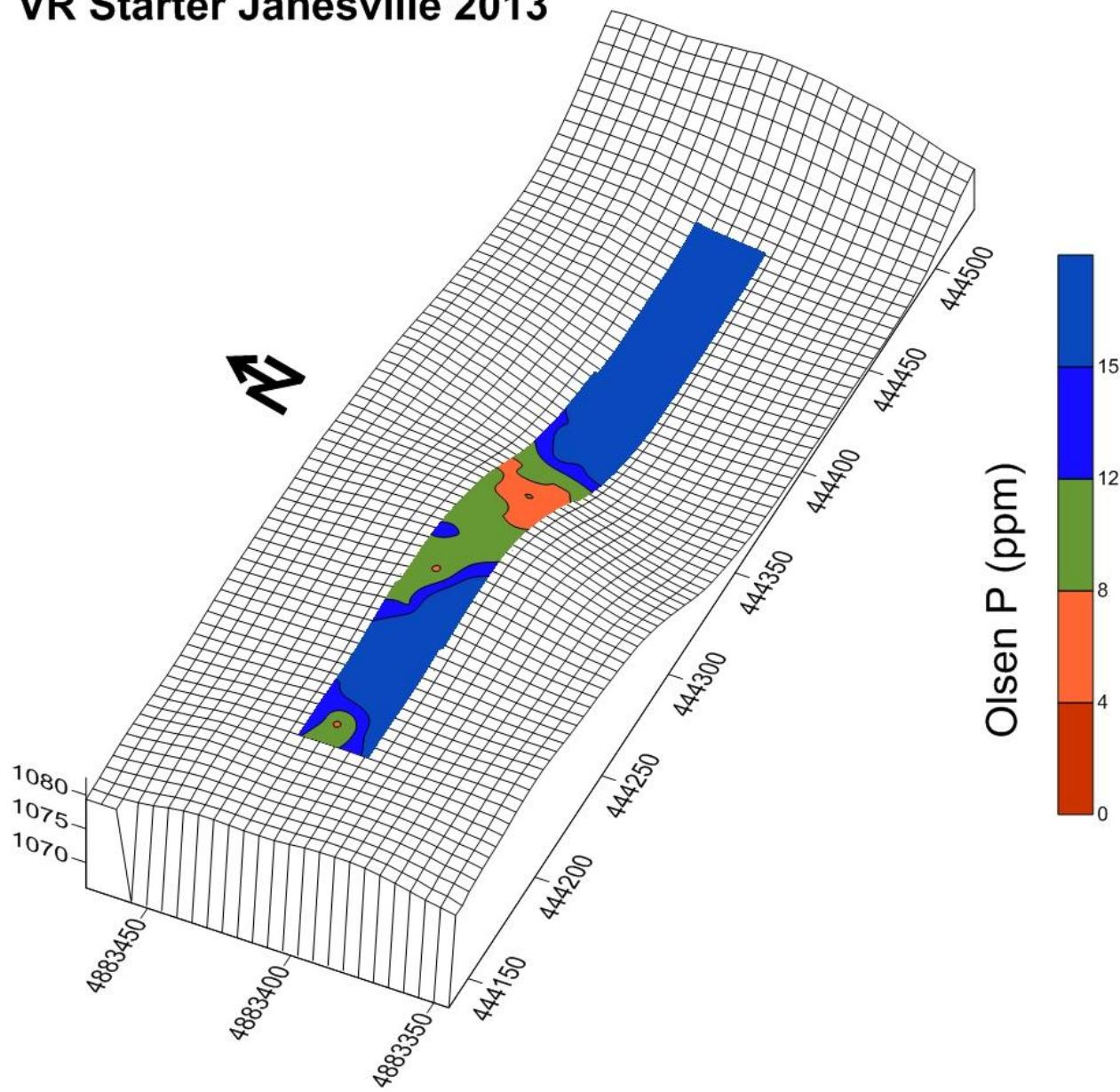


Figure D. Inherent variability in soil test phosphorus (Olsen P) at Janesville in 2013.

VR Starter New Richland 2013

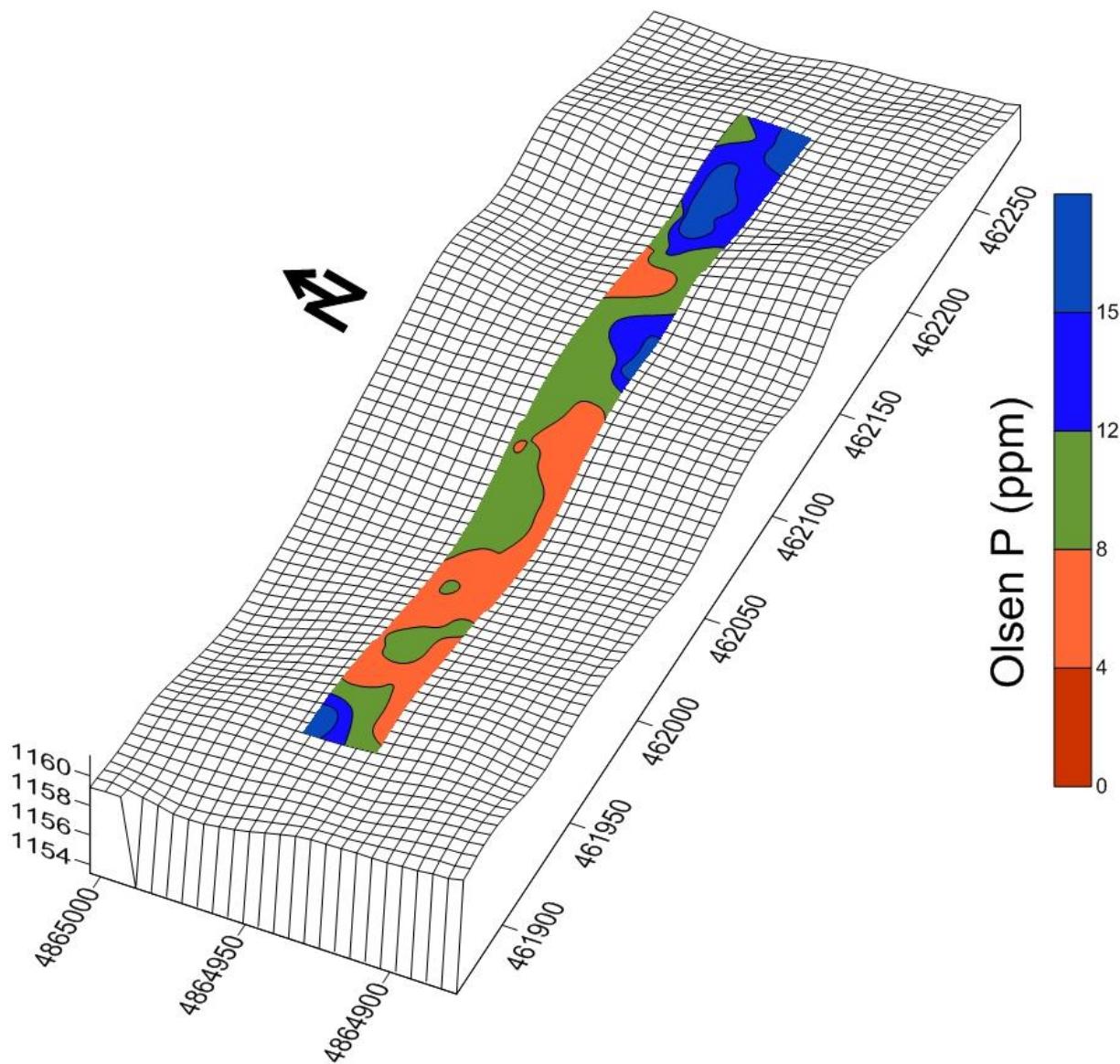


Figure E. Inherent variability in soil test phosphorus (Olsen P) at New Richland in 2013.

New Richland 2014

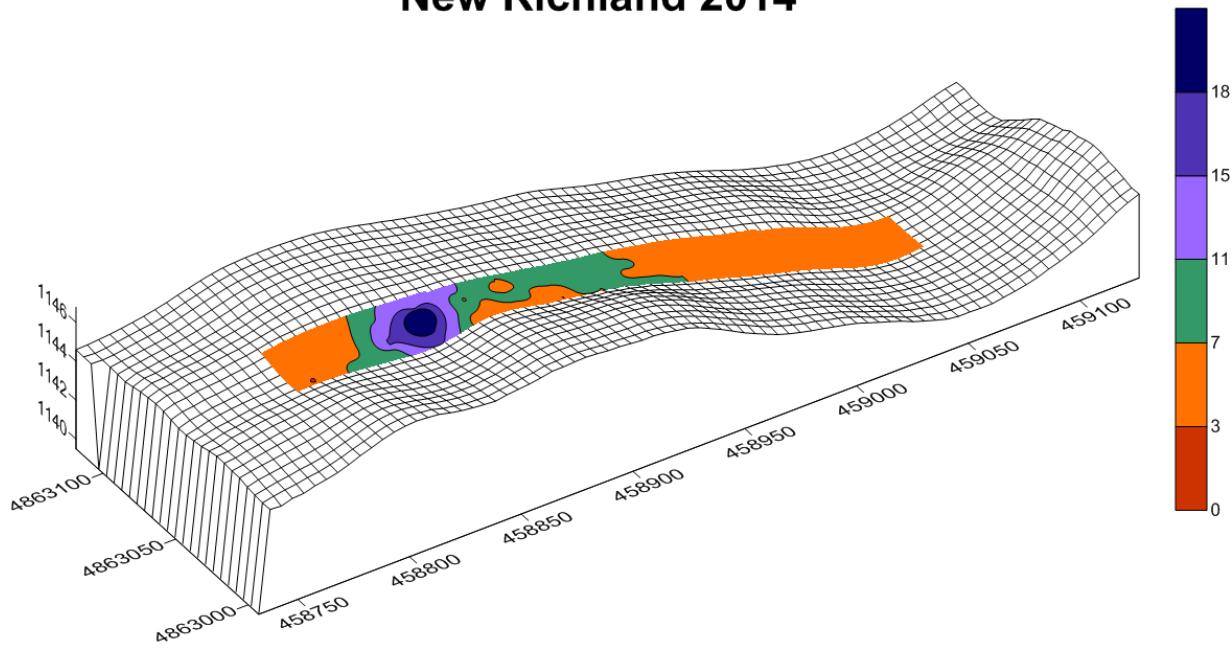


Figure F. Inherent variability in soil test phosphorus (Olsen P) at New Richland in 2014.

Saint Charles 2014

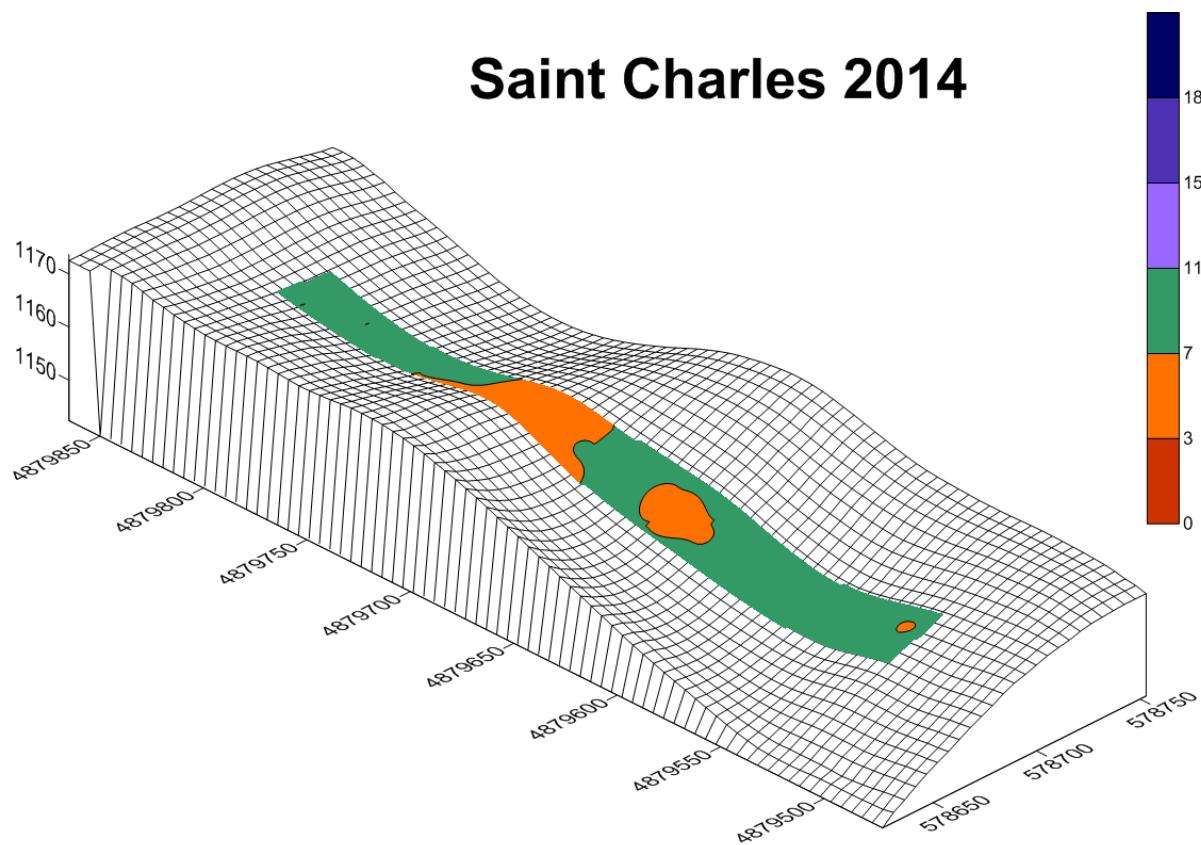


Figure G. Inherent variability in soil test phosphorus (Olsen P) at St. Charles in 2014.

Waseca 2014

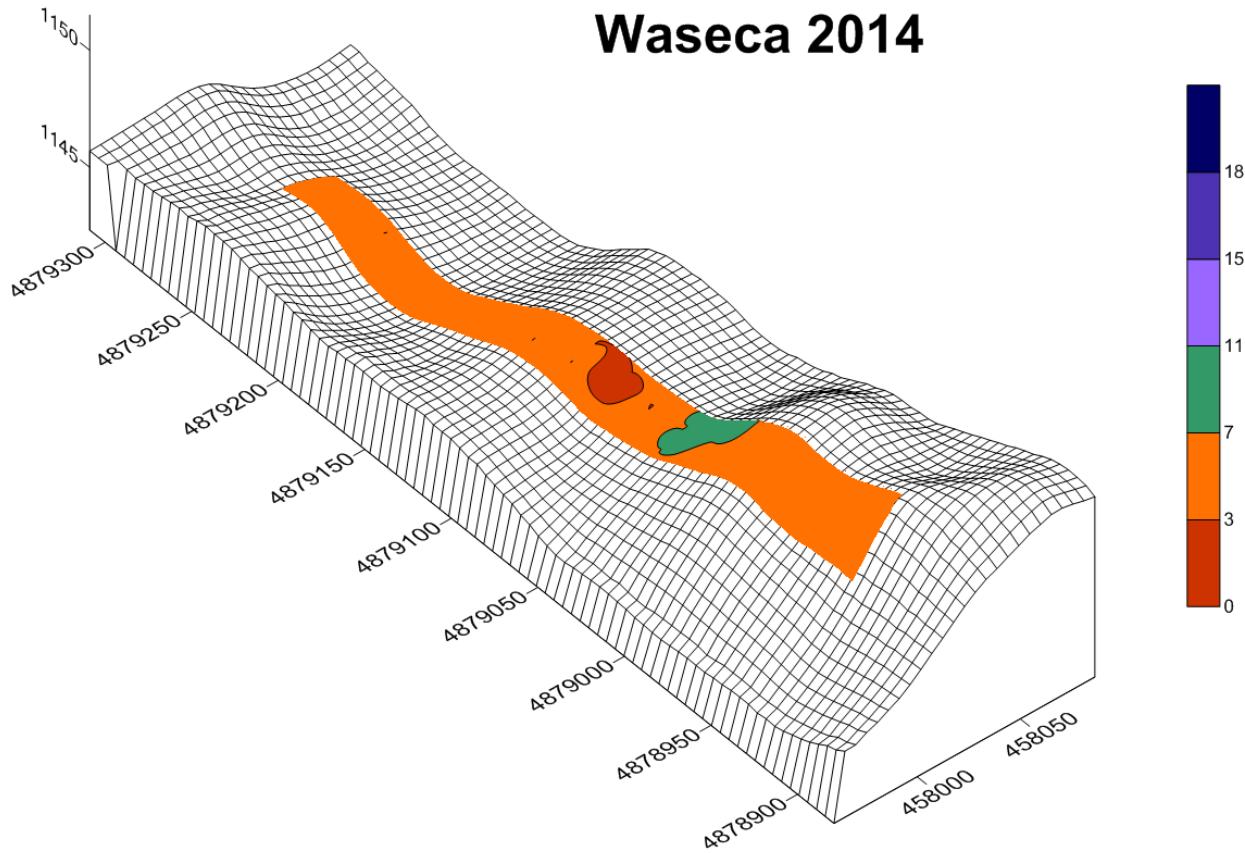


Figure H. Inherent variability in soil test phosphorus (Olsen P) at Waseca in 2014.

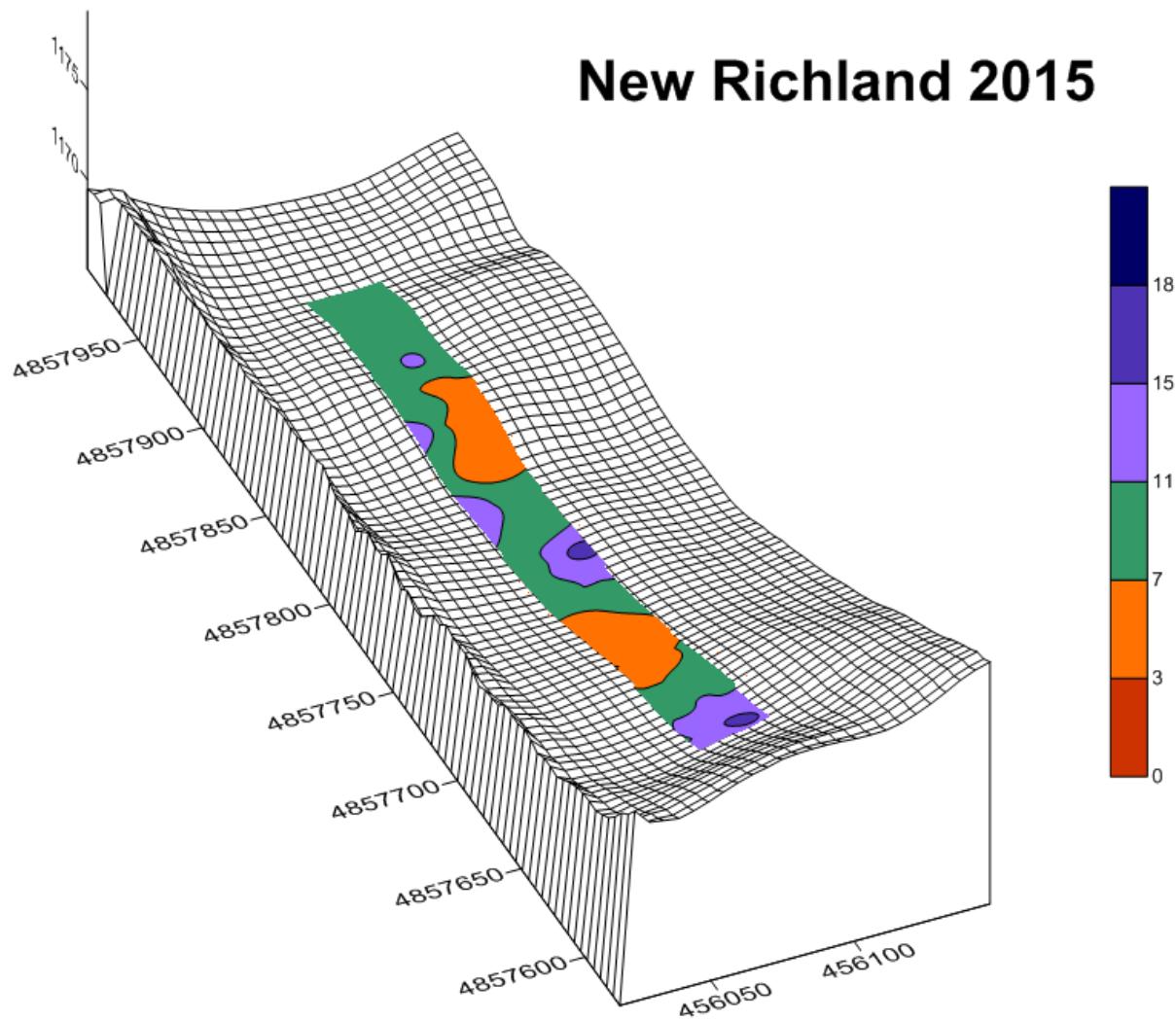


Figure I. Inherent variability in soil test phosphorus (Olsen P) at New Richland in 2015.

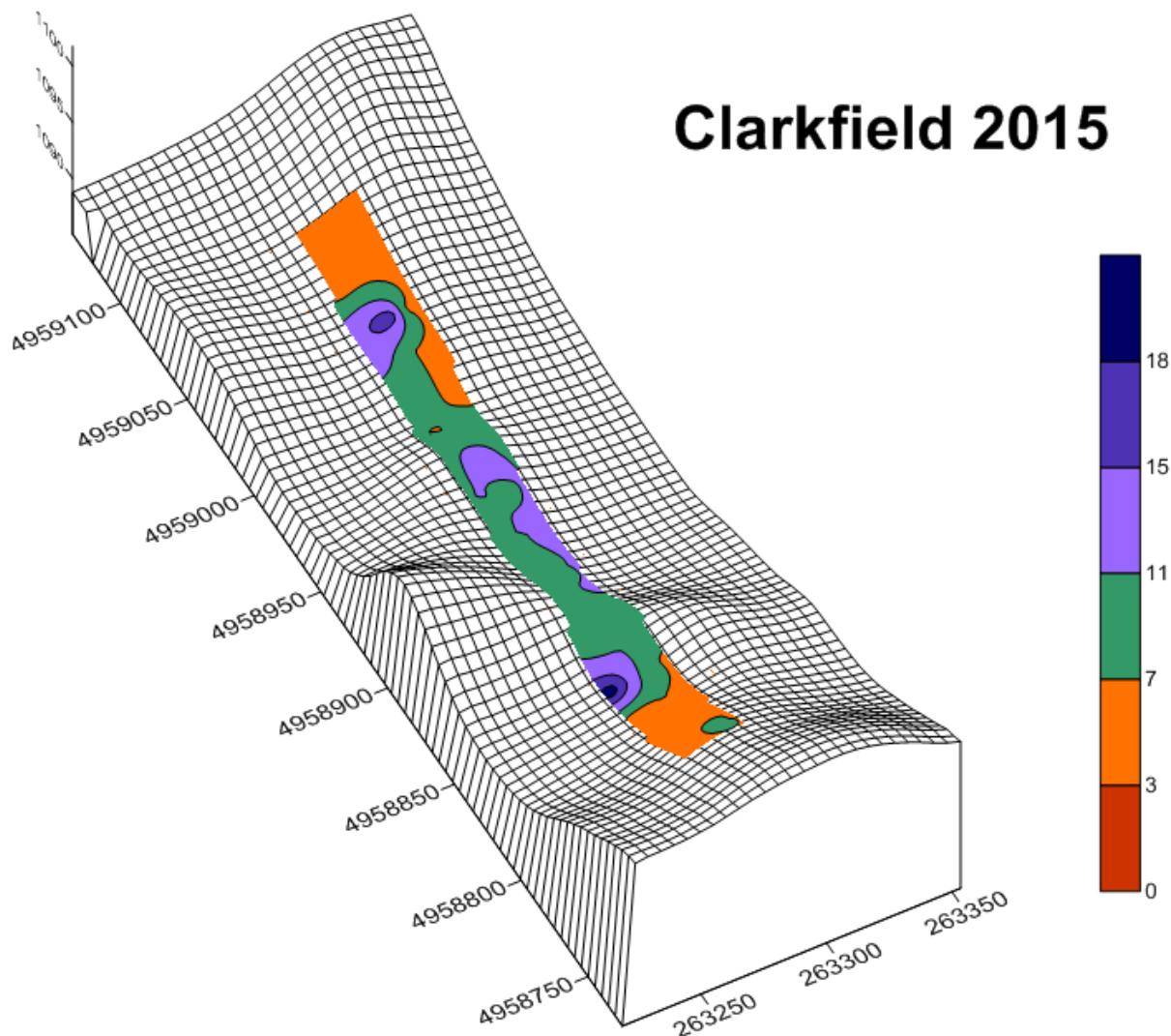


Figure J. Inherent variability in soil test phosphorus (Olsen P) at Clarkfield in 2015.

Table 11. Summary of statistical significance of treatment main effects by location.

Parameter	Location	Broadcast P	Starter P	Broadcast*Starter
-----P > F-----				
Plant Population	Gaylord 2012	0.981	0.184	0.688
	Stewart 2012	0.824	0.481	0.735
	New Richland 2013	0.950	0.480	0.056
	Willmar 2013	0.781	0.562	0.374
	Janesville 2013	0.998	0.423	0.217
	New Richland 2014	0.034	0.771	0.548
	St. Charles 2014	0.994	0.354	0.134
	Waseca 2014	no data	no data	no data
	New Richland 2015	0.346	0.747	0.890
	Clarkfield 2015	0.346	0.075	0.156
V5 Plant Wt.	Gaylord 2012	0.474	0.160	0.101
	Stewart 2012	0.356	0.781	0.161
	New Richland 2013	0.460	<0.001	0.211
	Willmar 2013	0.045	0.015	0.783
	Janesville 2013	0.004	<0.001	0.079
	New Richland 2014	0.001	0.017	0.583
	St. Charles 2014	0.007	0.002	0.271
	Waseca 2014	0.016	<0.001	0.578
	New Richland 2015	0.109	0.044	0.838
	Clarkfield 2015	0.956	0.046	0.311
V5 Plant P Conc.	Gaylord 2012	0.371	0.314	0.531
	Stewart 2012	0.071	0.015	0.138
	New Richland 2013	<0.001	0.051	0.335
	Willmar 2013	0.028	0.450	0.562
	Janesville 2013	0.066	0.092	0.234
	New Richland 2014	<0.001	0.382	0.526
	St. Charles 2014	<0.001	0.092	0.314
	Waseca 2014	<0.001	0.916	0.925
	New Richland 2015	0.027	0.226	0.634
	Clarkfield 2015	0.986	0.752	0.876
V5 Plant P Uptake	Gaylord 2012	0.532	0.507	0.234
	Stewart 2012	0.126	0.310	0.217
	New Richland 2013	0.007	<0.001	0.214
	Willmar 2013	0.011	0.043	0.783
	Janesville 2013	0.001	<0.001	0.623
	New Richland 2014	<0.001	0.029	0.873
	St. Charles 2014	<0.001	<0.001	0.110
	Waseca 2014	0.001	<0.001	0.390
	New Richland 2015	0.068	0.122	0.931
	Clarkfield 2015	0.997	0.296	0.607

Table 11. Summary of statistical significance of treatment main effects by location (cont.)

Parameter	Location	Broadcast P	Starter P	Broadcast*Starter
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		P > F		
Corn Grain Yield	Gaylord 2012	0.090	0.433	0.050
	Stewart 2012	0.050	0.689	0.916
	New Richland 2013	0.004	0.029	0.123
	Willmar 2013	<0.001	0.922	0.608
	Janesville 2013	0.427	0.386	0.118
	New Richland 2014	0.032	0.073	0.028
	St. Charles 2014	0.348	0.972	0.125
	Waseca 2014	0.005	0.032	0.279
	New Richland 2015	0.644	0.253	0.954
	Clarkfield 2015	<0.001	0.498	0.156
Grain Moisture	Gaylord 2012	0.329	0.051	0.508
	Stewart 2012	0.622	0.966	0.259
	New Richland 2013	0.197	0.007	0.869
	Willmar 2013	0.053	0.490	0.969
	Janesville 2013	0.031	0.003	0.049
	New Richland 2014	0.250	0.932	0.560
	St. Charles 2014	0.353	0.086	0.586
	Waseca 2014	0.089	0.012	0.072
	New Richland 2015	0.614	0.927	0.691
	Clarkfield 2015	0.320	0.698	0.410
Grain P Conc.	Gaylord 2012	0.212	0.709	0.762
	Stewart 2012	0.237	0.785	0.093
	New Richland 2013	<0.001	0.923	0.439
	Willmar 2013	0.005	0.821	0.448
	Janesville 2013	0.917	0.617	0.942
	New Richland 2014	0.046	0.047	0.320
	St. Charles 2014	0.258	0.145	0.734
	Waseca 2014	0.554	0.369	0.465
	New Richland 2015	0.106	0.260	0.432
	Clarkfield 2015	0.990	0.230	0.217
Grain P Removal	Gaylord 2012	0.170	0.590	0.880
	Stewart 2012	0.050	0.970	0.070
	New Richland 2013	<0.001	0.717	0.610
	Willmar 2013	0.004	0.838	0.748
	Janesville 2013	0.734	0.656	0.962
	New Richland 2014	<0.001	0.063	0.127
	St. Charles 2014	0.244	0.451	0.174
	Waseca 2014	0.007	0.018	0.125
	New Richland 2015	0.077	0.833	0.734
	Clarkfield 2015	0.184	0.315	0.251

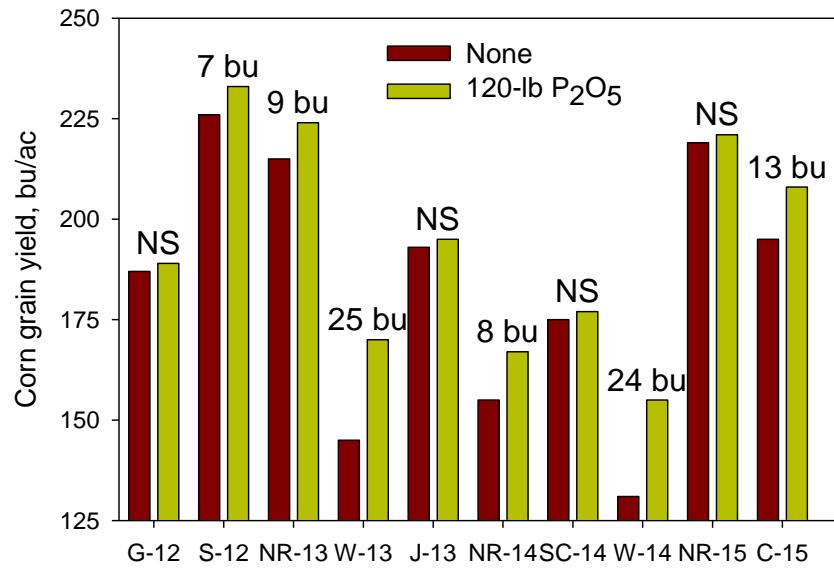


Figure K. Corn grain yield by locations as affected by the main effect of broadcast P rates, when averaged across starter P rates (location abbreviations are G-12=Gaylord 2012, S-12=Stewart 2012, NR=New Richland, W-13=Willmar 2013, J-13=Janesville 2013, SC-14=Saint Charles 2014, W-14=Waseca 2014 and C-15=Clarkfield 2015).

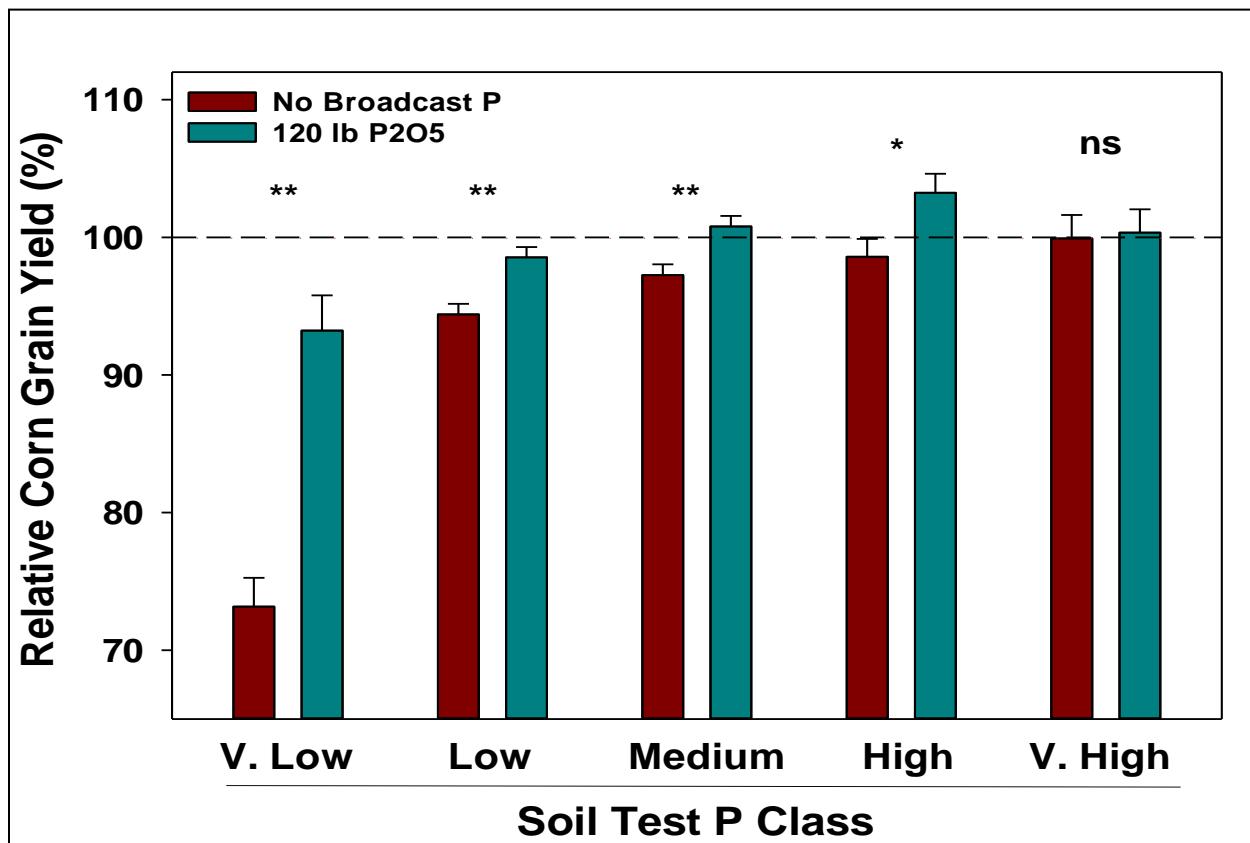


Figure L. Relative corn grain yield as affected by broadcast rates of fertilizer P and soil test P classes (Olsen P), when averaged across starter P rates and locations (** and * denotes significance at $\alpha=0.05$ and $\alpha=0.10$, respectively).

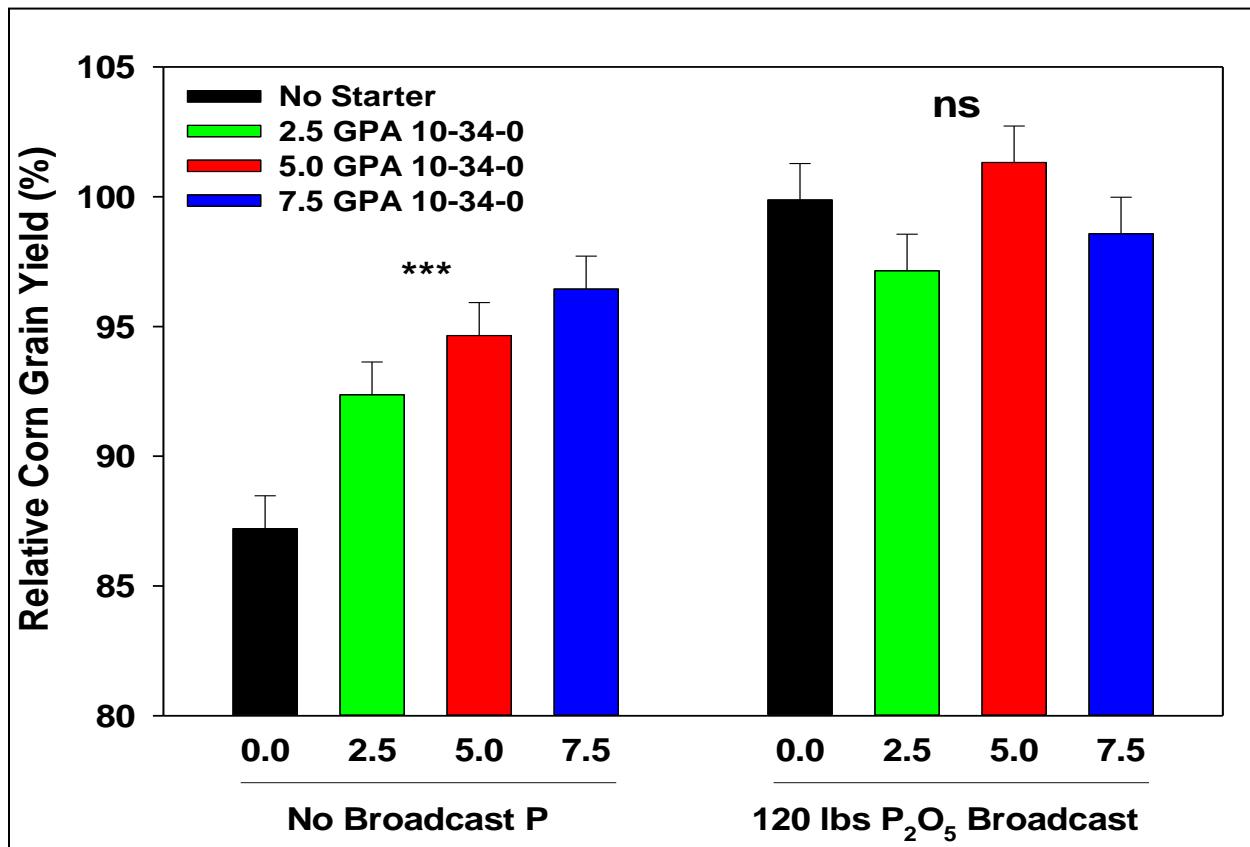


Figure M. Relative corn grain yield as affected by the interaction between broadcast and starter (APP, ammonium poly phosphate) rates of fertilizer P, when averaged across locations and soil test P levels (error bar denotes significance at $\alpha=0.05$).

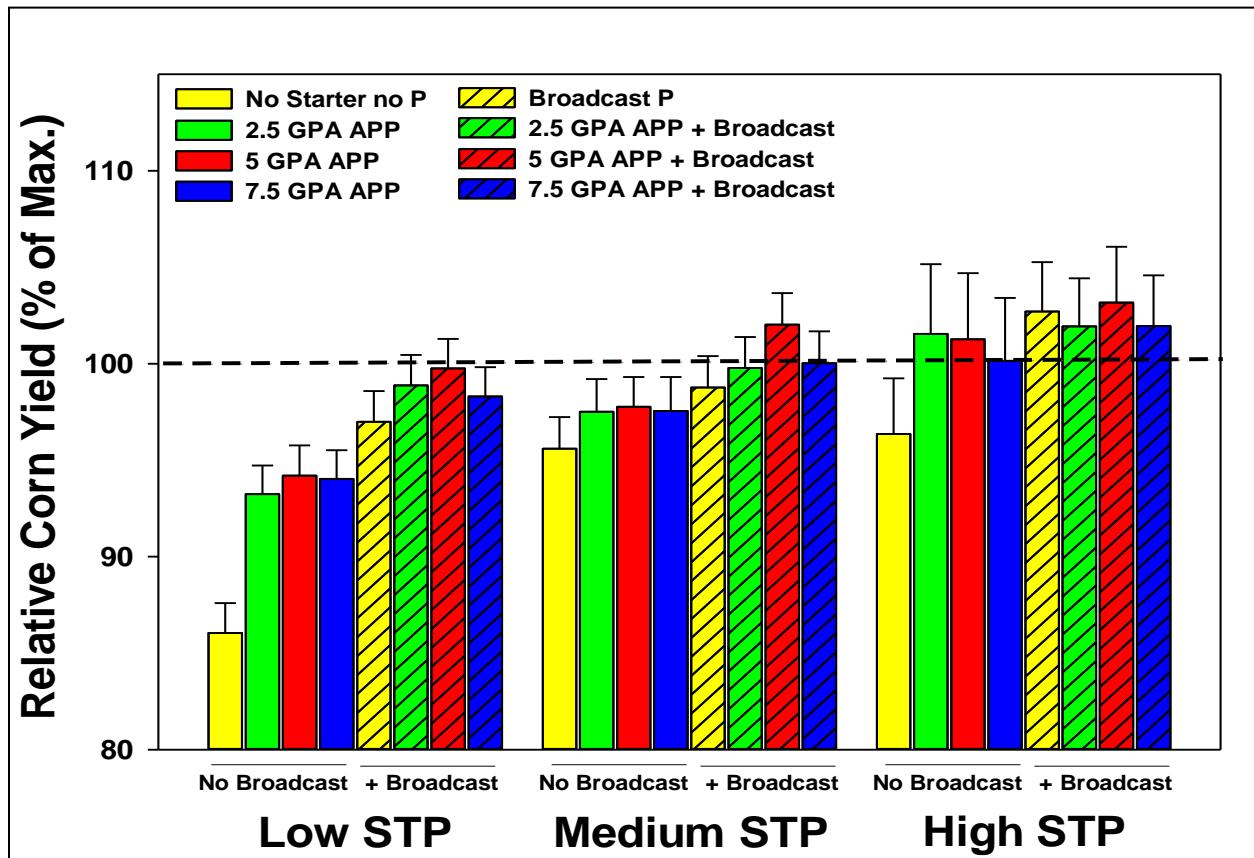


Figure N. Relative corn grain yield at various soil test levels (Olsen P) as affected by broadcast and starter rates of fertilizer P, when averaged across locations (error bar denotes significance at $\alpha=0.05$).