Seeding Rates for Precision Seeded Canola

2012 - 2014 Report

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EXECUTIVE SUMMARY

Non-uniform canola plant distribution within the row can result in greater intraspecific competition, potentially increasing seedling mortality and reducing yield potential. An evenly distributed canola population may allow producers to target lower plant populations and hence use lower seeding rates without reductions in yield. SeedMaster proposes that its UltraPro canola meter can seed canola more uniformly potentially allowing producers to reduce seeding rates while maintaining maximum yield potential. The objectives of this experiment were 1) to determine if the UltraPro canola roller produces more uniform canola seed placement than conventional fluted rollers and 2) to determine if more uniform plant density has the potential for allowing lower canola seeding rates. The treatments were a factorial arrangement of seeding rates at 10, 20, 40, 80, 160 and 320 seeds m^{-2} metered with either the traditional fluted Valmar roller or SeedMaster's UltraPro roller. Seeding rate was the only factor to significantly affect plant density, maturity and seed yield. There were generally no differences in plant density in spring or fall, seed yield or maturity between the roller types at any level of seeding rate. Although there appeared to be more uniform distribution of seedlings, on average, with the UltraPro roller than the Valmar at 10-80 seeds m^{-2} seeding rates, this did not translate into improvements in seed yield. Differences in uniformity generally disappeared at fall plant population assessment, likely due to the self-thinning nature of canola.

INTRODUCTION

Spatial patterns in a plant community play an important role in many ecological events, such as community stability, interplant competition, diversity maintenance, and community productivity, which can alter interspecific competition or pest pressure (Ahmed et al. 2008; Perry et al. 2002). Also, the performance of individual plants within a community largely depends on the level of competition for resources with their neighboring plants (Uriarte et al. 2004). For example, when plants are non-uniformly distributed within the community, competition for available resources can become severe as the number and size of nearby plants increase (Wilson and Tilman 1991). A uniform stand distribution within a plant community increases plant biomass and productivity compared with a non-uniform stand distribution due to the availability of resources such as light, soil water, and organic carbon (Pronk et al. 2007; Jasso de Rodríguez et al. 2002).

Despite the availability of results from previous studies on spatial patterns in natural ecosystems (Legendre and Fortin 1989), similar results on the productivity of field crops is limited. A few studies have shown that non-uniform spatial distribution of plant stands can negatively influence the grain yield of sorghum (*Sorghum vulgare*), wheat (*Triticum aestivum*), and maize (*Zea mays*) compared to uniform spatial patterns (Olsen et al. 2005; Tokatlidis and Koutroubas 2004). However, the effect of spatial uniformity on other economic crops, such as canola (*Brassica napus* L.) remains limited.

The establishment of an adequate and even canola stand is essential to reaching yield potential; however, poor seed bed conditions or soil to seed contact, late spring frosts or insect damage often results in poor establishment and uneven plant stands. Non-uniform plant distribution within the row can result in greater intraspecific competition, reducing yield potential. For example, trials conducted at Swift Current in 1999-2001 found that reducing a uniformly distributed plant population from 80 to 40 plants m^{-2} did not affect yield; however, the same reduction in plant density under non-uniform conditions reduced yields (Angadi et al. 2003). A uniform plant distribution may also result in uniform interspecific competition with weeds. In more recent research conducted in western Canada, Yang et al. (2014) found that spatially uniform stands produced 20-32 % higher yields, with the increase being more pronounced at low plant populations.

With less intraspecific competition of crop plants within a row, evenly distributed populations may allow producers to target lower plant populations and hence use lower seeding rates without reductions in yield. Recent field studies have shown that modern hybrid canola can reach maximum yield potential with as little as 28 plants m^{-2}, on average, which is lower than the current guidelines which suggest that yield begins to decline at plant populations below 40-50 plants m^{-2} (Kirk et al. 2013). An analysis of the yield components of *Brassica napus* found that the number of branches per plant, pods per plant and seeds per pod increased at low seeding rates (Clarke and Simpson 1978).

SeedMaster proposes that its UltraPro canola meter can seed canola more uniformly allowing producers to significantly reduce seeding rates and maintain maximum yield potential (SeedMaster 2010). If this "precision" seeding equipment can produce a uniform plant stand using low seeding rates, it has the potential to reduce seed input costs. While studies have been performed looking at the effect of seeding rate and plant uniformity, third party independent research needs to be performed on the UltraPro canola meter to test its claims.

OBJECTIVES

The objectives of this project were to: 1) to determine if the UltraPro canola roller produces more uniform canola seed placement than conventional fluted rollers and 2) to determine if more uniform seed placement has the potential to allow for lower canola seeding rates.

MATERIALS AND METHODS

Field trials were conducted near Scott, Melfort, Redvers and Indian Head, Saskatchewan in 2012, 2013 and 2014. The experimental design was a randomized complete block design with four replicates. The treatments combination were six seeding rates and two metering roller types (Table 1). The hybrid canola variety L150 was direct seeded at all locations in 2012 and 2013 seasons on cereal stubble. In 2014 the variety L130 was seeded at all locations on cereal stubble. Seeding equipment varied between sites and row spacing ranged from 20 to 30 cm. Plot size ranged from 25 to 40 m^2. Fertilizer was applied according to soil test recommendations and herbicides and fungicides were applied as required. The plots were straight combined at Indian Head and Scott and swathed at Melfort.

Data collection included spring and fall seedling density and uniformity, days to maturity and seed yield. Plant uniformity was evaluated by measuring the distance between 10 plants in four rows per plot at the 2-3 leaf stage in spring and again after harvesting plots in fall. Variability of within-row plant spacing was determined by standardizing each measured spacing and calculating the mean distance between plants for each treatment as well as the standard deviation of those observed distances. Spring plant density was calculated from the spring seedling uniformity measurements. The number of days from planting to maturity was recorded with plants declared mature when 60% of seeds along the main raceme showed colour change. Seed yield was calculated from clean seed weight per plot and adjusted for moisture content.

Data from all site years were combined and analyzed using the GLIMMIX Procedure in SAS 9.3. Data from Scott in 2012 was removed from the analysis due to the large number of removed data entries, resulting from errors during seeding. Roller type and seeding rate were fixed factors while site year and replicate were considered random effects. Treatment means were separated using the Tukey method and considered significant at $P < 0.05$. Orthogonal polynomial contrasts in the

Mixed Procedure were conducted to determine the nature of the response to seeding rate and plant density for individual rollers. Boxplots were used to illustrate the variability in distance between plants in both spring and fall using the Boxplot Procedure. Distance means and standard deviations of each treatment were estimated using the Means Procedure.

RESULTS AND DISCUSSION

Plant Density & Uniformity

Spring plant density was affected only by seeding rate ($P < .0001$) (Table 4). Plant density increased linearly and quadratically with seeding rate with both rollers (Table 5). Plant populations were significantly higher at 160 and 320 seeds m^{-2} compared to all other seeding rates using either rollers (Table 4). There were no differences in plant density between rollers at any level of seeding rate (Table 4). Mean spring plant density was above the lower critical threshold of 50 plants m^{-2} with seeding rates $\geq$ 80 seeds m^{-2} (Table 4). When combined across site-years, approximately 72% of the seeds resulted in spring seedlings, which is higher than many studies where approximately 40% emergence is common. At individual site years, there were generally no significant differences in spring plant density between the two rollers at each level of seeding rate, except at the 320 seeds m^{-2} rate at Scott (2013, 2014), Redvers (2012, 2013) at 320 seeds m^{-2}, Melfort (2012) at both 160 & 320 seeds m^{-2}, and Indian Head (2012) at 160 seeds m^{-2} (Table 9). Emergence at individual sites ranged from 40 to 100%. In a number of locations, there was a trend for higher spring plant densities with the Valmar, particularly at the higher planting densities. It is felt that this was not due to a higher percentage of seedling emergence with the Valmar, but that the Valmar was metering more seed than what was calibrated at the higher densities. In other words, it is speculated that the UltraPro more accurately metered the seed in some situations. Mean distance between seedlings was also similar for both rollers at each level of seeding rate and there was a general decrease in variability (standard deviation) within plants with increased seeding rates (Table 6).

The trends seen in spring plant density were consistent in the fall plant density sampling results. Seeding rate again was the only factor which significantly affected fall plant density ($P < .0001$) (Table 4). Fall plant density response to seeding rate was also linear and quadratic (Table 5). All seed rates $\geq$ 80 seeds m^{-2} resulted in plant populations above the lower critical threshold. Plant density at 320 seeds m^{-2} was significantly higher than at seeding rates $\leq$ 80 seeds m^{-2}, and there were no differences in fall plant density between the two rollers at any level of seeding rate (Table 4). At individual site years, the only differences in fall plant density between rollers was at Scott (2014) at 320 seeds m^{-2}, Redvers (2012, 2013) at 320 seeds m^{-2} and at Melfort (2012) at 160 & 320 seeds m^{-2} (Table 10). As seen in the spring, mean distance between seedlings was similar for both rollers at each level of seeding rate; however, standard deviation appeared to be more uniform than the spring, likely due to self-thinning of the plants over the course of the season. Because self-thinning likely resulted in similar distance and distribution of plants within the row, regardless of earlier variability, any advantage that the UltraPro roller may provide would appear to have minimal effects on intraspecific competition in canola.

Days to Maturity

Similar to plant density, maturity was affected, on average, by seeding rate (P <.0001) but not by roller (P = 0.073) and there was no interaction between the two factors (P = 0.873) (Table 4). As seeding rate increased, days to maturity decreased linearly with both rollers (Table 5). The two highest seeding rates had significantly shorter average days to maturity compared to the lowest two seeding rates, that is ~4.2 days for the UltraPro roller. The two highest seeding rates using the Valmar roller also had significantly shorter maturity dates than the 20 seeds m^{-2} treatment and was numerically shorter than the 10 seeds m^{-2} treatment (Table 4). The Valmar had, on average, ~4.8 days difference between the two highest and two lowest seeding rates. This is consistent with previous studies where canola maturity was delayed as plant populations declined (i.e. Kirk et al. 2013).

Seed Yield

Seeding rate, again, was the only factor that affected seed yield (P < 0.001) (Table 4). There was generally a lack of significant differences among treatments. The exception was that both treatments seeded at 10 seeds m^{-2} were significantly lower than those seeded at 320 seeds m^{-2} using both rollers (Table 4). There were both linear and quadratic responses to seeding rate using both Valmar and UltraPro rollers (Table 5), indicating that perhaps, the yields had reached a plateau.
Broken line regression with yield against plant desity (spring plant population) indicates that at both the low and high-yielding sites, yield reached a plateau with no significant differences between roller types (Figure 1). At low-yielding sites, maximum yield was attained at 22 plants/m^2 compared to 39 plants/m^2 at high-yielding sites. This corresponds to seeding rate of 40 seeds/m^2 in a combined analysis (12 site years). The results shows that, irrespective of the roller used, yield was maximized at 40 seed/m^2. It appears that canola reached maximum yield potential at lower than recommended plant populations, however, there was no advantage of using the UltraPro roller at those lower densities. This is consistent with previous results, indicating that canola can compenstate at very low plant populations, resulting in similar yield potential over a range of plant densities. That said, growers are generally advised to use higher seeding rates (> 80 seeds m^{-2}) to insure against potential loss of seedlings to early season stresses and to improve yield stability, seed quality and maturity.

CONCLUSIONS

Seeding rate was the only factor to significantly affect plant density, maturity and seed yield. There were generally no differences in plant density in spring or fall, uniformity of seedling distribution, seed yield or maturity between the rollers at any level of seeding rate. Irrespective of the roller type used, yield was maximized or reached a plateau at 40 seeds/m^2. Differences in uniformity generally disappeared at fall plant population assessment, likely due to the self-thinning nature of canola.

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Appendix A – Treatment List

Table 1. Treatment list.

Treatment	Roller	Seeding Rate (seeds m^{-2})
1	Valmar	10
2	Valmar	20
3	Valmar	40
4	Valmar	80
5	Valmar	160
6	Valmar	320
7	UltraPro	10
8	UltraPro	20
9	UltraPro	40
10	UltraPro	80
11	UltraPro	160
12	UltraPro	320

Appendix B – Weather Conditions in 2012, 2013 and 2014

Table 2. Mean monthly temperatures and long-term (1971-2000) normals for the 2012 - 2014 growing seasons at Indian Head, Redvers, Melfort and Scott SK.

Location	Year	May	June	July	August	September	Average
	Mean Temperature (°C)						
Indian Head	2012	9.9	16.5	19.2	17.1	12.6	15.1
	2013	11.9	15.3	16.3	17.1	14.3	15.0
	2014	10.2	14.4	17.3	17.4	12.3	14.3
	Long-term	*10.8*	*15.8*	*18.2*	*17.4*	*11.5*	*14.7*
Redvers	2012	11.3	17.0	20.8	18.2	12.9	16.0
	2013	10.9	15.2	17.6	18.6	14.4	15.3
	2014	10.8	14.2	17.6	18.9	13.0	12.9
	Long-term	*11.1*	*16.2*	*18.7*	*18.0*	*12.5*	*15.3*
Melfort	2012	9.6	15.2	18.9	17.1	12.4	14.6
	2013	12.0	14.9	16.4	17.7	14.4	15.1
	2014	10.0	14.0	17.5	17.6	11.9	14.2
	Long-term	*10.7*	*15.9*	*17.5*	*16.8*	*10.8*	*14.3*
Scott	2012	9.7	15.1	18.6	17.0	12.2	14.5
	2013	12.6	14.8	16.5	17.4	14.0	15.1
	2014	9.3	13.9	17.4	16.8	11.2	13.7
	Long-term	*10.8*	*15.3*	*17.1*	*16.5*	*10.4*	*14.0*

Table 3. Total monthly precipitation amounts and long-term (1971-2000) normals for the 2012 - 2014 growing seasons at Indian Head, Redvers, Melfort and Scott SK.

Location	Year	May	June	July	August	September	Total
	Precipitation (mm)						
Indian Head	2012	79.4	51.0	124.6	30.4	0.0	285.4
	2013	17.1	103.8	50.4	6.1	14.8	192.2
	2014	36.0	199.2	7.8	142.2	42.3	427.5
	Long-term	*49.0*	*77.4*	*63.8*	*51.2*	*34.1*	*275.5*
Redvers	2012	53.0	70.0	65.0	15.8	13.5	217.3
	2013	84.0	85.0	143.5	38.0	22.5	373.0
	2014	44.0	55.0	27.0	120.5	43.0	289.5
	Long-term	*53.2*	*95.2*	*65.5*	*46.6*	*32.7*	*293.2*
Melfort	2012	55.2	112.3	97.8	68.1	12.6	346.0
	2013	18.0	96.9	100.0	10.6	17.0	242.5
	2014	24.3	167.3	38.8	57.9	9.4	297.7
	Long-term	*39.8*	*54.3*	*76.7*	*52.4*	*34.3*	*257.5*
Scott	2012	50.6	164.6	56.4	51.4	24.4	347.4
	2013	38.9	113.5	26.1	63.3	0.0	241.8
	2014	23.1	60.4	128.0	30.1	23.6	265.2
	Long-term	*4.8*	*61.8*	*72.1*	*45.7*	*32.9*	*217.3*

Appendix C – Combined Analysis

Table 4. Least squared means and analysis of variance of measured variables (12 site years combined)

Roller	Seeding Rate (seeds m^{-2})	Spring Plant Density (plants m^{-2})[z]	Days to Maturity[z]	Seed Yield (kg ha^{-1})[z]	Fall Plant Density (plants m^{-2})[z]
		Least Squared Means			
Valmar	10	13^{e}	99.7^{a}	1873^{b}	11^{g}
Valmar	20	20^{de}	99.3^{a}	2292^{ab}	19^{fg}
Valmar	40	36^{de}	97.9^{abc}	2333^{a}	31^{efg}
Valmar	80	72^{cd}	96.6^{bcde}	2472^{a}	57^{cde}
Valmar	160	136^{b}	95.07^{de}	2464^{a}	91^{bc}
Valmar	320	212^{a}	94.4^{e}	2467^{a}	139^{a}
Ultra	10	12^{e}	99.4^{a}	1883^{b}	12^{g}
Ultra	20	17^{e}	98.8^{ab}	2154^{ab}	16^{fg}
Ultra	40	36^{de}	97.2^{abcd}	2421^{a}	32^{efg}
Ultra	80	60^{de}	97.2^{abcd}	2517^{a}	52^{def}
Ultra	160	118^{bc}	95.3^{cde}	2519^{a}	88^{bcd}
Ultra	320	193^{a}	94.5^{e}	2460^{a}	120^{ab}
		Analysis of Variance (P Value)			
Seeding Rate		<.0001	<.0001	<.0001	<.0001
Roller		0.1676	0.7354	0.8711	0.2815
Seeding Rate*Roller		0.9124	0.8733	0.8660	0.8129

[z] Treatments means separated using the Tukey Method. Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

Table 5. Orthogonal contrasts by roller type on measured variables (12 site years combined)

	Spring Plant Density		Days to Maturity		Seed Yield		Fall Plant Density	
Orthogonal Contrast	Valmar	Ultra	Valmar	Ultra	Valmar	Ultra	Valmar	Ultra
Linear	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Quadratic	<.0001	<.0001	0.7294	0.6812	0.0097	0.0019	0.0004	0.0035
Cubic	0.7942	0.5188	0.2655	0.9735	0.3604	0.8850	0.7840	0.7853

Table 6. Mean and standard deviation of measured distance between plants in spring by seeding rate and roller type (12 site years combined)

	Valmar		Ultra	
Seeding rate	Mean Distance	Standard Deviation	Mean Distance	Standard Deviation
10 seeds m^{-2}	44.6	21.8	47.5	20.7
20 seeds m^{-2}	27.2	13.1	31.6	20.8
40 seeds m^{-2}	15.1	8.7	14.5	7.2
80 seeds m^{-2}	7.1	3.7	9.3	9.4
160 seeds m^{-2}	3.8	2.4	4.2	1.8
320 seeds m^{-2}	2.5	2.2	3.0	2.1

Table 7. Mean and standard deviation of measured distance between plants in fall by seeding rate and roller type (12 site years combined)

	Valmar		Ultra	
Seeding rate	Mean Distance	Standard Deviation	Mean Distance	Standard Deviation
10 seeds m^{-2}	44.7	17.9	45.6	20.8
20 seeds m^{-2}	28.9	17.6	32.7	16.1
40 seeds m^{-2}	18.8	13.3	17.7	11.2
80 seeds m^{-2}	9.3	6.1	10.2	5.9
160 seeds m^{-2}	5.7	3.6	5.9	2.7
320 seeds m^{-2}	4.1	2.9	4.6	2.6

Appendix D – Individual Site Year Analysis

Table 8. Analysis of variance for spring and fall plant density, days to maturity and seed yield at Scott, Redvers, Melfort and Indian Head from 2012-2014.

		Scott		**Redvers**			**Melfort**			**Indian Head**		
Variable	Effect	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
		Analysis of Variance (*P values*)										
Spring Plant Density	Seeding Rate	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Roller	<.0001	<.0001	0.1229	0.0008	0.0960	0.7955	0.7702	0.3067	0.0008	0.0891	0.5679
	Seeding Rate*Roller	0.0002	0.1519	0.0768	0.0051	0.1271	<.0001	0.3901	0.7486	0.2410	0.5168	0.7001
Days to Maturity	Seeding Rate	<.0001	*n/a	n/a	0.1218	n/a	<.0001	<.0001	0.0105	<.0001	n/a	<.0001
	Roller	0.0143	n/a	n/a	0.1762	n/a	0.6203	0.8193	0.2157	0.7752	n/a	0.5704
	Seeding Rate*Roller	0.0019	n/a	n/a	0.0562	n/a	0.2814	0.9048	0.0171	0.7903	n/a	0.7066
Seed Yield	Seeding Rate	<.0001	<.0001	0.0271	0.8045	0.2923	0.0007	<.0001	0.0009	<.0001	<.0001	<.0001
	Roller	0.7461	0.0004	0.6132	0.8941	0.2424	0.6116	0.0056	0.2509	0.1522	0.8843	0.2413
	Seeding Rate*Roller	<.0001	0.0017	0.5492	0.9450	0.7534	0.7754	0.0887	0.0442	0.6211	0.3563	0.0744
Fall Plant Density	Seeding Rate	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Roller	0.8687	0.0376	0.0102	0.6829	0.2374	0.4356	0.6837	0.5847	0.0419	0.9681	0.8919
	Seeding Rate*Roller	0.5980	0.0584	0.5631	0.0143	0.0198	<.0001	0.9960	0.1167	0.2977	0.9290	0.9998

*n/a means data not available

Table 9. Least squared means for spring plant density at each site year. Means followed by the same letter within a column are not significantly different at $P \leq 0.05$.

		Scott		Redvers			Melfort			Indian Head		
Roller	Seeding Rate	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
Valmar	10	9^{ef}	12^{f}	10^{c}	19^{f}	36^{bc}	7^{f}	6^{e}	21^{d}	10^{e}	10^{d}	6^{e}
Valmar	20	12^{ef}	19^{ef}	15^{c}	31^{def}	13^{c}	16^{ef}	9^{e}	61^{d}	16^{e}	13^{d}	13^{e}
Valmar	40	23^{ef}	48^{def}	35^{c}	47^{def}	23^{c}	26^{ef}	13^{e}	94^{cd}	28^{e}	30^{cd}	32^{de}
Valmar	80	49^{def}	84^{de}	50^{c}	68^{bcd}	42^{bc}	54^{de}	35^{de}	178^{c}	80^{cd}	81^{bc}	73^{cd}
Valmar	160	89^{cd}	149^{bc}	90^{b}	109^{b}	110^{ab}	125^{ab}	63^{cd}	352^{ab}	164^{ab}	135^{b}	142^{b}
Valmar	320	174^{b}	272^{a}	171^{a}	174^{a}	131^{a}	105^{bc}	116^{a}	431^{a}	204^{a}	264^{a}	251^{a}
Ultra	10	8^{f}	6^{f}	11^{c}	17^{f}	21^{c}	11^{ef}	7^{e}	24^{d}	8^{e}	8^{d}	6^{e}
Ultra	20	28^{ef}	6^{f}	15^{c}	25^{ef}	16^{c}	13^{ef}	12^{e}	37^{d}	14^{e}	12^{d}	12^{e}
Ultra	40	61^{def}	23^{ef}	29^{c}	33^{def}	40^{bc}	22^{ef}	18^{e}	89^{cd}	27^{e}	32^{cd}	33^{de}
Ultra	80	68^{cde}	46^{def}	49^{c}	63^{cde}	39^{bc}	44^{def}	34^{de}	162^{c}	48^{de}	48^{cd}	67^{cd}
Ultra	160	124^{bc}	102^{cd}	103^{b}	92^{bc}	84^{abc}	70^{cd}	69^{bc}	312^{b}	100^{c}	127^{b}	118^{bc}
Ultra	320	296^{a}	199^{b}	129^{b}	108^{b}	60^{abc}	165^{a}	96^{ab}	444^{a}	164^{ab}	264^{a}	261^{a}

Table 10. Least squared means for fall plant density at each site year. Means followed by the same letter within a column are not significantly different at P ≤ 0.05.

		Scott		Redvers			Melfort			Indian Head		
Roller	Seeding Rate	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
Valmar	10	13^{de}	9^{e}	18^{e}	13^{e}	2^{e}	12^{d}	6^{c}	20^{f}	9^{e}	7^{d}	7^{b}
Valmar	20	14^{de}	18^{de}	30^{de}	19^{de}	14^{de}	17^{d}	7^{c}	59^{ef}	15^{de}	12^{cd}	14^{b}
Valmar	40	29^{de}	32^{de}	38^{bcde}	31^{cde}	20^{de}	22^{cd}	11^{c}	92^{de}	30^{de}	21^{cd}	24^{b}
Valmar	80	60^{cde}	64^{cd}	55^{abc}	32^{cde}	46^{cd}	49^{b}	24^{bc}	139^{d}	61^{bc}	60^{bc}	40^{b}
Valmar	160	121^{ab}	86^{bc}	81^{a}	62^{ab}	84^{ab}	77^{a}	52^{a}	217^{bc}	82^{b}	94^{b}	49^{b}
Valmar	320	162^{a}	179^{a}	75^{a}	87^{a}	100^{a}	47^{b}	71^{a}	320^{a}	113^{a}	195^{a}	154^{a}
Ultra	10	7^{e}	10^{e}	17^{e}	23^{de}	9^{de}	14^{d}	6^{c}	27^{ef}	8^{e}	6^{d}	6^{b}
Ultra	20	24^{de}	10^{e}	18^{e}	16^{e}	13^{de}	15^{d}	8^{c}	47^{ef}	12^{de}	11^{cd}	11^{b}
Ultra	40	50^{cde}	28^{de}	34^{cde}	31^{cde}	27^{cde}	22^{cd}	12^{c}	88^{def}	25^{de}	23^{cd}	21^{b}
Ultra	80	60^{cde}	51^{cde}	45^{bcd}	45^{cd}	41^{bc}	41^{bc}	23^{c}	150^{cd}	38^{cd}	50^{bcd}	32^{b}
Ultra	160	104^{abc}	90^{bc}	63^{ab}	83^{ab}	50^{b}	50^{b}	47^{ab}	243^{b}	72^{b}	95^{b}	52^{b}
Ultra	320	151^{a}	125^{b}	58^{bc}	58^{bc}	93^{a}	93^{a}	69^{a}	266^{ab}	114^{a}	205^{a}	156^{a}

Table 11. Least squared means for seed yield at each site year. Means followed by the same letter within a column are not significantly different at $P \leq 0.05$.

		Scott		Redvers			Melfort			Indian Head		
Roller	Seeding Rate	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
Valmar	10	2718^{d}	3319^{bc}	1363^{a}	1192^{a}	2251^{a}	2546^{b}	908^{c}	1862^{b}	1906^{ab}	2567^{d}	681^{c}
Valmar	20	2826^{cd}	3997^{ab}	1355^{a}	1222^{a}	2485^{a}	2947^{ab}	1308^{bc}	1969^{ab}	1967^{ab}	3504^{bc}	1590^{ab}
Valmar	40	3111^{bcd}	4321^{a}	1298^{a}	1373^{a}	2511^{a}	2912^{ab}	1369^{bc}	2131^{ab}	1778^{abc}	3910^{ab}	1624^{ab}
Valmar	80	3301^{ab}	4330^{a}	1552^{a}	1336^{a}	2331^{a}	3451^{ab}	1961^{ab}	2243^{ab}	1502^{abcd}	4123^{ab}	1917^{a}
Valmar	160	3548^{a}	4064^{ab}	1478^{a}	1503^{a}	2189^{a}	3433^{ab}	2049^{ab}	2225^{ab}	1399^{bcd}	3994^{ab}	1611^{ab}
Valmar	320	3467^{ab}	3810^{ab}	1540^{a}	1538^{a}	2054^{a}	3622^{a}	2671^{a}	2031^{ab}	1189^{d}	4045^{ab}	2089^{a}
Ultra	10	2120^{e}	2614^{c}	1125^{a}	1317^{a}	1888^{a}	2635^{ab}	1533^{bc}	1926^{ab}	2050^{a}	2491^{d}	1024^{bc}
Ultra	20	3156^{abc}	2920^{c}	1271^{a}	1264^{a}	2430^{a}	3123^{ab}	1728^{abc}	2256^{ab}	1832^{ab}	3270^{c}	970^{bc}
Ultra	40	3321^{ab}	3728^{ab}	1434^{a}	1324^{a}	2141^{a}	3312^{ab}	2053^{ab}	2286^{a}	2014^{a}	3951^{ab}	1716^{ab}
Ultra	80	3539^{a}	4167^{a}	1481^{a}	1448^{a}	2300^{a}	3336^{ab}	2175^{ab}	2322^{a}	1601^{abcd}	3936^{ab}	1647^{ab}
Ultra	160	3506^{ab}	4205^{a}	1502^{a}	1305^{a}	2132^{a}	3398^{ab}	2669^{a}	1955^{ab}	1621^{abcd}	4262^{a}	1627^{ab}
Ultra	320	3425^{ab}	4002^{ab}	1587^{a}	1418^{a}	2158^{a}	3474^{ab}	2233^{ab}	2047^{ab}	1222^{cd}	4170^{a}	1873^{a}

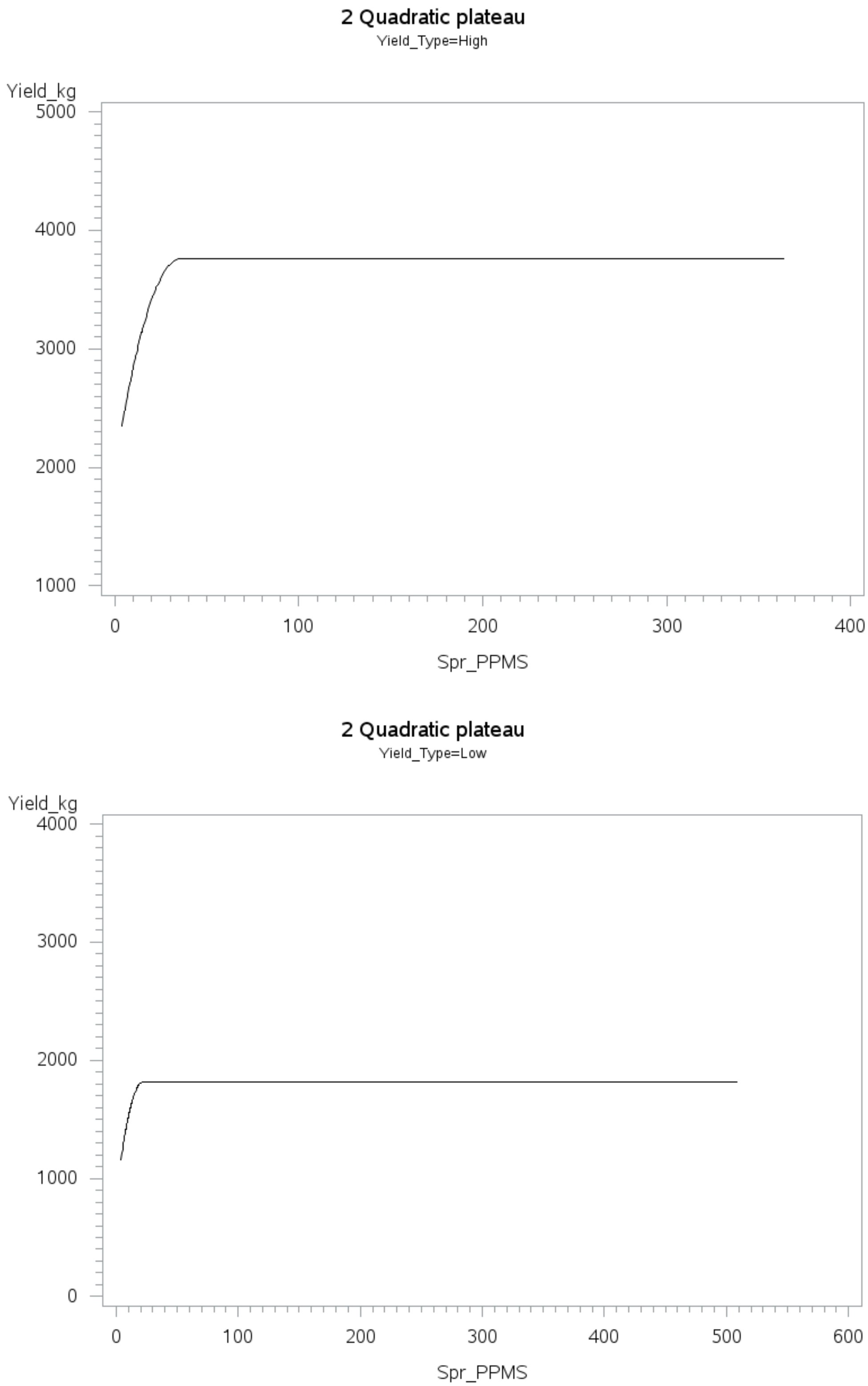

Figure 1. Broken line regression of yield vs plant population at high (top) and low-yielding (bottom) showing plateau in yield

Appendix E – Boxplots

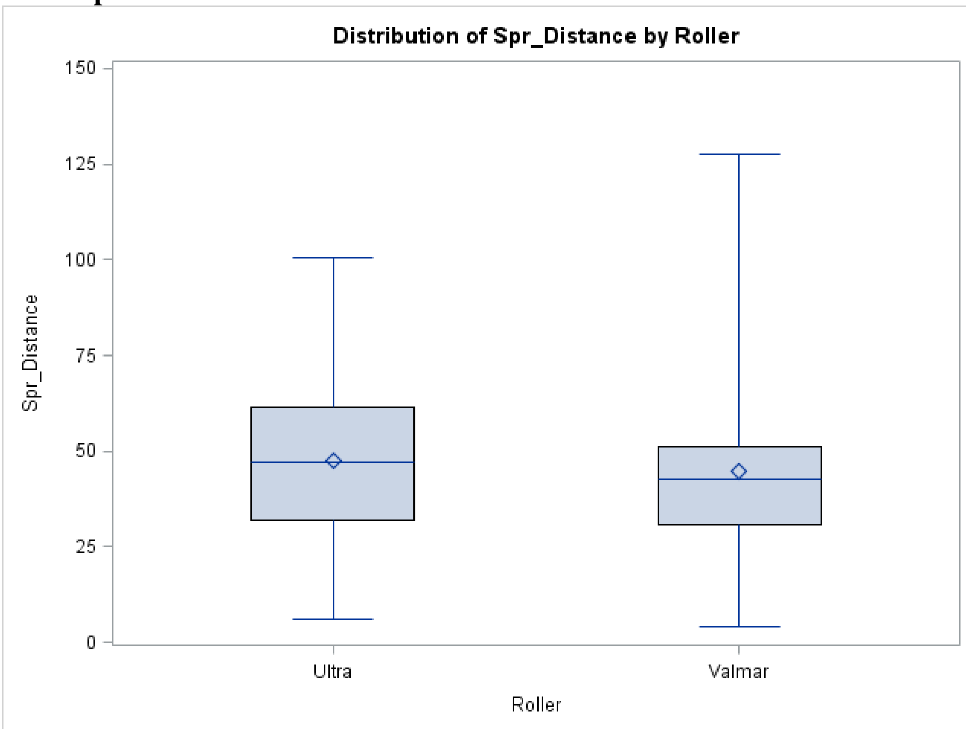

Figure 2. Boxplots representing mean and spread of distance between plants in spring seeded at 10 seeds m^{-2} with the UltraPro or Valmar rollers.

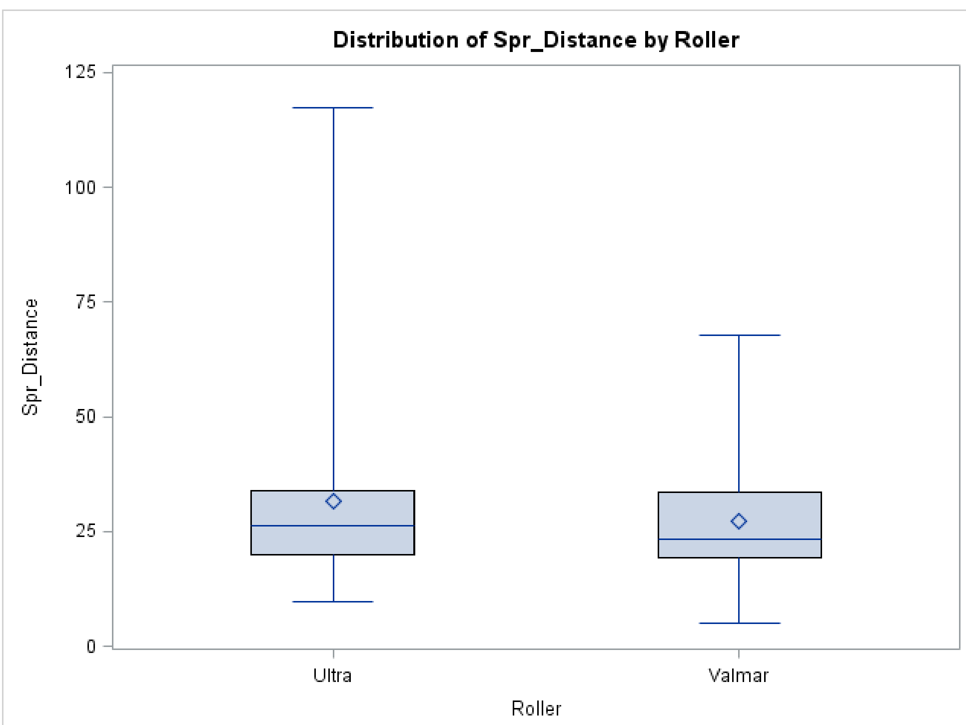

Figure 3. Boxplots representing mean and spread of distance between plants in spring seeded at 20 seeds m^{-2} with the UltraPro or Valmar rollers.

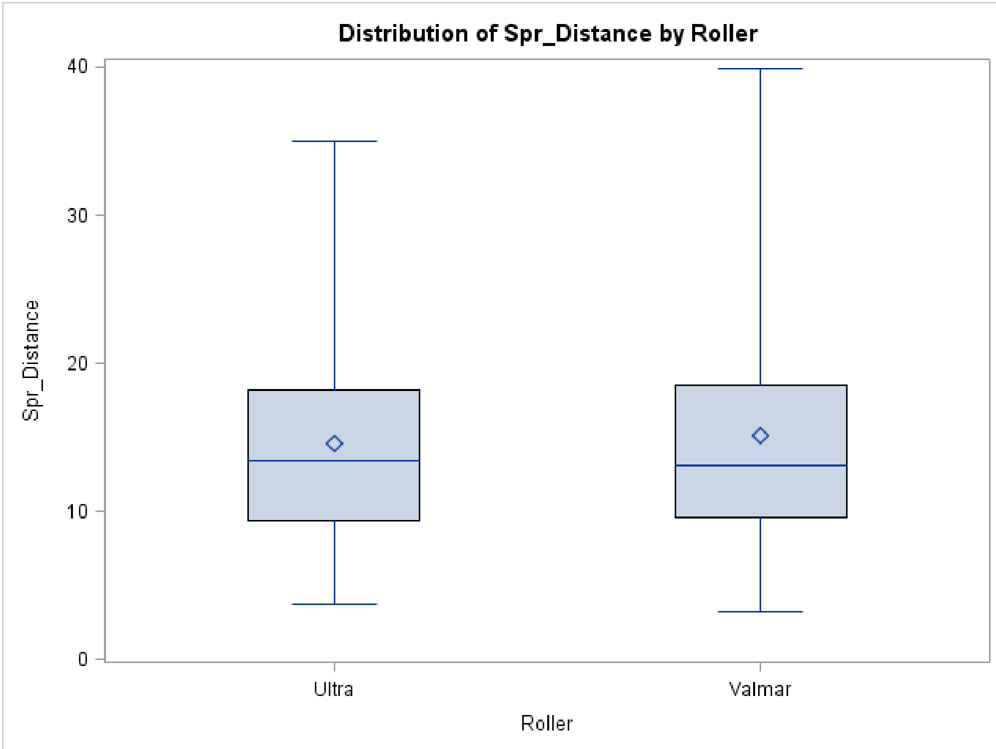

Figure 4. Boxplots representing mean and spread of distance between plants in spring seeded at 40 seeds m^{-2} with the UltraPro or Valmar rollers.

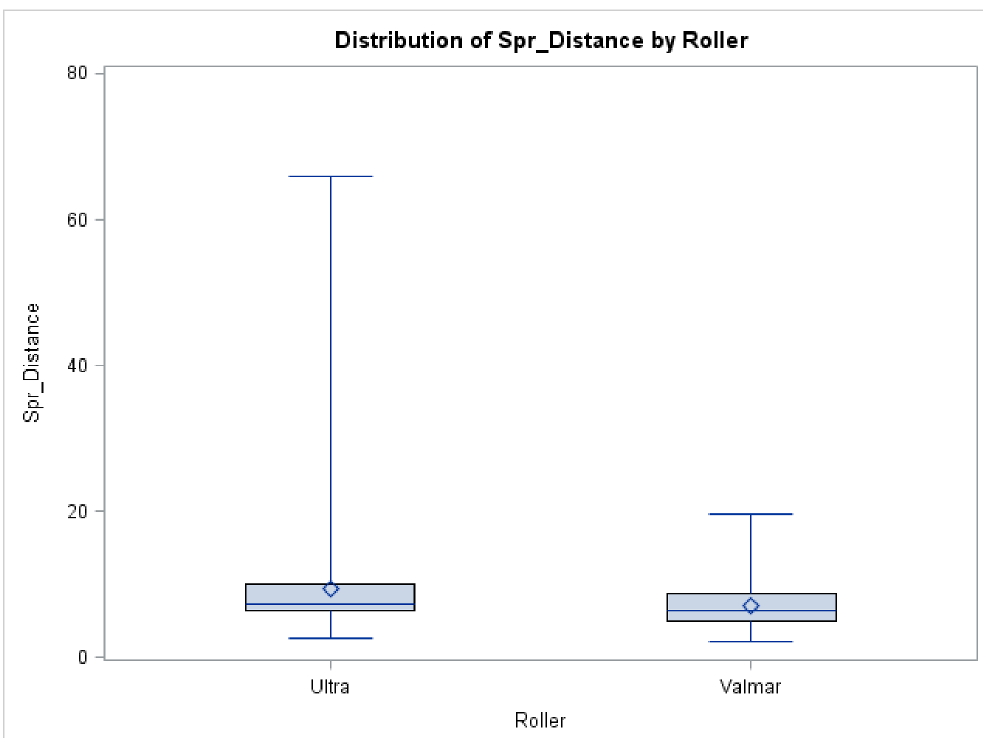

Figure 5. Boxplots representing mean and spread of distance between plants in spring seeded at 80 seeds m^{-2} with the UltraPro or Valmar rollers.

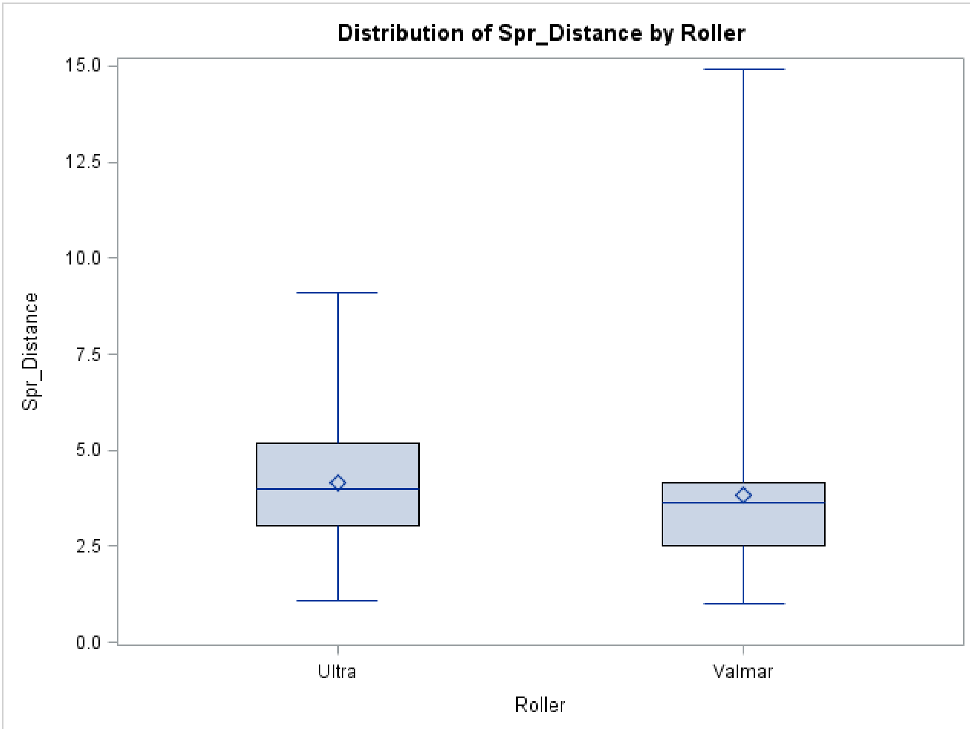

Figure 6. Boxplots representing mean and spread of distance between plants in spring seeded at 160 seeds m^{-2} with the UltraPro or Valmar rollers.

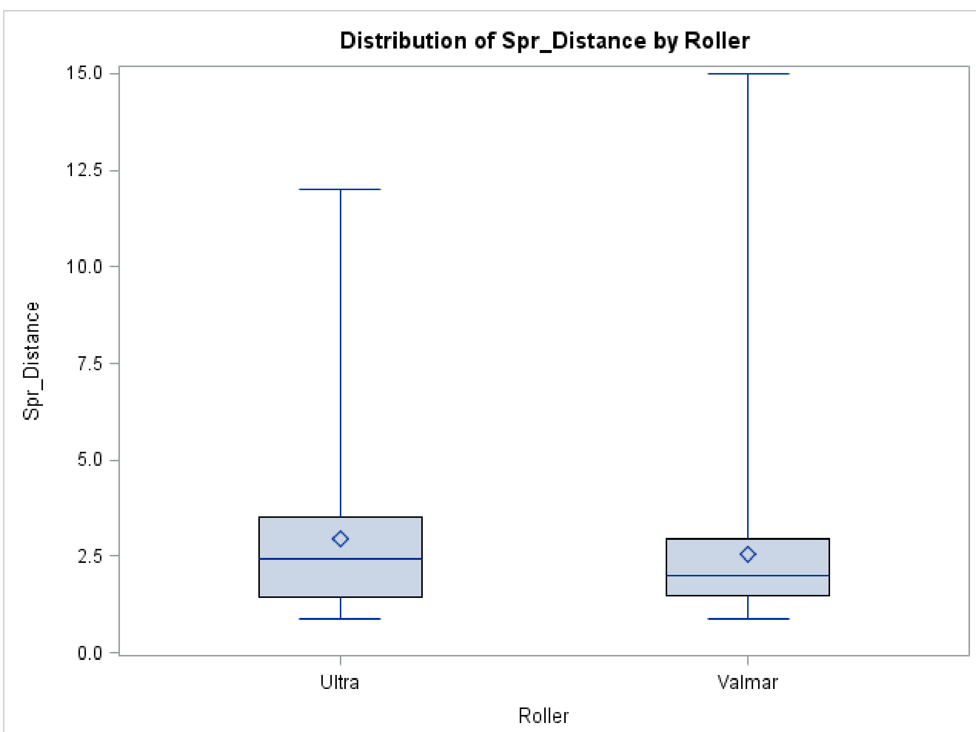

Figure 7. Boxplots representing mean and spread of distance between plants in spring seeded at 320 seeds m^{-2} with the UltraPro or Valmar rollers.

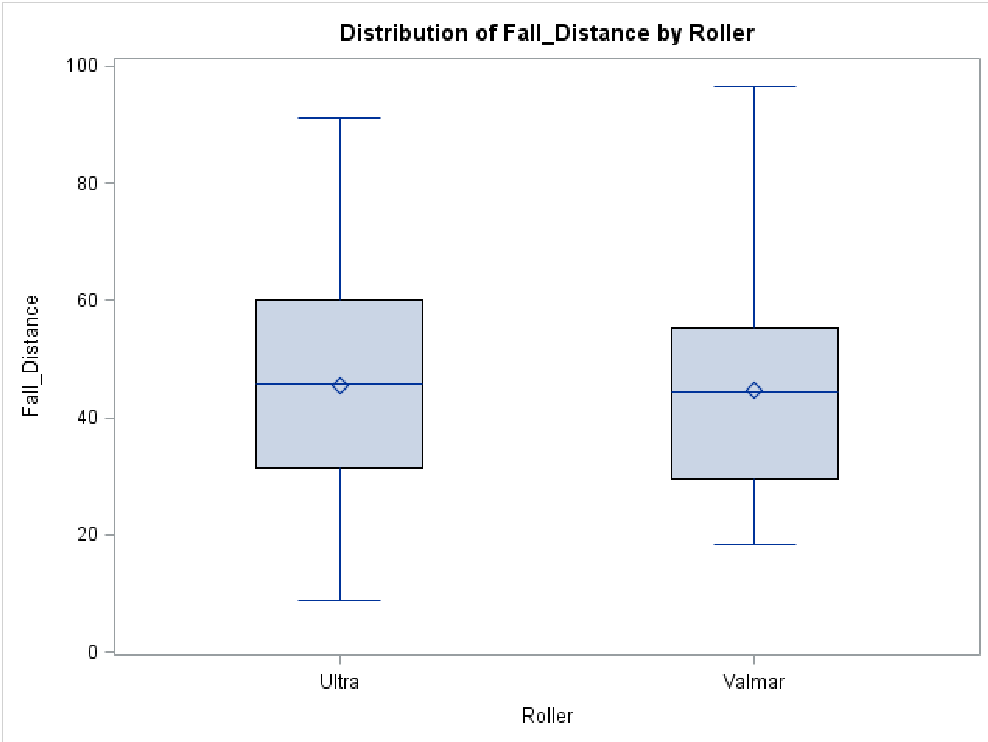

Figure 8. Boxplots representing mean and spread of distance between plants in fall seeded at 10 seeds m^{-2} with the UltraPro or Valmar rollers.

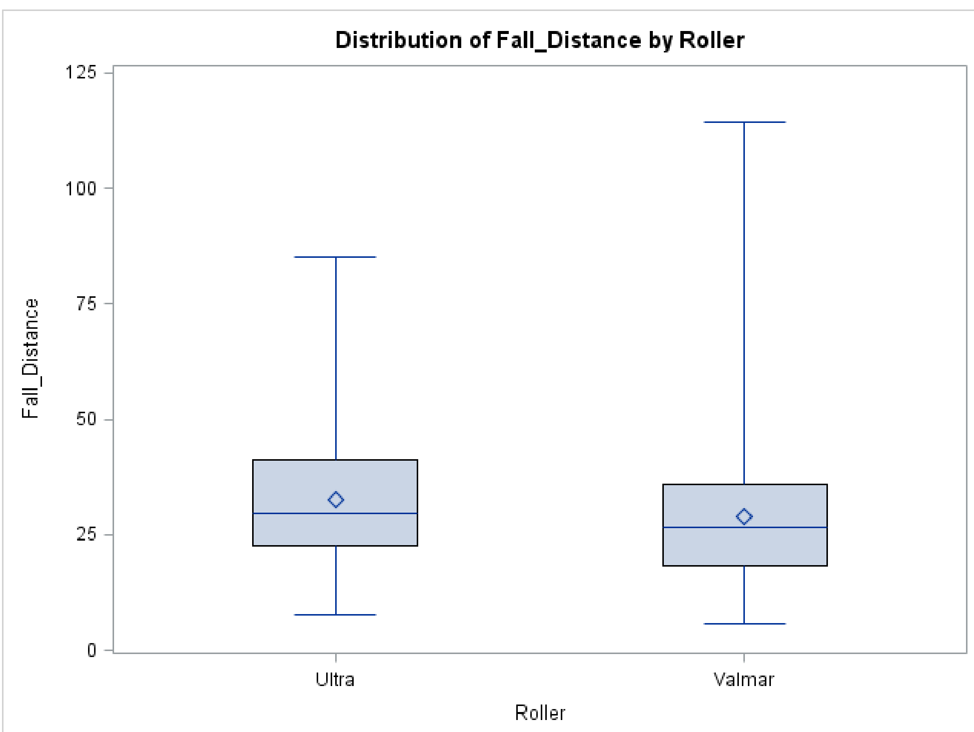

Figure 9. Boxplots representing mean and spread of distance between plants in fall seeded at 20 seeds m^{-2} with the UltraPro or Valmar rollers.

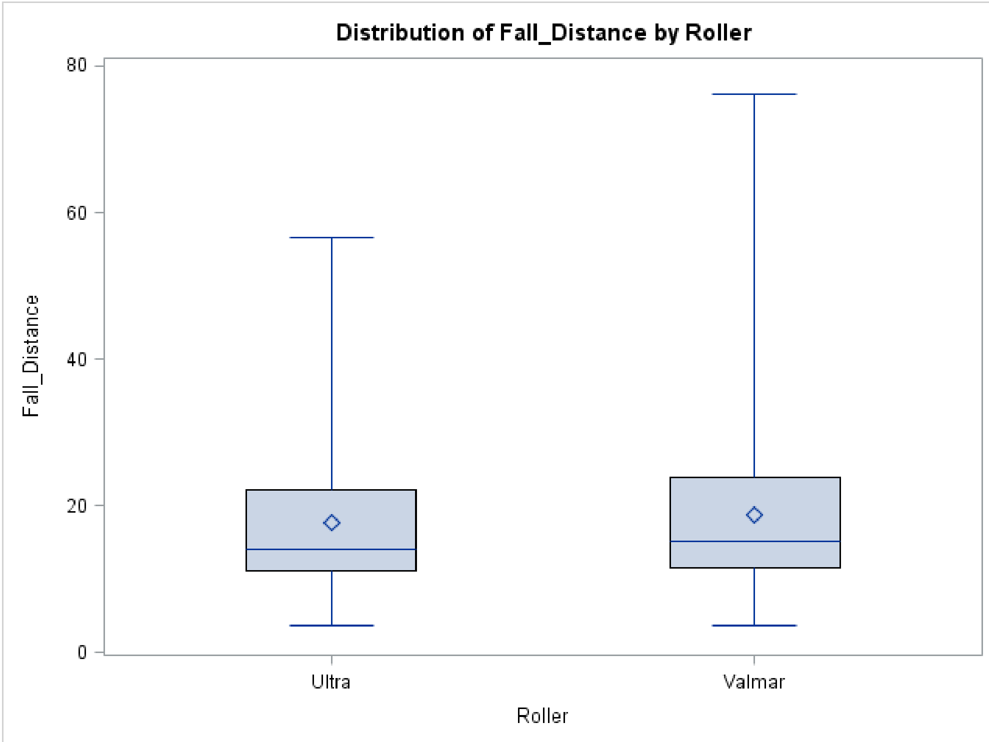

Figure 10. Boxplots representing mean and spread of distance between plants in fall seeded at 40 seeds m^{-2} with the UltraPro or Valmar rollers.

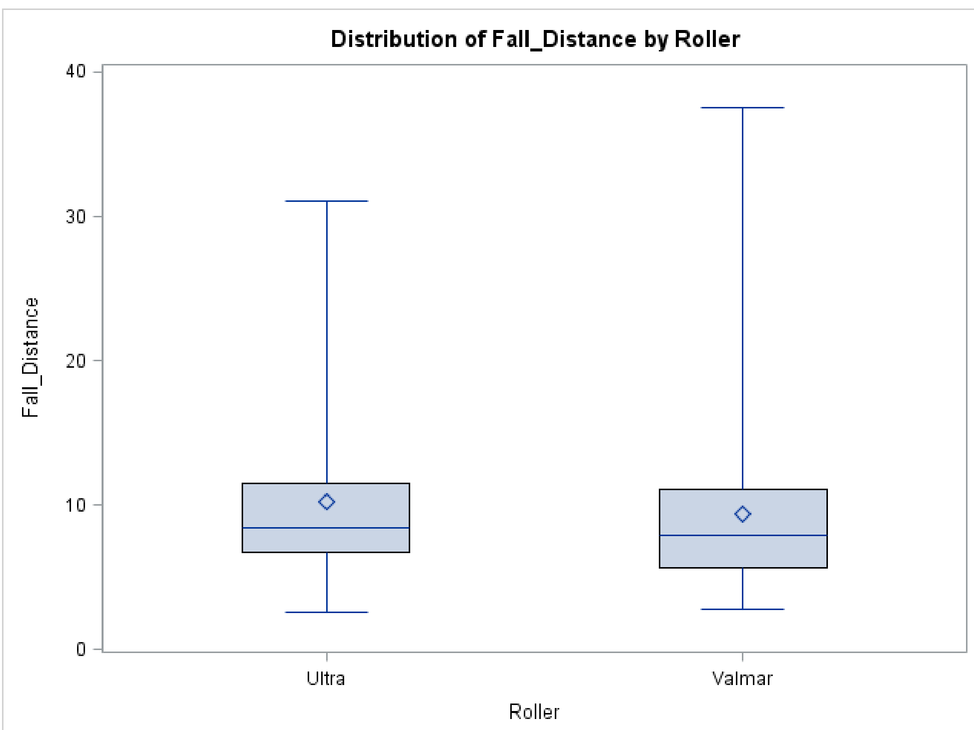

Figure 11. Boxplots representing mean and spread of distance between plants in fall seeded at 80 seeds m^{-2} with the UltraPro or Valmar rollers.

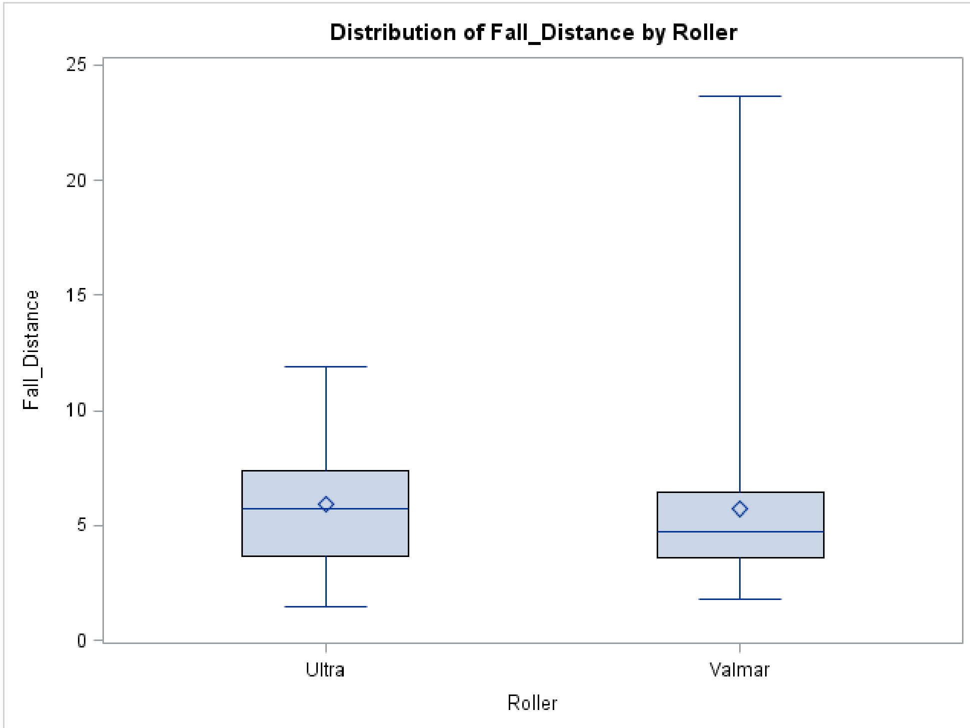

Figure 12. Boxplots representing mean and spread of distance between plants in fall seeded at 160 seeds m^{-2} with the UltraPro or Valmar rollers.

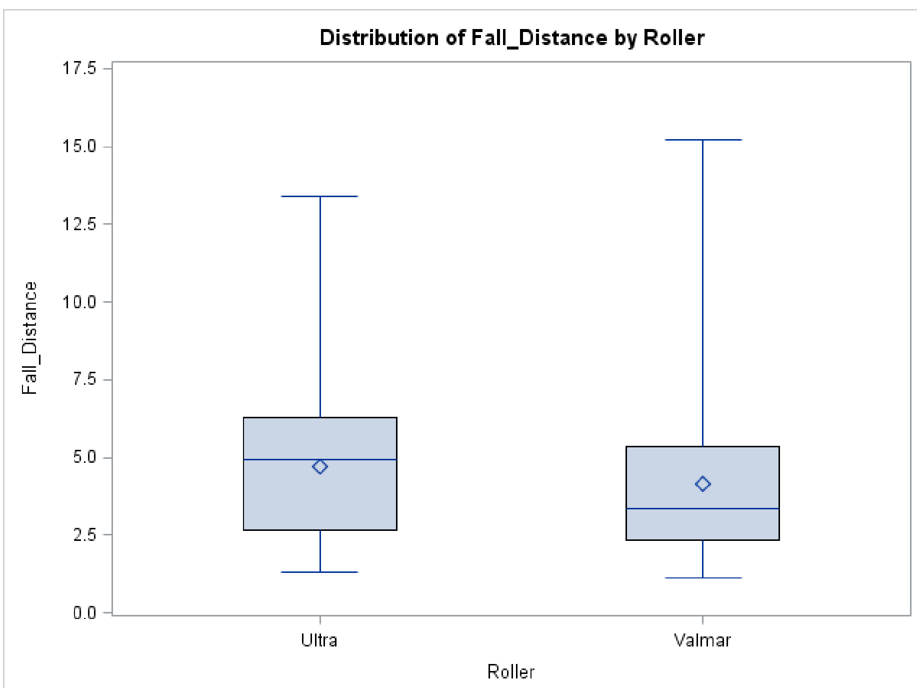

Figure 13. Boxplots representing mean and spread of distance between plants in fall seeded at 320 seeds m^{-2} with the UltraPro or Valmar rollers.

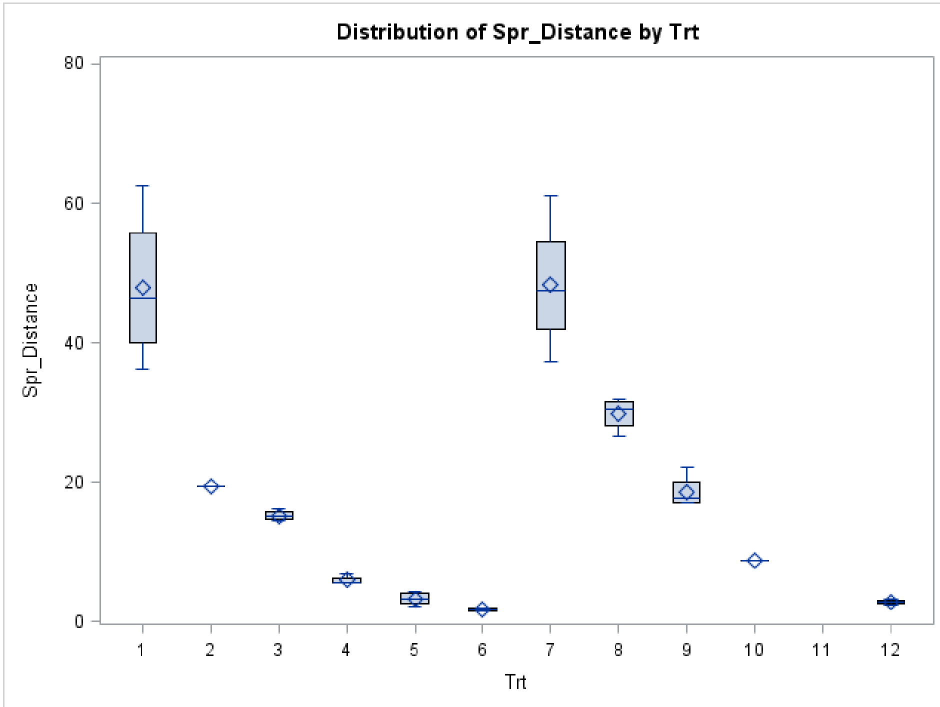

Figure 14. Boxplots representing mean and spread of distance between plants in spring at Scott in 2012

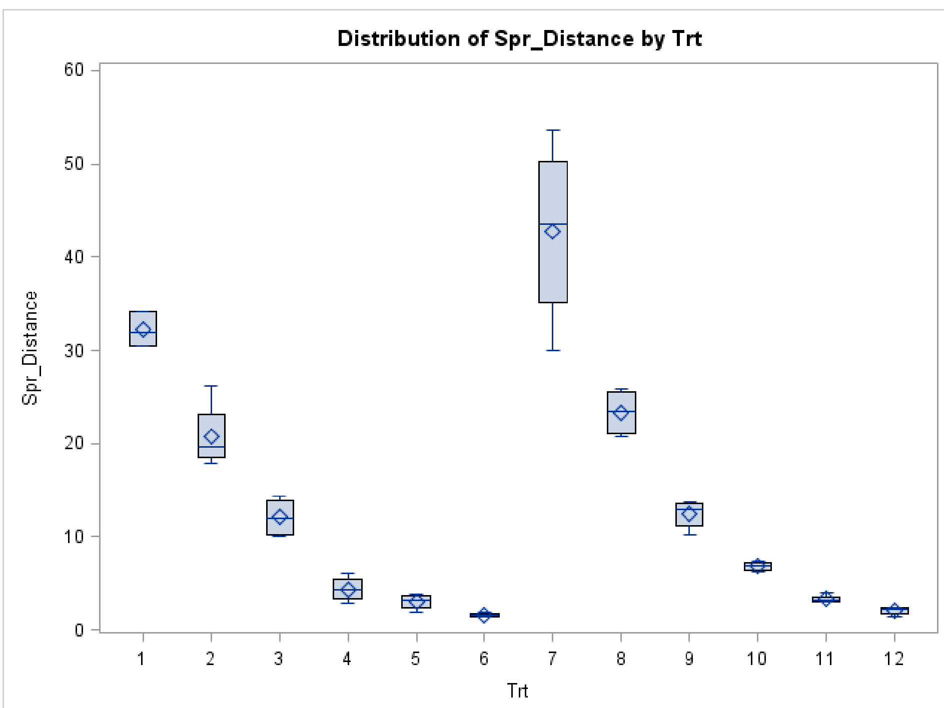

Figure 15. Boxplots representing mean and spread of distance between plants in spring at Redvers in 2012

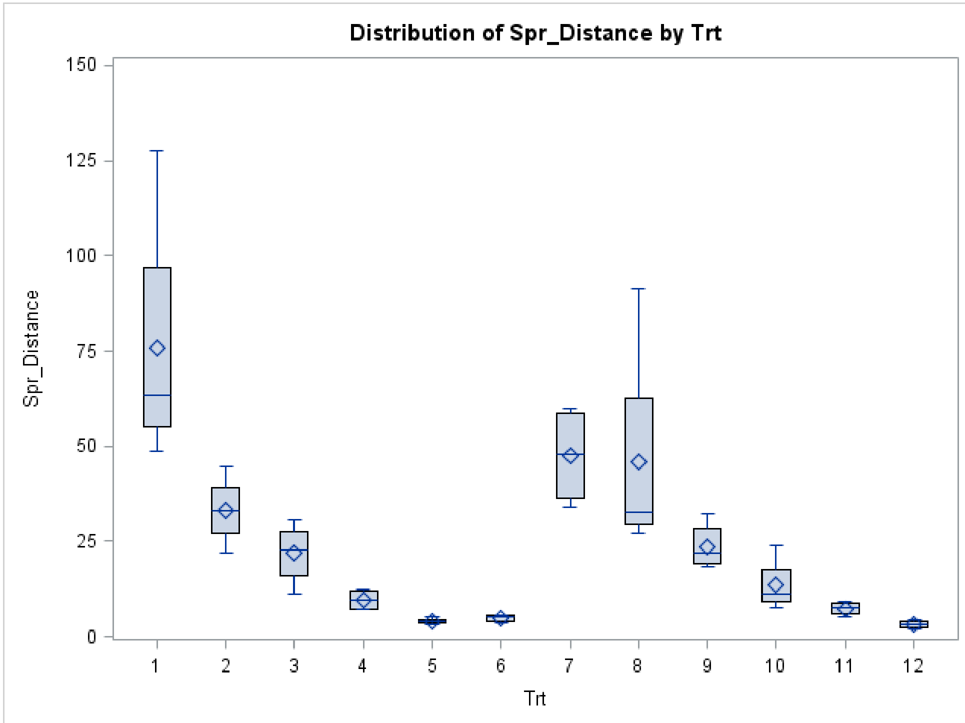

Figure 16. Boxplots representing mean and spread of distance between plants in spring at Melfort in 2012

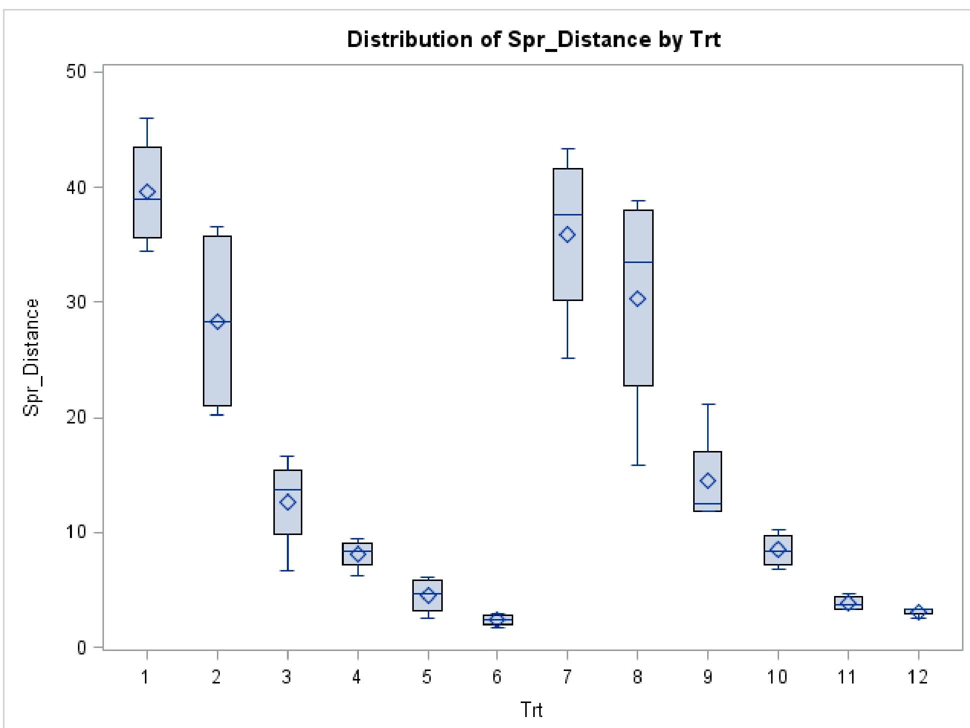

Figure 17. Boxplots representing mean and spread of distance between plants in spring at Indian Head in 2012

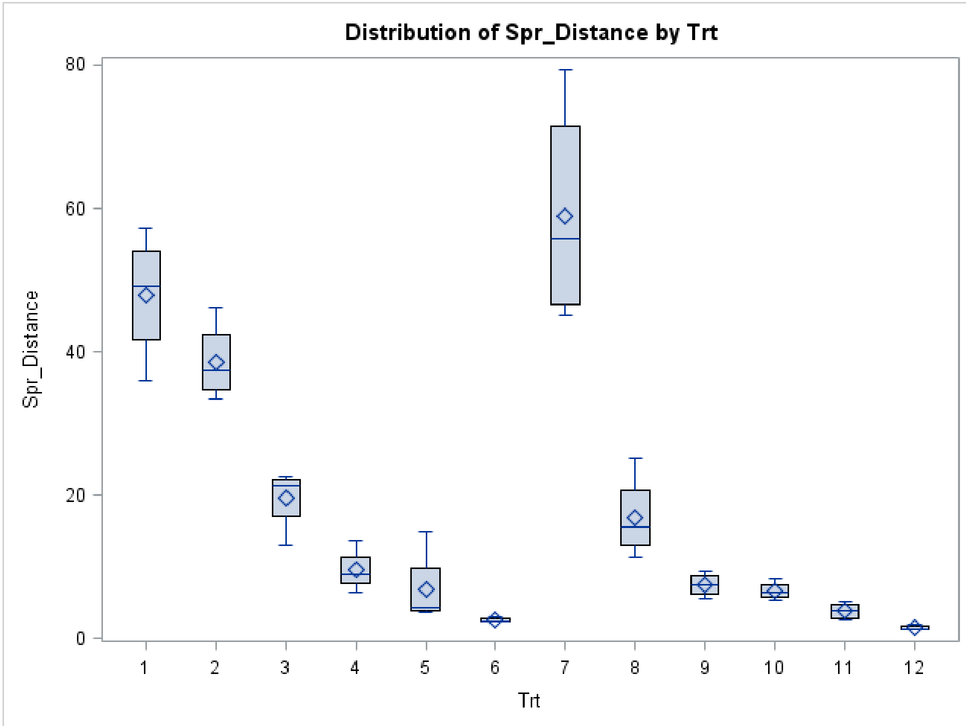

Figure 18. Boxplots representing mean and spread of distance between plants in spring at Scott in 2013

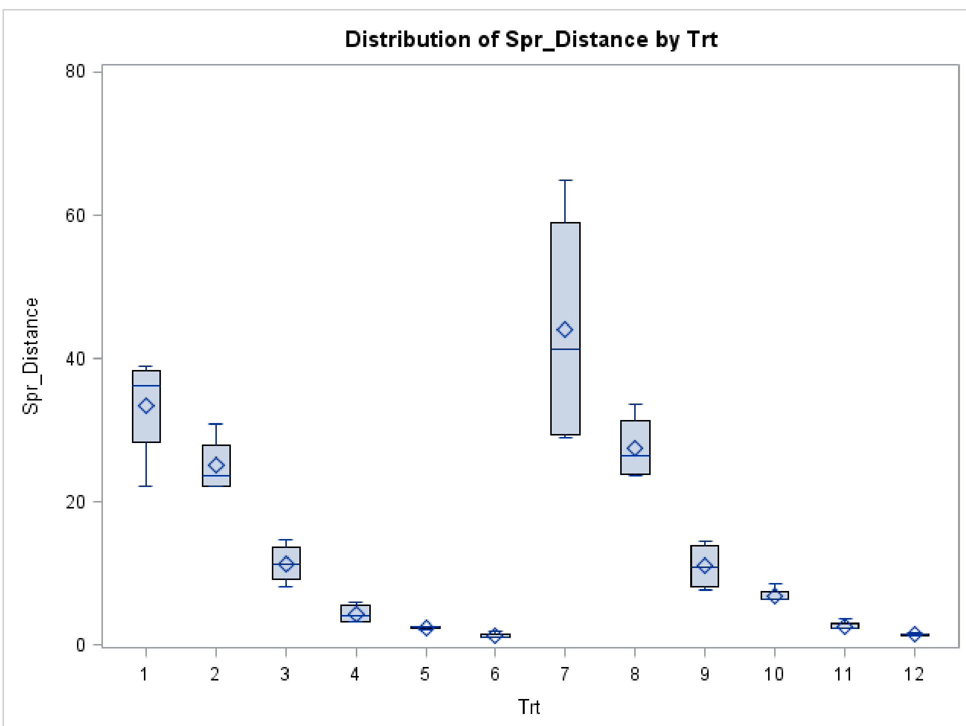

Figure 19. Boxplots representing mean and spread of distance between plants in spring at Redvers in 2013

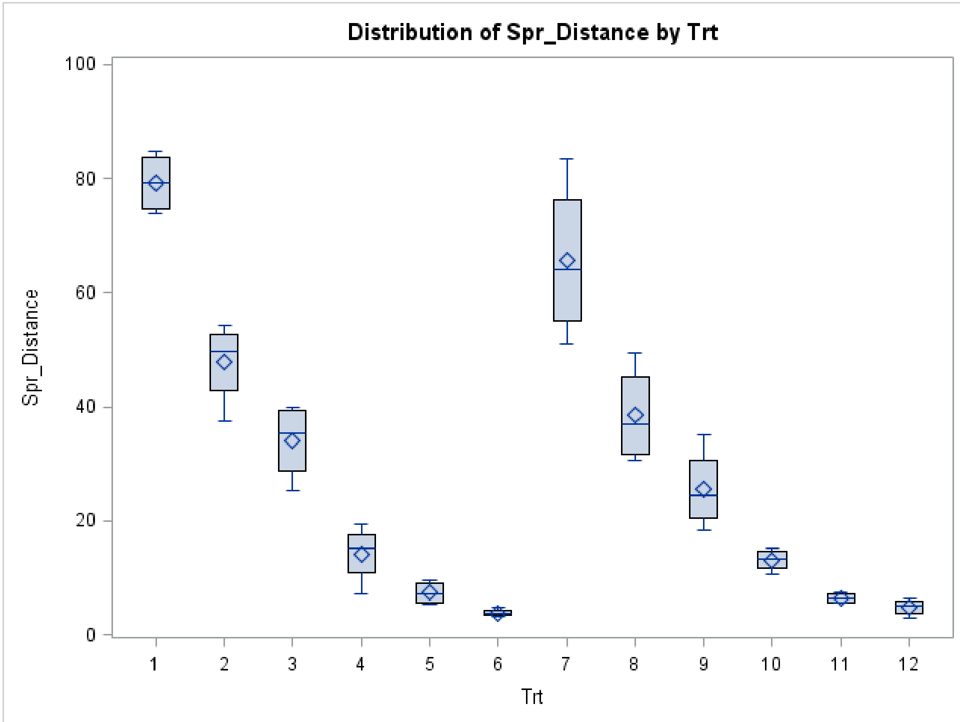

Figure 20. Boxplots representing mean and spread of distance between plants in spring at Melfort in 2013

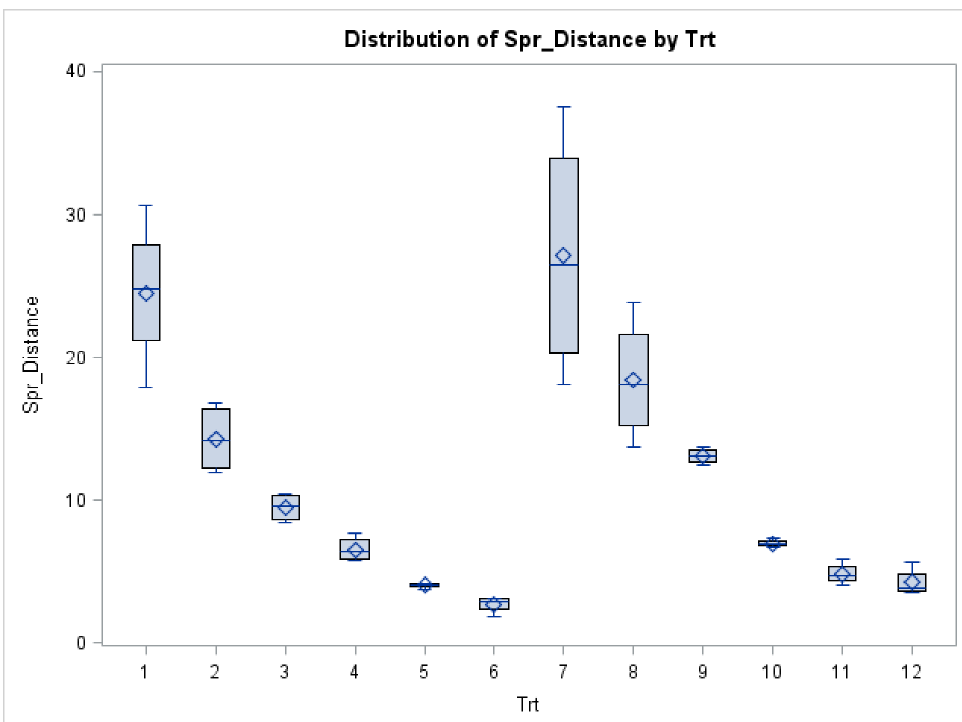

Figure 21. Boxplots representing mean and spread of distance between plants in spring at Indian Head in 2013

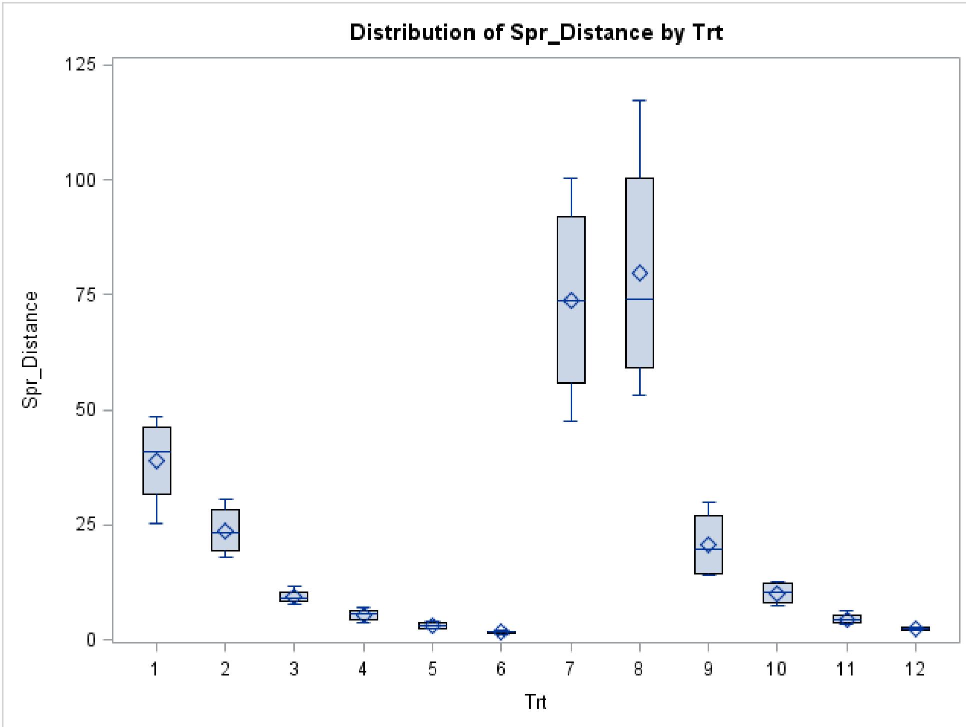

Figure 22. Boxplots representing mean and spread of distance between plants in spring at Scott in 2014

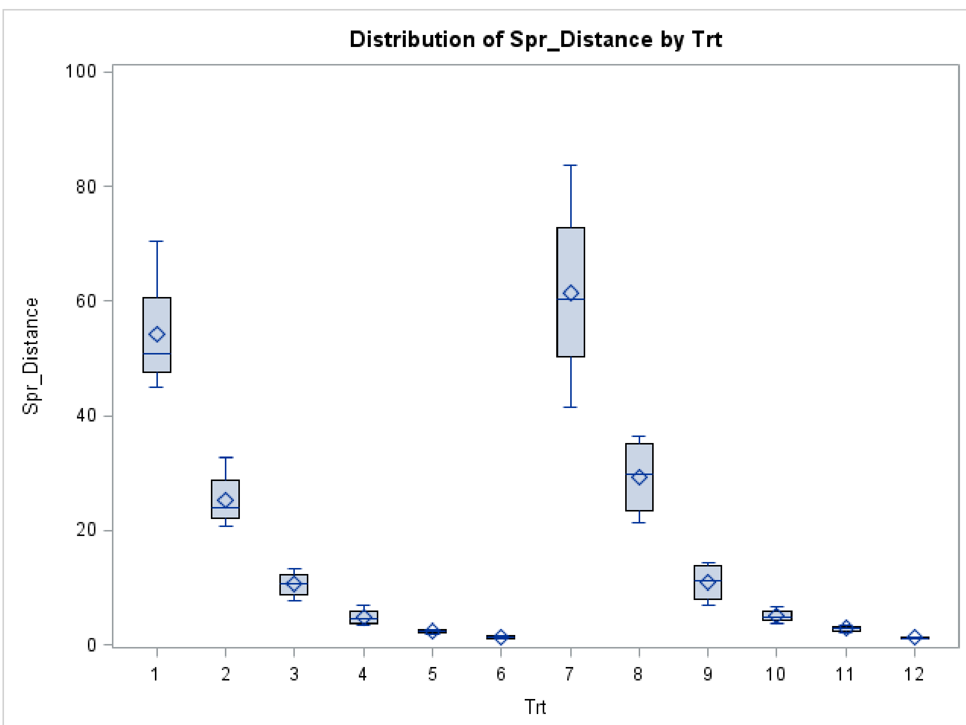

Figure 23. Boxplots representing mean and spread of distance between plants in spring at Redvers in 2014

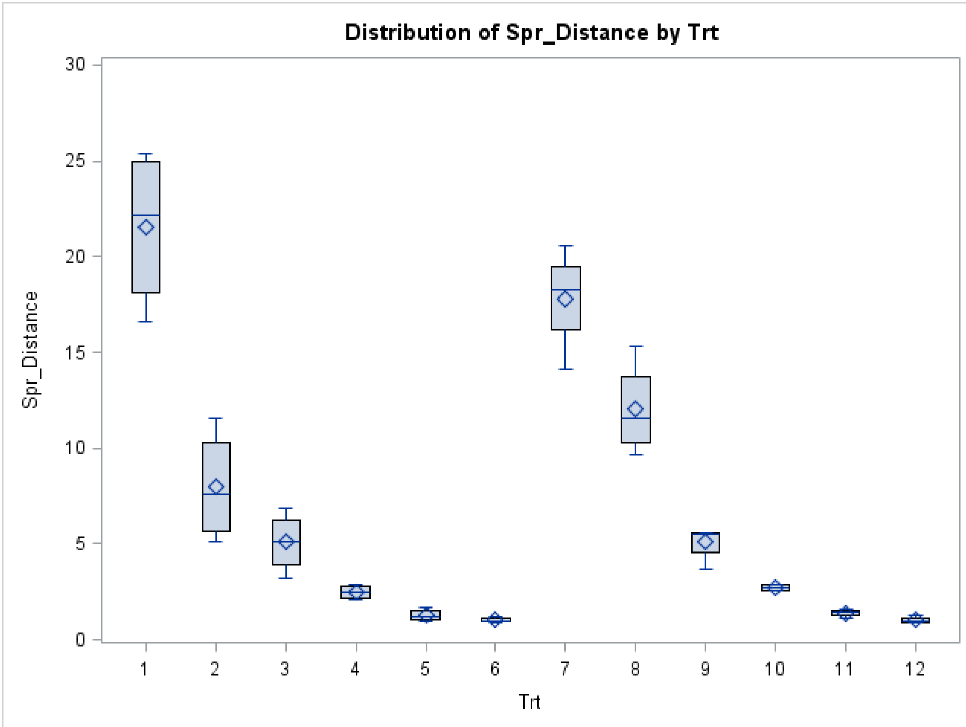

Figure 24. Boxplots representing mean and spread of distance between plants in spring at Melfort in 2014

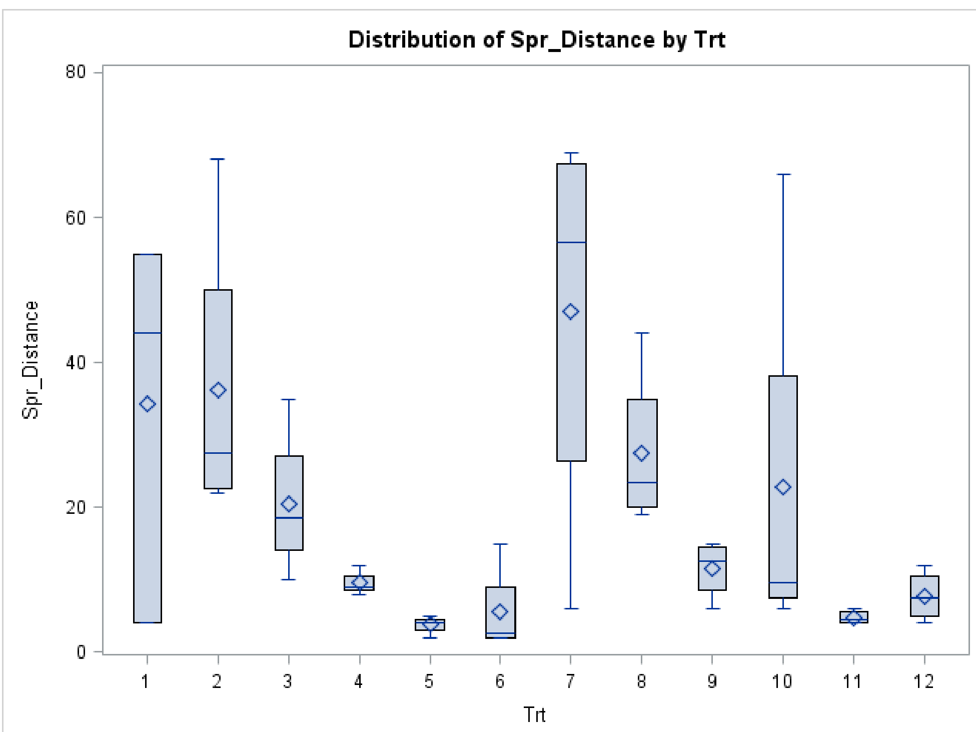

Figure 25. Boxplots representing mean and spread of distance between plants in spring at Indian Head in 2014

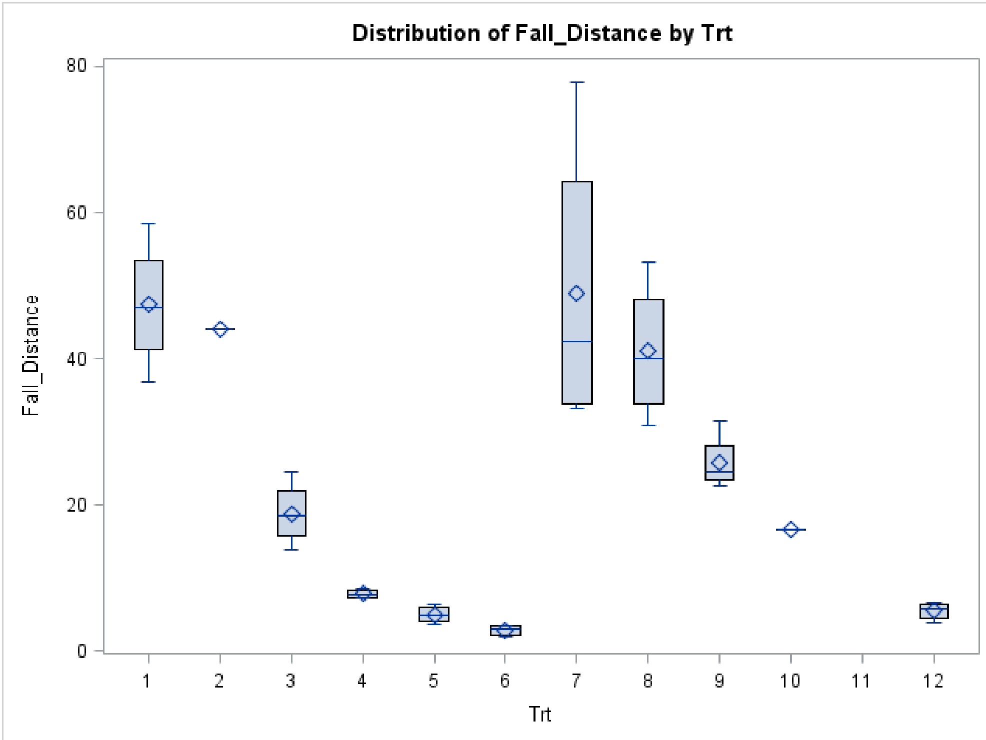

Figure 26. Boxplots representing mean and spread of distance between plants in fall at Scott in 2012

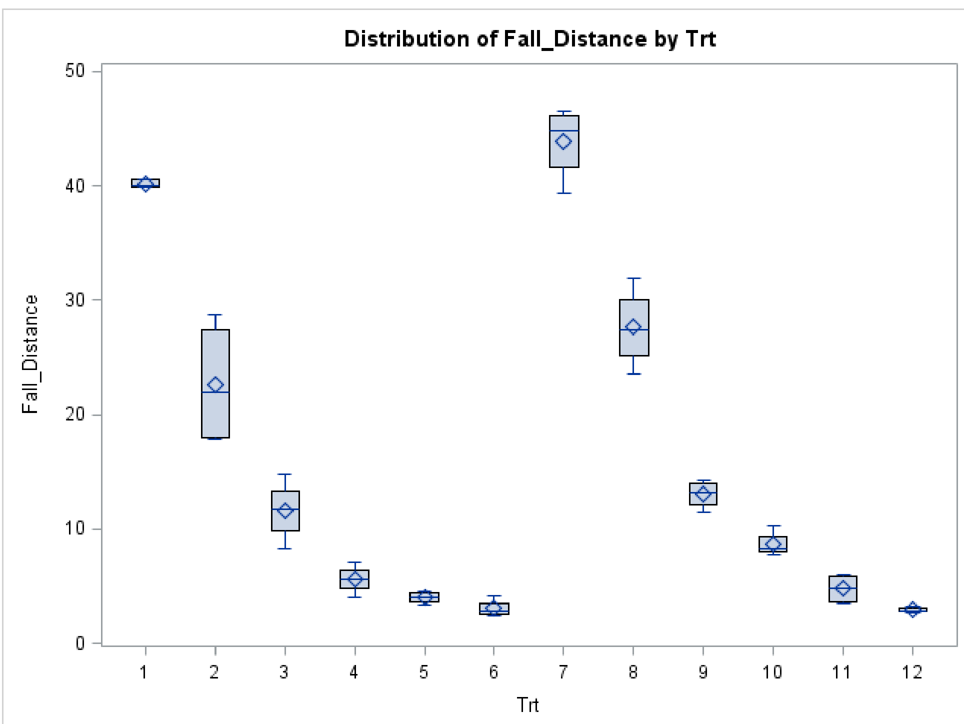

Figure 27. Boxplots representing mean and spread of distance between plants in fall at Redvers in 2012

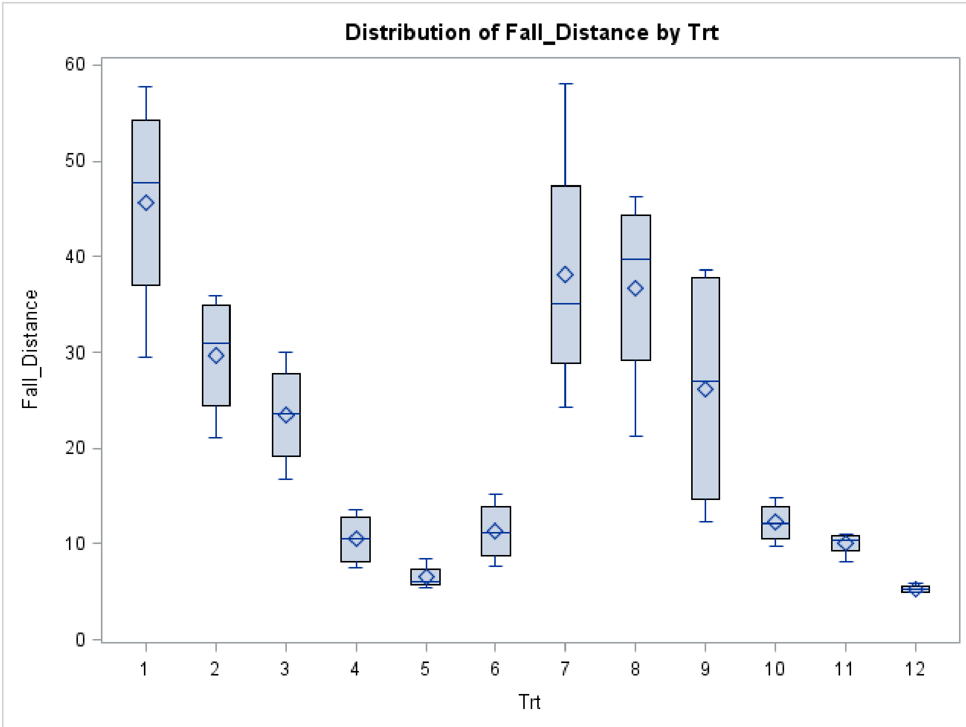

Figure 28. Boxplots representing mean and spread of distance between plants in fall at Melfort in 2012

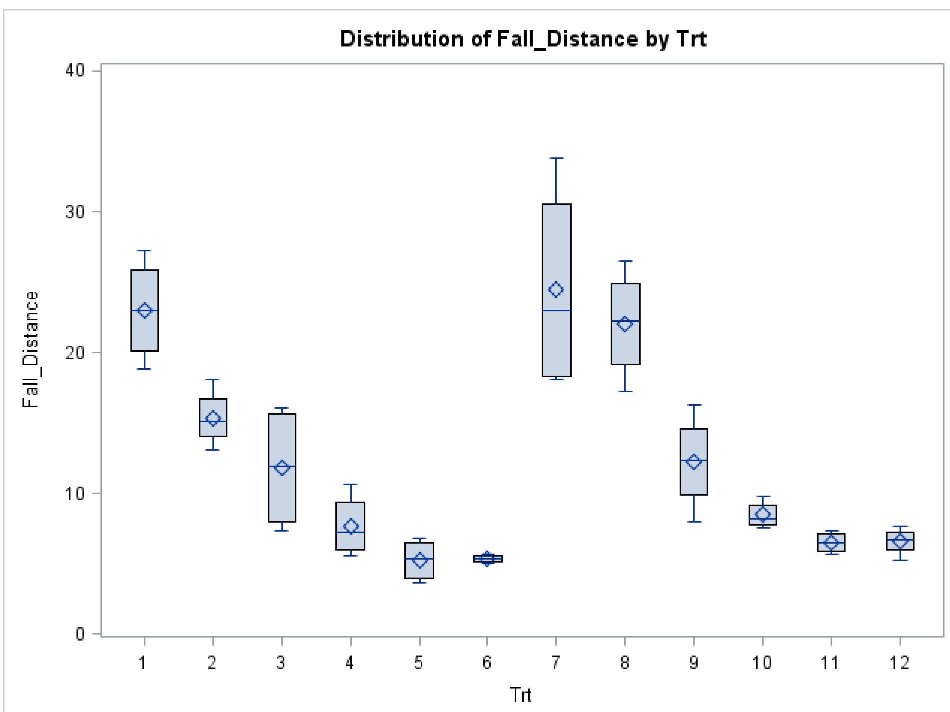

Figure 29. Boxplots representing mean and spread of distance between plants in fall at Indian Head in 2012

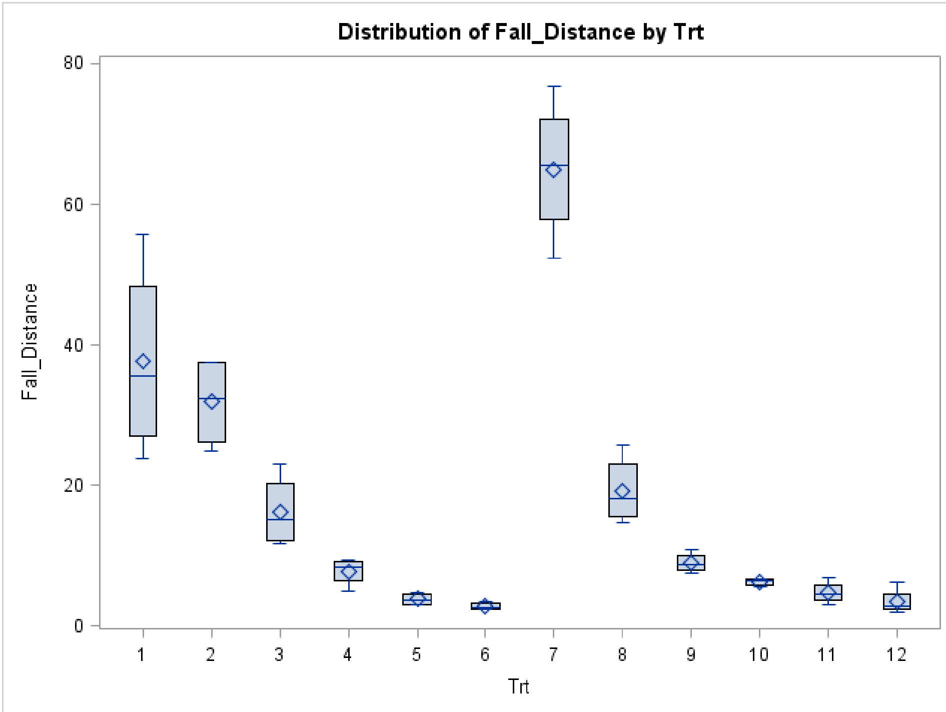

Figure 30. Boxplots representing mean and spread of distance between plants in fall at Scott in 2013

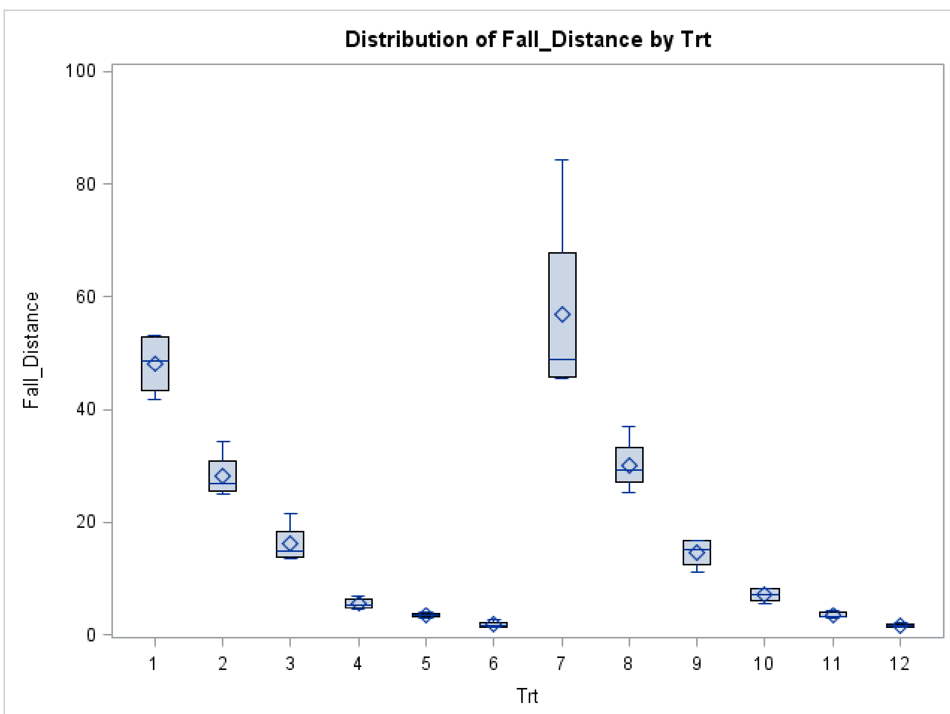

Figure 31. Boxplots representing mean and spread of distance between plants in fall at Redvers in 2013

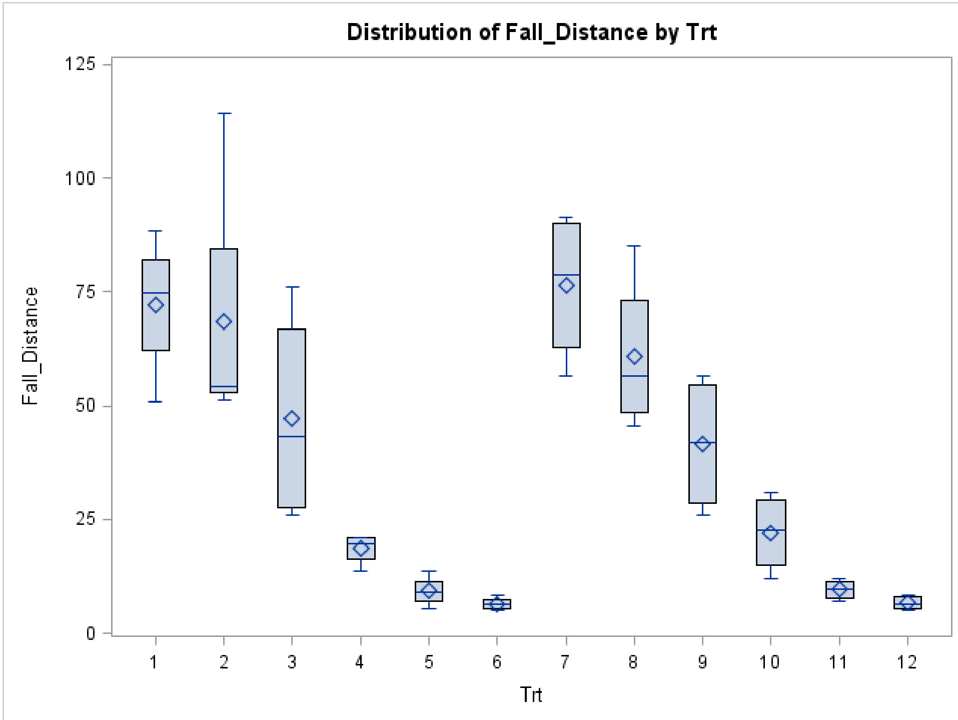

Figure 32. Boxplots representing mean and spread of distance between plants in fall at Melfort in 2013

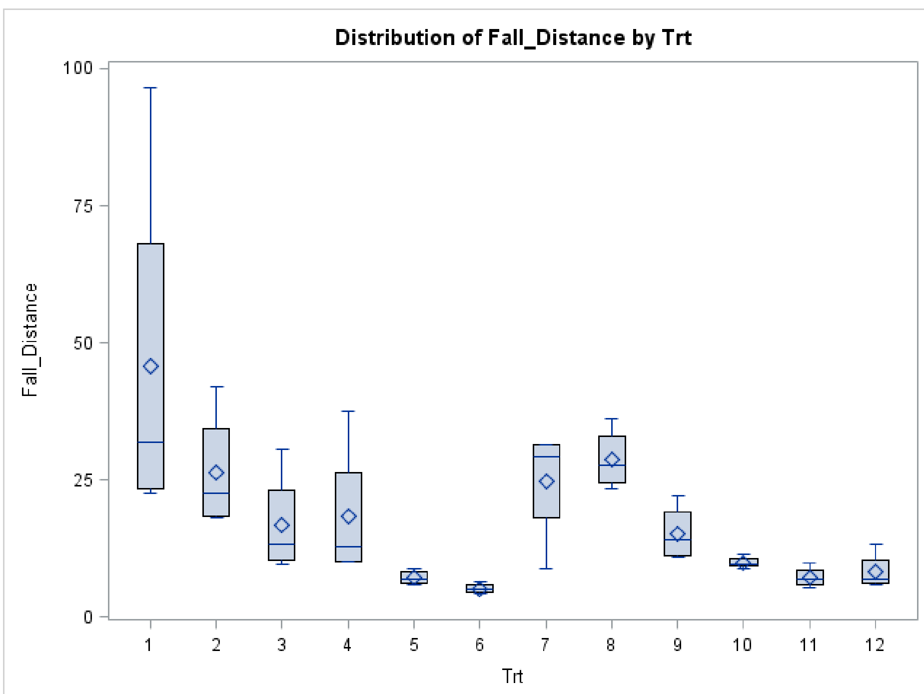

Figure 33. Boxplots representing mean and spread of distance between plants in fall at Indian Head in 2013

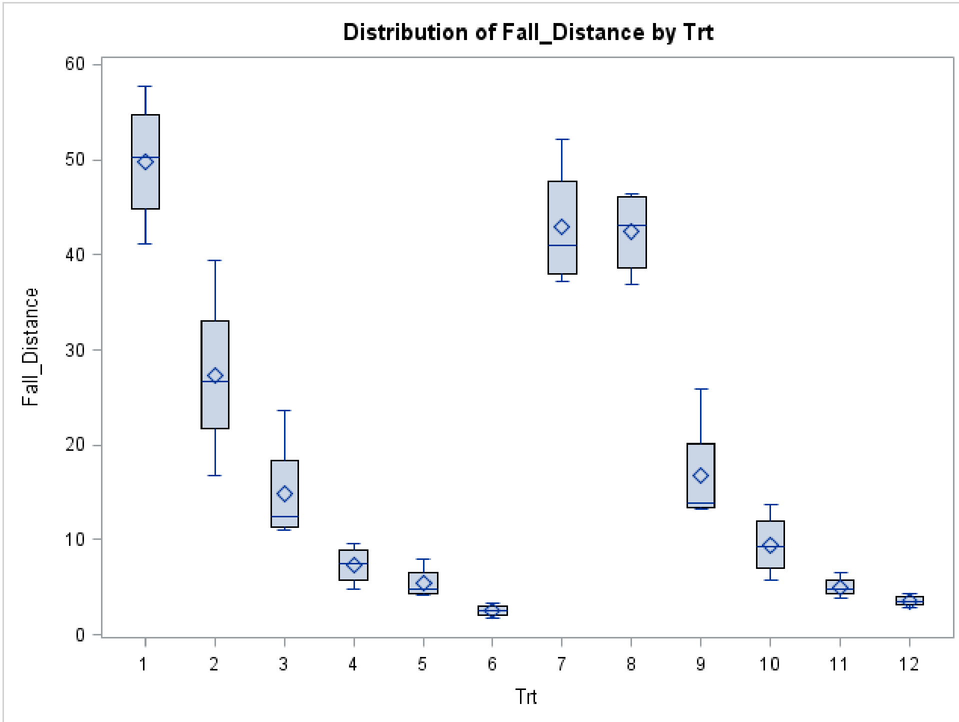

Figure 34. Boxplots representing mean and spread of distance between plants in fall at Scott in 2014

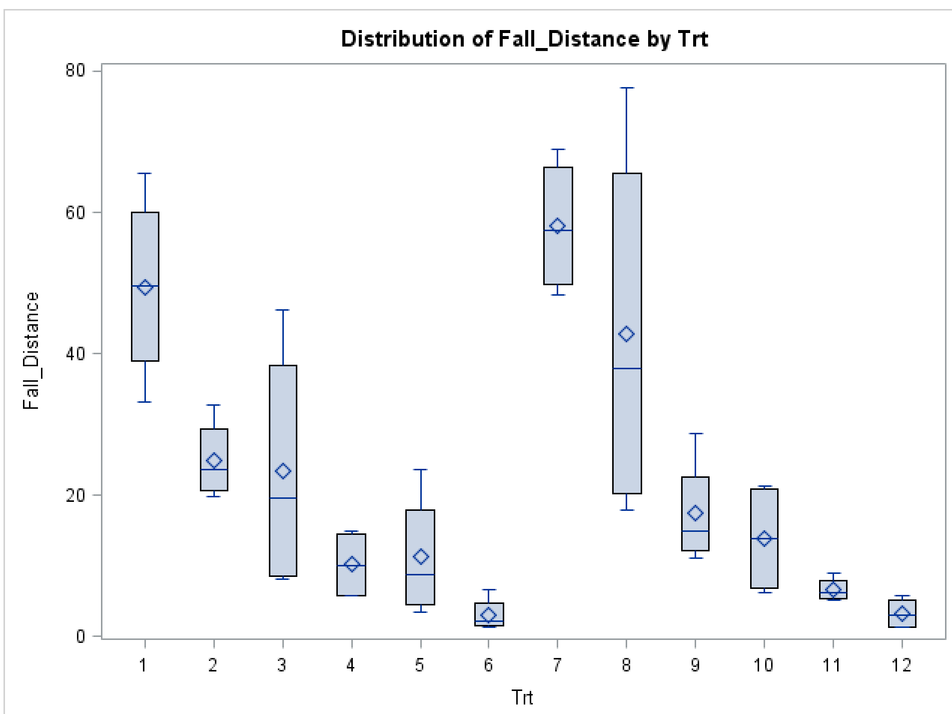

Figure 35. Boxplots representing mean and spread of distance between plants in fall at Redvers in 2014

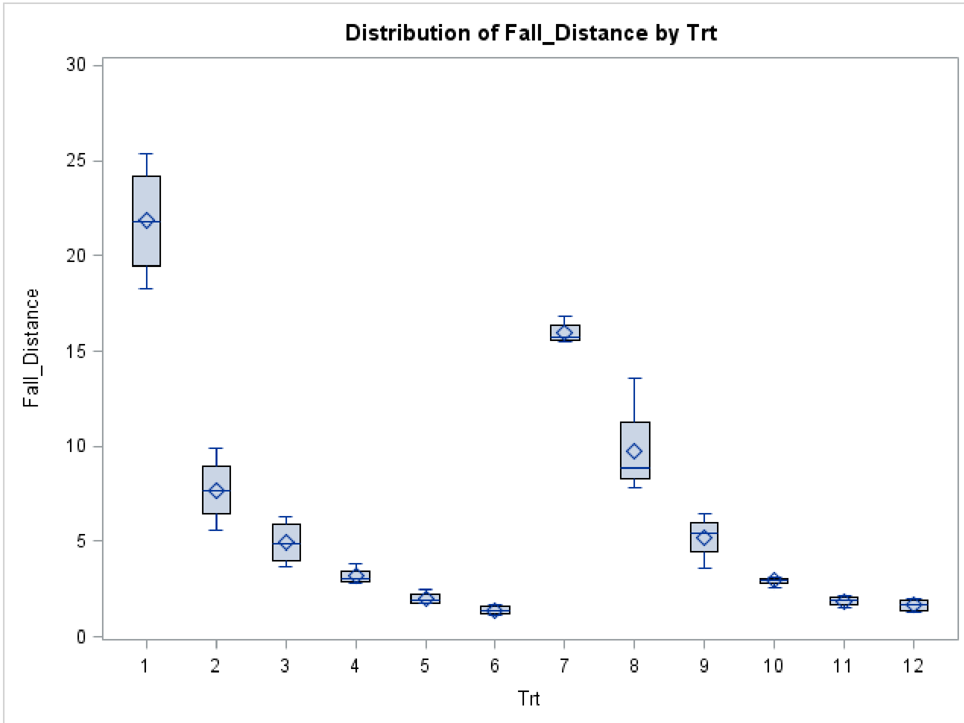

Figure 36. Boxplots representing mean and spread of distance between plants in fall at Melfort in 2014

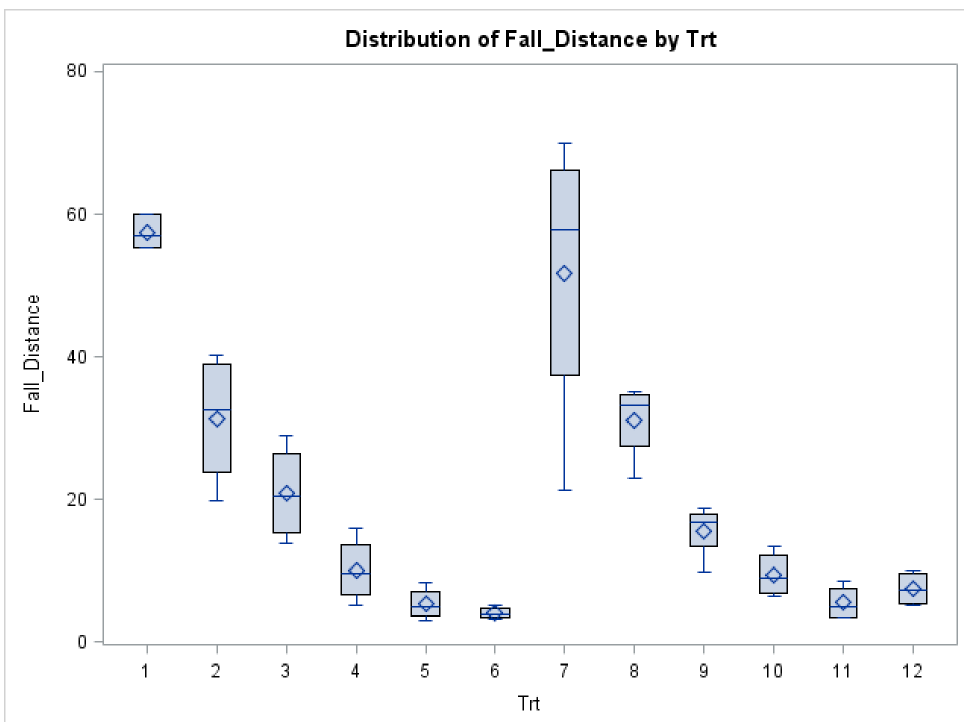

Figure 37. Boxplots representing mean and spread of distance between plants in fall at Indian Head in 2014