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A comparison of soybean maturity groups for phenology, seed yield, and seed quality components between eastern Ontario and southern Manitoba

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Abstract

The expansion of soybean [*Glycine max* (L.) Merr.] production onto the Canadian Prairies has resulted in new environmental constraints that affect soybean phenology, seed yield, and seed quality. This study examined these factors for 10 soybean cultivars differing in maturity group (MG) rating from 000.9 to 1.3 in southern Manitoba (MB) and eastern Ontario (ON). Detailed climate and phenological data collected at both locations were used to explore the environmental factors and differences in measurements among MG and between locations. In MB, more time was spent in vegetative growth and less time developing flowers and seeds than in ON. The longer vegetative growth stage in MB resulted in more leaves produced on the main stem at flowering than in ON. The leaf appearance rate was consistent between locations and the rate of phenological development in the vegetative stage was greater in ON because of its warmer mean temperature and shorter photoperiod. In MB, seed yield was positively correlated with precipitation in all growth stages and had a strong correlation with precipitation during reproductive development. In ON, increasingly warmer temperatures during reproductive development had the greatest influence on seed yield, particularly in the seed development stage. This study is a baseline for soybean phenology, seed yield, and seed quality components for early MG and will aid in the optimization of soybean breeding and production in the Canadian Prairies.

Key words: soybean, yield, grain quality, phenology

Résumé

L'expansion de la culture du soja [*Glycine max* (L.) Merr.] dans les Prairies canadiennes a engendré de nouvelles contraintes environnementales qui affectent la phénologie de la plante, son rendement grainier et la qualité des graines. Les auteurs ont examiné ces facteurs chez dix variétés de soja à précocité différente, réparties en groupes de maturité (GM) notés de 000,9 à 1,3, dans le sud du Manitoba (MB) et l'est de l'Ontario (ON). Les données détaillées sur le climat et la phénologie glanées aux deux endroits ont servi à préciser les paramètres environnementaux et la variation des résultats entre les GM et les sites. Au MB, le soja demeure plus longtemps au stade végétatif, la floraison et la montaison survenant plus vite qu'en ON. Le stade végétatif prolongé observé au MB entraîne la production d'un nombre de feuilles plus élevé qu'en ON pendant la floraison, le long de la tige principale. Les feuilles apparaissent à la même vitesse aux deux endroits, mais le développement phénologique au stade végétatif s'avère plus rapide en ON, car la température moyenne y est plus élevée et la photopériode, plus courte. Au MB, le rendement grainier présente une corrélation positive avec les précipitations, peu importe le stade de croissance, et est étroitement lié à leur importance durant le développement des caractères reproducteurs. En ON, ce sont les températures de plus en plus chaudes lors du développement de ces caractères qui influent le plus sur le rendement grainier, surtout au stade du développement de la graine. Cette étude servira de point de départ aux recherches sur la phénologie du soja, son rendement grainier et les qualités de la graine chez les variétés plus précoces et concourra à optimiser l'hybridation ains que la culture du soja dans les Prairies canadiennes. [Traduit par la Rédaction]

Mots-clés : soja, rendement, qualité du grain, phénologie

Introduction

Soybean [*Glycine max* (L.) Merr.] seeded area has increased from 232700 to 465200 ha in Manitoba (MB) over the past decade, peaking at 926700 ha in 2017 (Statistics Canada 2020). This has been made possible by the commercialization of short-season cultivars that can reach maturity prior to a fall frost event. In MB, the frost-free period ranges from 65 to 135 days (Manitoba Agriculture 2019). This represents a distinctly shorter growing season compared with well-established soybean growing regions in Canada, such as Ontario (ON), where the frost-free period ranges from 90 to 190 days (Roddy 2013).

The environmental conditions that influence soybean phenology, seed yield, and seed quality components include air temperature (T), precipitation or soil moisture availability, soil fertility, and photoperiod (P) (Major et al. 1983; Purcell et al. 2014). Vegetative growth is most influenced by T and soil moisture (Tenorio et al. 2017), while physiological development during vegetative growth, such as floral induction, is further controlled by P (Garner and Allard 1920). The vegetative growth rate increases with T until a maximum threshold is reached, approximately 30 °C, and declines thereafter (Egli and Wardlaw 1980; Piper et al. 1996). Drought conditions can shorten the vegetative period (Hanway and Thompson 1967), while excess precipitation can increase the duration of growth stages (Sallam and Scott 1987). Optimal T for reproductive development is lower than that for vegetative growth (Hesketh et al. 1973; Grimm et al. 1994), and soybean is most sensitive to water stress during reproductive development (Morrison et al. 2006).

Soybean is classified as a "short-day" plant requiring long nights to stimulate flowering (Garner and Allard 1920). Days longer than a critical P extend the duration of vegetative growth and delay beginning bloom (R1) (Thomas and Raper 1983; Setiyono et al. 2007). Soybean begins to measure P as early as the unifoliate stage (Borthwick and Parker 1938; Thomas and Raper 1976) and has been reported to respond to P during reproductive development (Sinclair 1993), albeit to a lesser degree than when it is in vegetative growth progressing to R1 (Hodges and Doraiswamy 1979). Sensitivity to P in soybean varies among cultivars and maturity group (MG) and a general trend is that later MG is more sensitive to P than earlier MG (Purcell et al. 2014; Salmerón and Purcell 2016).

Relationships between growing season environmental conditions and the concentrations of seed protein and oil are inconsistent and further investigations in northern environments are warranted (Morrison et al. 2006; Rotundo and Westgate 2009; MacMillan and Gulden 2020), but what has been well agreed upon is that the environment during reproductive development has the greatest impact on seed quality components. In some studies, greater T during reproductive development increased protein and oil concentrations (Vollmann et al. 2000; Song et al. 2016), while in others similar environmental conditions were found to reduce the concentration of seed protein but not oil (Mourtzinis et al. 2017).

The MG system is used to classify a soybean cultivar based on the duration of time from planting (PL) to harvest maturity (R8) and is assigned by a cultivar's respective developer. An MG can range from 10, which are grown in South America and in the southern United States, to 000, which are most commonly produced in more northern environments such as MB and ON (Zhang et al. 2007). A cultivar assigned an MG greater in value can be expected to require more time to reach R8 than a cultivar assigned an MG lesser in value. The MG system is often further subdivided by a decimal grouping that describes time to R8 within an MG using the same scale (Zhang et al. 2007).

The expansion of soybean production onto the Canadian Prairies has resulted in new environmental constraints that affect soybean phenology, seed yield, and seed quality components. The objective of this study was to examine these three areas in 10 soybean cultivars differing in MG rating in southern MB and eastern ON. This research was done in partial fulfillment of an MSc thesis (Ort 2020). Detailed climate and phenological data were collected at both locations and were used to explore the relationships between T, precipitation, time, and seed yield and seed quality components. The findings from this study will aid in the expansion and optimization of soybean production for the northern edge of the North American soybean producing region and serve as a starting point for future soybean studies in this new environment.

Materials and methods

The two locations examined in this study were eastern ON, representing a well-established soybean production region in Canada, and southern MB, a relatively new location for soybean production. Field experiments in MB were planted at the Agriculture and Agri-Food Canada (AAFC) Research and Development Centre in Morden (latitude 49.18, longitude −98.08) in 2008, 2009, and 2010 (MB08, MB09, and MB10, respectively) and at the Ian N. Morrison Research Station, University of Manitoba, in Carman (49.50, −98.03) in 2017 and 2018 (MB17 and MB18, respectively). Field experiments in ON were located at the AAFC Ottawa Research and Development Centre in Ottawa, ON (45.39, −75.72) in 2008, 2009, 2010, 2017, and 2018 (ON08, ON09, ON10, ON17, and ON18, respectively). The 5 years in both MB and ON are hereafter referred to as "all site-years". Soils in Morden were fine loamy clays of the Eigenhof series (Orthic Black Chernozems). In Carman, the soils were loams of the Eigenhof series (Orthic Black Chernozems). Soils in Ottawa were sandy loams of the Matilda series (Melanic Brunisols).

Latitude differences between MB (Morden: 49.18°N; Carman: 49.50°N) and ON (Ottawa: 45.39°N) resulted in different P on the same calendar date (Fig. 1). Weather data were recorded daily at a weather station within 0.5 km of each field site managed by Environment and Climate Change Canada—Meteorological Service of Canada at all locations. The 1981–2010 climate normal data were obtained from Environment Canada (2020). Daily P data were determined by a sunrise/sunset calculator (National Research Council Canada 2020). Civil twilight defined as the duration of time from when the center of the sun is 6° below the horizon to sunrise, and from sunset until the center of the sun is 6° below the horizon, was included in daily P calculations.

The field experiments were designed as a randomized complete block design with four replications. The treatments were 10 soybean cultivars from the same source selected to represent relative soybean MG grown in MB and ON (Table 1). Crop and agronomic management were based on the recommended practices for the location. Plots were seeded using a plot seeder and planting dates between MB and ON were coordinated to be as close together as possible (Table 2).

Fig. 1. Daily photoperiod (h) including civil twilight, in Carman, MB (49.50°N), Morden, MB (49.18°N), and Ottawa, ON (45.39°N), during a common year (National Research Council Canada 2020).

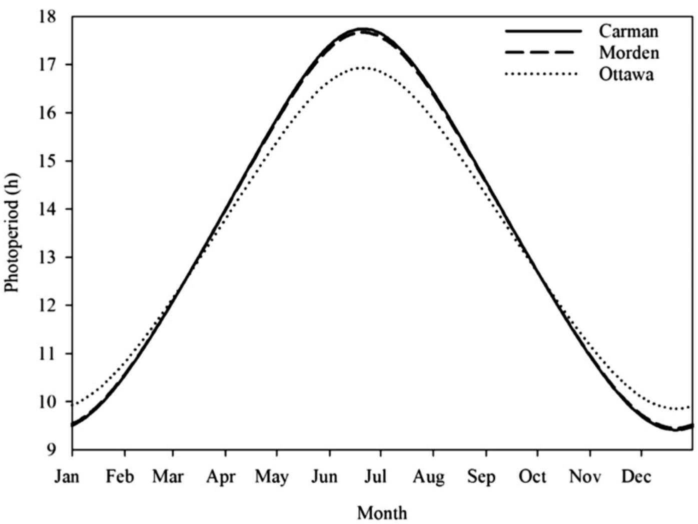

Table 1. Soybean cultivars grown in field experiment with respective assigned MG rating.

Cultivar	MG*
Maple Presto	000.9
90 A01	00.0
Maple Ridge	00.3
Alta	00.4
Montcalm	00.7
Roland	0.0
Rodeo	0.3
9063	0.5
Dundas	0.8
CeryxRR	1.3

*MGs greater in numerical value have been rated as later in maturity than MGs lesser in numerical value.

Table 2. Planting dates for 2008, 2009, 2010, 2017, and 2018 field experiments in MB and ON.

	Location	
Year	MB	ON
2008	23 May	30 May
2009	21 May	26 May
2010	17 May	20 May
2017	24 May	2 June
2018	23 May	30 May

The greatest difference between planting dates was 9 days in 2017 with the MB location seeded first. Target plant densities were achieved by adjusting the planting rate for individual cultivar germination percentage and 20% mortality. Seeds were planted approximately 2.5 cm below the soil surface at 550000 seeds ha^{-1} at MB sites and in ON seeds were planted approximately 2.5 cm deep at 500000 seeds ha^{-1}.

In both MB and ON, seeds were treated with Vitaflo 280 (carbathiin + thiram at 0.83 g a.i. kg^{-1} seed; Chemtura) at a rate of 260 mL per 100 kg of seeds. The seeds were inoculated with *Bradyrhizobium japonicum* (Kirchner) Jordan prior to planting to ensure that inadequate nodulation did not limit normal plant growth. Weed control in MB was preplant incorporated Edge (ethafluralin at 1.4 kg a.i. ha^{-1}; Gowan Canada) at 30.1 kg ha^{-1} and an in-crop application of Basagran Forte (bentazon at 1075 g a.i. ha^{-1}; BASF Canada) at a rate of 2.24 L ha^{-1} at the third trifoliate (V3) stage in all MB site-years. In ON, preplant incorporated Pursuit (imazethapyr at 1.5 kg g a.i. ha^{-1}; BASF Canada) was used at a rate of 312 mL ha^{-1}. Mechanical weed removal was used when necessary.

The calendar dates of PL, emergence (VE), beginning bloom (R1), beginning seed (R5), and R8 were recorded following the Fehr et al. (1971) description of soybean development stages in each experimental unit (plot) for all site-years. A plot was considered to have reached a development stage when at least 50% of the plants in the plot had reached at that stage and plants were observed three times a week until the last plot reached R8. From these data, the number of days between stages was calculated for the following growth stage intervals (GSIs): planting to emergence (PL–VE), emergence to beginning bloom (VE–R1), beginning bloom to beginning seed (R1–R5), beginning seed to full maturity (R5–R8), the total reproductive development period (R1–R8), and the total crop growth duration (PL–R8) and paired with weather data for all site-years tested. The leaf appearance rate (LAR) was calculated by dividing the number of days spent in the VE–R1 GSI by the recorded number of leaves on the main stem observed at R1 for 2017 and 2018 site-years only.

Plots were harvested using a plot combine. Harvested seeds from each plot were air-dried prior to being weighed to measure seed yield, seed moisture concentration, and thousand seed weight (TSW) in all site-years. Protein and seed oil concentrations were measured for 2017 and 2018 site-years using an FOSS Infratec Grain Analyser (FOSS, Hilleroed, Denmark). Protein and oil concentrations were measured for the 2008, 2009, and 2010 site-years as well but were omitted from the analysis because different analytical instruments between MB and ON were used. All seed yield and quality measurements were adjusted to 13% seed moisture concentration prior to statistical analysis.

All data collected followed a normal distribution. An analysis of variance (ANOVA) in PROC GLIMMIX was used to assess the potential significance of cultivar and location, and interactions between location × year and cultivar × location were included in the model as fixed effects (SAS Institute Inc., Cary, NC). The random effects of the model were replication (nested within years) and the interactions of year × cultivar and year × cultivar × location. Least-squares means are presented for seed yield and seed constituent measurements and the same letter following a value indicates that there is no significant difference ($P < 0.05$) among cultivars within a location. An asterisk following a value was used to denote a significant difference ($P < 0.05$) for the same cultivar between MB and ON. Mean separation among cultivars was determined according to the Tukey–Kramer's test ($P < 0.05$) to control for inflation of the family-wise error rate due to multiple testing (Day and

Quinn 1989). Correlations were conducted using the PROC CORR procedure in SAS to investigate the relationships between seed yield, TSW, and seed protein and oil concentrations with precipitation, mean daily T, and time in the GSI. The PL–VE GSI was omitted from the correlation analysis because the precipitation and T during this period of growth affect early season growth and vigor, and not final seed yield, TSW, or seed constituent concentrations.

Results and discussion

Growing season conditions

Mean daily T was cooler in MB site-years than the corresponding site-years in ON and the total precipitation was greater in ON than in MB by 54, 188, 63, 528, and 160 mm in 2008, 2009, 2010, 2017, and 2018, respectively, for the months of May through October (Table 3). The 2008 and 2009 site-years in both MB and ON were cooler than their respective 1981–2010 climate normal and the remaining site-years were warmer than normal (Table 3). Site-years MB09, MB17, MB18, ON08, and ON18 accumulated less precipitation than their respective 1981–2010 climate normal from May through October (Table 3). The daily P in ON is shorter than it is in MB from 15 May to 15 September (Fig. 1) and on 21 June the duration of P in Carman MB is 49 min longer than it is in Ottawa ON.

The ANOVA results for all parameters measured are presented in Table 4. There were significant differences in the number of days in all GSIs among cultivars and between MB and ON, except in the PL–VE GSI. There were significant differences among the site-years for all GSIs tested, but there was no cultivar × location interaction in the duration spent in all GSIs measured. There were significant differences in the number of leaves at R1 among cultivars and between MB and ON and the LAR was statistically different between the two years used for these analyses. There were significant differences among cultivars, site-years, and between MB and ON for seed yield, TSW, and seed protein and oil concentrations. Seed yield, TSW, and oil concentration had significant cultivar × location interactions (Table 4).

Phenology

The assigned MG had little influence on the time to flower in either MB or ON (Table 5). Previous studies have reported that cultivars rated greater in MG flower later than earlier rated MG when planted at the same time and location (Major et al. 1975; Purcell et al. 2014). Salmerón and Purcell (2016) reported greater photosensitivity in later maturing cultivars and that a longer duration in the PL–R1 GSI can occur in later MG because of this. This was not observed in the current experiment and may be because the MGs tested were similar in the P requirement or optimal P to induce flowering. Mourtzinis and Conley (2017) and Zhang et al. (2007) found that MG 0 is best suited for latitudes greater than 46° and Zhang et al. (2007) further reported that the region of adaptation for MG 0 to III was within approximately 2°. Based on this, the regions of adaptation for MG 1, 0, 00, and 000 are 43–45, 45–47, 47–49, and 49–51°N, respectively, and support the adaptability for all MGs tested in the current experiment in ON, but only MG 00 and 000 in MB. A difference in time to flower may have been evident if a greater sample size, range of MG, or latitudes were included.

The mean duration from VE to R1 was 24 days in ON and 42 days in MB among all site-years (Table 5). ON has warmer T and shorter P than MB in May and June when soybean is developing toward R1, which led to a faster rate of development through the vegetative stages and a shorter amount of time to R1. In 2017 and 2018 only, the number of trifoliates at R1 was 4.5 and 4.0 and the duration of the VE–R1 GSI was 33 and 29 days ($P \leq 0.0001$) in MB and ON, respectively. The LAR, however, was consistent (Table 4) between MB and ON in these years, indicating that the vegetative growth rate was equal between the two growing environments. This may mean that the T requirements were achieved in both MB and ON because of their consistent LAR, and the long P in MB slowed plant physiological development. The plants then grew for longer periods in MB and more leaves were produced prior to R1. Long P and cool T have been reported to slow the rate of phenological development in this GSI before by Major et al. (1975) and Câmara et al. (1997) and occurred in these MB site-years. This P effect must be tested in additional site-years, in field with supplemental lighting, or in a controlled environment to confirm as the sample size used in this analysis was small. The T and P interaction is challenging to isolate in a field setting but the concept is well supported by the literature.

The R1–R5 GSI duration was consistent among cultivars in both MB and ON, while the R5–R8 GSI was significantly different among cultivars in MB and increased in duration with increasingly later MG (Table 5). These reproductive phenological differences in MB are comparable to Boote (1981) and Kane and Grabau (1992), who reported a longer duration of this development period for later than earlier MG. Cultivars assigned to a later MG may have a greater sensitivity to the longer P experienced post R1 in MB than the earlier MG, which can slow reproductive development and delay R8 (Grimm et al. 1994; Summerfield et al. 1998; Nico et al. 2015). Soybean in ON required 27 and 42 days in the R1–R5 and R5–R8 GSIs, respectively, while in MB, 20 and 39 days were recorded (Table 5). This resulted in a total reproductive development period (R1–R8 GSI) in ON and MB of 70 and 59 days, respectively (Table 5). Mean daily T in MB was cooler in August and September than it was in ON (Table 3), when reproductive development occurs, but did not slow growth and extend the R1–R8 GSI in MB to be equal with ON. This may be because the VE–R1 GSI in ON was a shorter duration than in MB, leading to soybean in ON spending more of its life cycle in the R1–R8 GSI. When a greater duration of time is spent in the R1–R8 GSI, there is a greater opportunity for the crop to capture and utilize essential plant inputs, including precipitation, sunlight, and T, earlier in and over the total growing season.

The duration of the total life cycle, the PL–R8 GSI, was greater for cultivars assigned to a later MG than those with an earlier rated MG designation. This was consistent for most cultivars, except for the cultivar rated MG 0.5 that matured earlier than the nearest earlier maturing cultivar, MG 0.3

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Table 3. Monthly total precipitation, mean temperature, and a comparison of precipitation and mean temperature to the 1981–2010 climate normal from 1 May to 31 October for site-years in MB and ON.

	Month														
	May		June		July		August		September		October		May–October		
Site-year	Actual	± of normal	Actual	± of normal	Actual	± of normal	Actual	± of normal	Actual	± of normal	Actual	± of normal	Actual	± of normal	% of normal
Precipitation (mm)															
MB08	32	– 27	155	62	33	– 47	49	– 22	91	47	61	11	420	25	106
MB09	54	– 5	73	– 20	57	– 22	37	– 34	107	62	33	– 17	361	– 35	91
MB10	133	75	54	– 39	103	24	77	6	72	27	66	16	505	109	128
MB17	25	– 44	64	– 32	23	– 55	23	– 52	75	26	14	– 30	224	– 188	54
MB18	48	– 22	98	2	43	– 36	31	– 44	43	– 6	37	– 7	300	– 112	73
ON08	76	– 11	121	28	78	– 7	67	– 17	55	– 38	78	– 8	474	– 52	90
ON09	67	– 20	63	– 30	199	114	77	– 7	51	– 42	93	7	549	23	104
ON10	35	– 51	105	12	20	– 65	185	101	148	55	76	– 10	568	42	108
ON17	182	95	137	44	128	44	86	2	51	– 42	168	82	752	226	143
ON18	44	– 43	65	– 28	153	69	69	– 15	76	– 17	53	– 33	460	– 66	87
MB mean	58	– 5	89	– 5	52	– 27	43	– 29	77	31	42	– 5	362	– 40	90
ON mean	81	– 6	98	5	116	31	97	13	76	– 17	94	8	561	35	107
Mean daily T (°C)															
MB08	9.0	– 3.7	15.6	– 2.0	18.4	– 1.6	18.9	– 0.6	12.7	– 0.7	6.3	0.3	13.5	– 1.4	90.7
MB09	8.7	– 4.0	15.2	– 2.4	16.9	– 3.1	17.5	– 2.0	17.4	4.0	3.2	– 2.8	13.2	– 1.7	88.5
MB10	11.2	– 1.5	16.7	– 0.9	20.6	0.6	19.7	0.2	12.6	– 0.8	8.9	2.9	15.0	0.1	100.6
MB17	12.1	0.5	17.1	– 0.1	19.4	0.0	17.7	– 0.8	13.7	0.3	6.4	1.0	14.4	0.2	101.1
MB18	14.8	3.2	19.0	1.8	19.9	0.5	19.0	0.5	10.5	– 2.9	2.8	– 2.6	14.3	0.1	100.6
ON08	11.9	– 1.6	19.2	0.5	20.3	– 0.9	19.0	– 0.9	15.2	– 0.1	7.5	– 0.9	15.5	– 0.6	96.0
ON09	12.0	– 1.5	17.6	– 1.1	18.9	– 2.3	19.5	– 0.4	14.3	– 1.0	6.7	– 1.7	14.8	– 1.3	91.8
ON10	15.5	2.0	18.1	– 0.6	22.6	1.4	20.0	0.1	15.2	– 0.1	8.0	– 0.4	16.6	0.4	102.5
ON17	12.2	– 1.3	18.2	– 0.5	20.4	– 0.8	19.1	– 0.8	17.4	2.1	12.0	3.6	16.6	0.4	102.4
ON18	15.4	1.9	18.2	– 0.5	23.1	1.9	21.5	1.6	16.5	1.2	7.0	– 1.4	17.0	0.8	104.9
MB mean	11.2	– 1.1	16.7	– 0.7	19.0	– 0.7	18.6	– 0.5	13.4	0.0	5.5	– 0.2	14.1	– 0.6	96.3
ON mean	13.4	– 0.1	18.3	– 0.4	21.1	– 0.1	19.8	– 0.1	15.7	0.4	8.2	– 0.2	16.1	– 0.1	99.5

Table 4. ANOVA for the measured parameter days in GSIs, beginning bloom (R1) leaf number, LAR, seed yield, TSW, and protein and oil concentrations.

	Fixed effect			
Parameter	Cultivar	Location	Site-year	Cultivar × location
GSI				
PL–VE	ns†	ns	**	ns
VE–R1	**	**	**	ns
R1–R5	*	**	**	ns
R5–R8	**	*	*	ns
R1–R8	**	**	**	ns
PL–R8	**	**	*	ns
R1 leaf number‡	ns	*	**	ns
LAR‡	ns	ns	**	ns
Seed yield	**	**	**	**
TSW	**	**	**	**
Protein‡	*	**	*	ns
Oil‡	*	**	*	*

Note: Fixed effects tested included cultivar, location (MB and ON), site-year, and the interaction between cultivar and location. Growth stages for days in GSI included PL–VE, VE–R1, R1–R5, R5–R8, R1–R8, and PL–R8.
†Levels of significance indicated: ns = not significant, * significant at $P < 0.05$, and ** significant at $P < 0.01$.
‡2017 and 2018 site-years only.

Table 5. Mean number of days among all site-years in MB and ON for soybean GSIs PL–VE, VE–R1, R1–R5, R5–R8, R1–R8, and PL–R8 for cultivars assigned MGs 000.9–1.3.

			GSI (days)					
Location	Cultivar	MG	PL–VE	VE–R1	R1–R5	R5–R8	R1–R8	PL–R8
MB	M. Presto	000.9	14a*	42ab	19a	32a	50a	107a
	90A01	00.0	14a	41ab	17a	33ab	50a	106a
	M. Ridge	00.3	14a	41ab	19a	33ab	52ab	107a
	Alta	00.4	14a	42ab	18a	34ab	52ab	108a
	Montcalm	00.7	14a	40a	20a	37abc	57bc	111ab
	Roland	0.0	14a	40a	20a	40bcd	60cd	113b
	Rodeo	0.3	14a	40a	24a	44cde	67ef	122c
	9063	0.5	14a	44b	20a	43cde	62de	121c
	Dundas	0.8	14a	43ab	21a	46de	68f	124cd
	CeryxRR	1.3	14a	42ab	22a	50e	71f	127d
		Mean	14	42	20	39	59	115
ON	M. Presto	000.9	14a	24a	28a	36a	64a	102a
	90A01	00.0	14a	23a	27a	38a	66ab	103ab
	M. Ridge	00.3	14a	25a	25a	38a	64a	103ab
	Alta	00.4	14a	25ab	25a	42a	67ab	106abc
	Montcalm	00.7	14a	25a	28a	42a	70ab	108abc
	Roland	0.0	14a	24a	28a	45a	73ab	111abcd
	Rodeo	0.3	14a	27ab	29a	44a	73ab	113bcd
	9063	0.5	14a	30b	25a	42a	67ab	111abcd
	Dundas	0.8	14a	27ab	29a	47a	76ab	117cd
	CeryxRR	1.3	14a	28ab	30a	48a	79b	120d
		Mean	14	24	27	42	70	109

*Least-squares mean values followed by the same lowercase letter (a–f) within MB or ON for a GSI are not significantly different, determined by the Tukey–Kramer grouping.

(Table 5). The decimal place subgroup was implemented into the MG classification system to further divide MG into subgroups (Mourtzinis and Conley 2017). The cultivars tested in this experiment included 25 MG decimal subgroups (Table 1), and the number of days in the PL–R8 GSI was 20 days from the earliest MG subgroup to the latest MG (Table 5), meaning that these cultivars have been assigned an accurate MG relative to each other in both MB and ON.

Table 6. Mean plot seed yield (kg ha^{-1}) and TSW (g) for all site-years, and seed protein and oil concentrations (mg g^{-1}) for 2017 and 2018 site-years adjusted to 13% moisture concentration for 10 soybean cultivars ranging in MG 000.9–1.3 in MB and ON.

		Seed yield (kg ha^{-1})		TSW (g)	
Cultivar	MG	MB	ON	MB	ON
Maple Presto	000.9	2753a†	2846a	160.7a*	186.6abc*
90A01	00.0	2789a	3039a	159.6a*	178.0a*
Maple Ridge	00.3	2873abc	2980a	158.0a*	180.1ab*
Alta	00.4	2903abc*	3411a*	182.5c*	234.8f*
Montcalm	00.7	2827ac*	3364a*	159.6a*	187.4abc*
Roland	0.0	3126abcd*	4158b*	176.5bc*	196.5cd*
Rodeo	0.3	3461d*	4256b*	166.0ab*	198.7cde*
9063	0.5	3334bcd*	4333b*	168.2abc*	212.9e*
Dundas	0.8	3416bd*	4652b*	178.4bc*	204.2de*
CeryxRR	1.3	3341bcd*	4520b*	166.2ab*	194.3bcd*
	Mean	3124*	3707*	167.6*	197.4*
		Protein (mg g^{-1})		Oil (mg g^{-1})	
		MB	ON	MB	ON
Maple Presto	000.9	38.8abc†	41.1bc	20.5a	20.0a
90A01	00.0	39.7a	42.3a	21.8cd*	20.6ab*
Maple Ridge	00.3	38.9ab	41.6ab	20.8ab	20.2a
Alta	00.4	36.0e	40.3cd	22.8e*	21.4bcd*
Montcalm	00.7	38.6bc	42.4a	22.4cde*	20.8abc*
Roland	0.0	37.8cd	40.3cd	21.6bc	21.7de
Rodeo	0.3	38.9ab	41.5ab	22.8e	22.3e
9063	0.5	36.9de	40.8bc	22.1cde*	21.1bcd*
Dundas	0.8	39.2ab	41.2bc	21.7bc	21.7cde
CeryxRR	1.3	36.5e	39.5d	22.7de*	21.6cde*
	Mean	38.1*	41.1*	21.9*	21.1*

†Least-squares mean values followed by the same lowercase letter for a parameter within a location are not significantly different as determined by the Tukey–Kramer grouping. Least-squares mean values for parameter value followed by an asterisk are significantly different between MB and ON at a level of significance of $P < 0.05$.

Seed yield and thousand seed weight

In both MB and ON, seed yield was greater for cultivars rated with later MG (Table 5), consistent with Dunphy et al. (1979) and Cober and Morrison (2010). The phenology results from the current experiment reported that the R5–R8 GSI lasted longer for cultivars assigned to a later than earlier MG in MB, suggesting that this duration may be critical for seed production and yield. Soybean seed yield between MB and ON was equal for the three earliest rated MG cultivars, while the remaining cultivars tested had greater yield in ON (Table 6). A recent study in the United States reported that later MG had a greater optimal T for maximum seed production in the R5–R8 GSI than earlier rated MG (Mourtzinis et al. 2017). The T in MB during this GSI may not reach the optimal T of the later MG in the current experiment, resulting in lower seed yield for the later rated MG in MB compared to ON.

In MB, seed yield was positively correlated with the duration of time in all GSIs and daily mean T in the VE–R1, R5–R8, and PL–R8 GSIs, and was negatively correlated with daily mean T in the R1–R5 GSI mean T (Table 7). These correlations support that seed yield in MB was limited in site-years with cooler T during the VE–R1, R5–R8, and PL–R8 GSIs, and that warmer T during the R1–R5 GSI also reduced seed yield. The positive correlation between the duration of time in the PL–R8 GSI and seed yield in both MB and ON confirms that seed yield was greater for cultivars assigned a later than earlier MG (Table 7).

Precipitation in all GSIs was positively correlated with seed yield in MB (Table 7). The total amount of precipitation over the life of soybean required for maximum yield potential has been reported to be between 450 to 800 mm (Souza et al. 2013), which was only achieved in MB in 2010 (Table 3). Furthermore, Desclaux et al. (2000) reported that drought stress during reproductive development reduced yield more than when drought occurred during vegetative growth. These correlations, particularly between the PL–R8 GSI and seed yield, support that seed yield was most limited by an inadequate amount of growing season precipitation in MB site-years, and that specifically, precipitation in the R5–R8 GSI had the greatest influence on seed yield.

Seed yield in ON had the greatest positive correlation with the duration of time in the R5–R8 GSI and with mean daily T in the same GSI (Table 7). Mourtzinis et al. (2017) reported similar results in which seed yield increased when T was greater in GSI R5–R8 in Wisconsin and Minnesota. Positive correlations were also found between seed yield and the duration of time in PL–R8 and R1–R8 GSIs, and a negative correlation with time was found in GSI VE–R1. Seed yield in ON

Table 7. Pearson correlation coefficients for parameters seed yield and TSW among all site-years and protein and oil concentrations between 2017 and 2018 site-years only with total precipitation, daily mean temperature, and the duration of GSI in days from PL–VE, VE–R1, R1–R5, R5–R8, R1–R8, and the total life cycle duration (PL–R8) in MB and ON.

Environmental parameter	Location	Yield and seed quality parameter	GSI				
			VE–R1	R1–R5	R5–R8	R1–R8	PL–R8
Precipitation	MB	Seed yield	0.51*†	0.30*	0.77*	0.78*	0.95*
		TSW	0.30*	0.24	0.75*	0.73*	0.79*
		Protein	− 0.11	0.16	− 0.40	− 0.10	− 0.06
		Oil	0.21	− 0.02	0.33	0.17	0.21
	ON	Seed yield	− 0.30*	− 0.17	0.08	− 0.07	− 0.28*
		TSW	− 0.06	− 0.44*	0.32*	− 0.01	− 0.15
		Protein	− 0.38	0.05	− 0.15	− 0.35	− 0.38
		Oil	− 0.66*	0.67*	− 0.68*	− 0.46*	− 0.64*
Daily mean temperature	MB	Seed yield	0.46*	− 0.28*	0.36*	0.04	0.48*
		TSW	0.24	− 0.12	0.35*	0.14	0.38*
		Protein	− 0.26	0.01	− 0.37	− 0.17	− 0.36
		Oil	0.04	0.18	0.48*	0.39	0.43
	ON	Seed yield	− 0.31*	− 0.17	0.54*	0.47*	0.45*
		TSW	0.00	− 0.39*	0.42*	0.24	0.27
		Protein	− 0.53*	− 0.19	0.34	0.22	0.00
		Oil	− 0.53*	0.34	0.35	0.48*	0.49*
Duration of GSI	MB	Seed yield	0.49*	− 0.28	0.37*	0.09	0.57*
		TSW	0.27	− 0.09	0.27	0.13	0.41*
		Protein	− 0.22	− 0.01	− 0.41	− 0.29	− 0.37
		Oil	0.01	0.20	0.41	0.42	0.32
	ON	Seed yield	− 0.23	− 0.31*	0.55*	0.41*	0.37*
		TSW	0.09	− 0.50*	0.39*	0.13	0.09
		Protein	− 0.52*	− 0.29	0.20	0.00	− 0.31
		Oil	− 0.54*	− 0.02	0.13	0.10	− 0.06

†Pearson correlation coefficients followed by an asterisk are significant at $P < 0.05$.

was negatively correlated with precipitation during the VE–R1 and PL–R8 GSIs, which is the inverse of what was found in MB (Table 7). Thus, soybeans in MB had lower seed yield in this experiment because of limited precipitation, while in ON, yield was reduced by excess precipitation.

As daily mean T increased in the R5–R8 and PL–R8 GSIs, soybean seed yield increased in both MB and ON. If soybean can reach R1 earlier in the MB growing season by earlier planting or by growing cultivars insensitive to MB's P and flower earlier, the R5–R8 GSI might shift to warmer summer T and increase seed yield. A study in MB found that seed yield decreased by 14 and 22 kg ha^{-1} for cultivars assigned MG 00.1 and 00.8, respectively, for each calendar day delay in planting after 27 April (Tkachuk 2017). MacMillan and Gulden (2020) also reported a 15% reduction in seed yield when the planting date was between 6 and 24 June compared to 24 May to 12 June and 31 May to 16 June. The optimal planting dates discussed in these studies may have led to warmer T during the R5–R8 GSI, resulting in greater yield. In this study, the MB planting dates (Table 2) were within the optimum planting date window defined by provincial guidelines (Anonymous 2022). There are, however, also potential challenges to planting early, such as cool air and soil T resulting in slow emergence or a late spring frost resulting in plant death.

The TSW varied among cultivars in MB and ON and was always greater in ON than in MB (Table 6). The genetic background of a cultivar influences source–sink relationships, including assimilates and seed size (Egli 2019), and is a probable cause for the differences among MGs. The duration of the R1–R5 GSI, a critical period for TSW (Poeta et al. 2016; Egli 2019), was longer in ON than in MB (Table 5), which likely contributed to greater TSW in ON. In MB, TSW was correlated with the duration of time in the PL–R8 GSI, with precipitation during all GSIs except R1–R5, and with daily mean T during the R5–R8 and PL–R8 GSIs (Table 7). Morrison et al. (2006) had consistent correlations for soybeans in an ON study for the R5–R8 and PL–R8 GSIs. In ON, the TSW had a negative relationship with the amount of time, precipitation, and daily mean T in the R1–R5 GSI, and the opposite relationship with the same parameters when developing in the R5–R8 GSI (Table 7). This suggests that soybean is sensitive to increasing T and precipitation in the R1–R5 GSI, leading to smaller seeds, and that increased precipitation and T in the R5–R8 GSI are favorable for greater TSW. In both MB and ON, seed yield and TSW were positively correlated with each other (Table 8), which was expected because yield was calculated on a weight by area basis.

Table 8. Pearson correlation coefficients for parameters seed yield, TSW, and protein and oil concentrations for relationships with each other in MB and ON for 2017 and 2018 site-years only.

	Location					
	MB			ON		
Parameter	Seed yield	TSW	Protein	Seed yield	TSW	Protein
TSW	0.84*†			0.52*		
Protein	0.06	− 0.12		− 0.01	− 0.25	
Oil	0.13	0.17	− 0.53*	0.93*	0.49*	− 0.05

†Pearson correlation coefficients followed by an asterisk are significant at $P < 0.05$.

Seed protein and oil concentrations

The seed protein and oil concentrations were different among cultivars in both environments (Table 6). Differences among cultivars have been reported in northern environments before (MacMillan and Gulden 2020) and can be attributed to the genetic background of the cultivar. Mean seed protein concentration was 38.1% and 41.1% in MB and ON, respectively (Table 6). The concentration of protein is influenced by the environment (Morrison et al. 2006; Song et al. 2016; MacMillan and Gulden 2020) and the site-year environmental differences between MB and ON included greater precipitation and warmer daily mean T in ON compared to MB (Table 3), a possible explanation for the greater protein in ON. There were no correlations with precipitation, T, or time in any GSI with protein in MB, while in ON it was negatively correlated with the duration of time and mean daily T in the VE–R1 GSI (Table 7). Protein accumulated in vegetative biomass prior to R1 is remobilized to the seed during reproductive development stages (Staswick 1988). If the plant fails to accumulate adequate protein in vegetative structures during the VE–R1 GSI, there may be a reduced supply of protein for remobilization.

Cultivars in MB spent less time in all reproductive GSIs compared to ON, which may have contributed to greater oil concentration in MB because of an inadequate amount of time to accumulate the same concentration of seed protein in ON. Protein and oil concentrations in MB had an inverse relationship (Table 8), further supporting this concept. This was not found in ON and may have been because the maximum level of protein was established in the seed. Cultivars with higher oil concentrations in MB may prefer these environmental conditions and should be investigated further for oil production optimization in MB. The mean oil concentration in MB was only positively correlated with daily mean T in the R5–R8 GSI (Table 7), consistent with the results from Vollmann et al. (2000) and Song et al. (2016).

The oil concentration in ON had relationships with phenology and mean daily T that were consistent with protein and had positive correlations with precipitation during the R1–R5 GSI and negative correlations during the VE–R1, R5–R8, R1–R8, and PL–R8 GSIs (Table 7). The relationships between oil concentration and mean daily T and phenology might have occurred for the same reason as proposed for protein synthesis: assimilates accumulated in vegetative structures during the VE–R1 GSI and remobilized during reproductive development. A limited supply of water during reproductive development can also increase oil concentration (Specht et al. 2001) but the opposite was found in the current experiment (Table 7). These results are consistent with Miransari (2016), who reported a reduction in oil concentration because of water stress. Increasingly warmer T in the R1–R8 and PL–R8 GSIs was positively correlated with oil concentration, suggesting that warmer T is optimal for maximum oil concentration.

Oil concentration was positively correlated with seed yield and TSW in ON but not in MB (Table 8). Mourtzinis et al. (2017) reported the same relationships as ON. Inverse relationships between seed yield and protein have been found before (Cober and Voldeng 2000; Mourtzinis et al. 2017), but were not observed in this experiment. The seed quality correlations with precipitation, T, and time, as well as with each other, were limited to 2017 and 2018 site-years and further investigation is encouraged.

Conclusion

This experiment investigated soybean phenology, seed yield, TSW, and seed protein and oil concentrations for 10 cultivars assigned different MGs in two different growing environments. Temperature requirements in 2017 and 2018 were achieved in both MB and ON for optimal plant growth because their LARs were consistent and it was likely longer P in MB that delayed flowering and led to more trifoliates produced prior to R1. In MB, phenology among cultivars was equal until R5 and once this occurred the later MG slowed in development and achieved R8 later than the earlier MG. These differences among MGs were negligible in ON and could have occurred in MB because of a response to the daily rate of change or the length of P during reproductive development that has been reported to delay time to R8. Future studies isolating this phenomenon in a controlled environment are recommended. The total amount of time in the PL–R8 GSI increased when cultivars were assigned to an increasingly later MG, validating the accuracy of their MG designation relative to each other.

This experiment has provided a baseline of environmental and phenological trends with yield and seed quality components for early MG soybean in northern environments and additional research is encouraged to support or build off this study. A greater understanding of genetics, environment, and management practices that influence seed yield, TSW, and seed protein and oil concentrations is required to optimize soybean production in northern environments and meet the high global demand for soybean.

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