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Relationship between Planting Date, Growing Degree Days and the Winter Rye (*Secale cereale* L.) Variety "Rymin" in Minnesota

Michael Kantar* and Paul Porter

Abstract

This study evaluated the influence of fall planting date on winter rye (*Secale cereale* L.) anthesis at three Minnesota locations for five dates from late August through October. This represents the time when fall-planted cover crops would likely be seeded in Minnesota. Earliness to anthesis is important in organic production systems where timing of rye management is affected by rye growth stage. The relationships among growing degree days (GDD), growth stage, and aboveground biomass were evaluated to predict how these factors influence anthesis date and how late in the fall rye could be planted without delaying anthesis. The study occurred in 2006 and 2007, which happened to have abnormally warm and cool growing seasons, with the earliest anthesis dates in 2007 being 25 May, 28 May, and 5 June at St. Paul, Lamberton, and Roseau, respectively, and dates in 2008 of 10 June, 11 June, and 17 June. Our results indicate that there was no fall biomass requirement but also that it was critical to accumulate at least 309 GDD in the fall so as not to delay spring anthesis. This information enables growers to choose appropriate planting dates for rye that will not delay anthesis. The optimal planting date corresponded to planting by late September (~20) in southern and early September (~8) in northern Minnesota.

M. Kantar, Agronomy and Plant Genetics, Univ. of Minnesota, 411 Borlaug Hall, 1991 Buford Circle, St. Paul, MN 55108; P. Porter, Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, 411 Borlaug Hall, 1991 Buford Circle, St. Paul, MN 55108-6026.
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*Corresponding author (kant0063@umn.edu).

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Introduction

CORN (*Zea mays* L.) and soybean (*Glycine max* L.) are currently grown by many farmers in the Midwestern United States. Postharvest tillage following corn and soybean leaves the landscape bare for much of the year, which increases the likelihood that nutrient leaching and erosion will occur. Nutrient leaching and soil erosion have led to a loss of soil fertility and have contributed to environmental problems such as hypoxia in the Gulf of Mexico (Randall et al., 2003). The use of cover crops may help alleviate some of the environmental pressure caused by tillage in a typical corn–soybean rotation without jeopardizing the livelihood of producers (Kaspar et al., 2007; Strock et al., 2004).

Cover crops such as winter rye, hairy vetch (*Vicia villosa*), and white clover (*Trifolium* repens L.) were used extensively before widespread development and adoption of synthetic chemical fertilizers, herbicides, and insecticides in the mid-20th century (Hartwig and Ammon, 2002). Cover crops are again being evaluated for use in farming systems due to their beneficial environmental effects and their positive impact on production, particularly in organic production systems (Baldwin and Creamer, 2000; Kaspar et al., 2012). Cover crops can decrease erosion, improve weed control, and affect soil physical properties (Creamer et al., 1996). Recently, the potential for a fall-seeded cereal grown as a double-cropped, biofuel feedstock within a corn–soybean rotation was investigated (Feyereisen et al., 2013).

Small grains were commonly grown as cash crops (Oelke et al., 1990); however, they possess excellent cover crop characteristics (De Bruin et al., 2005). Among small grains, winter rye appears most promising in northern regions of the United States for several reasons: (i) winter rye has good winter hardiness and has been shown to withstand temperatures as low as −36°C (Sattell et al., 1998); (ii) winter rye can grow on marginal landscapes (low moisture, poor fertility, and a wide range of soil pH, 4.5–8.0); (iii) winter rye can accumulate large amounts of N (Slootmaker, 1973); and (iv) winter rye has been shown to reduce subsurface N leaching (Kaspar et al., 2007; Strock et al., 2004).

The timing of fall planting date and spring management are two of the most important aspects with regard to successfully utilizing cover crops in a corn–soybean rotation (McLeod et al., 1992). Early fall planting dates have been shown to increase total biomass production in small grains (Schwarte et al., 2005). Cereals planted in early fall (August or September) have been reported to have earlier anthesis dates (Aitken, 1966); however, soybean and corn are typically harvested in mid to late October. This phenomenon has been observed in winter rye, with the timing of the fall planting date reportedly resulting in up to a two week difference in spring maturity (Nuttonson, 1958). Quick maturation in the spring allows for greater flexibility in spring management options. However, the longer cover crop residue persists, the greater the potential weed control it can provide (Lu et al., 2000). Organic growers should wait until anthesis to manage a winter rye cover by mowing, because mowing before anthesis rarely results in termination and subsequent regrowth from stubble can be substantial (De Bruin et al., 2005).

The objectives of this study were to: (i) evaluate the relationship between planting date, growing degree days (GDD), and rye development; and (ii) identify the optimum planting window for a winter rye as a cover crop in Minnesota.

Experimental Design

This study was conducted at three Minnesota locations: Roseau (49°0′ N lat) in the north, and St. Paul (45°0′ N lat) and Lamberton (44°20′ N lat) in the south. The study was conducted over two years: 2006–2007 and 2007–2008. The soil types were a Zippel very fine sandy loam (coarse-silty, mixed, frigid Typic Endoaquoll) at Roseau; a Hamerly clay loam (fine, loamy, frigid Aeric Calciaquoll) at St. Paul; and a moderately well-drained Normania clay loam (fine-loamy, mixed, mesic, Aquic Haplustoll) at Lamberton. The experimental design at each location was a randomized complete block with five planting dates and four replications. Planting dates spanned two months, from August 22 through October 25, representing the range when a fall-planted cover crop would most likely be seeded in Minnesota (Table 1). Plot size was 1.83 × 3.66 m. At each location, the winter rye cultivar, Rymin, was seeded at 109 kg ha^{-1} on 20.3 cm row widths with a Marliss no till drill (Sukup Manufacturing Co, Sheffield, IA). Plots were not fertilized at any location or in either year. Rye biomass data were recorded to focus attention on the influence of planting date at a given location and year combination on biomass. Soil samples were not taken just before the winter rye plantings, but previous samples indicated that the fertility at St. Paul was high due to repeated additions of compost with particularly high P levels (Tom Warnke, personal communication, 2014). Previous crops included corn for silage at Lamberton and spring wheat at St. Paul and Roseau.

Data Collection and Analysis

Aboveground biomass samples were harvested 2.54 cm above the ground in each plot from a 1.00 × 0.23 m quadrant once in mid-November and four times in the spring, from early May through mid-June each year (Table 1). At these dates, winter rye maturity was recorded using the Zadoks growth stage (Zadoks et al., 1974). Date of anthesis, defined here as first pollen shed, was recorded for each plot. Plots at Roseau were sampled three times each spring due to snow cover. Samples were dried at 60°C for 72 h with biomass yield being determined from the dry weight. No reliable data was reported from early June at Lamberton during the 2007 growing season because samples were not dried properly. The authors also question the last June sample at St. Paul as the biomass numbers were unusually high, perhaps to lack of complete drying, and thus these data were not included in the analysis.

Climatic conditions were obtained for each location from the University of Minnesota Climatology Working Group (University of Minnesota Climatology Working Group, 2013). Daily GDD were calculated with a base temperature of 4°C. Daily GDD were calculated using the equation GDD = [(daily maximum temperature + daily minimum temperature)/2] – base temperature. Cumulative GDD were calculated by summing the daily GDD values over the following time frames: monthly, from planting to anthesis (GDDT), from planting to Dec. 31 (Fall GDD), and from March 31 to anthesis (Spring GDD). Air temperature was less than 40°C. Confidence intervals (CI) at the 95% level were calculated for long-term (30-year) monthly GDD averages at all locations.

Table 1. Planting dates and biomass and growth stage sampling dates for Rymin rye planted on five dates at three Minnesota locations in 2006 and 2007.

	St. Paul	Lamberton	Roseau	St. Paul	Lamberton	Roseau
			Planting dates			
		2006			2007	
Late Aug.	22 Aug.	26 Aug.	24 Aug.	30 Aug.	22 Aug.	24 Aug.
Early Sept.	5 Sept.	6 Sept.	8 Sept.	6 Sept.	5 Sept.	3 Sept.
Late Sept.	19 Sept.	19 Sept.	20 Sept.	24 Sept.	20 Sept.	22 Sept.
Early Oct.	3 Oct.	4 Oct.	7 Oct.	5 Oct.	5 Oct.	4 Oct.
Late Oct.	17 Oct.	17 Oct.	25 Oct.	24 Oct.	19 Oct.	20 Oct.
			Biomass and growth stage sampling dates			
		2007			2008	
Fall	15 Nov.	10 Dec.	25 Nov.	14 Nov.	7 Nov.	4 Nov.
Early May	30 Apr.	9 May	–†	1 May	4 May	–†
Mid-May	18 May	21 May	16 May	14 May	18 May	16 May
Early June	1 June	4 June‡	31 May	28 May	1 June	30 May
Mid-June	15 June	21 June	13 June	14 June‡	15 June	12 June

†Rye biomass was not sampled in early May at Roseau because of snow cover.

‡Denotes the locations where the data wasn't used.

Data were subjected to analysis of variance, and means were separated using Fisher's protected least significant difference (LSD) test at the $P = 0.05$ level (R Core Team, 2012). Locations, years, and replications were considered as random effects and all other factors were considered fixed. The Cate-Nelson test (Cate and Nelson, 1971) was done to identify a critical value of Fall GDD needed to ensure no delay in anthesis (Schwarte et al., 2005). The Cate-Nelson test splits the data examined into two groups by maximizing the R^2 value where the means of the groups are used as the predictor (Cate and Nelson, 1971). Best fit regression lines were calculated and plotted (R Core Team, 2012). Regression analysis was used to examine the relationship between growth stage and GDD.

Variability in Growing Degree Days between Location and Growing Season

The weather patterns in 2006–2007 and 2007–2008 were distinctly different. The spring 2007 GDD were well above the 95% confidence interval for the previous 30 years, while spring 2008 was cooler than normal in terms of GDD accumulation (Table 2). Monthly precipitation was near normal each year at each location, and the 95% confidence interval was never exceeded (data not shown). The higher temperatures in the 2006–2007 growing season impacted winter rye maturity, as increasing temperature is known to hasten developmental phases in vernalized plants (Davidson and Christian, 1984).

Optimum Planting Date to Achieve an Early Anthesis Date

Rye behaves as a facultative long-day plant. In long-day plants, daylength must exceed a critical photoperiod (about 14 h for rye) before the plant enters into the reproductive stage of growth (Burger et al., 2007). Time to anthesis can be shortened under certain conditions involving adequate fertility, moisture, and heat units (Aitken, 1966; Burger et al., 2007). At the locations we studied, daylength reached 14 h by late April; thus, anthesis would come some period after that date. Depending on date of planting and location, winter rye anthesis date first occurred on 25 May 2007 and 10 June 2008 (Table 3). Daylength on 25 May, the earliest date we observed anthesis, was 1507 h at Lamberton, 1512 h at St. Paul, and 1543 h at Roseau.

For each planting date, GDDT (from planting to anthesis) was greatest at St. Paul and least at Roseau. Anthesis occurred with as little as 515 GDDT for the early October planting at Roseau in 2008, and with as many as 1360 GDDT for the late August planting at St. Paul in 2007. At any one location, later-planted winter rye generally required fewer GDDT to reach anthesis than earlier planted winter rye. Depending on planting date, winter rye first reached anthesis after GDDT reached 956 to 1360 and 974 to 1358 in St. Paul, 821 to 1204 and 872 to 1201 in Lamberton, and 738 to 936 and 662 to 825 at Roseau in 2007 and 2008, respectively. This indicated that GDDT was not a good predictor of winter rye anthesis date, which was consistent with the findings of Nuttonson (1958). Spring GDD (from 1 March to anthesis) was not a much better predictor of anthesis date. In 2007 and 2008, anthesis was reached after 647 and 574 Spring GDD in St. Paul, 546 and 517 Spring GDD in Lamberton, and 427 and 356 Spring GDD in Roseau, respectively (Table 3).

Winter rye anthesis occurred one to two weeks earlier in 2007 compared to 2008 at all three locations for all five planting dates (Fig. 1; Table 3). First pollen shed occurred on 25 May 2007 and 10 June 2008 at St. Paul; 28 May 2007 and 11 June 2008 at Lamberton for the first three planting dates, whereas first pollen shed occurred on 5 June 2007 and 17 June 2008 at Roseau for the first two planting dates. All later planting dates at each location and each year had delayed anthesis (Table 3). Research by Mirsky et al. (2009) at 40°44′ N latitude in Pennsylvania indicated a slightly earlier anthesis date for the winter rye cultivars they evaluated.

Table 2. Monthly growing degree days (GDD; 4°C base) at three Minnesota locations in 2006–2007 and 2007–2008 in comparison with the long-term average.

	2006–2007			2007–2008			30-yr average†			95% CI		
Month	St. Paul	Lam.‡	Roseau	St. Paul	Lam.	Roseau	St. Paul	Lam.	Roseau	St. Paul	Lam.	Roseau
Aug.§	167	163	145	196	186	148	169	162	132	161–176	154–170	122–142
Sept.	345	319	291	443	390	271	399	377	275	341–457	320–435	230–320
Oct.	156	142	71	278	242	101	189	167	92	172–205	152–182	79–106
Nov.	58	42	2	33	28	3	30	27	6	21–40	19–36	3–10
Dec.	0	2	0	0	0	0	1	1	0	0–3	0–2	0
Jan.	0	0	0	0	0	0	0	0	0	0	0–1	0
Feb.	1	0	0	0	0	0	2	3	0	0–4	1–6	0
Mar.	96	57	2	5	4	0	28	25	4	20–36	19–31	1–7
Apr.	188	142	81	120	80	32	150	126	70	130–170	107–145	56–84
May	445	398	279	302	288	160	351	337	251	328–374	312–361	226–275
June	533	518	435	479	464	358	484	487	377	468–500	472–502	357–396
Total	1989	1784	1306	1855	1680	1073	1804	1713	1207	1735–1873	1648–1778	1155–1255

†Long-term average based on data from 1971–2000.

‡Lam. = Lamberton.

§August only has GDD from the 22nd due to rye being planted on or after that day.

Table 3. Rye anthesis date and cumulative growing degree days (GDD; 4°C base) from: (i) date of planting until Rymin rye anthesis (GDDT); (ii) date of planting until 31 Dec. (Fall GDD); and (iii) early spring until anthesis (Spring GDD), for five planting dates at three Minnesota locations in 2006–2007 and 2007–2008.

Date planted	2007 Anthesis date	2006–2007 GDDT	2006 Fall GDD	2007 Spring GDD	2008 Anthesis date	2007–2008 GDDT	2007 Fall GDD	2008 Spring GDD
				St. Paul				
Late Aug.	25 May	1360	726	647	10 June	1358	784	574
Early Sept.	25 May	1162	499	647	10 June	1225	651	574
Late Sept.	25 May	956	309	647	10 June	974	405	574
Early Oct.	1 June	893	182	745	13 June	896	276	620
Late Oct.	2 June	846	86	759	15 June	710	80	630
				Lamberton				
Late Aug.	28 May	1204	668	546	11 June	1202	685	517
Early Sept.	28 May	1000	455	546	11 June	1082	565	517
Late Sept.	28 May	821	275	546	11 June	872	355	517
Early Oct.	2 June	772	159	613	14 June	798	236	562
Late Oct.	5 June	738	69	669	16 June	657	66	591
				Roseau				
Late Aug.	5 June	936	509	427	17 June	757	401	356
Early Sept.	5 June	738	311	427	17 June	662	306	356
Late Sept.	10 June	633	135	480	19 June	553	170	383
Early Oct.	17 June	609	53	573	22 June	514	87	427
Late Oct.	19 June	646	5	641	28 June	544	21	523

In 2007, anthesis for any given planting date typically occurred one to three days later at Lamberton and 11 to 17 days later at Roseau compared to St. Paul. In 2008, anthesis occurred one day later at Lamberton and 7 to 13 days later at Roseau compared to St. Paul. With respect to latitude and anthesis dates, our data could be separated into northern (Roseau) and southern (Lamberton and St. Paul) sites, with southern sites reaching anthesis earlier, most likely in response to receiving more GDD sooner in the spring than at Roseau (Fig. 2, Tables 3 and 4).

Previous studies have attempted to utilize GDD to predict anthesis and yield. Nuttonson (1958) identified the average total degree-day requirement across locations in North America as 1846 GDD from planting to harvest, and about 602 GDD from 1 March to heading with a base temperature of 40°F (4.4°C). A minimum of 300 GDD in fall was reported as a critical value needed for triticale grown in Iowa to prevent a delay in anthesis date (Schwarte et al., 2005). Utilizing the Cate-Nelson test we identified a critical value of 309 fall GDD (Fig. 1) needed to prevent delayed anthesis in the following spring (Cate and Nelson, 1971). This value was achieved at St. Paul and Lamberton with the first three planting dates and at Roseau with only the first two planting dates (Table 4). Note that in 2007 at Lamberton for the third

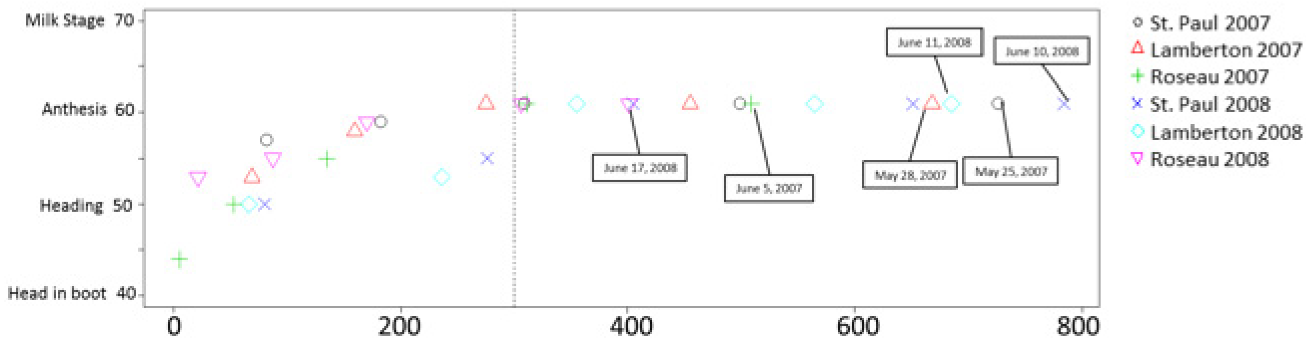
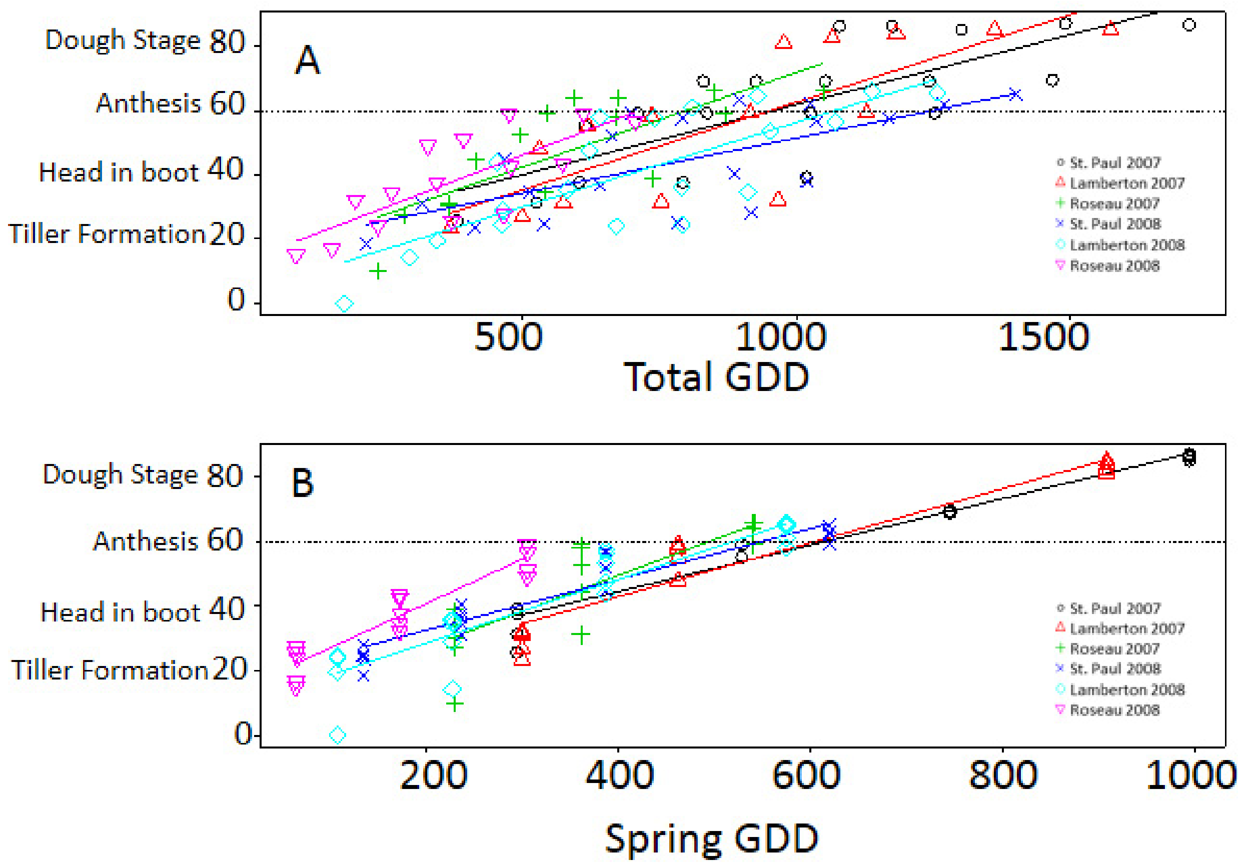


Figure 1. Relationship between Fall growing degree days (GDD) and Zadoks growth stage for Rymin rye at earliest anthesis for five fall planting dates at three Minnesota locations in 2006 and 2007. Dates in the boxes indicate earliest anthesis date at that location that year. The five planting dates are plotted at the sampling date that was closest to anthesis (Zadoks 61). The vertical line indicates the critical value, 309, obtained using the Cate-Nelson test to separate the data into two populations. This value identifies the number of Fall GDD needed to ensure no delay in anthesis.



C	GDDT	Spring GDD
St. Paul 2007	Growth Stage = 18.3 + 0.04 GDDT	Growth Stage = 15.7 + 0.07 Spring GDD
Lamberton 2007	Growth Stage = 7.97 + 0.05 GDDT	Growth Stage = 9.67 + 0.08 Spring GDD
Roseau 2007	Growth Stage = 23.7 + 0.04 GDDT	Growth Stage = 13.68 + 0.10 Spring GDD
St. Paul 2008	Growth Stage = 17.1 + 0.03 GDDT	Growth Stage = 16.8 + 0.08 Spring GDD
Lamberton 2008	Growth Stage = 10.1 + 0.04 GDDT	Growth Stage = 13.4 + 0.09 Spring GDD
Roseau 2008	Growth Stage = 13.7 + 0.06 GDDT	Growth Stage = 13.4 + 0.14 Spring GDD

Figure 2. Relationship between Zadoks growth stage and GDD for (A) GDDT and (B) Spring GDD for five fall planting dates of Rymin rye at three Minnesota locations in 2006 and 2007, and (C) linear regression equations for each location year combination. Linear regression lines are for ease of viewing each location by year combination.

Table 4. Latest of five fall planting dates at three Minnesota locations in 2006 and 2007 that did not have delayed anthesis dates relative to earlier planting dates for Rymin rye. Growing degree days (GDD; 4°C base) are calculated from planting until anthesis (GDDT), date of planting until 31 Dec. (Fall GDD), and early spring until anthesis (Spring GDD).

Date planted	Anthesis date	Location	GDDT	Fall GDD	Spring GDD	LT† GDDT	LT Fall GDD	LT Spring GDD
PD‡				%				
3.) 19 Sept.	25 May 2007	St. Paul	956 (116)§	309 (086)	647 (141)	822	360	459
3.) 24 Sept.	10 June 2008	St. Paul	974 (95)	405 (133)	574 (83)	998	305	690
3.) 24 Sept.	28 May 2007	Lamberton	821 (115)	275 (103)	546 (124)	711	267	442
3.) 20 Sept.	11 June 2008	Lamberton	872 (91)	355 (116)	517 (80)	954	305	645
2.) 8 Sept.	5 June 2007	Roseau	738 (115)	311 (112)	427 (118)	640	278	362
2.) 3 Sept.	17 June 2008	Roseau	662 (79)	306 (91)	356 (70)	843	338	505

†LT = Long-term average based on data from 1971–2013.

‡PD is the planting date – either the 3rd or 2nd planting date.

§The number in parentheses is the percentage of the long-term average.

Table 5. Fall growing degree days (GDD; base 4°C) and rye aboveground biomass in the fall for Rymin rye planted on five dates at three Minnesota locations in 2006 and 2007.

Planting date	Fall GDD 2006	Fall GDD 2007	Aboveground biomass 2006	Aboveground biomass 2007
			kg ha^{-1}	
St. Paul				
Late Aug.	726	784	1368a	4568a
Early Sept.	499	651	931a	3026b
Late Sept.	309	405	75b	436c
Early Oct.	182	276	21b	61c
Late Oct.	82	80	NA†	NA
LSD (0.05%)	–	–	801	470
Lamberton				
Late Aug.	668	685	887a	946a
Early Sept.	455	565	393b	844a
Late Sept.	275	355	249bc	407b
Early Oct.	159	236	74c	14c
Late Oct.	69	66	NA	NA
LSD (0.05%)	–	–	188	393
Roseau				
Late Aug.	509	401	2415a	2080a
Early Sept.	311	306	1600a	684b
Late Sept.	135	170	111b	262c
Early Oct.	53	87	14b	11c
Late Oct.	5	21	NA	NA
LSD (0.05%)	–	–	841	237

†NA = not applicable since the last planting date had negligible biomass at sampling.

planting date (19 September) there were adequate Fall GDD (275) to achieve anthesis with no delay, whereas in 2008 at St. Paul for the fourth planting date (3 October) a similar number of Fall GDD (276) was not enough, and the anthesis date was delayed relative to earlier planted winter rye. This implies that an earlier planting date could influence the critical value needed such that there would be no delay in anthesis date, especially if the following spring had above average GDD accumulation (Table 4; Fig. 1).

The warm fall in 2007 compared to 2006 (Table 3; Table 4) had less of an influence on winter rye anthesis date than the warm spring in 2006 compared to 2007. Planting in early or late October resulted in delayed anthesis. Purvis (1948) showed that earlier plantings of winter rye tended to have an earlier anthesis date than later plantings; here we identified a critical value of 309 GDD (Fig. 1) in the fall necessary for anthesis not to be delayed. Receiving more fall GDD than this value had no impact on earliness to anthesis. Our data suggest that there is a minimum number of fall GDD needed for winter rye to reach timely (early) anthesis, but having Fall GDD beyond this value does not hasten anthesis.

Biomass Production of Winter Rye Cover Crop at Different Harvest Dates

Fall 2007 accumulated more GDD than fall 2006 in St. Paul and Lamberton but not in Roseau (Table 3). This contributed to a higher biomass in fall 2007 compared to 2006. St. Paul produced more fall biomass than Roseau or Lamberton during both years (Table 5). In 2006 Roseau produced more fall biomass than Lamberton, but in 2007 Lamberton produced more fall biomass than Roseau. Roseau likely produced more biomass in 2006 because there was grazing damage from deer to winter rye plots at Lamberton. Fall biomass yield was sequentially greater based on the earliness of the planting (Table 5).

Biomass yield and earliness to anthesis varied by environment, with St. Paul having the highest biomass and the earliest anthesis dates, followed by Lamberton and Roseau (Table 6). St. Paul has a history of high fertility and the urban heat island likely increased GDD (Zhang et al., 2004). Fertility has been previously reported not to affect winter rye anthesis date (Purvis, 1934). Plantings in August and September consistently outperformed October plantings for biomass at all locations at all samplings (Table 6). Winter rye at Roseau behaved differently from winter rye at St. Paul and Lamberton, likely due to fewer cumulative GDD, which delayed rye maturity (Tables 3 and 4).

Plantings in August or September produced more biomass by anthesis (Table 6), while reaching anthesis earlier, than plantings in October (Table 4). Plantings in early October had a greater biomass yield than late October plantings. August and September planting dates

Table 6. Total growing degree days from planting until anthesis (GDDT), aboveground biomass (in kg ha^{-1}), and Zadoks growth stage at four spring sampling dates for Rymin rye planted on five dates at three Minnesota locations in the fall of 2006 and 2007.

	St. Paul						Lamberton						Roseau					
	GDDT		Biomass		Growth stage		GDDT		Biomass		Growth stage		GDDT		Biomass		Growth stage	
Spring date 1:	30 Apr.	1 May	30 Apr.	1 May	30 Apr.	1 May	9 May	4 May	9 May	4 May	9 May	4 May	NA	NA	NA	NA	NA	NA
Planting date	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Late Aug.	1760	1598	5310	3899	39.0	28.0	1668	1391	2936	326	32.0	24.2	NA	NA	NA	NA	NA	NA
Early Sept.	1359	1361	6751	3885	37.5	25.0	1297	1179	2617	424	31.5	24.0	NA	NA	NA	NA	NA	NA
Late Sept.	1024	1036	3259	1673	37.5	24.5	981	907	1231	475	31.2	24.5	NA	NA	NA	NA	NA	NA
Early Oct.	803	701	1630	335	31.2	23.5	793	601	1014	19	26.8	19.5	NA	NA	NA	NA	NA	NA
Late Oct.	625	358	582	115	25.5	18.5	639	305	502	NA	23.5	NA	NA	NA	NA	NA	NA	NA
LSD P = 0.05	–	–	*1830*	*2509*	*3.8*	*3.2*	–	–	*507*	*213*	*1.5*	*2.5*	–	–	–	–	–	–
Spring date 2:	18 May	14 May	18 May	14 May	18 May	14 May	21 May	18 May	21 May	18 May	21 May	18 May	16 May	16 May	16 May	16 May	16 May	16 May
Planting date	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Late Aug.	2192	1791	15872	4554	59.0	38.0	1952	1600	4044	1426	59.0	34.5	1266	788	2197	4350	39.0	27.5
Early Sept.	1791	1554	11159	4728	59.0	40.5	1581	1460	3565	1550	59.0	36.0	932	621	2241	2866	34.5	25.5
Late Sept.	1456	1229	8293	4146	59.0	36.5	1265	116	3419	1331	58.0	35.5	630	441	1397	1891	30.2	24.0
Early Oct.	1235	894	5208	1368	59.0	34.5	1077	810	2735	302	55.0	29.0	489	243	248	97	27.5	17.0
Late Oct.	1057	551	6198	495	55.0	31.0	923	514	1644	43	48.0	14.2	406	133	131	44	10.2	15.0
LSD P = 0.05	–	–	*9445*	*1421*	*0.3*	*5.5*	–	–	*651*	*952*	*2.7*	*7.8*	–	–	*1058*	*686*	*15*	*2.53*
Spring date 3:	1 June	28 May	1 June	28 May	1 June	28 May	4 June	1 June	4 June	1 June	4 June	1 June	31 May	30 May	31 May	30 May	31 May	30 May
Planting date	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Late Aug.	2574	2076	13894	7755	69.5	57.5	2292	1882	NA	6300	NA	56.5	1493	933	3623	4597	59	43.5
Early Sept.	2173	1836	11784	7405	69.0	56.5	1921	1742	NA	6067	NA	53.5	1159	786	4598	3754	58	42.5
Late Sept.	1838	1514	8322	7100	69.0	57.5	1605	1398	NA	5048	NA	57.5	857	606	2444	3230	52.5	37.5
Early Oct.	1617	1179	8758	3855	69.0	52.0	1417	1092	NA	1731	NA	47.5	716	408	1877	931	44.5	34.5
Late Oct.	1439	836	8220	3361	69.0	45.0	1263	796	NA	684	NA	44.0	633	298	277	611	31.25	32.0
LSD P = 0.05	–	–	*6546*	*1494*	*0.7*	*4.4*	–	–	–	*1638*	–	*7.09*	–	–	*1617*	*1048*	*15.8*	*3.45*
Spring date 4:	15 June	14 June	15 June	14 June	15 June	14 June	21 June	15 June	21 June	15 June	21 June	15 June	13 June	12 June	13 June	12 June	13 June	12 June
Planting date	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Late Aug.	2939	2408	NA	NA	86.5	65.0	2740	2213	9951	9311	85.0	65.5	1809	1325	11464	6896	66.0	56.5
Early Sept.	2538	2171	NA	NA	87.0	62.0	2369	2001	8700	8947	85.0	66.0	1475	1038	7216	7158	66.0	59.0
Late Sept.	2203	1846	NA	NA	85.0	62.0	2053	1729	10591	7638	84.0	64.5	1173	858	5310	5558	64.0	59.0
Early Oct.	1982	1511	NA	NA	86.0	63.0	1865	1423	9326	5005	82.5	61.0	1032	660	6081	3201	64.0	51.0
Late Oct.	1804	1168	NA	NA	86.0	59.0	1711	1127	7871	2561	81.0	58.0	949	550	1353	23095	59.0	49.0
LSD P = 0.05	–	–	NA	NA	*2.5*	*4.8*	–	–	*2592*	*2734*	*2.17*	*2.6*	–	–	*4686*	*1143*	*2.88*	*3.83*

matured more quickly (Table 3). The differences in winter rye biomass and maturity among planting dates were greatest in late April and early May (Table 6). This was similar to triticale where later plantings had decreased leaf area, decreased solar radiation interception, which then decreased biomass yield (Puckridge and Donald, 1967; Schwarte et al., 2005; Thill et al., 1978). In our study the reduced rate of winter rye growth in the spring was reflected in lower biomass for all planting dates compared to the late August planting date, but lower biomass did not delay anthesis dates for the winter rye planted in early and late September at Lamberton, St. Paul, and for the rye planted in early September at Roseau.

The Spring GDD value from 1 March to 10 June in 2008 at St. Paul was 574, 83% of the long-term norm (Table 4), and that year winter rye also achieved anthesis relatively late (10 June). This indicated the influence of both planting date and Fall GDD on anthesis timing, with the latter being more important (Table 4). In unpublished research, the authors screened numerous accessions of winter rye in Minnesota and found that in unusually warm springs visual observations found little variation in early anthesis dates among the accessions. Based on other research conducted by the authors, in southern Minnesota the anthesis date of the variety 'Rymin' winter rye is typically around 4 June (data not shown). Increased GDD during a warm spring (as in 2007) hastened anthesis by as much as 11 days. Conversely, a cool spring (as in 2013) delayed anthesis by as much as 11 days (P. Porter, unpublished data, 2014).

Conclusions

The optimal planting date in the fall for winter rye can be limited by the harvest of the previous crop, which is typically mid to late October for corn or soybean in Minnesota. This study evaluated the influence of fall planting date on anthesis at three locations in Minnesota in the north and south on five dates, from late August through October, in 2006 and 2007. The two seasons studied represented an abnormally warm (2007) and an abnormally cool (2008) growing season, with the earliest anthesis dates in 2007 being 25 May, 28 May, and 5 June at St. Paul, Lamberton, and Roseau, respectively, whereas in 2008 they were 10 June, 11 June, and 17 June. Our results indicate that no required amount of biomass accumulation was necessary in the fall, but that it was critical for anthesis to have accumulated at least 309 GDD in the fall so as not to be delayed the following spring. We did observe an exception to this rule in one site year (Lamberton in 2007) where winter rye planted relative early in the fall (by early September) received only 275 Fall GDD yet still achieved early anthesis.

For a given GDDT and Spring GDD, the growth stage of winter rye was further along at Roseau compared to St. Paul or Lamberton. Winter rye grown at Roseau required fewer GDD to reach anthesis compared with winter rye grown at St. Paul or Lamberton. This information will enable growers to know how late in the fall they can plant winter rye without delaying time to anthesis, which corresponds to planting by late September (~20) and early September (~8) in southern and northern Minnesota, respectively.

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