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Agronomic Factors Affecting Dryland Grain Sorghum Maturity and Production in Northeast Colorado

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ABSTRACT

Grain sorghum [*Sorghum bicolor* (L.) Moench] is an important dryland crop in southeastern Colorado, but expansion into northeastern Colorado is thought to be limited due to the shorter growing season. The study examined whether sorghum production could be expanded into northeastern Colorado. A 2-yr study in northeastern Colorado at Akron (2010, 2011), Fort Collins (2011), and Stratton (2010) investigated row orientation, seeding rate, and row spacing effects for three hybrids within early to medium-early maturity classes on the time to physiological maturity and grain yield. All treatments reached physiological maturity in the four trial environments. Hybrid selection and seeding rate significantly impacted the thermal time to reach physiological maturity. The medium-early hybrid (5745) matured significantly later than the early maturity hybrids (88P68 and DKS29-28). The seeding rate of 20 seeds m^{-2} matured significantly earlier than 11 seeds m^{-2}, which matured much earlier than 3 seeds m^{-2}. Row orientation and row spacing did not influence maturity. Yields were generally acceptable across all environments, hybrids, and agronomic treatments, and average yields among environments ranged from 1690 to 4845 kg ha^{-1}. Probabilities of the hybrids reaching maturity were high at Akron and Stratton (at least 62 and 86%, respectively, for the latest simulated planting date), but low for Fort Collins (highest of 75% for the earliest simulated planting date). Grain sorghum can successfully be grown in northeast Colorado, especially if planting early maturity hybrids using 0.76 m row spacing at a seeding rate close to 11 seeds m^{-2}.

Grain sorghum is an important dryland crop in southeastern Colorado. More than 146,000 t were produced in Colorado in 2013 (USDA, 2014), with more than 50% being grown in southeastern Colorado. Grain sorghum is grown on few acres in northeastern Colorado, as successful production is thought to be limited by the short growing season and cool night temperatures in the spring and fall. This prevents the crop from reaching physiological maturity, and therefore it can significantly reduce grain yield and test weight (Staggenborg and Vanderlip, 1996). Many of the commercial grain sorghum hybrids are bred and marketed for producers in the southern High Plains region of the United States, where the growing season length is not a concern.

Many grain producers in semiarid northeastern Colorado practice crop rotations that include winter wheat (*Triticum aestivum* L.) followed by a spring crop, and then a fallow period before planting back to winter wheat again (Kramer and Ross, 1970). Grain sorghum is an attractive crop for producers to include in the rotation due to its high adaptability to semiarid regions and the relatively low cost of production compared to corn (*Zea mays* L.) (Jones and Johnson, 1991; Staggenborg et al., 2008). Rarely is sorghum selected over corn as part of the rotation given the perceived problems of growing sorghum and the ease of weed control, well-developed marketing systems, and improved drought tolerance of corn in recent years (Staggenborg et al., 2008). Grain sorghum is more drought tolerant than corn and has higher yield than corn in dry years in eastern Colorado when all other factors are held equal (Norwood, 1999; Staggenborg et al., 2008).

Although research has increased our understanding of grain sorghum yield in the semiarid High Plains, much less research is available to address questions related to growing sorghum in areas with short growing seasons. Producer decisions play a large role in improving the chance that grain sorghum reaches maturity, especially when choosing which hybrid to grow. Hybrid selection is the most important factor affecting maturity since the number of required growing degree-days (GDD) to maturity is primarily determined by genetics (Poehlman, 1987; Rooney and Aydin, 1999; Quinby and Karper, 1945). Hybrids in later maturity classes tend to tiller more than early maturity class hybrids, and the grain-fill period is longer than in shorter season hybrids, which extends

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Abbreviations: COAGMET, Colorado Agricultural Meteorological Network; GDD, growing degree-days; WRCC, Western Regional Climate Center.

or increases the total GDD to maturity (Baumhardt et al., 2005; Schaffer, 1980).

Hybrid maturity has been known to affect yield since hybrids in the later maturity classes almost always yield higher than early maturing hybrids when all hybrids are well adapted for the growing conditions and season length (Roozeboom and Fjell, 1998). If the growing season is short though, late maturity hybrids have a much higher chance of reduced yield and test weight due to frost occurring before physiological maturity is reached (Staggenborg and Vanderlip, 1996). Yield of earlier maturing hybrids is generally more stable than late maturing ones since the grain-fill period is shorter and less variable (Saeed and Francis, 1983).

Producers can adjust agronomic practices such as seeding rate, row spacing, and row orientation, which can affect the time for the sorghum crop to reach physiological maturity. In rainfed conditions in southeastern Colorado, Larson and Thompson (2011) found that increasing the seeding rate of sorghum decreased the time required to reach maturity. Much of this response can be explained by the negative interaction of seeding rate and tillering of a plant (Baumhardt et al., 2005; Lafarge et al., 2002), with tillering controlled both by competition of shoots within the plant for resources (e.g., assimilates, water, nutrients) and also light quality mediated by the phytochrome system (Casal, 1988; Kasperbauer and Karlen, 1986, McMaster, 1997, Skinner and Simmons, 1993). A positive relationship exists between time of shoot appearance and maturity, where main shoot panicles reach maturity before tillers. Therefore, the seeding rate effect on time to maturity is strongly correlated to the number of tillers and their time of appearance on a plant, resulting in delaying the time to maturity at low plant populations when considering all shoots within a stand.

Different row spacing widths have also been shown to significantly affect the number of tillers produced by plants. For example, field studies by Jones and Johnson (1991) and Staggenborg et al. (1999) demonstrated that as the row spacing widened, tiller number decreased significantly due to the increased within-row plant competition, leading to earlier maturity. The effects of row orientation on maturity have not been studied directly, but in Kansas, Witt et al. (1972) concluded that row orientation did not significantly affect evapotranspiration or light interception by the plants, suggesting that row orientation would not significantly impact tillering or maturity since available plant resources would be unchanged.

Jones (1995) found grain yield in a dry year was higher in treatments with low plant populations and wide rows than in treatments with high populations and narrow rows. Bond et al. (1964) had similar results and noted that sorghum grown in wide rows (1 m) had a higher yield than when it was grown in narrow rows (0.5 m) during a drought year.

Steiner (1986) measured water use and plant growth for two row orientations, along with other treatments, at Bushland, TX. No significant yield differences were found between North/South and East/West row orientation. Steiner (1986) also reported that plants in wide rows used less water during the vegetative growth phase, and therefore more water was available during the reproductive phase.

If grain sorghum production is to be expanded into northeastern Colorado, information is needed on "best" agronomic practices for ensuring that the crop reaches maturity and has an acceptable yield. The primary objective of this research was to determine how multiple agronomic factors of row spacing, seeding rate, row orientation, and hybrid selection affect the required thermal time for sorghum to reach physiological maturity and the grain yield and test weight. This information was used to determine the probability of sorghum reaching maturity in different environments in northeastern Colorado based on long-term climate data.

MATERIALS AND METHODS

The field study was conducted in four different environments over 2 yr in northeastern Colorado. In 2010, trials were conducted at the Colorado State University Dryland Agro-ecosystems Project site near Stratton, CO (39°17′ N, −102°31′ W, 1325 m elevation), and at the USDA Central Great Plains Research Station near Akron, CO (40°09′ N, −103°08′ W, 1384 m elevation). In 2011, the trials were conducted at the Agricultural Research, Development and Education Center, near Fort Collins, CO (40°40′ N, −105°0′ W, 1558 m elevation), and at Akron, CO. The average long-term annual precipitation ranged from 384 mm (Fort Collins), to 421 mm (Akron) to 444 mm (Stratton; Western Regional Climate Center, 2012). At Akron the trial was planted on a Rago silt loam (fine, smectitic, mesic Pachic Argiustoll), at Stratton on a Richfield silty clay loam soil (fine, smectitic, mesic Aridic Argiustoll), and at Fort Collins on a Connerton–Barnum complex (fine-loamy, mixed, superactive, mesic Torriorthentic Haplustoll and fine-loamy, mixed, superactive, calcareous, mesic Ustic Torrifluvent; National Cooperative Soil Survey, 2003, 2005, 2006a, 2006b). All trials were rainfed, although the Fort Collins site had been irrigated in previous years and may have had some residual soil water carried over to the 2011 growing season.

Study Design

Treatments within each row orientation (North/South or East/West) were arranged in a split-plot design, with row spacing as the main plot, and the hybrid and seeding rate treatments as the subplots with four replications. The North/South row oriented treatments included three cultivars (88P68, DKS29-28, and 5745), two row spacing treatments (0.76 and 1.5 m), and three seeding rates (3, 11, and 20 seeds m^{-2}) for a total of 18 treatments. In the East/West row oriented treatments, a single (intermediate) seeding rate treatment of 11 seeds m^{-2} was used along with the two row spacing (0.76 and 1.5 m) and three hybrid (88P68, DKS29-28, and 5745) treatments for a total of six treatments. The North/South row oriented treatments were planted at all four environments, while the East/West oriented treatments were planted at the Akron location in 2010 and 2011 (two environments). The two row orientation treatments (North/South and East/West) were planted adjacent to each other in the same field and since they were not replicated or randomized due to field limitations, statistical analyses were not possible. Comments were made on general effects or trends that row orientation may have had on time to maturity, grain yield, and test weight.

Plot dimensions were 3 m wide by 9.1 m long. The three hybrids used in the study were selected from different seed companies to ensure a wide range of genetics. The 88P68 cultivar is an early maturity class hybrid from Pioneer Hi-Bred International (62 d to mid-bloom). The 88P68 cultivar has a semi-open panicle with red grain. The DKS29-28 cultivar is an early maturing hybrid from DeKalb (59 d to mid-bloom) and exhibits a semi-open panicle with a bronze grain color. The 5745 hybrid from Syngenta is considered a medium-early maturing cultivar (62 d to mid-bloom) and has an open panicle with red grain.

In 2010, the Akron trial was planted into no-till proso millet (*Panicum miliaceum* L.) stubble on 26 May and harvested on 28 October. The average soil temperature (5-cm depth) on the planting date was 18.4°C. Nitrogen was broadcast as urea on 27 May at a rate of 44.8 kg N ha^{-1} and early season weeds were controlled with Lumax(Syngenta Crop Protection, Inc., Greensboro, NC) (mix of S-metolachlor [acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-,(S)], atrazine [2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine], and mesotrione [2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione]) and glyphosate [Isopropylamine salt of N-(phosphonomethyl)glycine] herbicides before crop emergence. Weed infestations later in the growing season were controlled using 2,4-D (dimethyl-amine salt) and hand weeding when necessary. The Stratton location was planted on 4 June 2010 into mowed and disked corn stubble, and harvested on 4 November. The average soil temperature (5-cm depth) on the planting date was 29.7°C. Nitrogen was applied as urea on 6 June at a rate of 44.8 kg N ha^{-1}. Glyphosate was used to control weeds before emergence and weed infestations later in the growing season were controlled by spot spraying using glyphosate with a covered row hooded sprayer and by hand weeding. No insect or disease infestations were noted for either trial location during the 2010 cropping season.

In 2011, the Akron trial was planted into no-till wheat stubble on 6 June and harvested on 24 October. The soil temperature on the planting date was 23.9°C. Nitrogen was broadcast as urea on 9 June at a rate of 44.8 kg N ha^{-1} and early season weeds were controlled using Lumax herbicide before crop emergence. The Fort Collins location was planted on 4 June into tilled winter wheat stubble and harvested on 11 November. The soil temperature on the planting date was 14.9°C. Soil crusting occurred before crop emergence, so a rotary hoe was used after planting to promote better stand establishment. No fertilizer was applied and early season weeds were controlled using glyphosate plus liquid ammonium sulfate. Weed infestations during the growing season were controlled using 2,4-D and hand weeding. A 3-m wide, four-row cone planter was used to plant all trials.

Data Collection

Daily maximum and minimum temperatures and precipitation for the growing season (1 May through 31 October) were obtained from the Colorado Agricultural Meteorological Network (COAGMET) for the three trial locations. The selected stations were located within 2 km of the trials (stations: akr02-Akron, ftc03-Fort Collins, and stn01-Stratton; Table 1). The daily maximum and minimum temperatures were used to calculate the GDD from planting to physiological maturity for the 18 different treatments. Long-term average GDD are mean values for 100 yr (1912–2011) at Akron, 113 yr (1900–2012) at Fort Collins, and 43 total years (1949–2008) at Stratton and were provided by the Western Regional Climate Center (WRCC) (2012), the USDA-ARS Central Great Plains Research Station, and the Colorado Climate Center (2013). Years with 10 or more missing daily maximum and minimum temperatures during the growing season (May through October) were not used. Years with 10 or fewer missing temperatures during the growing season were still used and missing daily maximum or minimum temperatures were estimated using the long-term average low and high temperatures for the day and month combination at the weather station. For the long-term average precipitation and temperature data (obtained from WRCC for all locations), months with five or more missing days, and years with one or more missing months were not used to calculate long-term averages.

Physiological maturity was the date when half of the kernels in half of the main stem panicles in the plot had a visible black layer at the base of the kernel (Eastin et al., 1973). Seed samples for determining black layer (and maturity) were taken from three random plants in the plot where three to five kernels were removed from the panicle to determine if a black layer had formed. Observations were made every 3 d as plots approached physiological maturity.

The thermal time from planting to physiological maturity was expressed as GDD, with the accumulation of thermal time beginning at planting and concluding as the plants approached physiological maturity. The GDD were calculated as:

$$\mathrm{GDD} = \sum_{i=1}^{n} \left(\frac{T\mathrm{max}_i + T\mathrm{min}_i}{2} \right) - T\mathrm{base} \qquad \mathrm{GDD} \geq 0 \quad [1]$$

where $T\mathrm{max}_i$ and $T\mathrm{min}_i$ are the daily maximum and minimum temperature (°C), respectively, Tbase is the base temperature (°C), and the value is summed daily over a period of n days. If $T\mathrm{max}_i$ exceeded 45°C (Norcio, 1976), $T\mathrm{max}_i$ was set to 45°C. When the average daily temperature ($T\mathrm{max}_i$ and $T\mathrm{min}_i$)/2) was below the base temperature (Tbase) of 7°C (Ercoli et al., 2004; Gerik et al., 2003), no GDD were accumulated for that day.

Historical daily climate data from weather stations associated with the Colorado Climate Center, the Western Regional Climate Center (WRCC), and the USDA Central Great Plains Research Center in Akron were used to calculate the probability of the three hybrids reaching maturity before the first fall frost. Daily maximum and minimum temperatures during the growing season for 100 yr at Akron, 112 yr at Fort Collins, and 43 yr at Stratton were used to calculate cumulative GDD at each location for every available year from each of the three simulated planting dates to the first freeze date for each location–year combination. The yearly freeze date was defined as the first date after 1 June when the minimum daily temperature dropped below –2°C. The threshold cumulative GDD for each hybrid to reach physiological maturity was based on actual cumulative GDD to maturity for each hybrid at each location observed during the study. Threshold GDD values were based on

Table 1. Long-term monthly rainfall, average temperature, and, cumulative growing degree-days (GDD) during the growing season (1 May–31 October) for the four trial environments.

Month	Rainfall	Long-term avg. rainfall†	Avg. temp.‡	Long-term avg. temp.†‡	GDD§	Long-term avg. GDD†§
	mm		°C			
Stratton, CO, 2010						
May	46	69	12.1	14.9	165	250
June	17	64	20.9	20.6	418	414
July	132	75	23.6	24.1	515	528
Aug.	85	63	23.2	23.1	503	492
Sept.	7	33	18.8	18.1	353	327
Oct.	7	28	11.6	11.7	150	164
Sum/Avg.	295	332	18.4	18.8	2104	2175
Akron, CO, 2010						
May	43	73	11.9	13.5	165	210
June	59	58	20.4	19.4	402	369
July	47	66	23.1	23.4	498	500
Aug.	43	58	23.0	21.9	497	464
Sept.	4	31	18.6	17.1	347	298
Oct.	17	23	11.9	10.1	160	133
Sum/Avg.	215	309	18.2	17.6	2069	1974
Akron, CO, 2011						
May	163	73	11.2	13.5	141	210
June	36	58	19.6	19.4	379	369
July	104	66	24.3	23.4	536	500
Aug.	2	58	24.4	21.9	540	464
Sept.	31	31	16.8	17.1	294	298
Oct.	26	23	10.1	10.1	138	133
Sum/Avg.	362	309	17.7	17.6	2028	1974
Fort Collins, CO, 2011						
May	90	70	10.8	13.1	130	196
June	51	46	18.7	18.3	351	339
July	46	41	22.9	21.4	494	450
Aug.	6	36	22.7	20.5	486	419
Sept.	24	32	16.2	15.7	275	263
Oct.	38	29	9.7	9.6	122	106
Sum/Avg.	255	254	16.8	16.4	1858	1773

† Long-term average rainfall, temperature, and GDD are mean values for 100 yr (1912–2011) at Akron, 113 yr (1900–2012) at Fort Collins, and 43 total years (1949–2008) at Stratton.

‡ Average monthly temperatures were calculated by averaging the daily maximum and minimum temperatures ((max. temp + min. temp)/2) for the month.

§ The GDD values were calculated using base temperature of 7°C and no maximum temperature. The GDD were not accumulated on days when the average temperature was below the base temperature.

the maturity of the plots under the best agronomic practices (i.e., those practices with the fewest GDD required to reach maturity) when treatment differences were significant. When treatment differences were not significant, the GDD results were pooled within each hybrid and location combination.

Grain yield and test weight data were collected for all treatments in both row orientations at Stratton in 2010. At Akron in 2011, all grain yield data was collected from all treatments, but test weight data for 88P68 at the 20 seeds m^{-2} seeding rate and 1.5-m row spacing were not available due to insufficient grain in the combine. All grain yield and test weight data were collected from all treatments in the North/South orientation in Akron in 2010, and Fort Collins in 2011. Grain was harvested from the plants in the two center rows of the four-row plots with the 0.76-m row width treatments. In the 1.5-m row spacing treatments, the single middle row of plants was harvested for yield to minimize plot border effects. Grain weight, moisture content, and test weight data were collected from each plot using a modified Gleaner plot combine equipped with a Harvest Master grain weighing system. All grain yields were adjusted to 14% grain moisture content.

Statistical Analysis

The MIXED procedure within the SAS program was used for analysis of variance (SAS Institute, 2011). For maturity and yield measurement analyses, fixed effects in the model were environment, row spacing, hybrid, and seeding rate, along with all of their interactions. Random variables in the model were replicates within environment and the row spacing by replicate interaction within environments. Mean separation tests were done using the pdiff and slice options in SAS proc mixed. An α level of 0.05 was used to determine significant effects.

RESULTS

Growing conditions during the growing season (May through October) differed among locations and years (Table 1). The mean average temperature of the growing season was above the long-term average for Akron during both 2010 and 2011 and Fort Collins in 2011, and below the long-term average for Stratton in 2010. The average temperature in May was below the long-term average for all four environments, although no other month showed consistent differences from the long-term average. The cumulative GDD over the course of the growing season reflected the average temperature pattern among environments, and the cumulative GDD was greatest at Stratton and lowest at Fort Collins.

The environment at Akron in 2010 had the least precipitation during the growing season (215 mm) and greatest deviation from the long-term average total precipitation (−94 mm), while Akron in 2011 had the most precipitation (362 mm) and was 53 mm above the long-term average total, of the four environments. Precipitation in Fort Collins during the 2011 growing season (255 mm) was very close to the long-term average total (254 mm), and although Stratton in 2010 had the second highest precipitation (295 mm) of the four environments, it was 37 mm below the long-term average total (332 mm). The 2011 environments were characterized by having above average rainfall totals during the early months of the growing season (May through July; Akron = 106 mm above average, Fort Collins = 30 mm above average), helping to alleviate the amount of water stress later in the growing season (August through October). The 2010 environments had below average rainfall early in the growing season (Akron = 94 mm below average, Stratton = 13 mm below average despite very high July precipitation). All four environments had below long-term average precipitation totals from August through October, but when considering just the months of September and October, the 2010 environments were below average and the 2011 environments were equal to the long-term average.

Maturity

North/South Row Orientation with Row Spacing, Hybrid, and Seeding Rate Treatments in Four Environments

Out of the four main effects and 11 interactions, five effects were significant at a *P* value ≤ 0.05 (Table 2), and all treatments in the four environments reached physiological maturity. Significant effects on cumulative GDD to maturity were observed for environment, hybrid, and seeding rate, as well as for the two-way interactions of environment × hybrid and environment × seeding rate. Among main effects, row spacing did not have a statistically significant effect on cumulative GDD to maturity. However, row spacing by hybrid was very close to being statistically significant at a *P* value of 0.053.

The environment × hybrid two-way interaction for maturity was significant ($P = 0.003$). The 88P68 hybrid was significantly earlier than DKS29-28 at both locations in 2010, however, in both locations in 2011 no significant difference was found between the two hybrids (Fig. 1). Significant differences were observed among hybrids within each environment (Table 3), but this was due to the 5745 hybrid requiring significantly more GDD to reach maturity (about 78 GDD) than DKS29-28 and 88P68 at all four environments. Growing season cumulative GDD to maturity across the different environments were not significantly different from one another within each year, but there was a significant difference of cumulative GDD between the 2 yr regardless of the location.

Table 2. Analysis of variance of cumulative growing degree-days to physiological maturity for treatments in the North/South row orientation for four trial environments, two row spacings, three seeding rates, and three hybrids.

Effect	Degrees of freedom	*P* value
Environment (ENV)	3	0.010
Row spacing (RS)	1	0.830
Hybrid (H)	2	<0.001
Seeding rate (SR)	2	<0.001
ENV × RS	3	0.568
ENV × H	6	0.003
ENV × SR	6	<0.001
RS × H	2	0.053
RS × SR	2	0.158
H × SR	4	0.441
ENV × RS × H	6	0.064
ENV × RS × SR	6	0.139
ENV × H × SR	12	0.886
RS × H × SR	4	0.294
ENV × RS × H × SR	12	0.081

On the average, sorghum reached maturity with 51 fewer GDD in the 2011 environments than in the 2010 environments when all other treatments (hybrid, row spacing, and seeding rate) were pooled.

The environment × seeding rate two-way interaction was highly significant ($P < 0.001$) as the environmental effects greatly influenced the time to maturity among the three seeding rates (Fig. 2). At Stratton (2010) and Fort Collins (2011), the lowest seeding rate (3 seeds m^{-2}) took significantly longer to mature than the medium and high seeding rate treatments. The medium rate (11 seeds m^{-2}) took significantly longer to reach maturity than the high rate (20 seeds m^{-2}) at both locations. At Akron in 2011, the lowest seeding rate took significantly more GDD to reach maturity, but the medium seeding rate took the least number of GDD to maturity instead of the high seeding rate, although the difference between the medium and high rates was not significant. At Akron in 2010, there were no significant differences among any of the seeding rate treatments. In a combined ANOVA of the Stratton (2010) and Fort Collins (2011) data (results not shown), the interaction with seeding rates was not significant, and as seeding rate increased from 3 to 20 seeds m^{-2} the

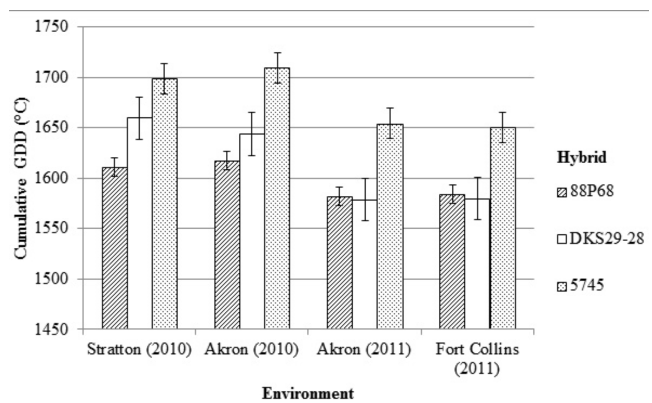

Fig. 1. Cumulative growing degree-days (GDD) from planting to physiological maturity for three hybrids within environments in the North/South row orientation. All treatments within a location are pooled within each environment.

Table 3. Cumulative growing degree-days (GDD) from planting to physiological maturity for North/South row orientation with two row spacings, three seeding rates, three hybrids, and four trial environments.

Main effect	Hybrid			Seeding rate, seeds m^{-2}			Overall avg.†
	88P68	DKS29-28	5745	3	11	20	
	cumulative GDD						
Row spacing, m							
0.76	1609	1612	1681	1651	1632	1618	1633
1.5	1586	1614	1671	1649	1617	1605	1623
Environment (loc. and year)							
Stratton (2010)	1611	1659	1699	1694	1659	1622	1656
Akron (2010)	1617	1644	1709	1648	1660	1660	1656
Akron (2011)	1582	1579	1654	1637	1588	1591	1605
Fort Collins (2011)	1584	1580	1650	1636	1601	1576	1605
Overall avg.†	1598	1613	1676	1650	1625	1611	1629

† Overall avg. values are weighted averages based on the number of data points for each treatment.

Table 4. Analysis of variance of cumulative growing degree-days to maturity in the East/West row orientation for two environments, two row spacings, and three hybrid treatments.

Effect	Degrees of freedom	*P* value
Environment (ENV)	1	0.005
Row spacing (RS)	1	0.901
Hybrid (H)	2	<0.001
ENV × RS	1	0.425
ENV × H	2	0.082
RS × H	2	0.824
ENV × RS × H	2	0.114

Table 5. Cumulative growing degree-days (GDD) from planting to physiological maturity for East/West row orientation with two row spacings and three hybrids in two trial environments.

Effect	Hybrid			Overall avg.†
	88P68	DKS29-28	5745	
	cumulative GDD			
Row spacing, m				
0.76	1598	1608	1659	1622
1.5	1600	1603	1660	1621
Environment				
Akron (2010)	1616	1637	1682	1645
Akron (2011)	1582	1573	1636	1597
Overall avg.†	1599	1605	1659	1621

†Overall avg. values are weighted averages.

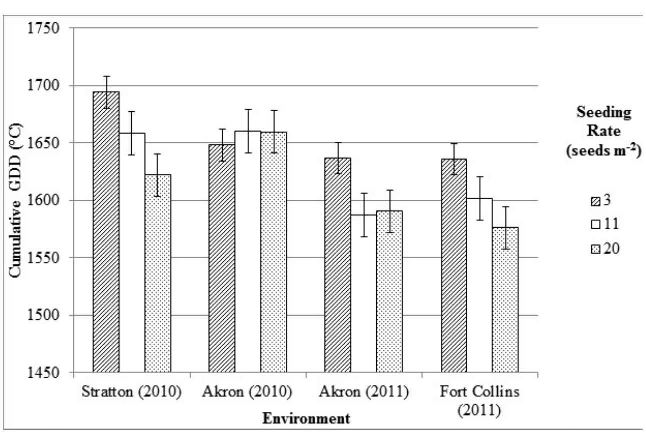

Fig. 2. Cumulative growing degree-days (GDD) from planting to physiological maturity for three seeding rates within environments in the North/South row orientation. All treatments within a location are pooled within each environment.

average thermal time to maturity significantly decreased. The 3 seeds m^{-2} treatment took more GDD (33) to reach maturity than planting 11 seeds m^{-2}, which took more GDD (29) to mature than the seeding rate of 20 seeds m^{-2}.

East/West Row Orientation with Row Spacing and Hybrid Treatments in Two Environments

As with the North/South row orientation, all treatments within East/West orientation reached maturity. Significant two-way interactions were found in rows oriented North/South (environment × hybrid and environment × seeding rate), but no significant two-way interactions were found in the East/West oriented rows. The main effects of hybrid ($P < 0.001$) and environment ($P = 0.005$) were significant in the East/West oriented rows, and row spacing was not significant ($P = 0.901$; Tables 4 and 5). Among hybrids, the medium-early cultivar (5745) required significantly more GDD (54) to reach maturity than the earlier maturing cultivar, DKS29-28 (Table 5). There was no significant difference in cumulative GDD to maturity between 88P68 and DKS29-28. For the environment main effect, significantly fewer GDD (48) were required for the treatments to reach maturity at Akron in 2011 than in 2010 (Table 5).

The East/West row oriented treatments main effect results were similar to the North/South oriented treatment main effects that were common between the two row orientations. Although the differences in maturity between the two row orientations cannot be analyzed for treatment differences, comparing data for the two row orientations did not indicate any differences in thermal time to maturity.

Probabilities of Hybrids Reaching Maturity at the Three Trial Environments in Northeast Colorado

The probability of each hybrid reaching physiological maturity before the first fall frost for different simulated planting dates at Akron, Fort Collins, and Stratton were compared using the required GDD from the treatments included in the North/South row orientation (Table 6). The probability of reaching maturity before the first fall freeze decreased when the simulated planting date was later in the season. The probably of reaching maturity was lowest for the medium-early maturity hybrid (5745) when compared to the early maturity class hybrids (88P68 and DKS29-28). The long-term average temperature and accumulated GDD from 1 May through 31 October varied among environments (Table 1) and

Table 6. Probability of each hybrid reaching physiological maturity before the first fall frost at three Northeast Colorado locations from three start (planting) dates based on historical weather data and required growing degree-days (GDD) for each hybrid at each location.†

Location	Hybrid	Required GDD‡	GDD accumulation start date		
			15 May	23 May	1 June
				%	
Akron, CO					
	88P68	1590	89	88	80
	DKS29-28	1603	89	88	80
	5745	1662	87	84	62
Fort Collins, CO					
	88P68	1538	75	67	49
	DKS29-28	1546	75	66	46
	5745	1637	57	40	25
Stratton, CO					
	DKS29-28	1630	91	86	86
	88P68	1594	91	88	86
	5745	1646	91	86	86

† Historical daily maximum and minimum temperatures at each location (100 yr at Akron, 112 yr at Fort Collins, and 43 yr at Stratton) were used to calculate cumulative GDD at each location for every available year.

‡ Required GDD for each hybrid and location combination were determined based on the best agronomic practices for each location. Nonsignificant practices were pooled and the same practices were used for all hybrids within each location.

considerably influenced the probability of reaching maturity. Stratton had the highest average temperature (18.8°C) and most accumulated GDD (2175) of all environments, and regardless of planting date or hybrid, the probability of reaching maturity ranged from 86 to 91%. Akron, with an average temperature of 17.6°C and 1974 accumulated GDD had probabilities of reaching maturity ranging from 80 to 89% for all simulated planting dates and hybrids except for 5745 hybrid planted on 1 June (62%). The probability of reaching maturity at Fort Collins was the lowest of three environments, with fairly low probabilities for the medium-early maturity 5745 hybrid (from 25 to 57%) and 1 June simulated planting dates (from 25 to 49%).

Yield

North/South Row Orientation with Row Spacing, Hybrid, and Seeding Rate Treatments in Four Environments

Significant factor effects on grain yield ($P \leq 0.05$) were environment, hybrid, and seeding rate, as well as the two-way interactions of environment × row spacing and environment × seeding rate (Table 7). As observed with GDD to maturity, the row spacing main effect on yield was not significant. The significant environment × row spacing two-way interaction can be explained as different optimal row spacing in different environments (Table 8). The grain yield at Fort Collins and Stratton was significantly higher in the 0.76 m row spacing than in the 1.5 m row spacing, but during both years at Akron, the yield was significantly higher in the 1.5 m row spacing. The 1.5 m row spacing had a significantly higher yield than the 0.76 m row spacing at Akron in 2010, but was not significantly different in 2011. The significant environment × seeding rate interaction for yield was due to the 3 seeds m^{-2} seeding rate having a significantly lower grain yield than the 11 seeds m^{-2} seeding rate at Fort Collins. No significant yield differences were observed as a result of the seeding rates in the three remaining environments. The hybrid main effect was significant as the 88P68 hybrid had a significantly lower yield than DKS29-28 and 5745 hybrids, which were not significantly different from each other.

Test Weight

North/South Row Orientation with Row Spacing, Hybrid, and Seeding Rate Treatments in Two Environments

Out of the four main effects and 11 interactions, eight effects were significant (Table 9). Significant effects on grain test weight were observed for environment, hybrid, and row spacing, as well as for the two-way interactions of environment × hybrid and row spacing × seeding rate. Significant three-way interactions were observed for environment × row spacing × hybrid, environment × row spacing × seeding rate, and row spacing × hybrid × seeding rate.

The three-way interaction of environment × hybrid × row spacing was significant because the 5745 hybrid had a significantly lower test weight than DKS29-28 in three of the four possible row spacing × environment combinations. At the Akron environment in the 0.76-m row spacing, the difference between 5745 and DKS29-28 was not significant (Table 10). The 88P68 hybrid had a significantly higher test weight than

Table 7. Analysis of variance of grain yield in the North/South row orientation for four environments, two row spacings, three hybrids, and three seeding rate treatments.

Effect	df	*P* value
Environment (ENV)	3	<0.001
Row spacing (RS)	1	0.163
Hybrid (H)	2	0.031
Seeding rate (SR)	2	<0.001
ENV × RS	3	0.002
ENV × H	6	0.273
ENV × SR	6	<0.001
RS × H	2	0.745
RS × SR	2	0.364
H × SR	4	0.537
ENV × RS × H	6	0.104
ENV × RS × SR	6	0.200
ENV × H × SR	12	0.678
RS × H × SR	4	0.990
ENV × RS × H × SR	12	0.973

Table 8. Grain yield for the North/South row orientation with two row spacings, three seeding rates, three hybrids, and four trial environments.

Main effect	Hybrid			Environment				
	88P68	DKS29-28	5745	Stratton (2010)	Akron (2010)	Akron (2011)	Fort Collins (2011)	Overall avg.†
	kg ha^{-1}							
Row spacing, m								
0.76	2862	3290	3147	2961	1298	2927	5213	3100
1.5	2771	3000	2903	1995	2083	3062	4467	2891
Seeding rate, seeds m^{-2}								
3	2410	2530	2652	2192	1514	2902	3559	2531
11	3143	3384	3192	2548	1882	3123	5404	3239
20	2895	3507	3232	2692	1675	2959	5518	3211
Overall avg.†	2816	3147	3025	2478	1690	2995	4845	2995

† Overall avg. values are weighted averages.

Table 9. Analysis of variance of grain test weight for treatments in the North/South row orientation for two trial environments (Akron 2011 and Fort Collins 2011), two row spacings, three seeding rates, and three hybrids.

Effect	df	*P* value
Environment (ENV)	1	0.007
Row spacing (RS)	1	0.006
Hybrid (H)	2	<0.001
Seeding rate (SR)	2	0.313
ENV × RS	1	0.821
ENV × H	2	0.001
ENV × SR	2	0.853
RS × H	2	0.894
RS × SR	2	0.042
H × SR	4	0.086
ENV × RS × H	2	0.008
ENV × RS × SR	2	0.049
ENV × H × SR	4	0.304
RS × H × SR	4	0.037
ENV × RS × H × SR	3	0.186

the other two hybrids in all of the environment × row spacing combinations.

The three-way interaction of row spacing × seeding rate × environment was significant. The test weights significantly decreased as the seeding rate increased in both row spacing treatments at Akron, while at Fort Collins there was no significant difference among the seeding rates in the 0.76 m row spacing, and in the 1.5 m row spacing the 11 seeds m^{-2} treatment had a significantly higher test weight than the 3 and 20 seeds m^{-2} treatments (Table 10).

The three-way interaction of row spacing × hybrid × seeding rate was significant due to the 5745 hybrid having a test weight that was not significantly different from DKS29-28 in the 0.76 m row spacing at the 20 seeds m^{-2} seeding rate (Table 10; when averaged across both locations). In the five remaining seeding rate by row spacing combinations, DKS29-28 had a significantly higher test weight than the 5745 hybrid.

Table 10. Grain test weight in 2011 for treatments in the North/South row orientation for two trial environments, two row widths, three planting populations, and three hybrids.

Location	Row spacing	Hybrid	Planting rate, seeds m^{-2}			Overall avg.†
			3	11	20	
	m		kg m^{-3}			
Akron						
	0.76		691	678	643	667
		88P68	730	696	689	700
		DKS29-28	699	662	593	640
		5745	656	674	658	663
	1.5		710	694	675	694
		88P68	766	717	–	745
		DKS29-28	704	692	689	695
		5745	670	686	663	674
Fort Collins						
	0.76		667	663	663	664
		88P68	739	717	697	718
		DKS29-28	671	660	664	665
		5745	590	612	629	610
	1.5		687	710	691	696
		88P68	737	753	739	743
		DKS29-28	668	708	682	686
		5745	655	670	652	659
Overall Avg.†			689	686	665	680

† Overall avg. values are weighted averages.

DISCUSSION

Maturity

Hybrid, environment, and seeding rate significantly influenced the thermal time to maturity, while row spacing and orientation did not. The first objective of this work addressed whether sorghum could reach physiological maturity during the growing seasons in northeast Colorado. The study examined main shoot panicles within four trial environments (Akron 2010 and 2011, Stratton 2010, and Fort Collins 2011). These environments varied for expected seasonal precipitation, average temperature, and accumulated GDD over the course of the growing season (Table 1). Given that all treatments in the four trial environments reached physiological maturity, sorghum can reach maturity in northeast Colorado. Saeed and Francis (1986) also found that 46 sorghum hybrids reached physiological maturity for 2 yr grown at Sidney (41°13′ N, −102°98′ W) and Mead, NE (41°23′ N, −96°49′ W).

Hybrids in different maturity classes will reach physiological maturity at different times due to genetic differences (Poehlman, 1987; Rooney and Aydin, 1999; Quinby and Karper, 1945), and this was confirmed in our study. The hybrid in the medium-early maturity class (5745) took significantly more time to reach maturity than the two hybrids in the early maturity class (88P68 and DKS29-28) in all trial environments. The significant hybrid × environment interaction was due to the 88P68 hybrid requiring fewer GDD to reach maturity than DKS29-28 in both 2010 environments while there was no difference between the two hybrids in the 2011 environments.

All hybrids required slightly more GDD to reach maturity in 2010 than in 2011 (Tables 3 and 5). Variation in thermal time is expected as other environmental factors such as water deficits, light (photoperiod, intensity, and quality), and nutrients can also influence the timing of maturity (McMaster et al., 2008). McMaster et al. (2013) proposed that water deficits delay sorghum flowering but shorten the grain-filling period, with the final result in thermal time to maturity determined by the dynamic interplay of the degree and timing of water stress during the two phases. Precipitation may serve as an indicator of water stress, and the seasonal precipitation in 2010 for both environments was less than the long-term average, while the seasonal precipitation in 2011 was greater than the long-term average for Akron and equal to the long-term average in Fort Collins, which also may have had greater than normal soil water at planting due to irrigation the previous season (Table 1). The trial environments varied considerably on the pattern of rainfall during the growing season, and this may have influenced time of flowering and grain-filling duration. Measurements of flowering were made (data not shown), and hybrid 88P68 reached flowering between 6 and 15 August, DKS29-28 between 12 and 20 August, and 5745 between 17 and 21 August when pooling all trial environments and treatments. The weather data in Table 1 were used to test for a correlation between precipitation from May through July (using 1 August as the date dividing pre- and post-flowering phases) and thermal time to anthesis, and no correlation was found. Similarly, no significant correlation was found between precipitation from August through October and the duration of grain filling. Therefore, the differing thermal time to maturity between years was negatively correlated with total seasonal precipitation, but precipitation within the growing season was not correlated with the time of flowering and duration of grain filling.

Thermal time to maturity generally decreased as seeding rate increased, although the interaction between the seeding rate and the four trial environments on cumulative GDD to maturity was due to different effect trends at Akron in 2010 compared to the three other trial environments. The seeding rate effect in 2010 at Akron was not substantial due to low growing season rainfall resulting in little available soil water by mid-grain filling in all treatments. This caused the different seeding rate treatments to mature about the same time. The difference between the highest and lowest seeding rate treatments in the thermal time of the main shoot panicles to reach maturity was –72 GDD (2010 Stratton), −60 GDD (2011 Fort Collins), −46 GDD (2011 Akron), and 12 GDD (2010 Akron; Table 3). Larson and Thompson (2011) found a negative correlation between seeding rate and time to maturity under dryland conditions in southeastern Colorado. They measured all shoots within the plot and not just the main shoot panicle. Because of the confounding effects of tillers reaching maturity later than main shoots, and that tiller number per plant increases as the seeding rate decreases, it is unknown if main shoot maturity was altered by seeding rate. Saeed and Francis (1986) measured main stem panicles for days to maturity for different seeding rates at Mead and Sidney, NE, for 2 yr, and while they did not find a significant difference, the highest seeding rate always reached maturity 1 to 2 d earlier than the lowest seeding rate. Lafarge et al. (2002) measured tillered and uniculm plants for non-limiting conditions in Queensland, Australia, and also found a nonsignificant trend of earlier maturity as seeding rate increased. Our experiment and Larson and Thompson (2011) showed a significant negative relationship between seeding rate and time to maturity while other studies showed trends. These other studies were conducted in very different environments, which likely altered the competition among plants and plant shoots.

Our results showed no significant effects of row spacing or orientation on time to maturity. Based on the relationship among seeding rate, tillering, and time to maturity, it could be postulated that wide row spacing should have decreased the cumulative GDD to maturity due to greater within-row populations, which should decrease tillering. Jones and Johnson (1991) reported tillering in a narrow row spacing (0.76 m) was significantly higher than in wide (1.5 m) row spacing in the Texas High Plains, which was confirmed by a study by Staggenborg et al. (1999) in northeastern Kansas. We do not know why, but the row spacing effect may not have significantly affected plant maturity in our study due to sufficient amounts of available water between the wide rows. The stored water between the rows could have offset the effect of the increased competition within the rows. Increased light between wide rows could have compensated for the reduced light within a row. No differences in light interception or evapotranspiration of sorghum were found for different row orientations at Manhattan, KS (Witt et al., 1972), or Bushland, TX (Steiner, 1986).

Our results and those of Saeed and Francis (1986) in western Nebraska show that sorghum can reach maturity in northeastern Colorado environments and that agronomic practices influence thermal time to maturity. We assessed the probability of reaching maturity occurring over trial locations. We hypothesized that the probability of reaching maturity would increase with longer growing seasons, earlier planting dates, and using early maturity hybrids, and this was found to be true (Table 6). Of the three trial locations, Fort Collins has the shortest average growing season and Stratton the longest. The probability of reaching maturity ranged from 86 to 91% for all simulated planting dates and hybrids at Stratton, from 80 to 89% for all planting dates of the two early maturity hybrids at Akron, and from 46 to 75% for all planting dates of the two early maturity hybrids at Fort Collins. These results suggest a reasonably high probability of reaching maturity for Stratton and Akron but probably an unacceptably low probability for Fort Collins, particularly if growing an early-medium maturity class hybrid and a late planting date (25%). The fact that sorghum in our trial reached maturity in 2011 at Fort Collins was likely due to warmer than historic average monthly temperatures from June through October. The fall frost date occurred 10 d later than expected based on 100-yr weather records.

The probability of reaching maturity could be significantly increased by planting earlier in the season at the two trial locations that are at higher latitudes, assuming soil temperature and moisture are conducive for seedling emergence and growth. If the 5745 cultivar was planted on 15 May at Fort Collins instead of 1 June, the probability of reaching maturity before the frost date of 9 October would increase from 25 to 57%. The planting date effect on the probability of reaching maturity is just as important as choosing an appropriate hybrid in the correct maturity class. If sorghum can be planted earlier in the season, a later maturing hybrid could be used to increase potential grain yield since more GDD units will be accumulated during the growing season. The calculated probabilities do not indicate how close to maturity the plant is if frost occurred before reaching maturity. It is likely that for Akron and Stratton, the majority of grain yield had occurred by the frost date and little yield reduction would be expected even if maturity was not reached. If two cultivars within the same maturity class take the same amount of time to reach physiological maturity (such as the two early maturity hybrids in our study), other hybrid characteristics such as yield or stalk strength should be taken into consideration as criteria for hybrid selection.

Yield and Test Weight

After determining whether sorghum could reach maturity, our second objective was to assess the yield and test weight responses at each location for different agronomic practices. The trial environment, hybrid, and seeding rate main factors, and the two-way interactions of environment with row spacing and environment with seeding rate, significantly affected grain yield (Table 7). The row spacing main factor, along with all three- and four-way interactions did not significantly impact yield.

Yields in our experiment varied among hybrids, environments, and some agronomic treatments (Table 8). When pooling hybrids and treatments within an environment, the 2010 Akron yield (1690 kg ha^{-1}) was significantly lower than the 2010 Stratton (2478 kg ha^{-1}) and 2011 Akron (2995 kg ha^{-1}), and the 2011 Fort Collins yield was significantly higher than the other environments (4845 kg ha^{-1}). Our yields were within the large variation of the reported mean yields of all hybrids in 2010 and 2011 at Brandon (4139 and 1191 kg ha^{-1}, respectively) and Walsh (5581 and 2697 kg ha^{-1}, respectively) in southeastern Colorado (Larson et al., 2010; 2011). No significant correlation between yield and growing season precipitation was found, partly because of the high Fort Collins 2011 yield which might be due to the site being irrigated in the previous years and possible carry-over of soil moisture.

When pooling environments and treatments, 88P68 had significantly lower yield (2816 kg ha^{-1}) than DKS29-28 (3147 kg ha^{-1}) and 5745 (3025 kg ha^{-1}), which were not significantly different (Table 8). Roozeboom and Fjell (1998) reported that yield is negatively related to maturity group, and while this was not consistently found in our experiment, our results might reflect individual varietal differences more than the real difference in maturity groups. Selecting a hybrid for northeastern Colorado should balance the length of the growing season with yield potential, and there appears to be a trade-off where 88P68 tends to mature earlier than DKS29-28, but also has lower yield.

We found a two-way interaction between environment and row spacing, and some studies have postulated this interaction to be related to available soil water. Bond et al. (1964) reported that wide row spacing treatments at Bushland, TX, had a higher yield than narrow rows when <13 cm of moisture was available in the soil profile. Vigil et al. (2008) also found skip-row yield at Akron, CO, was higher than in traditional 0.76 m row spacing during years when moisture was limited. Grain yield was significantly affected by row spacing at three of the four environments (not Akron 2011) in our study. In the driest environment at Akron in 2010, the wide/skip-row (1.5 m) treatment had a higher yield than the narrow row treatment, whereas in the much wetter Akron 2011 season there was no difference between the row spacing treatments. Narrow row spacing had significantly higher yield than skip-row spacing at both 2010 Stratton and 2011 Fort Collins. Our overall results show that precipitation cannot be used as a surrogate for soil moisture to verify a consistent relationship between yield and row spacing.

We found a significant environment × seeding rate interaction, and this was due to the lowest seeding rate (3 seeds m^{-2}) having a significantly lower yield than 11 or 20 seeds m^{-2} at Fort Collins 2011, which had the highest grain yield among the four environments. In general, seeding rate did not significantly change grain yield. In a dryland sorghum study at Bushland, TX (Steiner, 1986), a seeding rate of 18 seeds m^{-2} had a lower yield than seeding rates of 6 or 12 seeds m^{-2} during a dry year with low soil moisture. Presumably there is an optimal seeding rate, but Steiner's results and our results suggest this may be a fairly broad range based on available soil moisture conditions, perhaps in the range of 6 to 12 seeds m^{-2}.

Test weights varied between the two trial environments (2011 Akron and Fort Collins), hybrids, and some agronomic practices in our study (Table 9). Environment, row spacing, and hybrid main effects had a significant impact on grain test weight, along with two of the two-way interactions (environment × hybrid and row spacing × seeding rate), and three of the three-way interactions (environment × row spacing × hybrid; environment × row spacing × seeding rate; row spacing × hybrid by seeding rate). Test weights in our experiment (Table 10) are similar to the reported mean test weight of all hybrids in 2010 and 2011 at Brandon (734 kg m^{-3} and 656 kg m^{-3}, respectively) and Walsh (772 and 746 kg m^{-3}, respectively) in southeastern Colorado (Larson et al., 2010, 2011).

There was a negative relationship between grain yield and test weight for both main factor effects of hybrid and environment. Hybrid 88P68 had a significantly higher test weight and lower yield than both DKS29-28 and 5745, and Akron had a significantly higher grain test weight and lower grain yield than Fort Collins. The row spacing main effect was significant, with the test weight significantly higher in the 1.5 m spacing than the 0.76 spacing treatment. This is interesting because row spacing only occasionally affected yields, but in all cases (even in all three-way interaction combinations) the wide (1.5 m) row spacing improved grain test weights, which is an index of grain quality. We do not know why the wide row spacing improved the grain test weight (697 kg m^{-3}) compared to the narrow row spacing (0.76 m; 679 kg m^{-3}). Plant stress factors such as cold temperatures and drought can reduce the grain test weight.

CONCLUSIONS

We examined whether grain sorghum production could be expanded from southeastern Colorado into the Northeast region of Colorado, thereby providing a viable alternative crop in semiarid rotations. Major concerns were whether sorghum could reach physiological maturity before the first frost date and produce acceptable yields. At all four trial environments, all hybrids in all agronomic treatments reached maturity and had acceptable yields and test weight.

Hybrid selection, seeding rates, environment, and planting dates are factors we studied when evaluating whether grain sorghum will reach physiological maturity before the first fall frost. Our studies indicate that hybrid selection should mainly be based on cultivar maturity, followed by selection of hybrids within the maturity class that are capable of high yields and have specific characteristics important to the producer depending on growing conditions. Planting grain sorghum as early as possible increases the probability of reaching physiological maturity, as planting even 7 d earlier can substantially increase the probability of a hybrid reaching maturity. The required cumulative GDD to maturity decreased as the seeding rate was increased (especially in environments that had adequate soil moisture), but grain yield was highest in the medium (11 seeds m^{-2}) seeding rate treatment.

We determined the probability of different cultivars reaching maturity in different environments across Northeast Colorado for three different simulated planting dates. It was hypothesized that early maturity class grain sorghum would almost always reach maturity in northeastern Colorado. In the two lower latitude and elevation locations (Akron and Stratton), our hypothesis was confirmed (≥80% probability for Akron and 86% for Stratton), but at the northern location (Fort Collins) the probabilities were lower than most producers would probably be comfortable with (75% was highest probability and 25% was lowest), especially if an early planting date is not possible due to low soil temperatures.

The combination of the growing environment, agronomic practices, and hybrid selection are very important in ensuring the grain sorghum will reach physiological maturity before the first fall frost. In terms of balancing a high probability of the grain reaching maturity and an acceptable grain yield and test weight, the best selections based on the options from our study would be planting the DKS29-28 hybrid (early maturity class and high grain yield) as early as possible in the growing season (15 May if soil temperatures are suitable) in the Stratton environment, in the 0.76 m row spacing, at a seeding rate of 11 seeds m^{-2}.

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