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Simulating the Probability of Grain Sorghum Maturity before the First Frost in Northeastern Colorado

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Abstract: Expanding grain sorghum [*Sorghum bicolor* (L.) Moench] production northward from southeastern Colorado is thought to be limited by shorter growing seasons due to lower temperatures and earlier frost dates. This study used a simulation model for predicting crop phenology (PhenologyMMS) to estimate the probability of reaching physiological maturity before the first fall frost for a variety of agronomic practices in northeastern Colorado. Physiological maturity for seven planting dates (1 May to 12 June), four seedbed moisture conditions affecting seedling emergence (from Optimum to Planted in Dust), and three maturity classes (Early, Medium, and Late) were simulated using historical weather data from nine locations for both irrigated and dryland phenological parameters. The probability of reaching maturity before the first frost was slightly higher under dryland conditions, decreased as latitude, longitude, and elevation increased, planting date was delayed, and for later maturity classes. The results provide producers with estimates of the reliability of growing grain sorghum in northeastern Colorado.

Keywords: *Sorghum bicolor*; phenology; physiological maturity; simulation model

1. Introduction

Grain sorghum is an important dryland crop in semiarid southeastern Colorado and may be a valuable crop to add to traditional winter wheat-based (*Triticum aestivum* L.) crop rotations in semiarid northeastern Colorado. Interest in growing grain sorghum in northeastern Colorado is driven partly due to its high adaptability in semiarid regions and lower production costs compared to maize (*Zea mays* L.) [1,2]. Grain sorghum is also considered more drought tolerant than maize and higher yielding in dry years in eastern Colorado [2,3]. However, successfully growing grain sorghum in northeastern Colorado is thought to be limited by shorter growing seasons and cool night temperatures in the spring and fall. Shorter growing seasons can prevent sorghum from reaching physiological maturity before the first frost occurs in the fall (which kills sorghum), thereby negatively impacting grain yield and test weight if maturity has not occurred [4]. Within northeastern Colorado, generally the growing season shortens and cooler night temperatures occur as latitude increases and with proximity to the foothills of the Rocky Mountains (i.e., longitude increases), which is related to higher elevations.

Agronomic practices can influence maturity date and production in Colorado. Perhaps the most important factor influencing maturity is selecting the hybrid [5], because the thermal time required to reach maturity is determined by genetics [6–8]. Planting date also is important in determining the probability of reaching maturity by changing when thermal time accumulation begins to occur [5]. Given that dryland sorghum is planted in variable levels of available soil water in the seedbed zone, it is probably better to use the time of seedling emergence than planting date to begin the accumulation of thermal time. Other agronomic practices such as seeding rate, row spacing, row orientation, and nutrient availability can affect the timing of maturity [1,5,9–14].

Although initial analysis showed the probability of reaching maturity for some agronomic practices varied greatly for three locations in northeastern Colorado [5], more rigorous analysis should be useful to producers in determining the risk of growing grain sorghum in northeastern Colorado. To meet this objective, the Phenology Modular Modeling System (PhenologyMMS) decision support tool with a phenology science component was used to simulate the probability of grain sorghum reaching maturity using historical weather data for different locations in northeastern Colorado. The agronomic practices simulated were: (1) growing degree-day (GDD) estimates for "optimum" conditions such as fully irrigated or very high rainfall, and denoted as GN (for the GDD for non-stressed conditions), and non-terminal water-stressed conditions such as occurs in dry years in semiarid dryland production regions, and denoted as GS (for the GDD stressed conditions); (2) three maturity classes (early, medium, and late); (3) seven planting dates (1, 8, 15, 22, 29 May and 5, 12 June); and (4) four general estimates of soil water availability in the seedbed zone (optimum, medium, dry, and planted in dust).

2. Results

2.1. Mean First Frost Date and Mean Temperature of the Growing Season for Nine Locations

The nine locations used in this study differ in latitude, longitude, and elevation, which interact to influence the temperature and time of first frost (Table 1). Usually as latitude, longitude, and elevation increased, the mean first frost date occurred earlier and the mean temperature from 1 May to the first mean frost date decreased. The mean first frost date was earliest at the Hort Farm (5 October) and latest at Stratton (20 October). The westernmost locations near Fort Collins (Hort Farm; ARDEC—Agricultural Research, Development, and Education Center, 8 October; and Fort Collins, 9 October), which are closest to the foothills with higher elevations, had the three earliest mean first frost dates for all locations. Distributions of the first frost date in a year for each location are presented in Figure 1 for additional information.

Table 1. General weather information for nine locations in northeastern Colorado.

Location	Latitude	Longitude	Elevation (m)	Starting Date in Weather File	Ending Date in Weather File	Number of Useable Years	Mean First Frost Date [1]	Mean Temperature 1 May to First Frost Date (°C)
Akron	40°9′ N	103°8′ W	1383	1 January 1918	31 December 2013	96	11 October	18.6
ARDEC	40°39′ N	105° W	1558	8 May 1992	14 May 2014	22 [2]	8 October	17.6
Ault	40°34′ N	104°43′ W	1497	17 March 1992	18 May 2014	22	9 October	17.9
Drake Farm	40°36′ N	104°50′ W	1572	21 November 2001	14 February 2014	12	17 October	17.9
Fort Collins	40°35′ N	105°8′ W	1561	1 January 1895	1 September 2014	113	9 October	17.5
Greeley LIRF	40°26′ N	104°38′ W	1427	4 March 1992	8 April 2014	22	11 October	18.3
Hort Farm	40°36′ N	104°59′ W	1526	1 January 1987	31 December 2001	15	5 October	17.1
Sterling	40°16′ N	103°0′ W	1363	1 January 1950	5 July 2014	64	11 October	19.1
Stratton	39°17′ N	102°31′ W	1317	1 June 1934	25 June 2014	74 [3]	20 October	19.1

[1] The first frost event in a year was estimated when the daily minimum temperature was <−2 °C; [2] 1 May planting date not used in 1992 (missing data); [3] 1934, 1980, 1983–1986, and 2014 not used (missing data).

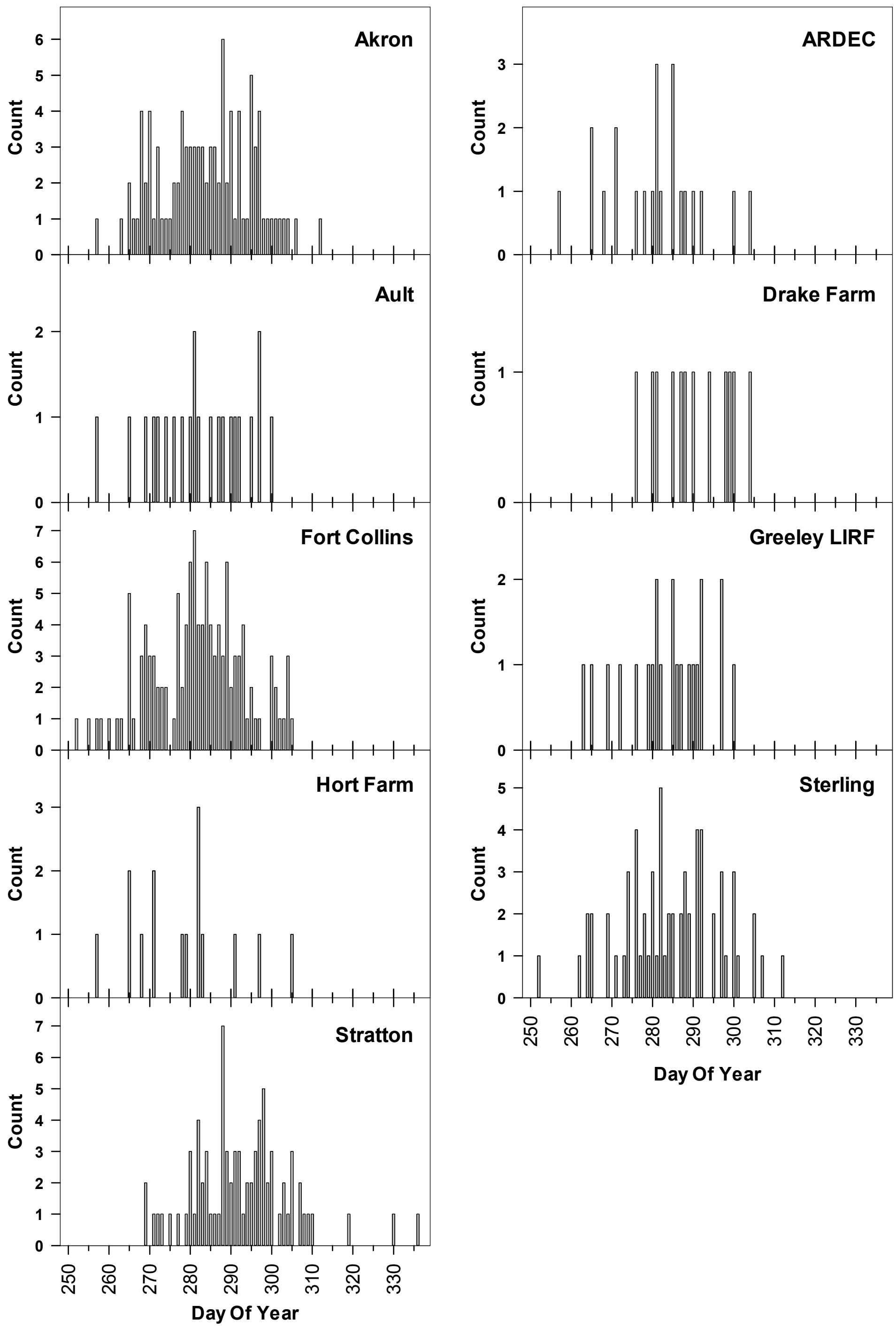

Figure 1. Frequency distribution of first frost date in a year for nine locations.

The mean potential growing season of a location can be estimated by the mean temperature from 1 May to the mean first frost date (Table 1). The potential growing season of locations generally followed the same pattern as observed for the mean first frost date, with the Hort Farm (17.1 °C) having the lowest mean temperature and Sterling the highest (19.1 °C), slightly higher than Stratton (19.0 °C). The three westernmost locations (Hort Farm; Fort Collins, 17.5 °C; and ARDEC, 17.6 °C) had the three shortest potential growing seasons for all locations.

2.2. Mean Maturity Date of Locations

Simulations were run for each location changing the phenological parameters (dryland, GS; irrigated, GN), maturity class (early, medium, and late), planting date (1, 8, 15, 22, 29 May and 5, 12 June), and seedbed water conditions at planting (optimum, medium, dry, and planted in dust) to estimate mean maturity date. The mean simulated maturity date differed among locations, phenological parameters, planting dates, maturity class, and seedbed water conditions (full data not shown). Consistent patterns were found for all locations, where maturity dates were earliest for GS parameters (primarily due to shorter grain filling duration), and increasingly later as: (1) maturity class changed from early to late (requiring more thermal time to reach maturity); (2) planting dates were delayed (delaying the beginning of accumulation of thermal time); and (3) soil moisture at planting decreased (delaying seedling emergence). Some of these patterns can be seen for simulations using the GS parameters for the Early variety planted into Optimum seedbed water conditions for the seven planting dates (Table 2). For instance, the maturity date is later as planting date is delayed for all locations.

Table 2. Mean maturity dates for seven planting dates at nine locations in northeastern Colorado.

Location	Mean Temperature 1 May to First Frost Date (°C)	Mean Temperature 1 May to 1 November (°C)	Mean First Frost Date [2] (DOY)	Maturity Date (DOY) [1]						
				1 May	8 May	15 May	22 May	29 May	June 5	12 June
Akron	18.6	17.6	284	254	259	263	269	278.1	**288**	**304**
ARDEC	17. 6	16.3	281	271	278	**284**	**303**	**312.6**	**332**	**345**
Ault	17.9	16.7	282	262	267	275	**288**	**299.2**	**312**	**336**
Drake Farm	17.9	17.1	290	258	262	268	281	**291.6**	**301**	**321**
Fort Collins	17.5	16.5	282	269	275	**282**	**294**	**307.8**	**323**	**337**
Greeley LIRF	18.4	17.2	284	255	260	266	275	**287.2**	**300**	**319**
Hort Farm	17.1	15.9	278	**282**	**291**	**300**	**322**	**332.9**	**351**	**361**
Sterling	19.1	18.0	284	247	251	255	262	268.6	277	**292**
Stratton	19.0	18.4	293	243	247	251	257	262.7	270	280

Each planting date used GS parameters, Early maturity class, and Optimum seedbed water. Values in Bold within parenthesis indicate mean maturity date is after the mean first frost date. [1] Mean DOY of maturity. If maturity was not predicted by the end of the year, maturity date was set to 31 December because the plant would be dead by 31 December, and due to lack of thermal time accumulation during the winter and early spring would result in simulated maturity many days later (e.g., DOY 100 or later). Using maturity dates in the following year would result in an earlier estimated mean maturity DOY than realistic for this table; [2] The first frost event in a year was estimated when the daily minimum temperature was <-2 °C.

Maturity dates within a planting date were later as latitude, longitude, and elevation of the location increased. For example, for the 1 May planting date, Stratton had the earliest maturity date (31 August) and the Fort Collins (26 September), ARDEC (29 September), and Hort Farm (9 October) locations had the latest maturity dates. Given the relationship of maturity date, mean first frost date, and mean temperature from 1 May to the first frost date of locations with latitude, longitude, and elevation, a relationship between maturity date and both first frost date and mean temperature would be predicted. A highly significant negative relationship between maturity date and both first frost date and mean temperature was found for all planting dates, as illustrated when using the dryland (GS) phenological parameters, Early maturity class, and Optimum seedbed water conditions (Figures 2 and 3). There appears to be a trend of increasingly negative slope as planting date was delayed, and it is likely that this is partly due to increased instances at locations with earlier first frost dates or lower temperatures where maturity was not reached by 31 December, and therefore set to 31 December in calculating the mean maturity date.

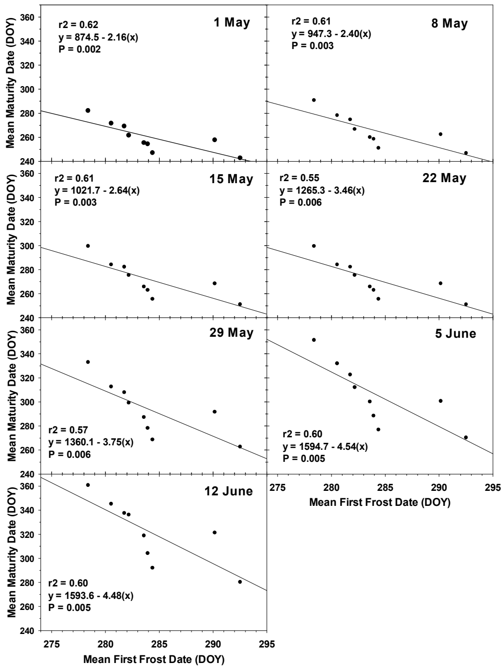

Figure 2. Relationship between mean first frost date and mean maturity date of nine locations in northeastern Colorado for seven planting dates. Dryland (GS) phenological parameters, Early maturity class, and Optimum seedbed water conditions at planting were used for simulating maturity date. If maturity was not predicted by the end of the year, maturity date was set to 31 December. Linear regression lines are given with associated r^2 and probability of significance.

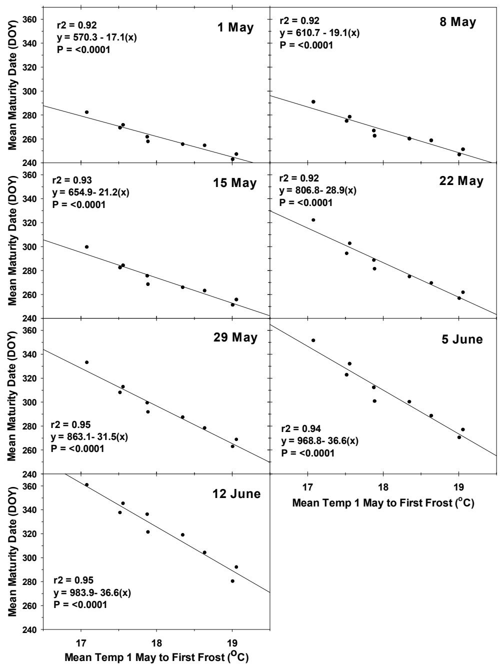

Figure 3. Relationship between mean temperature from 1 May to the mean first frost date and mean maturity date of nine locations in northeastern Colorado for seven planting dates. Dryland (GS) phenological parameters, Early maturity class, and Optimum seedbed water conditions at planting were used for simulating maturity date. If maturity was not predicted by the end of the year, maturity date was set to 31 December. Linear regression lines are given with associated r^2 and probability of significance.

2.3. Probability of Reaching Maturity at Locations

Simulations to estimate the probability of reaching maturity before the first frost date were run for each location changing the phenological parameters (dryland, GS; irrigated, GN), maturity class (early, medium, and late), planting date (1, 8, 15, 22, 29 May and 5, 12 June), and seedbed water conditions at planting (optimum, medium, dry, and planted in dust). The probability of reaching maturity at a location for each combination of GN/GS, planting date, maturity class, and soil water at planting scenario was calculated by determining whether the simulated maturity date for each year was before, or after, the first frost date for the year. Initial analysis of these simulations examined the dryland (GS) and irrigated (GS) phenological parameters. The GS and GN phenological parameters resulted in similar probabilities of reaching maturity before the first frost, although GS parameters usually had a slightly higher probability than GN parameters, regardless of maturity class, planting date, or seedbed water conditions at planting (data only shown for simulations using Early maturity class and Optimum seedbed soil water conditions at planting, Table 3).

Table 3. Probability of reaching maturity for seven planting dates at nine locations in northeastern Colorado using either non-water stressed phenological parameters (GN) or water-stressed phenological parameters (GS).

Location	GN or GS Parameters	Probability of Reaching Maturity						
		Planting Date						
		1 May (%)	8 May (%)	15 May (%)	22 May (%)	29 May (%)	5 June (%)	12 June (%)
Akron	GN [1]	91.7	90.6	87.5	80.2	**68.8**	**45.8**	**25.0**
	GS [2]	94.8	90.6	90.6	84.4	**74.0**	**55.2**	**28.1**
ARDEC	GN	**76.2**	**59.1**	**50.0**	**40.9**	**31.8**	**13.6**	**0.0**
	GS	**76.2**	**72.7**	**54.6**	**40.9**	**31.8**	**18.2**	**0.0**
Ault	GN	81.8	**72.7**	**68.2**	**50.0**	**40.9**	**18.2**	**4.6**
	GS	86.4	81.8	**68.2**	**54.6**	**45.4**	**18.2**	**4.6**
Drake Farm	GN	91.7	91.7	91.7	**75.0**	**66.7**	**41.7**	**16.7**
	GS	91. 7	91.7	91. 7	**75.0**	**66.7**	**50.0**	**33.3**
Fort Collins	GN	**69.9**	**64.6**	**56.6**	**41.6**	**29.2**	**15.0**	**6.2**
	GS	**71.7**	**68.1**	**62.8**	**46.9**	**30.1**	**18.2**	**8.0**
Greeley LIRF	GN	95.4	90.9	81.8	**68.2**	**54.6**	**36.4**	**13.6**
	GS	95.4	95.4	90.9	**72.7**	**54.6**	**45.4**	**13.6**
Hort Farm	GN	**53.3**	**26.7**	**20.0**	**13.3**	**6.7**	**6.7**	**6.7**
	GS	**60.0**	**26.7**	**20.0**	**13.3**	**13.3**	**6.7**	**6.7**
Sterling	GN	98.4	96.7	96.9	90.6	**78.1**	**62.5**	**40.6**
	GS	98.4	98.4	96.7	93.8	82.8	**67.2**	**45.3**
Stratton	GN	100	100	100	94.6	91.9	90.5	**75.7**
	GS	100	100	100	98.6	93.2	91.9	83.8

Each planting date used Early maturity class, and Optimum seedbed water conditions. Values in Bold within parenthesis indicate the probability of reaching maturity date is less than 80% (a general risk level unacceptable to producers based on personal communication). [1] Using non-stressed phenological parameters; [2] Using stressed phenological parameters.

Because sorghum is normally grown under dryland conditions, presentation of probabilities for reaching maturity at the nine locations will be shown using the GS parameters, maturity class, seedbed water conditions at planting, and planting date (Figures 3–11). All locations show similar patterns for the probability of reaching maturity based on maturity class (later maturity classes have lower probabilities), seedbed water conditions (lower soil water reduces probabilities), and planting dates (later planting dates lower the probabilities). The highest probabilities of reaching maturity at a location were for Early maturity class, Optimum seedbed water conditions, and the earliest planting date (1 May). The lowest probabilities were for Late maturity class, Planted in Dust seedbed water conditions, and the latest planting date (12 June). The Early and Medium maturity classes had relatively similar probabilities of reaching maturity for all locations except the Hort Farm; the Late Maturity class had the lowest probabilities for most sites, the exceptions tending to be the sites with the highest probabilities such as Stratton. Within the Early and Medium maturity classes, little differences in the probability of reaching maturity for a location were noted between Optimum and Medium seedbed soil water (except for the Hort Farm).

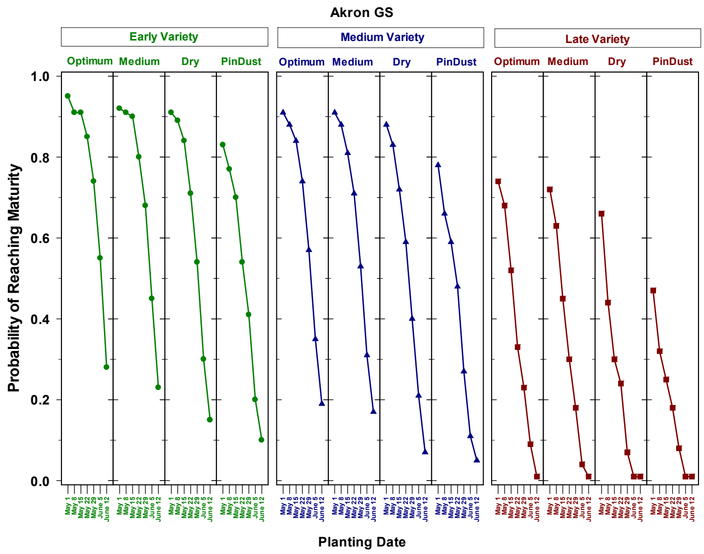

Figure 4. Probability of sorghum reaching physiological maturity at Akron, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

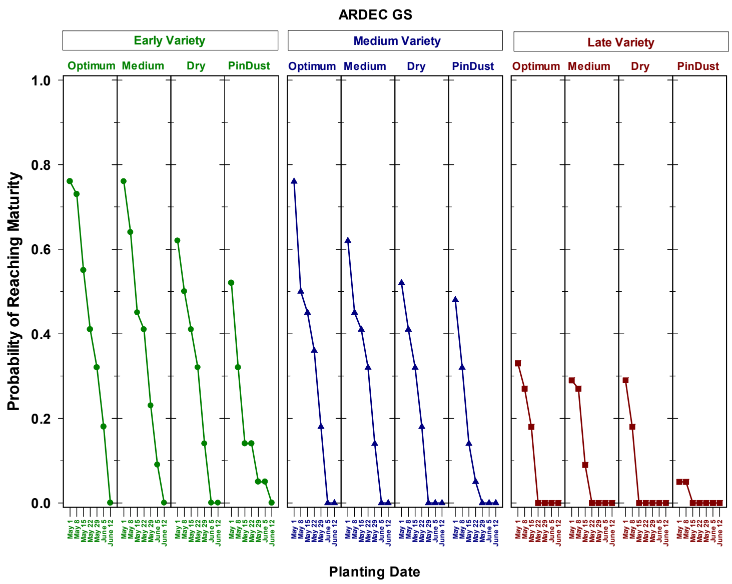

Figure 5. Probability of sorghum reaching physiological maturity at ARDEC, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

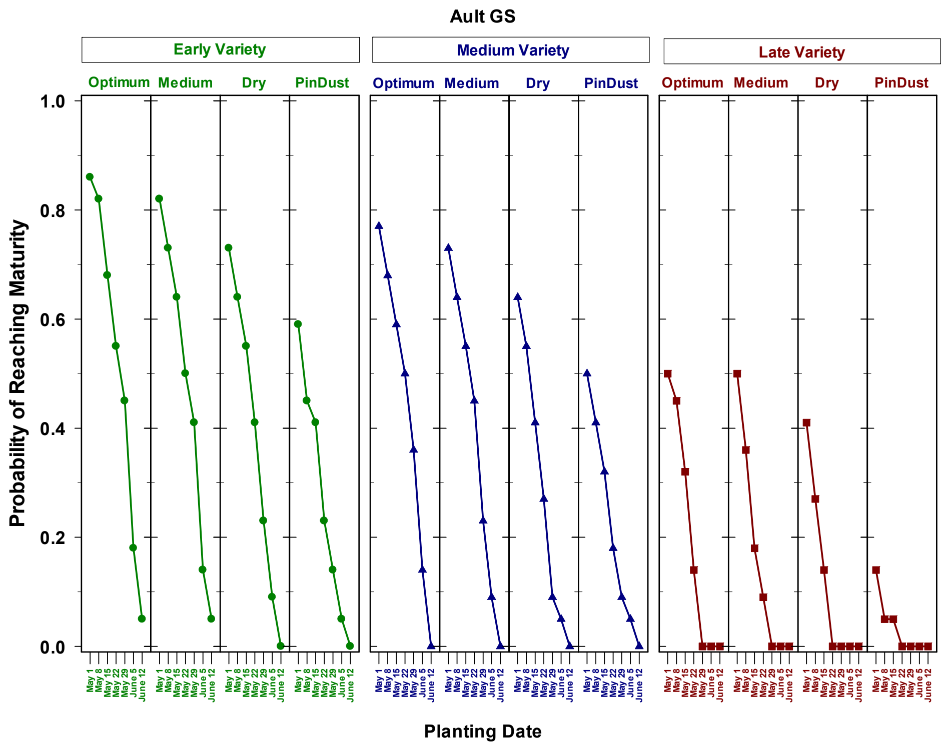

Figure 6. Probability of sorghum reaching physiological maturity at Ault, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

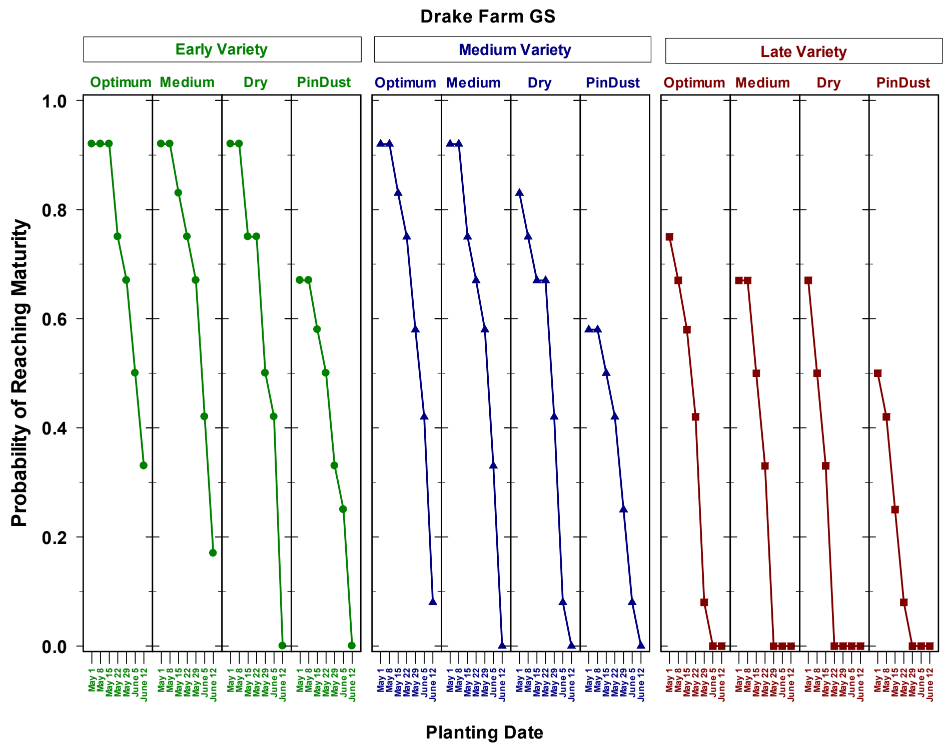

Figure 7. Probability of sorghum reaching physiological maturity at Drake Farm, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

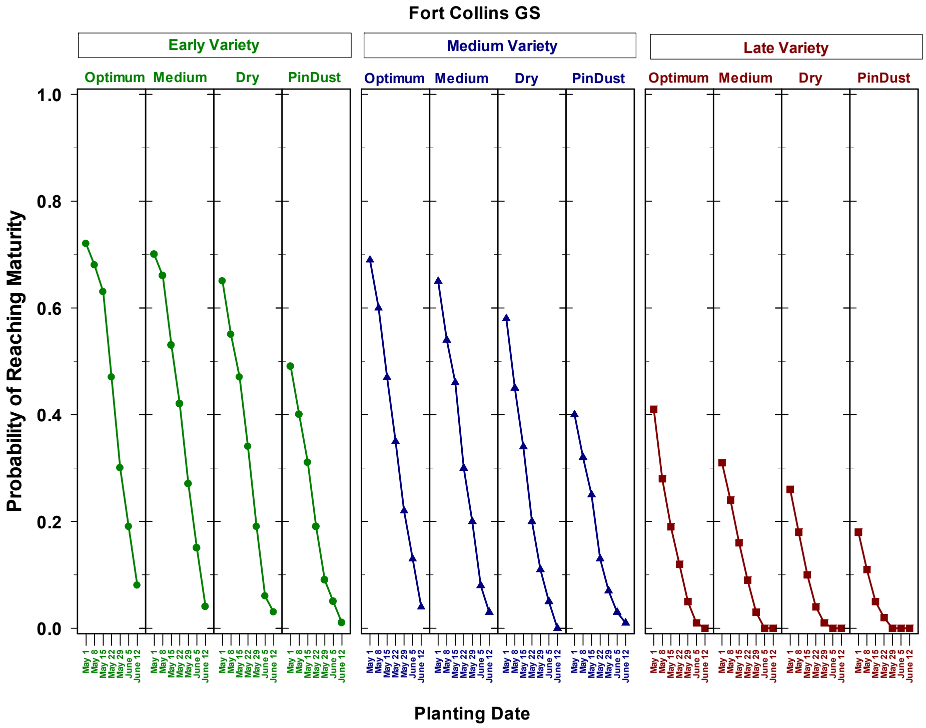

Figure 8. Probability of sorghum reaching physiological maturity at Fort Collins, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

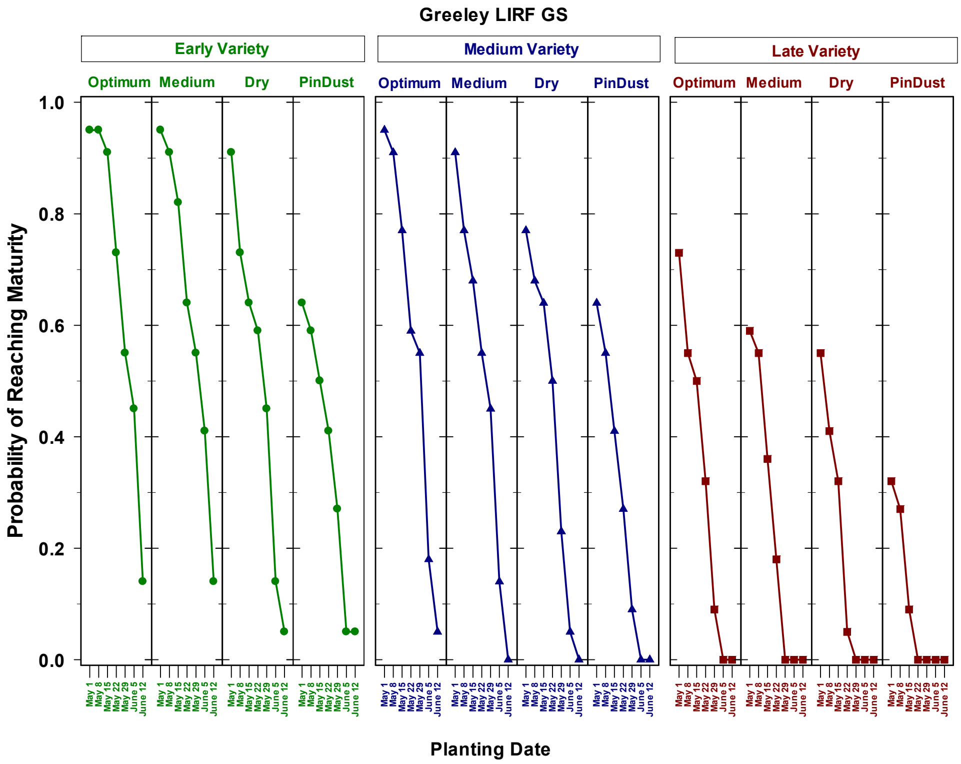

Figure 9. Probability of sorghum reaching physiological maturity at Greeley LIRF, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

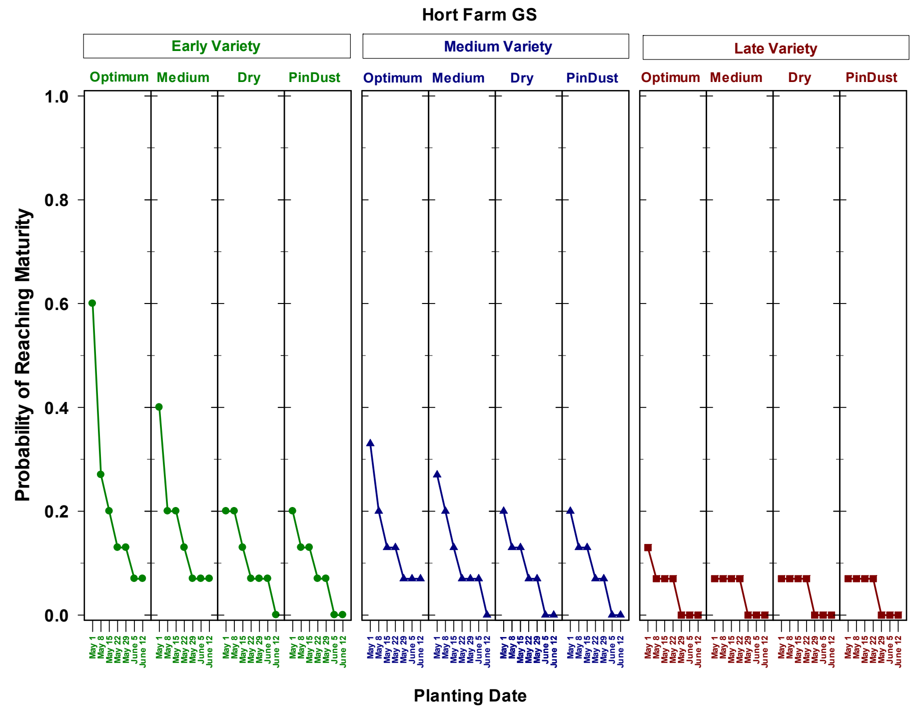

Figure 10. Probability of sorghum reaching physiological maturity at Hort Farm, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

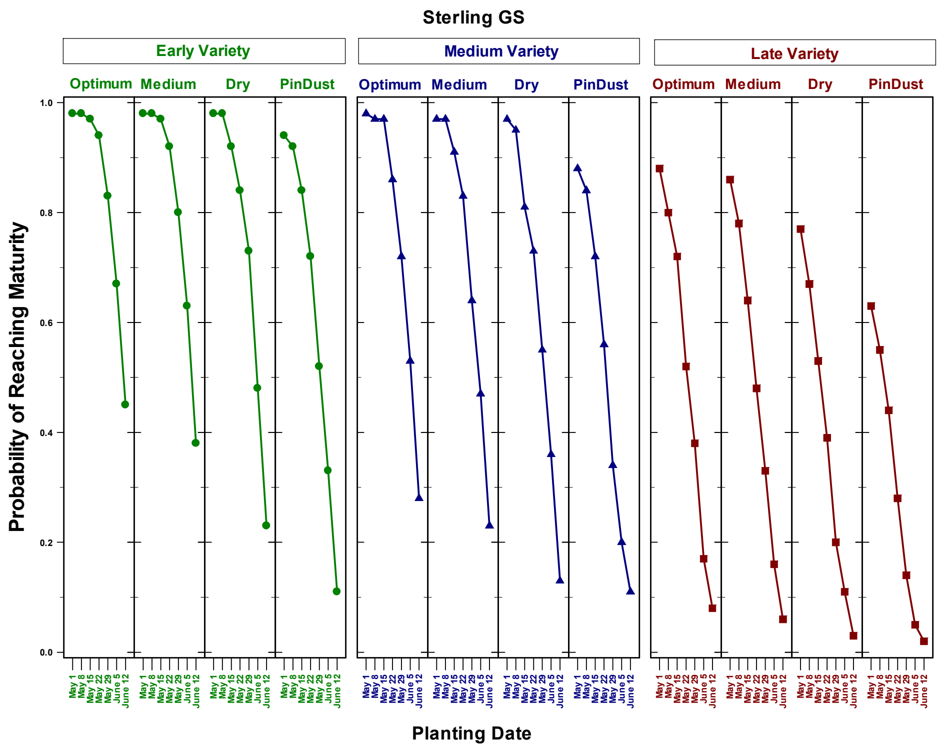

Figure 11. Probability of sorghum reaching physiological maturity at Sterling, Colorado for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

While agronomic practices influenced the probability of reaching maturity, the locations clearly differed in the likelihood of reaching maturity regardless of agronomic practices (Figures 4–12). For instance, all agronomic practices at Stratton resulted in higher probabilities of reaching maturity for specific agronomic practices than locations near Fort Collins. A general ranking of locations based on the highest probability agronomic practices of Early maturity class, Optimum seedbed water conditions, and 1 May planting date, and the lowest probability agronomic practices of Late maturity class, Planted in Dust seedbed water conditions, and 12 June planting date suggest the following ranking of locations from highest to lowest: Stratton (100%, 9.5%), Sterling (98.4%, 1.6%), Akron (94.8%, 1.0%), Greeley LIRF (95.5%, 0%), Drake Farm (91.7%, 0%), Ault (86.4%, 0%), ARDEC (76.2%, 0%), Fort Collins (71.7%, 0%), and Hort Farm (60.0%, 0%).

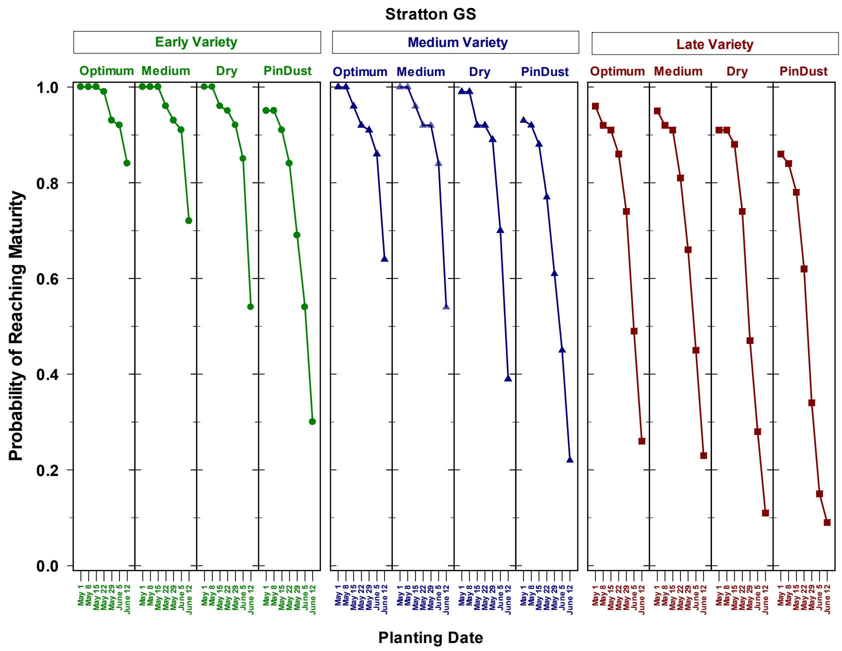

Figure 12. Probability of sorghum reaching physiological maturity at Stratton, Colorado, for seven planting dates using non-stressed (GS) phenological parameters, three maturity classes, and four seedbed water conditions at planting.

3. Discussion

As expected, a general relationship was observed, that as the latitude, longitude, and elevation of a location increased, the mean first frost date occurred earlier and the mean temperature from 1 May to the first frost date (i.e., the potential growing season) was lower. Further, highly significant negative relationships between the mean maturity date for a location and both the mean first frost date and mean temperature from 1 May to the first frost date were found. Therefore, it was not surprising that simulated probabilities of reaching maturity before the first frost date differed among locations, and could be grouped based on latitude, longitude, and elevation. The scenario using the dryland phenological parameters (GS), Early maturity class, 1 May planting date, and optimum seedbed soil water conditions at maturity, which had the highest probability of reaching maturity at all locations, illustrates this point. Five locations had probabilities over 90% of reaching maturity: Stratton (100%), Sterling (98.4%), Greeley LIRF (95.5%), Akron (94.8%) and Drake Farm (91.7%), and these locations had the combination of being at lower latitudes, longitudes, and elevations. Conversely, the three locations with the highest combination of latitude, longitude, and elevations had the lowest probabilities of reaching maturity (ARDEC, 76.2%; Fort Collins, 71.7%; and Hort Farm, 60.0%). Previous work of Sauer et al., 2014 [5] calculated simulated probabilities for emergence date of 15 May for two early maturity class hybrids for three of our locations and found comparable results: Stratton (91%), Akron (89%), and Fort Collins (75%). These simulation results suggest there are many areas in northeastern Colorado where sorghum can usually reach maturity before the first frost, if agronomic practices maximizing the likelihood of sorghum reaching maturity are used.

Selecting agronomic practices maximizing the probability of reaching maturity, such as choosing an early maturity class hybrid and practices that result in beginning the accumulation of thermal time as early as possible (e.g., earlier planting dates with optimum seedbed water conditions), may result in lower yield. Likely yield reductions can partly be attributed to early maturity hybrids almost always having lower yields than late maturing hybrids, less tillering, and shorter grain filling periods [9,15,16]. Further, very early planting dates with cooler soil and air temperatures are not conducive to optimal sorghum emergence and early growth [17]. Our simulation results indicate that usually selecting medium maturity classes and medium seedbed water conditions at planting, and often the first 2–3 planting dates, will have minimal reductions of the probability of reaching maturity. However, it would be beneficial to do additional field studies to verify these results, and also to try to quantify additional known agronomic practices (e.g., seeding rate, row spacing, nutrient availability) for inclusion in simulation models such as PhenologyMMS. Nevertheless, these simulation results provide producers with more suggestions for successfully growing sorghum in northeastern Colorado and improving yield potential.

4. Materials and Methods

The Phenology Modular Modeling System (PhenologyMMS V1.3), developed by the United States Department of Agriculture—Agricultural Research Service, was run using historical weather data for nine locations in northeastern Colorado to predict the date of physiological maturity and whether this occurred before the first frost in the fall. Two sets of phenological parameters estimating the thermal time (i.e., growing degree-days, GDD) between developmental stages were used in the simulations. One set provides GDD estimates for "optimum" conditions such as fully irrigated or very high rainfall, and denoted as GN (for GDD non-stressed). The other set is for extremely dry, but not lethal, conditions indicative of dryland conditions with below average rainfall in semiarid production regions, and denoted as GS (for GDD stressed). For each location, all combinations of seven planting dates (1, 8, 15, 22, 29 May and 5, 12 June), three maturity classes (early, medium, and late), and four general categories of soil water in the seedbed at planting (optimum, medium, dry, and planted in dust) were simulated for each year of historical weather data using both GN and GS parameter values. The probability of reaching maturity at a location for each combination of GN/GS, planting date, maturity class, and soil water at planting scenario was calculated by determining for each year whether the simulated maturity date was before, or after, the first frost date for the year. Additional details on PhenologyMMS, locations, and input files are provided below.

4.1. Locations and Weather Data

General details of the nine locations used in the study are listed in Table 1. Location names in Table 1 are shortened for the manuscript:

- Akron is located at the USDA-ARS Central Great Plains Research Station, about 185 km southeast of Fort Collins. Additional location details provided in [18].
- ARDEC is the Colorado State University Agricultural, Research, Education, and Development Center about 7 km northeast of Fort Collins. Additional location details provided in [18,19].
- Ault is about 24 km east of Fort Collins.
- Drake Farm is located on a producer's farm about 15 km east of Fort Collins. Additional location details provided in [20].
- Fort Collins is located at the foothills of the Rocky Mountains. Three weather stations located within the city were used to get the entire historical weather records and fill in missing data.

- Greeley LIRF is located at the USDA-ARS Limited Irrigation Research Farm immediately north of Greeley and about 45 km southeast of Fort Collins. The airport weather station immediately to the east of the site was used for the initial years, and in 2008 a weather station was installed at the research site and used for later years. Additional location details provided in [21].
- Hort Farm is located at the Colorado State University Horticultural Farm on the northeast edge of Fort Collins. Additional location details provided in [22,23].
- Sterling is located about 160 km east of Fort Collins.
- Stratton is located about 330 km southeast of Fort Collins.

All weather data were either directly collected from previous experiments, CoAgMet (COlorado AGricultural Meteorological nETwork [24]), NOAA records, formerly the National Climatic Data Center (NCDC) [25], or Colorado Climate Center [26]. Occasional missing daily maximum or minimum temperature data were estimated with several different techniques (e.g., mean of previous and subsequent day, using values from another nearby weather station, etc.), otherwise larger gaps of missing data resulted in not using the year in the simulations. The first frost event in a year was estimated when the daily minimum temperature was <-2 °C [2,27].

4.2. PhenologyMMS Decision Support Tool Overview And Default Parameters Used in Simulations

PhenologyMMS is a decision support tool with a Java graphical user interface and a FORTRAN 90/95 science simulation model for simulating the phenological responses of different crops to varying levels of water deficits. The objectives of PhenologyMMS are to (1) provide a relatively easy tool to producers, consultants, and scientists to predict crop developmental stages and provide information about crop phenology; and (2) develop seedling emergence and crop phenology science simulation components that could be inserted into other crop simulation models. Additional details on PhenologyMMS not covered below can be found in [19,28–30], and PhenologyMMS can be downloaded at ARS Agricultural Software Download and Applications website [31].

Several different temperature response functions are used for calculating GDD in PhenologyMMS, and the method used for sorghum is calculated from [32]:

$$GDD = \sum_{i=1}^{n} \left(\frac{T\ \max_i + T\ \min_i}{2} \right) - Tbase, \quad 0 \leq GDD \leq Tupper \qquad (1)$$

where $T_{\max,i}$ and $T_{\min,i}$ are the daily maximum and minimum temperature for day i (°C), respectively, and T_{base} is the base temperature (°C) and T_{upper} (°C) is the crop-specific upper temperature threshold above which additional GDD are not accumulated. T_{base} and T_{upper} are also used in the manipulation of the equation, where if $T_{\max,i}$ and/or $T_{\min,i} < T_{base}$, $T_{\max,i}$ and/or $T_{\min,i} = T_{base}$ and if $T_{\max,i}$ and/or $T_{\min,i} > T_{upper}$, then $T_{\max,i}$ and/or $T_{\min,i} = T_{upper}$. Daily values greater than zero are summed over a period of n days. Grain sorghum T_{base} and T_{upper} were set to 10 °C and 40 °C, respectively.

The crop-specific default thermal time required between successive stages is adjusted between GN (i.e., non-water stressed conditions such as fully irrigated) and GS (i.e., non-terminal water stressed conditions such as semiarid, dryland conditions) for varying levels of water deficits. GN and GS phenological parameters for early, medium, and late maturity classes are provided for each crop, and grain sorghum parameters are given in Table 4.

Table 4. Sorghum growing degree-days (GDD) for no water stress (GN) and maximum non-terminal water stress (GS) phenological parameters for early, medium, and late maturity classes.

	Early Maturity		Medium Maturity		Late Maturity	
Interval	**GN**	**GS**	**GN**	**GS**	**GN**	**GS**
			GDD (°C·Day) [2]			
E to Growing Point Differentiation (GPD) [1]	405	405	450	450	495	495
GPD to End of Leaf Growth (ELG)	160	160	184	184	231	231
ELG to Anthesis Start (AS)	80	116	80	97	80	97
AS to Half Bloom (HB)	80	116	80	97	80	97
HB to Full Bloom	120	145	120	145	120	145
AS to Maturity	550	499	525	486	538	499

[1] **Bold** intervals denote successive stages leading to physiological maturity; [2] GDD are calculated using Equation (1).

The seedling emergence sub-model in PhenologyMMS is a simplified version of the SHOOTGRO model [33,34]. Three factors control the time of seedling emergence: soil moisture near the seed, temperature, and planting depth. It is assumed that soil moisture controls the beginning of imbibition and germination (*Germ*):

$$Germ = \sum_{i=Pdate}^{i=Gday} GDDGi \tag{2}$$

where the daily growing degree-days ($GDDG_i$), which are currently calculated using Equation (1), are summed from planting day (*Pdate*) until the required number of growing degree-days ($GDDG_{req}$) for germination is reached. *Gday* is the day that germination occurs. $GDDG_{req}$ is based on the soil moisture conditions of the seedbed zone. Table 5 presents the default sorghum values for $GDDG_{req}$. Once germination has occurred, temperature drives the rate of shoot growth ($ElongRate_i$) from the seed leading to emergence. The thermal time required for emergence ($GDDE_{req}$) is calculated by:

$$GDDEreq = \frac{Pdepth}{(ElongRate_i/10)} \tag{3}$$

where $ElongRate_i$ is the shoot elongation rate (mm/°C·day) for day *i* based on the soil water content (see Table 5 for default sorghum values) and *Pdepth* is the planting depth (cm). Seedling emergence (*Emerge*) is then determined by multiplying the daily elongation rate by the daily GDD (GDD_i) until the required GDD ($GDDE_{req}$) have been accumulated:

$$Emerge = \sum_{i=Gday}^{i=Eday} \left(\left(\frac{ElongRate_i}{10}\right) * \mathrm{GDDi} \right) \tag{4}$$

Seedling emergence occurs the day (*Eday*) that *Emerge* equals $GDDE_{rep}$.

Crop-specific parameters for germination and elongation rate in Table 5 are based on four general categories of soil moisture in the seedbed layer: Optimum (>45% water-filled pore space), Medium (35%–45%), Dry (25%–35%), and Planted in Dust (<25%). These values do not need to be precisely estimated; rather, the user can choose the category based on general conditions. PhenologyMMS lacks a soil water balance module. Therefore, a surrogate approach was to use precipitation during this time period to vary the soil moisture conditions for simulating seedling emergence. In the original seedling emergence sub-model in PhenologyMMS, daily rainfall amounts from 5–7 mm incremented the soil moisture category to the next higher level of soil moisture. Rainfall events from 7–12 mm incremented the soil moisture category two levels. Preliminary evaluation of the seedling emergence sub-model uncovered instances of emergence occurring too early when selecting Medium or Dry soil water conditions. One solution tested was to create intermediate categories between Dry and Medium and Medium and Optimum levels. Germination and elongation rate values for the intermediate categories are the mid-points between the initial soil water values for Optimum, Medium, or Dry as appropriate, and this is done internally so the user is not required to provide additional input values. The first rainfall event ≥7 mm increases the initial soil water level to the intermediate level between Dry and Medium or between Medium and Optimum. The second rainfall event ≥7 mm increments it to the Medium or Optimum level. However, if the original condition was Planted in Dust, then the model was modified so that if rainfall is from ≥7 to 12 mm the soil moisture level is advanced to Dry. Rainfall from ≥12 to 20 mm results in Medium level, and if rainfall ≥20 mm, the soil water condition is Optimum.

Table 5. Sorghum default parameters for seedling emergence.

Parameter	Value
Germination (∑GDD): [1]	
Optimum [2]	40
Medium	50
Dry	70
Planted in Dust [3]	500
Elongation rate ($mm \cdot GDD^{-1}$):	
Optimum	1.5
Medium	1.0
Dry	0.6
Planted in Dust	0.0
Planting Depth (cm)	5
Planting Date	1, 8, 15, 22, 29, May 5, 12 June

[1] Accumulated growing degree-days (GDD) required to initiate germination. Equation (1) is used for calculating GDD; [2] Seedbed water conditions are based on % water-filled pore space: optimum (>45%), medium (35%–45%), dry (25%–35%), and dust (<25%); [3] Soil moisture in this category is below the minimum threshold to initiate the imbibition process.

5. Conclusions

To avoid yield reductions due to a frost occurring prior to physiological maturity, selecting agronomic practices that maximize the probability of reaching maturity before the first frost. Our simulation results suggest choosing an early maturity class hybrid and practices that result in beginning the accumulation of thermal time as early as possible (e.g., earlier planting dates with optimum seedbed water conditions) result in the highest probability of reaching maturity before the first frost. However, planting as early as possible expands producer options of choosing hybrids in the medium maturity class and planting when less water is available in the seedbed without significantly reducing the probability of reaching maturity. However, it would be beneficial to do additional field studies to verify these results, and also to try to quantify additional known agronomic practices (e.g., seeding rate, row spacing, nutrient availability) for inclusion in simulation models such as PhenologyMMS.

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Abbreviations

The following abbreviations are used in this manuscript:

ARDEC	Colorado State University Agricultural, Research, and Development Center
AS	Anthesis Starts
CoAgMet	COlorado AGricultural Meteorological nETwork
DOY	Day of Year
E	Emergence
Eday	seedling emergence day

ELG	End of Leaf Growth
$ElongRate_i$	shoot elongation rate (mm/°C·day) for day *i*
Emerge	seedling emergence
Gday	germination day
GDD	growing degree-days (°C·day)
$GDDE_{req}$	thermal time required for emergence (°C·day)
$GDDG_i$	daily growing degree days (°C·day)
$GDDG_{req}$	required number of growing degree-days for germination (°C·day)
Germ	germination
GN	Growth parameters under non-stressed conditions
GPD	Growing Point Differentiation
Greeley LIRF	USDA-ARS Limited Irrigation Research Farm near Greeley, CO
GS	Growth parameters under stressed conditions
HB	Half Bloom
Hort Farm	Colorado State University Horticultural Farm
IES	Internode Elongation Starts
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
Pdate	planting date
Pdepth	planting depth (cm)
Phenology MMS	Phenology Modular Modeling System
PinDust	Planted in Dust
T_{base}	base temperature (°C)
$T_{max,i}$	daily maximum temperature for day *i* (°C)
$T_{min,i}$	daily minimum temperature for day *i* (°C)
T_{upper}	crop-specific upper temperature threshold (°C)

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