# SEEDING DATE AND GENOTYPE MATURITY INTERACTIONS ON GRAIN SORGHUM [*SORGHUM BICOLOR* –(L.) MOENCH] PERFORMANCE IN NORTH DAKOTA

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**Title**

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**MASTER OF SCIENCE**

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## ABSTRACT

Grain sorghum [*Sorghum bicolor* (L.) Moench] varieties fail to reach maturity in North Dakota's short and cool growing season. The study objective was to evaluate seeding date and white grain sorghum genotypes. A randomized complete block design study was conducted at Carrington, Oakes, and Prosper, ND, in 2018 and 2019. Genotypes included two commercial hybrids and four open-pollinated genotypes. Reaching heading and anthesis, hybrids required more heat units (GDDs), compared with the open-pollinated genotypes. Highest grain yield was obtained from the first and second seeding dates. Earlier-maturing open-pollinated genotypes maintained yield across seeding dates, whereas yield was reduced at later dates for the longer maturity hybrids. Hybrids produced the highest number of kernels per panicle at the first seeding date with fewer seeds at each successive seeding date. Although the open-pollinated genotypes out-yielded the hybrids at later seeding dates, the risk of lodging is too great to recommend their commercialization.

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# 1. INTRODUCTION

Grain sorghum [*Sorghum bicolor* –(L.) Moench] is an important warm-season, heat-tolerant crop used worldwide as food for human consumption and livestock feed. In the United States, grain sorghum is mostly used for animal feed. However, in Asia and Africa, non-tannin white, edible grain sorghum is a staple food for people. According to the Food and Agriculture Organization of the United Nations (FAO), grain sorghum is the fifth most important cereal crop worldwide (FAO, 2019). In the United States grain sorghum is among the top three commonly grown cereals. Most of the U.S. Great Plains states including Texas, Kansas, Oklahoma, Colorado, Nebraska, and South Dakota produce grain sorghum commercially with the exception of North Dakota. North Dakota's short and cool growing season prevents consistent yield performance due to inconsistent lifecycle completion of currently available sorghum varieties. Identification of early-maturing, high-yielding sorghum varieties would increase crop diversity for North Dakota producers and expand marketing opportunities while also diversifying crop rotations. As earlier-maturity sorghum varieties become available, the potential for grain sorghum production in North Dakota will increase. Variety maturity and seeding date are two management factors important for crop performance that require a decision before the spring seeding operation. Determination of optimum seeding dates for different production regions in North Dakota would enable the highest sorghum performance and promote improved agricultural sustainability at the farm and state level.

## 2. LITERATURE REVIEW

The length of the growing season and the genotype maturity affect the optimum crop seeding date for a growing region (Saini et al., 2018). Determination of the optimum seeding date and variety maturity are key factors for improving cropping systems and grain sorghum yield, grain quality, and economic return (Martin and Vanderlip, 1997; Can and Yoshida, 1999; Conley and Wiebold, 2003). Grain sorghum's development is negatively influenced by cooler temperatures and sorghum exhibits greater low temperature sensitivity than for corn (*Zea mays* L.) (Neild, 1982; Antony et al., 2019). Assefa et al. (2014) reported reduced sorghum germination percentage and stand establishment at lower temperatures. Later planting resulted in greater sorghum yield reduction due to the nicking of reproductive development with cooler temperatures late in the season (Martin and Vanderlip, 1997; Can and Yoshida, 1999). Early-maturing grain sorghum hybrids use water more efficiently under water-limited conditions resulting in increased yield and crop value compared with late-maturing hybrids (Martin and Vanderlip, 1997; O'Shaughnessy et al., 2014). Optimizing performance of new warm-season crops in the northern Great Plains such as grain sorghum requires determination of best management practices including seeding date for their successful production (Schatz et al., 1990).

Maximum kernel dry weight accumulation indicates attainment of physiological maturity and occurs with formation of a black or dark cellular layer in the placental area where the sorghum ovule (kernel) attaches to the ovary (Vanderlip, 1972; Eastin et al., 1973; Vanderlip, 1993; Vanderlip, 1998; Gerik et al., 2003; Roozeboom and Prasad, 2016). Attaining black layer formation before the end of the growing season is important for achieving maximum grain yield and grain quality. Also important regarding grain yield, is the duration of the grain filling period between anthesis and physiological maturity (Ciampitti et al., 2016). For these reasons, anthesis date and physiological maturity date are often positively correlated with grain yield because of temporal and metabolic efficiency effects on kernel dry weight accumulation (Eastin et al., 1973; Gerik et al., 2003; Roozeboom and Prasad, 2016; Subalakhshmi et al., 2019).

Schatz et al. (1990) reported a limitation of grain sorghum production in North Dakota is low temperatures during the growing season that result in insufficient growing degree day accumulations for sorghum plants to reach physiological maturity before freezing temperatures in the fall. In 1985, Schatz observed that early June planting with sorghum hybrids Dekalb DK-18 and Northrup King X3174 at Carrington (7 June) and Prosper (15 June) resulted in grain sorghum hybrids not reaching physiological maturity due to cooler than average growing season temperatures, fewer growing season days because of later planting, and reduced growing degree day (GDD) accumulations. In 1985, at Carrington there were, 1,599 GDDs as compared with the long-term average GDD accumulations of 1,906.

Pale et al. (2003) used four different methods i) calendar date, ii) accumulative air heat units, iii) accumulative soil heat units, and iv) soil temperature for estimating a seeding date to obtain maximum sorghum grain yield. The study was conducted in Nebraska from 1995 to 2001 on two different soil types with the sorghum hybrid Dekalb DK28. They found that using air-heat and soil-heat unit accumulations provided more accurate seeding date timing for determining maximum sorghum grain yield than calendar date and soil temperature for two soil types. The ideal sorghum seeding date for grain production under a Sharpsburg silty clay loam soil was with 308 air-heat unit and 307 soil-heat unit accumulations when sown after 1 April. Sorghum grown on the Ortello sandy loam soil produced maximum grain yield with 402 air-heat unit and 361 soil-heat unit accumulations when sown after 1 April. Delaying sorghum seeding beyond the maximum air-heat and soil-heat unit accumulations for optimum grain yield resulted in a 62 to 75% yield reduction with the Sharpsburg silty clay loam soil.

Experiments were conducted in 2011 at Hays and Colby, KS, by Kapanigowda et al. (2013) to evaluate how early (2 May) and normal (31 May) sorghum seeding dates affected emergence percentage, emergence index, and 50% anthesis date under both field and controlled environments. The researchers evaluated 48 genotypes that included landraces, elite and advanced breeding lines, recombinant inbred lines, and hybrids under cold and warm field conditions. Grain sorghum genotypes were negatively affected with early seeding on 2 May due to cold temperature stress that resulted in 27% lower seedling emergence compared with the normal 31 May seeding date. In contrast, emergence index, which is related to emergence rate was higher at the early seeding date (14.8 d) compared with the normal seeding date (8.9 d) (AOSA, 1993). Controlled environment experiments showed a similar trend as the field experiment in Hays and Colby, KS. Early planting with controlled conditions delayed 50% anthesis where 79 and 67 d were required to reach 50% anthesis for the 2 May and 31 May seeding dates, respectively. After the screening process, researchers found eight advanced breeding lines (ARCH10731, ARCH10732, ARCH10736, ARCH10737, ARCH10738, ARCH10739, ARCH10744, and ARCH10749) and one recombinant inbred line (RTx430/SQR-2) as chilling tolerant and tannin free. This research indicates that chilling tolerant genotypes exhibited increased germination, increased stand establishment, and reduced seedling damping off compared with non-chilling tolerant lines when grown under cool growing conditions.

Research by Antony et al. (2019) evaluated the seedling emergence of 18 sorghum genotypes compared with five commercial corn hybrids at Kansas State University at Manhattan, KS. Growth chamber conditions during a 31 d period where a control temperature (25Cº/20Cº day/night) and three low temperature phases (11Cº/8Cº 14 d, 12.5Cº/9.5Cº 14 d, and 14Cº/11Cº 3 d) were used. Grain sorghum seedlings emerged 3 d after planting in the control, but under low temperatures emergence required 11 d. Under the control temperature and low temperatures emergence for corn was 100% and 95%, respectively. Greater reduction in emergence was observed for sorghum, 78% and 24%, for the control and low temperatures, respectively, than with corn. Although starch concentration was the same in corn (68%) and grain sorghum (68%), corn seed was wider (7.9 mm) compared with grain sorghum seed (2.6 mm) and had greater food reserves on an individual seed basis. Larger seed with greater energy reserves provides an advantage to corn compared with the smaller sorghum seed in performing the metabolic processes associated with seed germination and seedling emergence under cooler conditions (Assefa et al., 2014; Berti et al., 2018; Antony et al., 2019).

Can and Yoshida (1999) evaluated seeding date and genotype interactions by using sorghum parents, $F_4$ populations, and hybrid cultivars at two seeding dates in 1996 and 1997 in northern Kyushu, Japan. Spring seeding dates were 10 and 20 April, and summer seeding dates were 29 July and 9 August. The effect of seeding date at the spring sowing season indicated 10 April (3320 kg $ha^{-1}$) and 20 April (3570 kg $ha^{-1}$) seedings did not affect sorghum grain yield and all genotypes reached physiological maturity. However, in the summer, the 9 August seeding delayed heading up to 10 d (67.4 d) compared with the 29 July seeding (56.8 d). This resulted in a 41% grain yield reduction at the late seeding date (2880 kg $ha^{-1}$) compared with the early seeding (4960 kg $ha^{-1}$). This study indicates that grain yield reduction was greater when low temperature stress occurred during grain development for summer seeding dates compared with low temperature stress during stand establishment for spring seeding dates (Can and Yoshida, 1999; Martin and Vanderlip, 2013).

Martin and Vanderlip (1997) studied the relationship between seeding date and sorghum hybrid maturity under dryland conditions from 1993 to 1995 at the Sandyland Experiment Station located at St. John, KS. Three grain sorghum varieties representing different maturity groups were from Dekalb, Golden Harvest, NC Plus Seeds Company, Northrup, and Pioneer. These varieties were planted mid-April, early-May, late-May, mid-June, late-June, early-July, and late-July. Grain yield was significantly influenced by seeding date. Optimum grain yield was obtained under late-May seeding in 1993 and 1994, however, in 1995 mid-June seeding provided optimum grain yield because of cool and wet conditions. Early (mid-April) and late (July) seedings resulted in lower grain yield due to low stand establishment, bird damage, high temperature and moisture stress during anthesis, and cool temperatures during the grain development stages. Bird damage resulted in more than 50% grain losses with early sorghum maturity groups from April seeding in 1995. Early seeding produced higher test weight compared with late seeding. They observed that early-maturity hybrids tended to fill grain more consistently compared with the mid- and late-maturing hybrids. Researchers determined the optimum seeding date was between 25 May to 5 June in Kansas.

Conley and Wiebold (2003) conducted an experiment on grain sorghum seeding date by using six-grain sorghum cultivars with early (Dekalb 28E and Pioneer 8855), mid (Asgrow Seneca and Golden Harvest H388W), and late (Asgrow Topaz and Pioneer 8379) maturity genotypes to identify the best seeding date in Columbia, MO. The study was conducted in 1992, 1993, and 1994 under six different seeding dates extending from mid-April, late-April, mid-May, late-May, mid-June, to late-June. They observed that when seeding date was delayed the number of vegetative growth days between planting to anthesis decreased. The experimental results also indicated that grain sorghum plants required 65 d to reach anthesis for a late-June planting and

80 d or more to reach anthesis when planted in early-April. All three hybrids reached physiological maturity even when planted 21 June. In general, maximum grain yield was obtained with a mid-May planting for all six cultivars. However, early-, mid-, and late-maturity cultivar groups showed different grain yield performances of 8339, 9011, and 9684 kg $ha^{-1}$, respectively when averaged across seeding dates. The lowest grain yield was obtained from the early-June planting for early-, mid-, and late-maturity groups and was 3968, 5380, and 5279 kg $ha^{-1}$, respectively when averaged across cultivar. The lowest grain yield and test weight were related to cooler temperatures during the grain fill period later in the season. Conley and Wiebold (2003) recommended a mid-May planting for Missouri sorghum growers for optimum grain yield.

Zandonadi et al. (2017) conducted an experiment in Sao Paulo, Brazil, to determine how sorghum seeding date affected grain yield, 1000-kernel weight, and nutrient (N, P, K, Ca, Mg, and S) uptake by using two early (Buster and 50A10) and two late (1G282 and 50A70) maturing hybrids with four different seeding dates (26 February, 15 March, 28 March, and 8 April) in 2013. The seeding date by variety interaction was significant for grain yield and 1000-kernel weight. Early-maturing hybrids, Buster and 50A10, produced the highest grain yields of 6186 and 4894 kg $ha^{-1}$ from a 26 February seeding, however, the same hybrids produced low grain yield under 15 March (3914 kg $ha^{-1}$) and 28 March (3178 kg $ha^{-1}$) with delayed seeding. In contrast, the late-maturity hybrids, 1G282 and 50A70, produced greater grain yield under 8 April (5247 kg $ha^{-1}$) and 28 March (4450 kg $ha^{-1}$) seeding dates, respectively, compared with the 15 March seeding date yields were 4233 and 3621 kg $ha^{-1}$ for 1G282 and 50A70, respectively. The 1000-kernel weight was positively correlated with grain yield indicating the importance of the final yield component for grain yield performance (Subalakhshmi et al., 2019). Averaged across varieties the lowest 1000-kernel weight (15.7 g) was from the first seeding date 26 February. The highest 1000-kernel weight (26.4 g) was obtained with the 28 March seeding. Nitrogen and sulfur absorption level was greater at the first and the second seeding dates compared with the third and fourth seeding dates (Zandonadi et al., 2017).

At Elizabeth and Stoneville, MS, Bruns (2019) studied grain yield response of four-grain sorghum hybrids Pioneer 83P17, Dekalb DKS-5400, and two Partners Brand hybrids SP6929 and KS735 at an 11 May and 10 June seeding date in 2016 and 11 May and 12 June seeding date in 2017. In 2016 and 2017, the average hybrid grain yield was higher (5167 kg $ha^{-1}$) from May seedings and lowest from June seedings (4626 kg $ha^{-1}$) in the lower Mississippi River Valley. A similar trend was observed for the number of heads $ha^{-1}$, which is an important yield component for grain sorghum. At the May seedings, hybrids produced 134,167 heads $ha^{-1}$ whereas with the later June seeding there were 118,504 heads $ha^{-1}$. Fewer heads was associated with a smaller source (leaf area) that produced less photosynthetic output for sink (flowers, kernel) development. Source size was also influenced by less plant available soil moisture with later seeding. The authors also noted that sugarcane aphid [*Melanaphis sacchari* (Zehntner)] and head worm [*Helicoverpa zea* (Boddie)] damage reduced yield more with late-June compared with early-May seeding.

In order to determine optimum seeding date, Saini et al. (2018) conducted an experiment from 2014 to 2016 in Surat, Gujarat, India, with four different sorghum seeding dates. The first seeding date was at the onset of the monsoon with subsequent seeding dates spaced at 15 d intervals. Four different genotypes GJ38, GJ42, SR2872, and SR1904 were used as potential lines for future cultivars. The highest mean plant height averaged across genotypes was 238-cm and was observed at the first seeding date. The lowest mean plant height averaged across genotypes was 219-cm and was observed 15 d after the first seeding date. Panicle length was greatest (31-cm) when seeded 15 d after monsoon onset, but the lowest panicle length (18-cm) was observed when seeded 30 d after monsoon onset. The 50% anthesis date ranged from 76 to 79 d among genotypes and did not change with different seeding dates, however, days from seeding to physiological maturity (PM) were fewest (117 d) with the first seeding date in 2014, and the longest (123 d) in 2015. Sorghum obtained the highest grain yield from the first seeding date for each genotype GJ38, GJ42, SR2872, and SR1904, which produced 3508, 2701, 3549, and 3253 kg ha$^{-1}$, respectively. Greater grain yield under the first seeding date was related to more favorable growing conditions during the grain filling period which occurred before the arrival of cooler temperatures. The researchers recommended that in order to obtain maximum grain yield and economic return sorghum should be planted at monsoon onset or within 15 d after monsoon onset. This strategy would also avoid or reduce pest pressures from the shoot fly [*Atherigona soccata* (Rondani)] and stem borer [*Chilo partellus* (Swinhoe)]. Those two pests caused late-season damage and reduced grain yield and economic income in the region.

Safari and Sanavy (2010) conducted an experiment to observe seeding date effects on grain sorghum phenological traits and grain yield in west Tehran, Iran, in 2007. Treatment factors were hybrids (Payam, Sepideh, and Kimia) and seeding dates (8 June, 28 June, and 18 July). Results indicated that under 8 June and 28 June seedings sorghum required 60 d to reach 50% heading, however, sorghum seeded on 18 July reached 50% heading 10 d earlier. They reported that genotypes reached physiological maturity earlier (95 d) under the first seeding date compared with the second (97 d) and third (100 d) seeding dates. The highest sorghum grain yield of 6677 kg ha$^{-1}$ was obtained with an 8 June seeding compared with 28 June (5849 kg ha$^{-1}$) and 18 July (5058 kg ha$^{-1}$) seedings.

Emeklier and Koksoy (1997) planted the grain sorghum cultivar Beydari for determining optimum grain sorghum management practices in Ankara, Turkey. Researchers used three seeding dates (20 April, 5 May, and 20 May) and three plant densities 10-, 15-, and 20-cm within row plant spacings, where rows were spaced 40-cm apart. The highest grain yield (4845 kg $ha^{-1}$) was obtained from the 20 April seeding however, the lowest grain yield (1443 kg $ha^{-1}$) was observed under the last seeding date 20 May within the 20-cm plant spacing. However, the results indicated that under the same plant density (20-cm) 1000-kernel weight was the highest (19.9 g) for the final seeding date (20 May) and the first and second seeding dates produced lower 1000-kernel weights of 13.7 and 13.4 g, respectively. The fewest days from planting to reach 100% anthesis was observed under the 15-cm plant spacing and 20 April (96 d), 5 May (93 d), and 20 May (85 d) seeding dates. The maximum grain yield was produced from the 20-cm plant spacing and earliest seeding date of 20 April at Ankara, Turkey.

SORKAM is an integrated and intelligent grain sorghum growth model that provides appropriate analysis by examining climate, soil type, crop variety, cultivar maturity, plant density, row spacing, seeding dates, and other cultural production practices for selected specific locations (Rosenthal et al., 1989; Rosenthal and Gerik, 1990; Baumhardt et al., 2005). Although SORKAM does not calculate unexpected crop damage such as from hail, storm, insect, disease, and weed pressure, the model utilizes long-term weather data and various edaphic factors to provide the best management practices for farmers, extension agronomists, and researchers for profitable grain sorghum production (Rosenthal and Gerik, 1990).

Baumhardt et al. (2005) examined three seeding dates (15 May, 5 June, and 25 June), two row widths (38 and 76-cm), and three cultivar maturity groups (early 95 d, medium 105 d, and late 120 d to reach physiological maturity) to determine optimum dryland grain sorghum grain yield by using the SORKAM simulation model based on 40 years of weather records at Bushland, TX. Results indicated that the highest grain yield was obtained from early- (4250 kg $ha^{-1}$) and medium- (4100 kg $ha^{-1}$) maturity groups with a 5 June planting because cultivars escaped the excessive summer heat and soil water deficit at anthesis and grain filling stages and reached physiological maturity before the fall frost. The number of kernels $panicle^{-1}$ was higher (3170) for the early-maturing cultivar compared with the medium- (2420) and late- (2070) maturing cultivars. In contrast M'Khaitir and Vanderlip (1992) observed that when sorghum seeding date was delayed, the number of kernels $panicle^{-1}$ significantly increased at Manhattan and St. John, KS. At the final seeding (25 June) 33% of the late-maturing cultivars simulated yields failed to reach physiological maturity compared with 16 and 5% for medium- and early-maturity group cultivars, respectively (Baumhardt et al., 2005).

Precipitation distribution is an extremely important consideration in determining optimum seeding date for highest grain yield and profitable grain sorghum production. Early-spring and late-summer rains at the anthesis and grain filling stages is vital for increasing yield and grower profits at Uvalde and Dallas in central Texas. In west Texas, at Amarillo and Lubbock, lack of adequate soil moisture at the anthesis and grain filling stages and freezing temperatures before physiological maturity resulted in grain yield reductions up to 1121 kg $ha^{-1}$ (Rosenthal and Gerik, 1990).

Baumhardt and Howell (2006) studied the effects on simulated grain sorghum yield under dryland, deficit irrigation (2.5 mm $d^{-1}$), and full irrigation (5.0 mm $d^{-1}$) conditions by using the SORKAM grain sorghum growth model. Sorghum grain yield increased 30 and 88% with deficit irrigation and full irrigation, respectively, compared with dryland production. Dryland simulated grain yield was 3940 kg $ha^{-1}$ whereas deficit irrigation and full irrigation yields were 5140 and

7400 kg $ha^{-1}$, respectively. The highest simulated grain yield was obtained from the 5 June seeding date (5730 kg $ha^{-1}$) compared with the early 15 May (5450 kg $ha^{-1}$) and late 25 June (5300 kg $ha^{-1}$) seeding. They also noted that irrigation promoted crop growth and development. Under full irrigation, the number of kernels $panicle^{-1}$ was the highest at 1960 compared with water deficit irrigation (1700) and dryland (1455).

Mastrorilli et al. (1995) reported that the water requirement for sorghum varied with growth stage. If grain sorghum has water stress during specific reproductive stages serious yield reductions can occur. At Rutigliano, in southern Italy 1991, researchers evaluated three water stress periods at sorghum reproductive stages anthesis, seed setting, and seed ripening on grain yield. Grain sorghum cultivar Aralba produced 1259 kernels $panicle^{-1}$ and yielded 6340 kg $ha^{-1}$ under non-stress conditions. The highest water sensitivity level was observed at anthesis, which resulted in 58% fewer kernels $panicle^{-1}$ and 61% less grain yield. The researchers recommended additional irrigation at the reproductive stages, especially the anthesis stage, benefits grain sorghum growth, development, and grain yield in Mediterranean production regions.

Grain sorghum final stand, grain yield, and water use efficiency vary with different maturity groups, seeding dates, and irrigation treatments (O'Shaughnessy et al., 2014). O'Shaughnessy et al. (2014) evaluated early-maturing sorghum hybrid NC+ 5C35 (planted late June) and late-maturing hybrid Pioneer 84G62 (planted late May to early June) at four irrigation levels 80, 55, 30, and 0% soil water deficit from field capacity in the top 1.5-m soil profile in Bushland, TX, from 2009 to 2011. Center pivot irrigation was used for irrigation and Neutron Probe instrumentation was used for determination of soil water content and scheduling irrigation. In 2009 and 2011, final stand for the early-maturing sorghum hybrid ranged from 66 to 93% and was greater compared with the late-maturing hybrid final stand that ranged from 57 to 69%. The researchers did not observe differences with the 30% and 0% soil water deficit treatments between early (1560 and 4130 kg $ha^{-1}$, respectively) and late (1610 and 4210 kg $ha^{-1}$, respectively) maturing hybrids. The early-maturing hybrid produced the lowest grain yield at 6060 and 6950 kg $ha^{-1}$ under 80% and 55% soil water deficit treatments, respectively, compared with late-maturing hybrid grain yields at 7110 and 8750 kg $ha^{-1}$ under 80% and 55% soil water deficit treatments, respectively. O'Shaughnessy et al. (2014) also noted that the late-maturing hybrid needed 13% to 51% more water than the early-maturing hybrid, respectively in 2009 and 2011. However, in 2010, the early-maturing hybrid required 14% more water than the late-maturing hybrid due to extremely high temperatures in August that coincided with the anthesis growth stage. The research reports that the early-maturing hybrid water use efficiency was 27% and 29% higher than the late-maturing hybrid in 2009 and 2011, respectively.

### 2.1. Summary early and late planting advantages and disadvantages

The previously sited research demonstrates that both early and late planting have some advantages and disadvantages for grain sorghum production that are dependent on genetics, soil, pests, and climatic factors. Optimum seeding date recommendations should be specific for a location, maturity group, and genotype, based on the variability of these factors for a production region.

For sorghum production in a region early planting is generally more advantageous than late planting. Early planting produces higher grain yield, test weight, and 1000-kernel weight compared with late planting (Martin and Vanderlip, 1997). Nitrogen and sulfur absorption were greater from early planting compared with late planting (Zandonadi et al., 2017). May plantings, in Mississippi, produced more heads $ha^{-1}$ compared with later June planting due to greater sink source size, available photosynthetic radiation, and available soil water (Bruns, 2019). Early planting avoids excessive summer heat, water deficit phases at the anthesis and grain filling stages, and enables attaining physiological maturity before the fall frost (Emeklier and Koksoy, 1997; Baumhardt et al., 2005; Safari and Sanay, 2010; Saini et al., 2018). Early planting may reduce pest pressures from the shoot fly and stem borer (Saini et al., 2018).

The disadvantages of the early planting are that low temperatures and wet soil can reduce germination and emergence resulting in low stand establishment (Neild, 1982; Martin and Vanderlip, 1997; Kapanigowda et al., 2013; Assefa et al., 2014; Berti et al., 2018; Antony et al., 2019). Early spring frost may damage grain sorghum at the seedling stage (Martin and Vanderlip, 1997). Bird damage potential varies with location and may be more severe for early-maturing genotypes when planted early (Martin and Vanderlip, 1997).

Researchers noted some advantages of late sorghum planting. Late planting increases the uniformity of germination, emergence, and stand establishment rate because of potentially more ideal soil and air temperatures (Kapanigowda et al., 2013; Assefa et al., 2014; Berti et al., 2018; Antony et al., 2019). The number of days between planting to heading and anthesis decreased 10-15 d compared with early planting because of more rapid heat unit accumulations. Late planting success increases with availability of earlier-maturity hybrids in areas with moderate length growing seasons (between 105 to 120 d) where wet and cool conditions cause delayed planting (Vanderlip, 1998; Conley and Wiebold, 2003; Kapanigowda et al., 2013). Late planting may reduce bird damage for some locations depending on pest occurrence, migration, and sorghum growth stage (Martin and Vanderlip, 1997). Late plantings can influence yield component expression where an increased number of kernels panicle$^{-1}$ (M’Khaitir and Vanderlip, 1992) and higher 1000-kernel weight have been reported with late- compared with early planting (Emeklier and Koksoy, 1997; Zandonadi et al., 2017). Irrigation can reduce crop heat stress at the anthesis and grain filling stages for sorghum and this would increase late planting success potential (Baumhardt et al., 2006; O'Shaughnessy et al., 2014).

Late planting, however may cause several drawbacks such as reduced grain yield and grain quality due to poor stands from inadequate soil water for germination and failure to reach physiological maturity at the end of the growing season (Martin and Vanderlip, 1997). Higher soil temperatures can suppress sorghum development at the seedling stage and result in delayed anthesis. High air and soil temperatures and soil water deficits typically occur at anthesis and are detrimental for final sorghum grain yield (Rosenthal and Gerik, 1990; Martin and Vanderlip, 1997). The lowest grain yield and test weight were related to cooler temperatures during the grain filling period later in the season (Martin and Vanderlip, 1997; Can and Yoshida, 1999; Conley and Wiebold, 2003) which resulted in slower accumulation of GDDs for attaining physiological maturity before fall frost. Frost occurrence before physiological maturity substantially reduces grain filling, 1000-kernel weight, and grain yield (Schatz et al., 1990; Martin and Vanderlip, 1997; Can and Yoshida, 1999; Pale et al., 2013). In addition to the risk of not reaching physiological maturity and reduced yield associated with late planting, insect pests like the sugarcane aphid and head worm reduced sorghum grain yield more with late June compared with early-May planting when maturity was attained (Bruns, 2019).

# 3. OBJECTIVES

The study objective was to identify seeding date effects on grain yield and other trait responses for edible early-maturing hybrids and open-pollinated white grain sorghum genotypes when grown at several locations in eastern North Dakota.

# 4. MATERIALS AND METHODS

Field research studies on grain sorghum were conducted at the Carrington Research Extension Center (REC), ND (-99º1215’W, 47º5152’N, 474 m elevation) in 2018 and (-99º1319’W, 47º5152’N, 474 m elevation) in 2019, Oakes Irrigation Research Site Robert Titus Research Farm (-98º0936’W, 46º0728’N, 400 m elevation) in 2018 and (-98º0936’W, 46º0730’N, 400 m elevation) in 2019, and North Dakota State University Prosper off-station Research Site (-97º1138’W, 46º9946’N, 284 m elevation) in 2018 and (-97º1076’W, 47º0015’N, 284 m elevation) in 2019 during the 2018 and 2019 field seasons.

The Carrington REC and North Dakota State University Prosper Research Site were selected as dryland study locations. In order to observe the irrigation effect on sorghum grain yield and maturity the study was also conducted at the Oakes Irrigation site with irrigation.

At Carrington, the soil complex was a Heimdal series (Coarse-loamy, mixed, superactive, frigid Calcic Hapludolls) and Emrick series (Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls) with 0 to 3% slopes. At Oakes, the soil was a Spottswood series (Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Aquic Hapludolls) with 0 to 3% slopes. At Prosper, the soil complex was a Kindred series (Fine-silty, mixed, superactive, frigid Typic Endoaquolls) and Bearden series (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls Endoaquolls) with 0 to 2% slopes (Web Soil Survey, 2019).

The previous crop at Prosper was hard red spring wheat (*Triticum aestivum* L.) both years of the study. Previous crops at the Carrington location were field pea (*Pisum sativum* L.) in 2017 and hard red spring wheat in 2018. At Oakes, fallow and soybean [*Glycine max* (L.) Merr.] preceded sorghum in 2018 and 2019, respectively.

Conservation tillage was practiced at all field locations with fall disking or chisel plowing the previous crop before planting sorghum the following spring. Spring seedbed preparation was a single pass with a field cultivator with harrow attachment at Prosper. At Carrington, a field cultivator was used for light tillage approximately 3-cm deep in both years for seedbed preparation. At Oakes, spring tillage was field cultivation for seedbed preparation in 2018 and 2019.

Fertilizer applications were based on four composite soil samples collected from each replicate at 0- to 15-cm and 15- to 60-cm depths, at each site, before the seeding operation (Franzen, 2018b). Soil samples were sent to the soil testing laboratory in Waldron Hall at NDSU in for determining appropriate fertilizer amendments based on North Dakota fertilizer recommendation tables and equations (Franzen, 2018a). Tested soil sample traits at 0- to 15-cm depth were $NO_3$-N, P, K, organic matter, and pH, and 15- to 30-cm depth $NO_3$-N was tested.

Soil tests showed nitrogen variability based on soil type and previous crop (Table 1). Nitrogen was applied when sorghum plants were at third leaf collar visible (growth stage 2) and fifth leaf collar visible (growth stage 3) on the main stem. This coincided with early vegetative growth and rapid nutrient uptake development stages (Vanderlip, 1993). In 2018 and 2019, the Carrington REC, Oakes irrigation research site, and Prosper off-station research site were fertilized with nitrogen based on a sorghum grain yield goal of 6,725 kg $ha^{-1}$ according to the North Dakota fertilizer recommendation tables and equations (Franzen, 2018a). According to the soil test results phosphorus and potassium were not applied at any research sites because these nutrients were between medium-high to very high levels in the soil. Organic matter levels were adequate for good crop production (Table 1).

Table 1. Soil test results before seeding for six environments at Carrington, Oakes, and Prosper, ND, in 2018 and 2019.

| Environment | Soil depth | $NO_3$-N | P | K | pH | OM† |
|---|---|---|---|---|---|---|
| | ---cm--- | ---kg $NO_3$-N $ha^{-1}$--- | ---mg $kg^{-1}$--- | | | ---g $kg^{-1}$--- |
| 2018 | | | | | | |
| Carrington | 0-15 | 123 | 8 | 170 | 7.7 | 38 |
| | 15-60 | - | - | - | - | - |
| Oakes | 0-15 | 63 | 27 | 239 | 6.9 | 31 |
| | 15-60 | 84 | - | - | 7.4 | - |
| Prosper | 0-15 | 19 | 34 | 220 | 7.8 | 30 |
| | 15-60 | 52 | 14.5 | 209 | - | - |
| 2019 | | | | | | |
| Carrington | 0-15 | 62 | 17 | 321 | 7.0 | 35 |
| | 15-60 | - | - | - | - | - |
| Oakes | 0-15 | 10 | 23 | 201 | 7.0 | 27 |
| | 15-60 | 10 | - | - | 7.6 | - |
| Prosper | 0-15 | 20 | 11.5 | 210 | 8.0 | 34 |
| | 15-60 | 50 | 5.5 | 138 | 8.3 | 23 |

† OM = Organic matter.

**4.1. Experimental design and experimental units (plots)**

The experimental design was a randomized complete block design (RCBD) with a split-plot arrangement with four replicates at each environment (location-year). The main plot was seeding date with three levels and the sub-plot was genotype with six levels. The two study years and three study locations resulted in six-location years which were each termed an environment. Each experimental unit/plot was 9.8 $m^2$ at the Carrington environments, 11.6 $m^2$ at the Oakes irrigated environments, and 13.9 $m^2$ at the Prosper environments. The number of rows and row spacing at each location was 4 rows at 35-cm apart, 4 rows at 35-cm apart, and 6 rows at 30-cm apart, for the Carrington, Oakes, and Prosper environments, respectively.

## 4.2. Seeding dates

The North Dakota Agricultural Weather Network (NDAWN, 2020) was used for daily air and soil temperatures and precipitation data at Carrington, Oakes, and Prosper in 2018 and 2019. In general, the last spring frosts end after the second week of May in East central North Dakota. For this reason, the first sorghum seeding date was targeted after mid-May to reduce the risk of frost damage to emerging sorghum seedlings.

The first seeding selection also considered soil temperature since sorghum is a warm-season crop and prefers soil temperatures above 15ºC for timely germination and emergence. North Dakota has approximately 120 growing days between the last spring frost and first fall frost. Therefore, the second and third seeding dates were spaced at approximately 7 to 10 d intervals with exact dates subject to suitable weather and field conditions for planting at the environments. Under these parameters, determination of the ideal seeding dates for eastern North Dakota were targeted at the third and last week of the May and the first week of the June (Table 2).

Table 2. Seeding dates for six environments at Carrington, Oakes, and Prosper, ND, in 2018 and 2019.

| | Seeding dates | | |
|---|---|---|---|
| Environment | Date 1 | Date 2 | Date 3 |
| Carrington 2018 | 24 May | 31 May | 7 June |
| Carrington 2019 | 23 May | 30 May | 6 June |
| Oakes 2018 | 30 May | 7 June | 15 June |
| Oakes 2019 | 28 May | 4 June | 10 June |
| Prosper 2018 | 22 May | 30 May | 7 June |
| Prosper 2019 | 29 May | 5 June | 12 June |

## 4.3. Genotypes

Four white open-pollinated sorghum genotypes were selected from 106 genotypes screened for adaptation in North Dakota over a three-year period from 2015 to 2017. The selection process occurred in two phases with the first phase including 56 genotypes evaluated in 2015, a second phase including 50 different genotypes evaluated in 2016, and a seed increase phase for the superior genotypes in 2017. The four most promising genotypes based on high grain production, early-maturity, cold tolerance, black spot formation (physiological maturity), seed size, and no or low green seed were used for this study.

The four white, open-pollinated, early-maturing, and high-yielding genotypes were: PI574595, SARE10, SARE14, and SARE17. Genotype PI574595 has compact panicles and other SARE lines have semi-open panicles. The two earliest-maturity commercial white grain sorghum hybrids were AG1401 from Alta Seed Company, Irving, TX, and RS320W from Richardson Seed Company, Vega, TX. Both hybrids are white-seeded, food-grade, compact panicle, and had the stay-green trait. Hybrid AG1401 is a mid-early hybrid with good grain yield under stress conditions and RS320W an early-maturing hybrid with good grain yield. Both hybrids had good standability and threshing ease. More information about the history of the open-pollinated, white grain sorghum genotype screening process appears in the Appendix A.

Two 50-seed samples were germinated by the ragdoll method (AOSA, 1993) at approximately 23ºC for each genotype. The genotypes were germinated each year of the study before planting. After the germination test the seeding rate was determined on a pure live seed (PLS) basis at 160,550 PLS $ha^{-1}$. In addition, 30% more PLS was added to account for an average expected seed/seedling mortality rate of 30%. The number of seeds per plot for each genotype was determined by dividing the PLS seeding rate by germination percentage and then dividing this value by 0.70. A bulk seed sample of each genotype and calculated actual number of pure live seed was provided for the studies at the Carrington REC and Oakes Irrigated site each year based on experimental unit/plot size (Table 3).

Table 3. Total number of planted seed for each experimental unit per genotype for six environments at Carrington, Oakes, and Prosper, ND, in 2018 and 2019.

| | Genotypes | | | | | |
|---|---|---|---|---|---|---|
| Environment | AG1401† | RS320W† | PI574595‡ | SARE10‡ | SARE14‡ | SARE17‡ |
| | -----------------------------------seeds per plot------------------------------------ | | | | | |
| Carrington 2018 | 239 | 229 | 255 | 303 | 261 | 288 |
| Carrington 2019 | 267 | 264 | 242 | 252 | 250 | 239 |
| Oakes 2018 | 285 | 273 | 304 | 361 | 311 | 343 |
| Oakes 2019 | 318 | 315 | 288 | 300 | 297 | 285 |
| Prosper 2018 | 342 | 328 | 366 | 435 | 374 | 413 |
| Prosper 2019 | 383 | 378 | 346 | 361 | 357 | 342 |

† Commercial hybrids

‡ Open-pollinated genotypes

### 4.4. Seeding planters

An Almaco six-row belt-cone planter with double-disk openers and twin-V packer wheels (ALMACO, Nevada, IA) was used at Prosper. The trial was planted with a Hege cone seeder with double-disk openers (Hans-Ulrich Hege Company, Waldenberg, Germany) at Carrington and a Wintersteiger Rowseed XL with double-opener plot disk drill (Salt Lake City, UT) was used for planting at the Oakes irrigated location.

### 4.5. Harvest procedure and equipment

The four-center plot rows were direct harvested with a Hege 125B plot combine (Hans-Ulrich Hege Company, Waldenberg, Germany) at Prosper in 2019. At the Prosper 2018 environment, the sorghum plots were hand harvested due to plant lodging caused from excessive rain (43.5 mm) between 7 and 10 October, freezing temperatures at 10 October (-9ºC) and 11 October (-11ºC), and heavy wet snow with high wind velocity (48 and 55.7 km $h^{-1}$) on 9 and 10 October (Figure C.1). Sorghum panicles were hand clipped and then threshed with the Hege 125B plot combine at Prosper in 2018. At Prosper, in 2018 and 2019 each field harvested plot grain sample was placed into a paper bag, transported to the Waldron Hall grain dryers in room 120, and dried to approximately 30 to 40 g $kg^{-1}$ grain moisture. The grain samples were then individually cleaned with an Office Tester model small grain clipper (Clipper, A.T. Ferrell Company, Bluffton, IN). The grain samples were then weighed, recorded, and mathematically adjusted to 140 g $kg^{-1}$ seed moisture.

The trial was harvested with a Zürn 150 plot combine (Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany) at Carrington and an Almaco SPC40 plot combine (ALMACO, Nevada, IA) at the Oakes irrigated location. A Hege 125B plot combine (Hans-Ulrich Hege Company, Waldenberg, Germany) was used for threshing at Prosper in 2018 and harvesting in 2019. The number of harvested rows and harvest dates at each site are indicated in Table 4.

Table 4. Harvested rows and harvest dates with six environments at Carrington, Oakes, and Prosper, ND, in 2018 and 2019.

| Environment | Rows harvested | Harvest dates |
|---|---|---|
| Carrington 2018 | 4 | 18 October |
| Carrington 2019 | 4 | 6 November |
| Oakes 2018 | 4 | 23 October |
| Oakes 2019 | 4 | 8 November |
| Prosper 2018 | 2† | 1 November |
| Prosper 2019 | 4‡ | 31 October§ |
| | | 1 November¶ |

† At Prosper, only center-two rows harvested due to severe lodging in 2018.
‡ At Prosper, only center-four rows harvested in 2019.
§ At Prosper, Date 1 and 2 were harvested on 31 October 2019.
¶ At Prosper, Date 3 was harvested on 1 November 2019.

## 4.6. Traits evaluated

### *4.6.1. Pure live seed emergence (PLSE)*

Seedling emergence was counted by hand in each row of each plot at 30 d after seeding to determine pure live seed emergence (PLSE). The experimental unit/plot PLSE was averaged across the six rows in each plot. The PLSE was calculated as:

$$\text{PLSE} = [(\text{number of emerged plants / number of pure live seeds planted}) \times 100] \quad \text{(Eq.1)}$$

### *4.6.2. Phenological evaluations*

Days to 50% heading (H50), 100% heading (H100), 50% anthesis (A50), 100% anthesis (A100), and physiological maturity (PM) were determined from the plants in the four-middle plot rows when: i) 50% of main stem heads were above the flag leaf collar (H50); ii) 100% of main stem heads were above the flag leaf collar (H100); iii) 50% of main stem heads were at first pollen shedding (A50); iv) 100% of main stem heads were at first pollen shedding (A100); and v) all main stem head bottom kernels exhibited black spot formation in the placental area (PM) (Vanderlip, 1993). Data for PM was expressed as the number of days from planting to physiological maturity (PM).

Growing degree days (GDD) were calculated daily based on sorghum minimum and maximum temperatures of 15ºC and 30ºC, respectively (NDAWN, 2020). The daily GDDs were cumulative from seeding date to trait determination and stated as accumulated growing degree days. This applies to traits: GDD 50% heading at 10ºC ($GDD_{10}H50$), GDD 50% heading at 15ºC ($GDD_{15}H50$), GDD 100% heading at 10ºC ($GDD_{10}H100$), GDD 100% heading at 15ºC ($GDD_{15}H100$), GDD 50% anthesis at 10ºC ($GDD_{10}A50$), GDD 50% anthesis at 15ºC ($GDD_{15}A50$), GDD 100% anthesis at 10ºC ($GDD_{10}A100$), GDD 100% anthesis at 15ºC ($GDD_{15}A100$), GDD physiological maturity at 10ºC ($GDD_{10}PM$), and GDD physiological maturity at 15ºC ($GDD_{15}PM$).

Accumulated growing degree days calculated both at 10ºC and 15ºC, base temperatures according to the following formulas:

$$GDD_{10} = [(\text{maximum temperature} + \text{minimum temperature})/2] - \text{base temperature } (10ºC) \quad \text{(Eq.2)}$$

$$GDD_{15} = [(\text{maximum temperature} + \text{minimum temperature})/2] - \text{base temperature } (15ºC) \quad \text{(Eq.3)}$$

### *4.6.3. Morphological evaluations*

Main stem plant height was measured from the ground surface to the top of the head/panicle after PM with a tape measure for three representative plants from the four-center plot rows.

Main stem head (panicle) height was measured similarly to plant height, but from the ground surface to the base of the head. Panicle length was measured from the head base to the top of the panicle. Main stem plant height and main stem panicle length were averaged across the same three plants.

Lodging score ranged from 0 (none) to 9 (all) and pertained to all plants from the experimental unit/plot four middle rows. A lodging score of 0 represents there is no lodging and all plants are upright. A lodging score of 9 represents all plants from the experimental units are being prostrate or completely flat. A lodging score 4.5 represents 50% of the plants from the experimental unit are tilted approximately at a 45-degree angle. Lodging scores were recorded at harvest.

### *4.6.4. Grain yield*

Plot grain yield was calculated at 140 g kg$^{-1}$ seed moisture and expressed in kg ha$^{-1}$. Expressing grain yield as kg ha$^{-1}$ was performed by multiplying the harvested plot area by a correction factor to convert grams of grain per plot to kg grain ha$^{-1}$. The correction factor was different for each environment due to different harvested plot areas.

Harvested grain yield (HGY) was the yield harvestable with the plot combines. This would be the grain yield that a farmer would expect with direct/straight combine harvesting. Normal combine harvesting was possible at the Carrington environments, Oakes 2019 environment, and Prosper 2019 environment. Normal combine harvesting was not possible at the

Oakes 2018 and Prosper 2018 environments since all or the majority of plants were lodged severely for pickup into the combine.

At the Oakes 2018 environment, snow caused the bird netting to collapse onto the sorghum panicles pushing plants/panicles from 45 cm to ground surface (Figure C.2). Panicles were combined the panicles from the ground by placing the header as low as possible and running the entire sorghum plant through the combine. This required barely moving the combine forward and backing up to prevent plugging the combine cylinder.

At the Prosper 2018 environment, harvest was delayed because of wet fall conditions followed by a snowstorm that caused nearly 100% lodging in the open-pollinated genotypes. The crop was ready to harvest before the snowstorm, but field conditions and plants/panicles were too wet for combining. After the snowstorm the decision was made to hand harvest the plots even where heads that were lower than combine accessibility or on the ground were harvested. The yields for the Prosper 2018 environment would accurately reflect an earlier, timely harvest before the bad weather conditions.

#### *4.6.5. Crop yield components*

The number of grain-producing panicles and number of tillers (fertile panicles) were counted by hand in each row of each plot. Panicle and tiller count were performed three to four weeks before harvest in order to determine panicle and tiller density m$^{-2}$ and tillers plant$^{-1}$, respectively.

Grain yield panicle$^{-1}$ and number of kernels panicle$^{-1}$ were calculated as:

$$\text{Grain yield panicle}^{-1} = [\text{total plot yield / total number of harvested panicles}] \quad \text{(Eq.4)}$$

$$\text{Number of kernels panicle}^{-1} = [(\text{grain yield panicle}^{-1} \times 1000) / \text{1000-kernel weight}] \quad \text{(Eq.5)}$$

$$\text{Panicle density} = [(\text{total number of counted panicles m}^{-2}) / \text{total plot size}] \quad \text{(Eq.6)}$$

$$\text{Tiller density} = [(\text{total number of counted tillers m}^{-2}) / \text{total plot size}] \quad \text{(Eq.7)}$$

$$\text{Tillers plant}^{-1} = [\text{total number of tillers} / \text{total number of main heads}] \quad \text{(Eq.8)}$$

Two hundred seeds were counted by hand and then weighed from the harvested grain sample for each experimental unit. The 200-kernel weight was then multiplied by five to provide a 1000-kernel weight. To determine test weight a 0.473 L metal cup, a striker wood stick, a metal grain funnel and stand, and an electronic scale were used. The test weight procedure described by GIPSA 2009 was followed.

#### ***4.6.6. Percent bird damage***

Bird damage at the Oakes location was observed during the 2018 and 2019 growing season by counting the number of damaged panicles and damage severity for each panicle and converting it to a percent mean damage value. A net with supports was installed over the sorghum plot at both Oakes environments to prevent further bird damage (Figure C.3).

#### ***4.6.7. Pest management (weeds, diseases, insects, and birds)***

##### *4.6.7.1. Weeds*

Pests (weeds, diseases, insects, and birds) and disease observations were made during data collection, daily regular visits, and plot maintenance events at the respective study environments. Herbicides were selected based on recommendations in the North Dakota Weed Control Guide (Ikley et al., 2020) and were applied at each location when broadleaf weeds were shorter than 4-cm and grassy weeds were at the 2- to 3-leaf stages. Weed pressure varied for each environment and therefore weed management was done with different chemicals and application rates. Disease and insect pests were incidental and did not reach pest populations or damage level (economic thresholds) that would warrant pesticide applications.

At the Carrington 2018 environment, herbicides were applied by an all-terrain-vehicle (ATV) mounted sprayer and boom system with TurboTee8002 nozzle tips at 207 kPa pressure to deliver 122 L $ha^{-1}$ at about 5 km $h^{-1}$. The most problematic weed species was green foxtail (*Seteria viridis* L.), but common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), powell's amaranth (*Amaranthus powellii* S. Watson), and kochia (*Bassia scoparia* (L.) A.J. Scott) were also present in small numbers in 2018. Quinclorac: 3,7-dichloro-8-quinolinecarboxylic acid (Facet® 1.6 L $ha^{-1}$) and atrazine: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine (Atrazine 4L® 2.3 L $ha^{-1}$) were sprayed post-emergence for weed control.

At the Carrington 2019 environment, the most common weed species were green foxtail, yellow foxtail, powell's amaranth, and kochia. Quinclorac: 3,7-dichloro-8-quinolinecarboxylic acid (Facet® 1.6 L $ha^{-1}$) was applied after emergence of the third seeding date. After that, pendimethalin: N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine (Prowl® $H_2O$ 3.5 L $ha^{-1}$), s-metolachlor (Dual Magnum® 1.75 L $ha^{-1}$), and pyroxasulfone: 3-[[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1*H*-pyrazol-4-yl]methyl]sulfonyl]-4,5-dihydro-5,5-dimethylisoxazole (Zidua® 0.36 L $ha^{-1}$) were pre (surface applied before weed emergence) applied two weeks later to prevent grass weed establishments. Pyrasulfotole+bromoxynil octanoate+bromoxynil heptanoate (Huskie® 1.1 L $ha^{-1}$) was post applied following the previous applications. Hand weeding and hoeing were performed as needed to control late-emerging weeds.

At the Oakes 2018 environment, kochia and common lambsquarters were the biggest weed problems. Dicamba: N,N-Bis-(3-aminopropyl)methylamine salt of 3,6-dichloro-o-anisic acid (Engenia® 0.1 L $ha^{-1}$) was post applied to control broadleaf weeds. Barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) and foxtails were hand weeded twice during the growing season. At the Oakes 2019 environment, redroot pigweed, common lambsquarters, barnyardgrass, and green foxtail were the predominant weed species. Atrazine: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine (Atrazine 4L® 0.47 kg $ha^{-1}$) and fluroxypyr: ((4-amino-3,5-dichloro-6-fluoro-2-pyridiniyl)oxy)acetic acid, 1-methylheptyl ester + bromoxynil: (2,6-dibromo-4-cyanophenyloctanoate) (Starane® NXT 1.02 L $ha^{-1}$) mixture was post sprayed for weed control.

At the Prosper 2018 environment, herbicides were not applied because weed pressure was low and hand weeding was performed across the study 7 d after each seeding date and was effective weed control. At the Prosper 2019 environment, excessive densities of redroot pigweed and green foxtail warranted the use of herbicide application. Herbicides were applied by $CO_2$-pressurized backpack sprayer and 2-m-wide boom system with TurboTee11001 nozzle tips at 276kPa pressure to deliver 80 L $ha^{-1}$ applied at the speed of approximately 5 km $h^{-1}$. The experiment was post sprayed with pyrasulfotole+bromoxynil octanoate+bromoxynil heptanoate (Huskie® 0.9 L $ha^{-1}$) for redroot pigweed control after weed emergence. Weed management was further conducted in the third replicate by hoeing and hand weeding as needed for green foxtail control.

Abiotic disorders were related to a single unknown source of paraquat dichloride (1,1'-dimethyl-4,4'-bipyridinium dichloride (Gramoxone®SL 2.0) drift injury at the Prosper 2018 environment. Paraquat drift was positively identified from contact injury symptoms observed between sorghum growth stages stage 4 (flag leaf visible) in the open-pollinated genotypes, but not for the hybrids. A scald like spot appearance on leaves addresses chemical damage symptoms however, these symptoms can be easily misidentified with foliar diseases. The appearance of paraquat injury has a dark, cherry-red color margin on sorghum leaves and patches of dead cells inside of the dark red margin holes (Jesse Ostrander, Kirk A. Howatt, Berlin Nelson, and Andrew J. Friskop, 2018, personal communications). These symptoms were observed on the upper leaves of plants (Figure C.4).

Another concerning abiotic factor was plant lodging and was only observed in the open-pollinated genotypes at the Prosper 2018 environment. Plant lodging occurred severely in 2018 at Prosper compared with other environments because of the heavy and excessive rainfall, icy rain, frost, that was followed by high wind velocity causing nearly complete lodging for all plots in the open-pollinated genotypes.

*4.6.7.2. Diseases*

Abiotic (non-living) and biotic (living) field disease observations/concerns were recorded and plant samples collected during the regular visits at the six study environments.

Grain sorghum diseases were diagnosed by Jesse Ostrander, a plant diagnostician at the NDSU Plant Diagnostic Lab, as well as Dr. Berlin Nelson and Dr. Andrew Friskop, professors in the Plant Pathology department at North Dakota State University. Biotic factors were bacterial leaf spot (*Pseudomonas syringae*) and *Fusarium* root and stalk rot (*Fusarium moniloforme*). According to the NDSU Plant Diagnostic Lab results, leaf spots were positive with bacteria for the hybrids AG1401 and RS320W at Carrington in 2018, Oakes in 2018, and Prosper in 2018 and 2019. Bacterium caused spots were irregular oval shape, small, yellow-orange to brown-orange in on the lesion borders with an ash-gray in the center of the lesion. These symptoms were observed in the upper leaves of the plants (Figure C.4).

Bacterial leaf spot was not observed on the open-pollinated genotypes. At the field observation, bacterial leaf spot density was higher for hybrid AG1401 compared with hybrid RS320W. The lesions are usually considered cosmetic and cause no yield reduction (A. Friskop, 2020, personal communication). At Prosper, *Fusarium* stalk rot was diagnosed in the open-pollinated genotype PI574595 in all replicates for the first seeding date and manifested from wet conditions in fall of 2018 related to heavy rain, frost, and wind that caused plant lodging. In 2019, *Fusarium* was confirmed by the plant diagnostic lab at NDSU on the lower, interior region of the crown of grain sorghum plants in the open-pollinated genotype PI574595 at the first seeding date, but only in the fourth replicates and only on five plants that were completely lodged.

#### *4.6.7.3. Insects*

Insects were identified by Alexander Knudson entomological diagnostician at the NDSU Plant Diagnostic Laboratory on sorghum plant samples. Assessment of insect pests and symptoms were evaluated based on information in the North Dakota Field Crop Insect Management Guide (Knodel et al., 2020) and Managing Insect and Mite Pests of Texas Sorghum (Knutson et al., 2018) extension bulletins. In 2018, at Carrington, Oakes, and Prosper, red-legged grasshopper [*Melanoplus femurrubrum* (De Geer)] and differential grasshopper [*Melanoplus differentialis* (Thomas)] were identified. There is no developed economic threshold levels for grasshoppers in sorghum in North Dakota. For this reason, North Dakota grasshopper management for wheat production was followed as a base recommendation.

In 2019, the two-striped grasshopper [*Melanoplus bivitatus* (Say)] was observed at Prosper. This grasshopper can cause economic grain yield losses when populations are above economic threshold levels. Field observations indicated that grasshopper damage was caused by chewing on sorghum leaves. The two-striped grasshopper preferred the hybrids AG1401 and RS320W, and the open-pollinated genotype PI574595 as compared with the three open-pollinated SARE lines 10, 14, and 17. In 2018, at Carrington, black blister beetle [*Epicauta* *pennsylvanica* (De Geer)] was observed on the sorghum plants. Larvae blister beetles are predators of grasshoppers and adults feed on many different plant species. They are generally considered beneficial insects, but they can become a localized pest problem when their populations are high. Typically, control is not recommended for black blister beetle.

In 2018, at Carrington and Oakes, corn leaf aphids [*Rhopalosiphum maidis* (Fitch)] were observed on the hybrid AG1401 plants leaves. Corn leaf aphids can transmit viral diseases, but only if johnsongrass [*Sorghum halepense* (L.) Pers.] is present in the field. Sorghum plants can tolerate many insects, so treatments are usually not necessary. In 2018, *Holcostethus abbreviatus* (Uhler) a species of stink bug in the *Pentatomidae* family was found on grain sorghum at Prosper. These bugs specifically invaded the hybrid RS320W at the second seeding date and the third replicate. There were 10 to 15 adult stink bugs sucking on the kernels at the soft dough stage and kernels looked brownish. *Holcostethus abbreviatus* (Uhler) was previously observed at Bottineau County from herbage in a depression in a pasture shrub filled clearing in the Turtle Mountains of Rolette County (Rider, 2012). Otherwise, *Holcostethus abbreviatus* has not been recorded on any *Poaceae* in North Dakota, but has been recorded on a few other plant species (David A. Rider, 2018, personal communication).

In 2018, at Oakes, the European corn borer [*Ostrinia nubilalis* (Hübner)] was identified on the hybrids AG1401 and RS320W. European corn borers do not frequently cause damage to sorghum, but they can cause damage to late-planted sorghum fields.

In 2019, at Prosper, corn earworm [*Helicoverpa zea* (Boddie)] was identified on the sorghum hybrid AG1401. Late planting and sorghum genotypes with compact panicles can increase the severity of corn earworm damage. For this reason, early planting and loose or open panicle type genotypes are recommended to reduce damage in areas where this pest is problematic. In addition, fall armyworm [*Spodoptera frugiperda* (J.E. Smith)] was identified at the same year and location. The hybrid AG1401 leaves had feeding injury that was consistent with fall armyworm feeding. The hybrid AG1401 exhibited rolled leaf symptoms from feeding injury, irregular sized oval lesions with a distinct brown-black border, and diffuse water-soaked lesions on the leaves ranging from 1.3- to 2.5-cm and tapering at the ends. Fall armyworm damage is not economically important until feeding advances to the panicle and developing seeds. Corn leaf aphids caused some purple blotches where they fed on AG1401 leaves.

*4.6.7.4. Birds*

The most serious bird pest problem was sparrow and blackbird invasion at Oakes in 2018 and 2019. The most problematic sparrow species were field sparrow (*Spizella pusilla*) and chipping sparrow (*Spizella passerina*), but grasshopper sparrow (*Ammodramus savannarum*) and clay-colored sparrow (*Spizella pallida*) were also observed in small numbers. Rusty blackbird (*Euphagus carolinus*) and red-winged blackbird (*Agelaius phoeniceus*) were also detected, but blackbird presence and damage severity was not as high as for the sparrow species (TCLO, 2020) (Figure C.5).

Local granivorous birds were attracted to the sorghum when grain development was at the soft dough stage. In 2018, the first bird attack was observed on 20 August and a bird net was placed over the whole experiment on 24 August. In 2019, the first bird attack was on 15 August and the experiment was covered with a bird net on 21 August. Bird damaged to panicles and percent head damage were collected. Percent bird damage severity was higher at the first seeding date and especially for the early-maturing, open-pollinated genotypes. Due to the longer vegetative phase for the commercial hybrids less damage was observed compare with the open-pollinated genotypes since grain development was not as advanced for the later maturity hybrids.

### *4.6.8. Statistical analysis*

All the data collected throughout the season were analyzed separately by environment (location-year). Analysis of variance (ANOVA) was performed by using the procedure GLM in SAS 9.4 statistical software (SAS Institute, 2019). Homogeneity of trait variances was tested to determine combining trait analysis across environments by the Hammond 10X rule (Levene's test for homogeneity a ration of <=10 for ANOVA) (Levene, 1960). Environment was considered a random effect for this reason as were interactions associated with environment: environment by seeding date, environment by genotype, and environment by seeding date by genotype were not discussed. Genotype and seeding date were fixed effects. Least significant differences (LSD) mean trait treatment comparisons were performed at $P \leq 0.05$ and $F$-protected (Petersen, 1994).

# 5. RESULTS AND DISCUSSION

## 5.1. Soil and air temperatures

The North Dakota Agricultural Weather Network (NDAWN, 2020) was used for daily air and soil temperatures and precipitation data at Carrington, Oakes, and Prosper in 2018 and 2019. In general, soil temperatures were lower in 2019 compared with 2018, for all locations, at the beginning of the growing season in late May and mid-to-late June (Figure 1). Seeding was delayed in 2019 because of the cool May temperatures and crop development was slower because of cool and wet field conditions compared with the 2018 growing season. Cool and wet soil and weather conditions at planting are a major yield-limiting factor because of delayed and reduced germination, reduced seedling vigor, and delayed anthesis and maturity (Espinoza and Kelley, 2004; Assefa and Staggenborg, 2010; Maulana and Tesso, 2013).

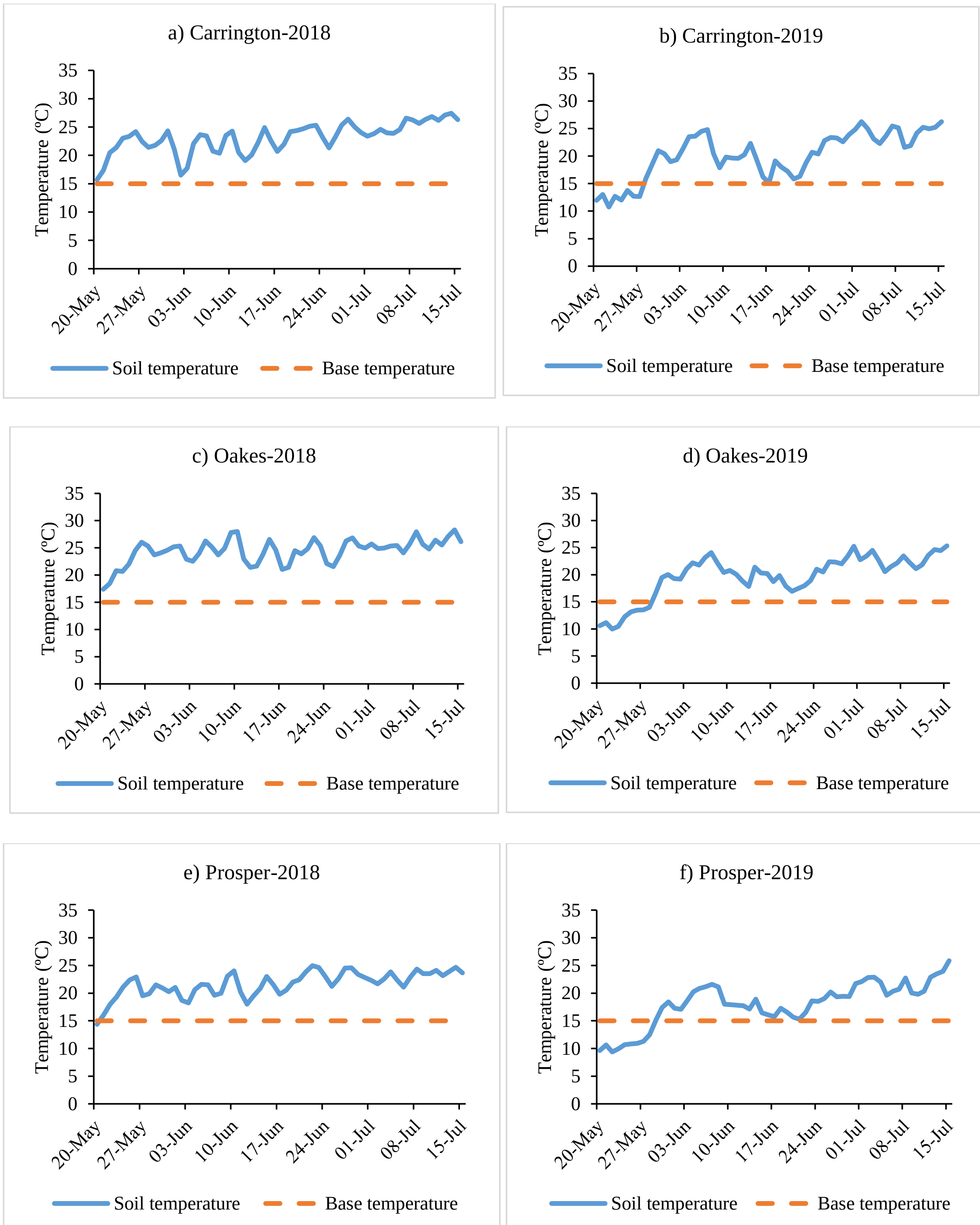



Figure 1. Bare soil average temperatures from seeding to the last pure live seed emergence count (30 d after each seeding date) for six environments: Carrington 2018, Oakes 2018, Prosper 2018, Carrington 2019, Oakes 2019, and Prosper 2019. The dashed red line indicates the base growth temperature for sorghum of 15ºC.

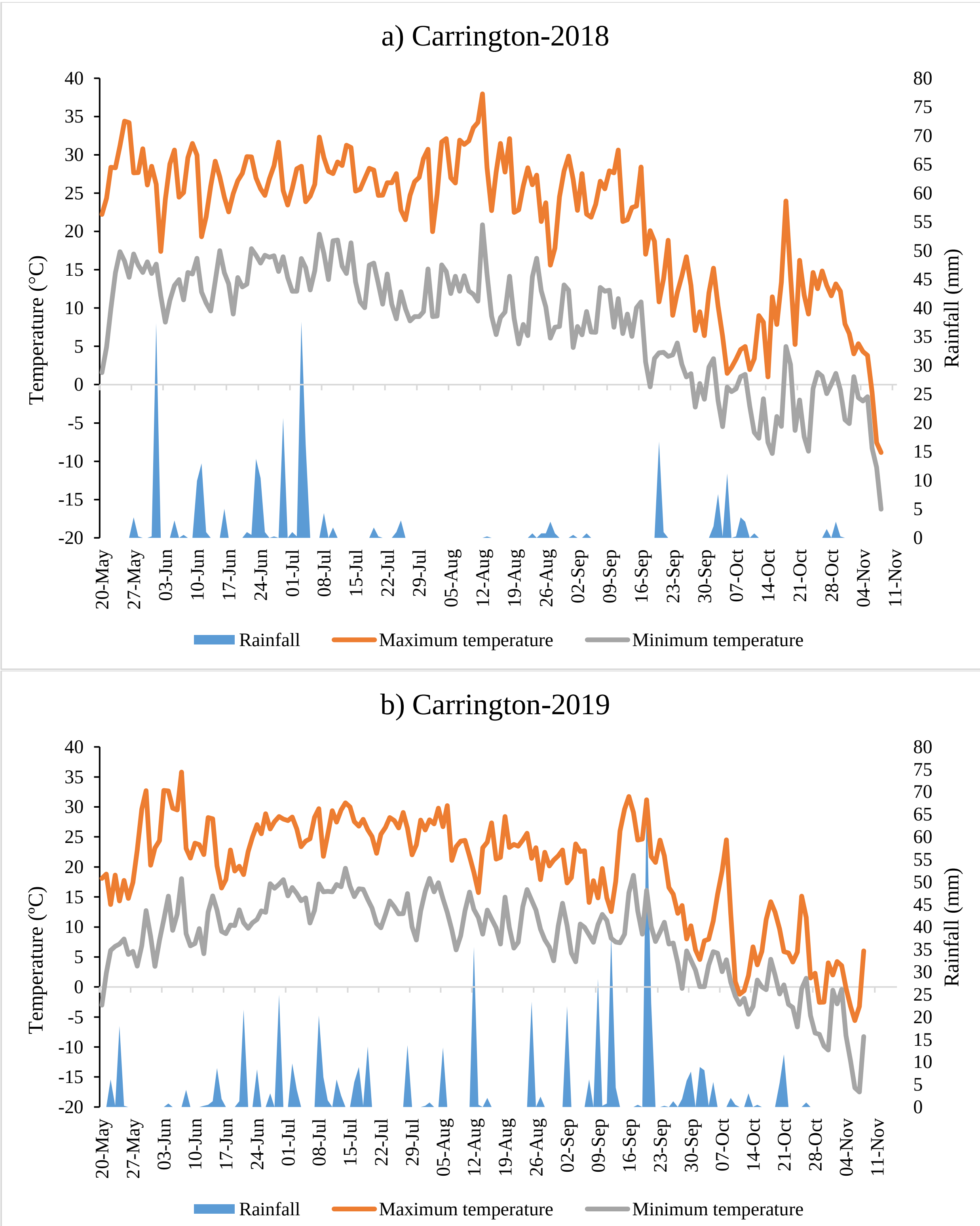



Figure 2. Weekly maximum and minimum air temperatures and rainfall from seeding to harvest for two environments: Carrington 2018 and Carrington 2019.

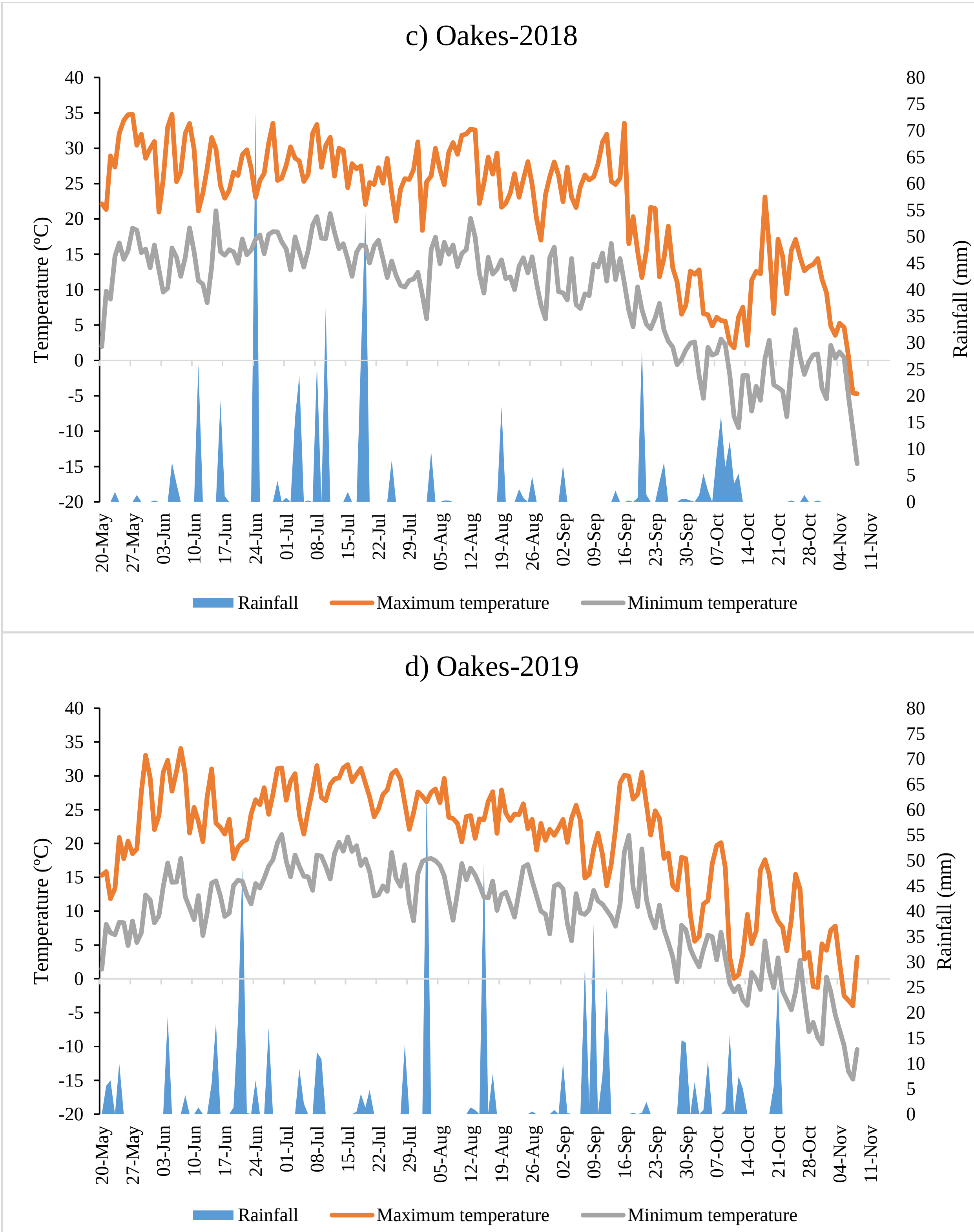
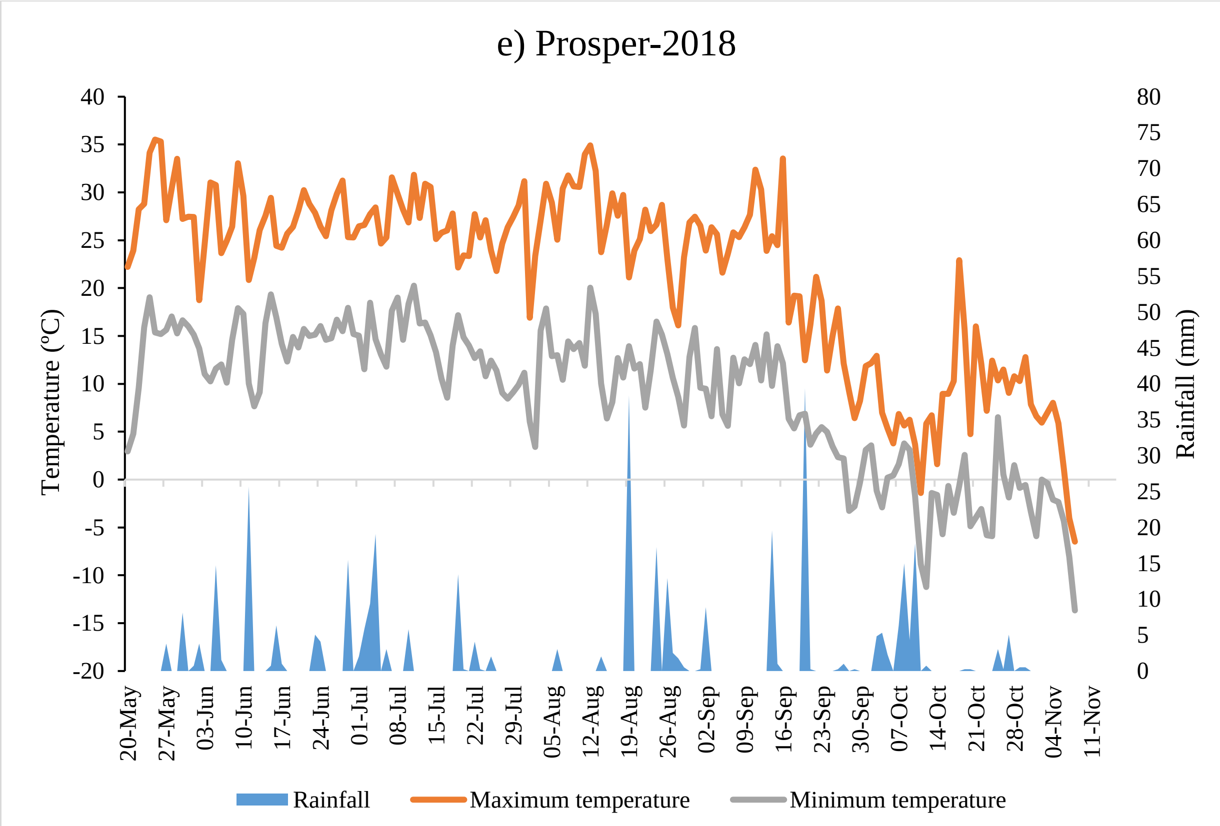



Figure 3. Weekly maximum and minimum air temperatures and rainfall from seeding to harvest for two environments: Oakes 2018 and Oakes 2019.



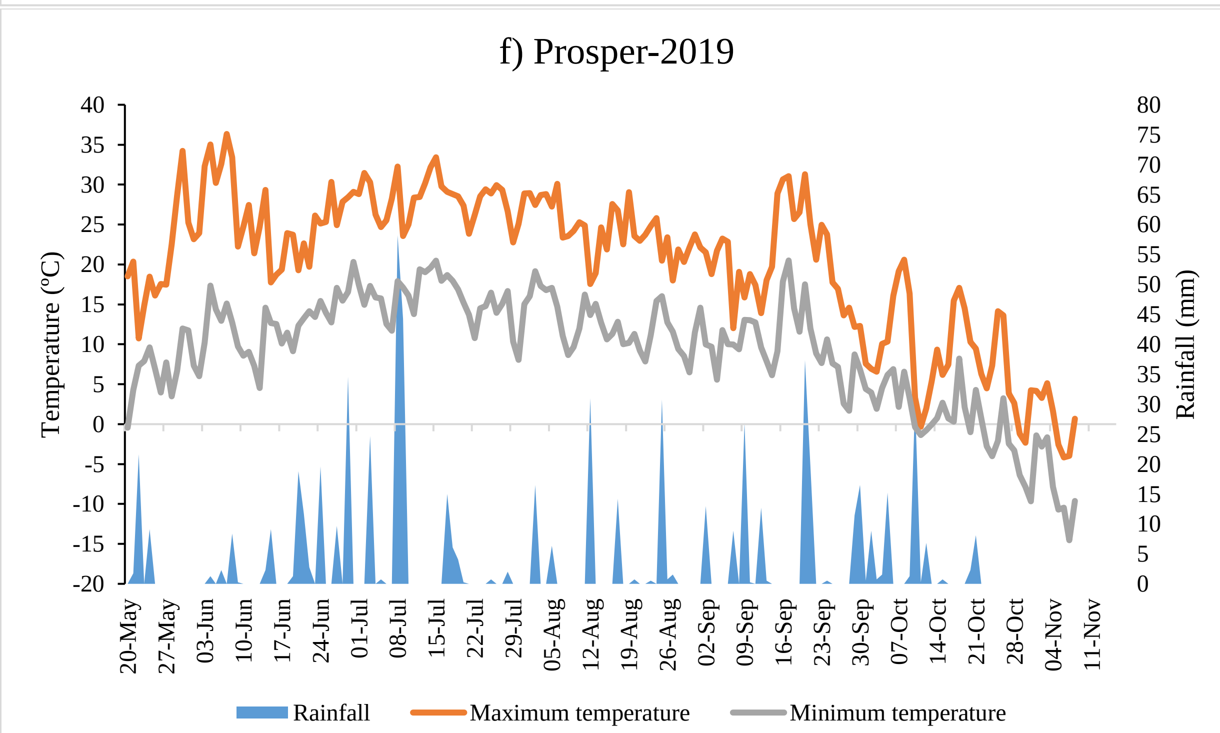




Figure 4. Weekly maximum and minimum air temperatures and rainfall from seeding to harvest for two environments: Prosper 2018 and Prosper 2019.

Table 5. Total monthly rainfall and departure from normal, monthly maximum, minimum, and average monthly temperatures and departure from normal (30-yr average) for six environments: Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018 and Prosper 2019.

| | | Rainfall | | Temperature | | | |
|---|---|---|---|---|---|---|---|
| Environment | Month | Total | ±Normal† | Max. | Min. | Avg. | ±Normal† |
| | | ----------mm---------- | | ------------------------ºC------------------------ | | | |
| Carrington 2018 | May | 32.4 | -37.7 | 24 | 8 | 16 | +3 |
| | June | 117.7 | +21.9 | 26 | 14 | 20 | +2 |
| | July | 67.4 | -18.7 | 27 | 13 | 20 | -1 |
| | Aug | 6.1 | -52.6 | 27 | 11 | 19 | -1 |
| | Sept | 19.1 | -29.5 | 20 | 6 | 13 | -2 |
| | Oct | 33 | -11.9 | 10 | -2 | 4 | -3 |
| Carrington 2019 | May | 37.1 | -33 | 17 | 3 | 10 | -3 |
| | June | 76.3 | -19.5 | 25 | 11 | 18 | 0 |
| | July | 92.5 | +6.4 | 27 | 14 | 20 | 0 |
| | Aug | 78.3 | +19.6 | 24 | 11 | 18 | -2 |
| | Sept | 209.7 | +161.2 | 20 | 9 | 15 | 0 |
| | Oct | 47 | +2 | 7 | -1 | 3 | -4 |
| Oakes 2018 | May | 21.7 | -53.5 | 25 | 9 | 17 | +4 |
| | June | 134.6 | +38.8 | 28 | 15 | 21 | +3 |
| | July | 194.7 | +112.9 | 27 | 15 | 21 | 0 |
| | Aug | 36 | -24 | 26 | 13 | 20 | -1 |
| | Sept | 52.4 | -11.6 | 21 | 8 | 15 | 0 |
| | Oct | 62.8 | +11.7 | 11 | -2 | 4 | -2 |
| Oakes 2019 | May | 84.5 | +9.3 | 17 | 5 | 11 | -2 |
| | June | 140.9 | +45.1 | 26 | 13 | 19 | +1 |
| | July | 58.5 | -23.3 | 28 | 16 | 22 | 0 |
| | Aug | 126.3 | +66.4 | 24 | 14 | 19 | -1 |
| | Sept | 143.3 | +79.3 | 22 | 10 | 16 | +1 |
| | Oct | 78.6 | +27.6 | 9 | 0 | 4 | -3 |
| Prosper 2018 | May | 53.9 | -23.6 | 25 | 9 | 17 | +3 |
| | June | 79.3 | -21.1 | 27 | 14 | 20 | +2 |
| | July | 65.3 | -22.6 | 27 | 14 | 20 | -1 |
| | Aug | 78.5 | +12 | 27 | 12 | 19 | -1 |
| | Sept | 70.9 | +5.4 | 21 | 7 | 14 | -1 |
| | Oct | 66.6 | +4.9 | 9 | -1 | 4 | -3 |
| Prosper 2019 | May | 60 | -17.5 | 17 | 4 | 11 | -3 |
| | June | 122 | +21.7 | 26 | 12 | 19 | 0 |
| | July | 156.1 | +68.2 | 28 | 16 | 22 | +1 |
| | Aug | 102.4 | +35.9 | 24 | 12 | 18 | -2 |
| | Sept | 147.7 | +82.1 | 21 | 10 | 15 | +1 |
| | Oct | 77 | +15.3 | 9 | 1 | 5 | -3 |

Weather data obtained from: https://ndawn.ndsu.nodak.edu/weather-data-monthly.html
† Based on 1981-2010 long-term averages.

## 5.2. Pure live seed emergence (PLSE)

The analysis of variance (ANOVA) across environments indicated that seeding date, genotype, and seeding date by genotype interaction were not significant for pure live seed emergence (PLSE) (Table 6). Environment by date, environment by genotype, and environment by date by genotype interactions were significant, but since environment is a random effect, they are not discussed, but these interactions are shown in Table B.1.

Table 6. Combined analysis of variance and mean square values for pure live seed emergence (PLSE) for the seeding date by genotype (gen) study conducted at six North Dakota environments (env) in 2018 and 2019.

| SOV | df† | PLSE |
|---|---|---|
| Environment | 5 | 13948* |
| Rep (Env) | 18 | 373* |
| Date | 2 | 1276 |
| Env x date | 10 | 856* |
| Env x rep x date | 36 | 68* |
| Genotype | 5 | 657 |
| Env x gen | 25 | 325* |
| Date x gen | 10 | 61 |
| Env x date x gen | 50 | 77* |
| Residual | 270 | 41 |
| CV, % | | 14 |

* Significant at $P \leq 0.05$ levels of probability.
† Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018, Prosper 2019.

Pure live seed emergence in sorghum seed is related to soil temperature and soil water content (Podder, 2019). Pure live seed emergence was not different among genotypes averaged across dates and this could be because soil temperatures were below or around 15ºC until the end of the May and beginning of the June (Figure 1). Minimum temperatures for germination for grain sorghum range between 14.5ºC to 15.5ºC (Deckard et al., 1994; Lofton et al., 2019).

The main effect of genotype was not significant for PLSE (Tables 6 and 7). The PLSE was lower than 50% for all genotypes (Table 7). All seedings negatively affected all genotypes, resulting in lower PLSE due to the cold temperature stress at the beginning of the season compared with normal and later season conditions (Kapanigowda et al., 2013). Espinoza and Kelley (2004) recommended that grain sorghum seeding should be delayed until the morning soil temperature reach to 18ºC at 5-cm below the soil surface.

Table 7. Mean pure live seed emergence (PLSE) in six grain sorghum genotypes averaged across three seeding dates and six environments at Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| Genotype | PLSE |
| --- | --- |
| | ---%--- |
| AG1401 | 49.6 |
| RS320W | 44.4 |
| PI574595 | 47.9 |
| SARE10 | 41.2 |
| SARE14 | 44.3 |
| SARE17 | 46.8 |
| LSD (0.05) | NS |

$P \leq 0.05$ levels of probability.

Previous authors have reported that PLSE was reduced by 27% (Kapanigowda et al., 2013) and 35% (Lofton et al., 2019) when soil temperatures were below 15.5ºC. Antony et al. (2019) observed that under optimum growing conditions corn PLSE was 100% and grain sorghum PLSE was only 78%. At the minimum temperature (10ºC), corn PLSE on average was 95%, however, grain sorghum PLSE was 24%. This result showed that grain sorghum seedling emergence is more sensitive to cold soil and air temperature than corn (Neild, 1982; Assefa et al., 2014; Antony et al., 2019).

## 5.3. Phenological evaluations

### *5.3.1. Accumulated growing degree days (GDD) to 50% and 100% heading*

Accumulated growing degree days to 50% heading with a base temperature of 10ºC ($GDD_{10}H50$) and 15ºC ($GDD_{15}H50$) were significant for genotype and the interaction between seeding date and genotype. However, GDDs at both 10ºC and 15ºC to 100% heading were significant only for genotype and not the interaction (Table 8).

Table 8. Combined analysis of variance and mean square values for accumulated growing degree days from seeding to 50% heading with base temperatures 10ºC ($GDD_{10}H50$) and 15ºC ($GDD_{15}H50$), 100% heading with base temperatures 10ºC ($GDD_{10}H100$) and 15ºC ($GDD_{15}H100$) for seeding date by genotype (gen) study conducted at five North Dakota environments (env) in 2018 and 2019.

| SOV | df† | $GDD_{10}H50$ | $GDD_{15}H50$ | $GDD_{10}H100$ | $GDD_{15}H100$ |
|---|---|---|---|---|---|
| Environment | 4 | 210712* | 72351* | 190732* | 64681* |
| Rep (Env) | 15 | 1038* | 369* | 869* | 295* |
| Date | 2 | 3167 | 2996 | 10399 | 7759 |
| Env x date | 8 | 5892* | 1774* | 8390* | 2423* |
| Env x rep x date | 30 | 510* | 167* | 391 | 141 |
| Genotype | 5 | 198744* | 66334* | 188461* | 60850* |
| Env x gen | 20 | 2642* | 737* | 3582* | 923* |
| Date x gen | 10 | 2262* | 910* | 1129 | 429 |
| Env x date x gen | 40 | 423* | 184* | 844* | 358* |
| Residual | 225 | 241 | 95 | 273 | 102 |
| CV, % | | 2.2 | 2.3 | 2.2 | 2.3 |

* Significant at $P \leq 0.05$ levels of probability.

$GDD_{10}$ were calculated with a 10ºC base temperature.

$GDD_{15}$ were calculated with a 15ºC base temperature.

† Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

Hybrid genotypes AG1401 and RS320W required more accumulated GDDs to reach the 50% and 100% heading stages at both base temperatures. The open-pollinated genotypes PI574595, SARE10, SARE14, and SARE17 had the same accumulated GDD requirements to reach the 50% and 100% heading stages that were less than the hybrids (Table 9).

Hybrid AG1401 required greater accumulated GDDs compared with hybrid RS320W to reach both the 50% and 100% heading stages at 10ºC and 15ºC (Table 9). Accumulated GDDs to reach developmental stages is influenced by genotype. Cool temperatures result in slow accumulation of GDDs and delay plant development (Saeed and Francis, 1984).

Table 9. Mean accumulated growing degree days from seeding to 50% heading with base temperatures 10ºC ($GDD_{10}H50$) and 15ºC ($GDD_{15}H50$), 100% heading with base temperatures 10ºC ($GDD_{10}H100$) and 15ºC ($GDD_{15}H100$) for six grain sorghum genotypes planted on three seeding dates averaged across five North Dakota environments: Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

| | $GDD_{10}H50$ | $GDD_{15}H50$ | $GDD_{10}H100$ | $GDD_{15}H100$ |
|---|---|---|---|---|
| Genotype | ----------------------Accumulated growing degree days---------------------- | | | |
| AG1401 | 788 | 468 | 827 | 489 |
| RS320W | 756 | 448 | 802 | 475 |
| PI574595 | 674 | 401 | 721 | 429 |
| SARE10 | 661 | 394 | 706 | 421 |
| SARE14 | 660 | 393 | 702 | 418 |
| SARE17 | 658 | 392 | 702 | 419 |
| LSD (0.05) | 20 | 10 | 23 | 12 |

$GDD_{10}$ were calculated with a 10ºC base temperature.
$GDD_{15}$ were calculated with a 15ºC base temperature.

As heat accumulation per day increases, fewer days are needed to reach 50% heading. Averaged across seeding dates, open-pollinated genotypes required the same accumulated GDDs for both 10ºC and 15ºC base temperatures for all seeding dates, however, Date 1 and Date 3 were different for hybrids AG1401 and RS320W (Table 10).

Neild (1982) reported hybrid response was likely due to the seasonal rapid heat unit absorption from leaves. Hybrids have more and wider leaves compared with the open-pollinated genotypes, which may enable a higher net photosynthetic rate that allows faster growth under warmer temperatures. In addition, slower development rates occur for later maturity sorghum genotypes at the same environmental conditions (Neild and Seeley, 1977).

Table 10. Mean accumulated growing degree days from seeding to 50% heading with base temperatures 10ºC ($GDD_{10}H50$) and 15ºC ($GDD_{15}H50$) interaction between genotypes and seeding dates averaged across five North Dakota environments: Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

| | Date 1 | | Date 2 | | Date 3 | |
|---|---|---|---|---|---|---|
| | $GDD_{10}H50$ | $GDD_{15}H50$ | $GDD_{10}H50$ | $GDD_{15}H50$ | $GDD_{10}H50$ | $GDD_{15}H50$ |
| Genotype | ------------------------Accumulated growing degree days------------------------ | | | | | |
| AG1401 | 808 | 483 | 790 | 469 | 767 | 451 |
| RS320W | 764 | 457 | 766 | 451 | 739 | 436 |
| PI574595 | 670 | 400 | 674 | 401 | 678 | 401 |
| SARE10 | 659 | 394 | 667 | 397 | 657 | 390 |
| SARE14 | 658 | 394 | 660 | 393 | 663 | 391 |
| SARE17 | 653 | 391 | 662 | 395 | 659 | 392 |
| $LSD_1$ (0.05) | 22 | 12 | | | | |
| $LSD_2$ (0.05) | 23 | 13 | | | | |
| $LSD_3$ (0.05) | 29 | 16 | | | | |

$LSD_1$= to compare among genotypes within the same seeding date at 0.05 level of significance.
$LSD_2$= to compare same genotypes between different seeding date at 0.05 level of significance.
$LSD_3$= to compare among genotypes on different seeding date at 0.05 level of significance.
$GDD_{10}$ were calculated with a 10ºC base temperature.
$GDD_{15}$ were calculated with a 15ºC base temperature.

### *5.3.2. Accumulated growing degree days (GDD) to 50% and 100% anthesis*

Accumulated growing degree days to 50% anthesis with base temperatures of 10ºC ($GDD_{10}A50$) and 15ºC ($GDD_{15}A50$) were significant for genotypes and the interaction between seeding date and genotypes, but $GDD_{15}A50$ was only significant for seeding date. Environment by date, environment by genotype, and environment by date by genotype interactions were significant, but since environment is a random effect, they are not discussed (Table 11).

Table 11. Combined analysis of variance and mean square values for accumulated growing degree days from seeding to 50% anthesis with base temperatures 10ºC ($GDD_{10}A50$) and 15ºC ($GDD_{15}A50$), 100% anthesis with base temperatures 10ºC ($GDD_{10}A100$) and 15ºC ($GDD_{15}A100$) for seeding date by genotype (gen) study conducted at several North Dakota environments (env) in 2018 and 2019.

| SOV | df† | $GDD_{10}A50$ | $GDD_{15}A50$ | df‡ | $GDD_{10}A100$ | $GDD_{15}A100$ |
|---|---|---|---|---|---|---|
| Environment | 5 | 166268* | 58222* | 4 | 181289* | 59398* |
| Rep (Env) | 18 | 994 | 356 | 15 | 1090* | 374 |
| Date | 2 | 5699 | 5598* | 2 | 15729 | 10804* |
| Env x date | 10 | 4545* | 1347* | 8 | 6684* | 1503* |
| Env x rep x date | 36 | 622* | 226* | 30 | 503* | 196* |
| Genotype | 5 | 234583* | 79111* | 5 | 160768* | 50827* |
| Env x gen | 25 | 2808* | 815* | 20 | 4521* | 1109* |
| Date x gen | 10 | 1560* | 711* | 10 | 1005 | 404 |
| Env x date x gen | 50 | 546* | 211* | 40 | 598* | 260 |
| Residual | 270 | 276 | 98 | 224 | 293 | 101 |
| CV, % | | 2.3 | 2.3 | | 2.2 | 2.2 |

* Significant at $P \leq 0.05$ levels of probability.
$GDD_{10}$ were calculated with a 10ºC base temperature.
$GDD_{15}$ were calculated with a 15ºC base temperature.
† Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018, Prosper 2019.
‡ Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

Accumulated GDDs for the early anthesis stage at $GDD_{10}A50$ and $GDD_{15}A50$ were different among genotypes. Hybrid AG1401 required the highest accumulated GDDs and all SARE lines needed the lowest accumulated GDDs for $GDD_{10}A50$ and $GDD_{15}A50$. The accumulated $GDD_{10}A100$ and $GDD_{15}A100$ were distinctive between all open-pollinated genotypes to hybrids (Table 12). At the 100% anthesis stage, both hybrids had the same accumulated GDD requirements. All open-pollinated genotypes required similar accumulated GDDs. For the 100% anthesis stage, the first pollen shed was delayed because of slower crop development. Narrow growth window to accumulate GDDs from 50% anthesis to 100% anthesis and uneven growth and development resulted two different groups at the later anthesis stage based on growing conditions. Neild and Seeley (1977) reported that accumulated GDDs provide more accurate prediction and crop development information than calendar day because hybrids perform similarly in response at early stages, but differences of development become greater later in the season due to different temperature regimes. This is the reason many researchers and seed companies use the 50% anthesis stage to classify sorghum maturity groups.

Table 12. Mean accumulated growing degree days from seeding to 50% anthesis with base temperatures 10ºC ($GDD_{10}A50$) and 15ºC ($GDD_{15}A50$), 100% anthesis with base temperatures 10ºC ($GDD_{10}A100$) and 15ºC ($GDD_{15}A100$) in six grain sorghum genotypes averaged across three seeding dates at several North Dakota environments in 2018 and 2019.

| | $GDD_{10}A50$† | $GDD_{15}A50$† | $GDD_{10}A100$‡ | $GDD_{15}A100$‡ |
|---|---|---|---|---|
| Genotype | ----------------------Accumulated growing degree days---------------------- | | | |
| AG1401 | 806 | 477 | 849 | 501 |
| RS320W | 782 | 464 | 825 | 488 |
| PI574595 | 702 | 417 | 753 | 447 |
| SARE10 | 681 | 405 | 735 | 437 |
| SARE14 | 680 | 404 | 731 | 435 |
| SARE17 | 680 | 405 | 734 | 437 |
| LSD (0.05) | 18 | 10 | 26 | 13 |

$GDD_{10}$ were calculated with a 10ºC base temperature.
$GDD_{15}$ were calculated with a 15ºC base temperature.
† Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018, Prosper 2019.
‡ Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

According to the combined analysis the open-pollinated genotypes were not affected by seeding date on average. However, hybrids responded differently to seeding Date 1 and Date 3 for $GDD_{10}A50$ stage. All open-pollinated genotypes had the same response at 15ºC temperatures at the 50% anthesis stage. Hybrid RS320W was not different between the first and second seeding date, but significant differences were observed between the first and third seeding date. Accumulated $GDD_{15}A50$ stage were different for all seeding dates for hybrid AG1401.

In temperature sensitive hybrids' different rates of growth and development are inevitable for different seeding dates, but seeding date conditions vary from year-to-year because of regional weather fluctuations (Neild and Seeley, 1977).

Table 13. Mean accumulated growing degree days from seeding to 50% anthesis with base temperatures 10ºC ($GDD_{10}A50$) and 15ºC ($GDD_{15}A50$) interaction between genotypes and seeding dates averaged across six environments at Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | Date 1 | | Date 2 | | Date 3 | |
|---|---|---|---|---|---|---|
| | $GDD_{10}A50$ | $GDD_{15}A50$ | $GDD_{10}A50$ | $GDD_{15}A50$ | $GDD_{10}A50$ | $GDD_{15}A50$ |
| Genotype | ---------------------Accumulated growing degree days---------------------- | | | | | |
| AG1401 | 823 | 491 | 807 | 478 | 788 | 463 |
| RS320W | 790 | 472 | 789 | 469 | 767 | 451 |
| PI574595 | 701 | 418 | 700 | 417 | 705 | 416 |
| SARE10 | 685 | 409 | 682 | 406 | 675 | 399 |
| SARE14 | 687 | 410 | 674 | 401 | 678 | 401 |
| SARE17 | 682 | 408 | 679 | 404 | 679 | 403 |
| $LSD_1$ (0.05) | 21 | 12 | | | | |
| $LSD_2$ (0.05) | 20 | 12 | | | | |
| $LSD_3$ (0.05) | 26 | 14 | | | | |

$LSD_1$= to compare among genotypes within the same seeding date at 0.05 level of significance.
$LSD_2$= to compare same genotypes between different seeding date at 0.05 level of significance.
$LSD_3$= to compare among genotypes on different seeding date at 0.05 level of significance.
$GDD_{10}$ were calculated with a 10ºC base temperature.
$GDD_{15}$ were calculated with a 15ºC base temperature.

### *5.3.3. Accumulated growing degree days (GDD) to physiological maturity*

The analysis of variance across environments indicated that seeding date was significant for accumulated GDDs for physiological maturity at 10ºC, but genotype and seeding date by genotype interaction were not significant (Table 14). Environment by seeding date and environment by genotype interactions were significant, but since environment is a random effect, they are not discussed. Accumulated GDDs for physiological maturity at 15ºC was significant only for the environment by seeding date by genotype interaction (Table 14).

Table 14. Combined analysis of variance and mean square values for accumulated growing degree days from seeding to physiological maturity with base temperatures 10ºC ($GDD_{10}PM$) and 15ºC ($GDD_{15}PM$) for seeding date by genotype (gen) study conducted at three North Dakota environments (env) in 2018 and 2019.

| SOV | df† | $GDD_{10}PM$ | $GDD_{15}PM$ |
|---|---|---|---|
| Environment | 2 | 2890 | 7641 |
| Rep (Env) | 9 | 353 | 69 |
| Date | 2 | 57164* | 28591 |
| Env x date | 3 | 1021 | 1032 |
| Env x rep x date | 12 | 197 | 48 |
| Genotype | 5 | 9718 | 2111 |
| Env x gen | 8 | 3098 | 1251 |
| Date x gen | 10 | 3209 | 1202 |
| Env x date x gen | 8 | 1017* | 3556* |
| Residual | 92 | 124 | 30 |
| CV, % | | 1.0 | 0.9 |

* Significant at $P \leq 0.05$ levels of probability.

$GDD_{10}$ were calculated with a 10ºC base temperature.

$GDD_{15}$ were calculated with a 15ºC base temperature.

† Oakes 2019, Prosper 2018, Prosper 2019.

Table 15. Mean growing degree days from seeding to physiological maturity with base temperatures 10ºC ($GDD_{10}PM$) and 15ºC ($GDD_{15}PM$) for six grain sorghum genotypes averaged across three seeding dates and three environments: Oakes 2019, Prosper 2018, and Prosper 2019.

| | $GDD_{10}PM$ | $GDD_{15}PM$ |
|---|---|---|
| Genotype | ---------Accumulated growing degree days--------- | |
| AG1401 | 1112 | 643 |
| RS320W | 1108 | 642 |
| PI574595 | 1083 | 629 |
| SARE10 | 1071 | 625 |
| SARE14 | 1069 | 624 |
| SARE17 | 1063 | 620 |
| LSD (0.05) | NS | NS |

$GDD_{10}$ were calculated with a 10ºC base temperature.

$GDD_{15}$ were calculated with a 15ºC base temperature.

$P \leq 0.05$ levels of probability.

Accumulated GDDs for physiological maturity at 10ºC was significant for seeding date with 1134, 1081, and 1038 GDDs for the first, second, and the third seeding date, respectively, where each date was unique (data not shown). According to Neild and Seeley (1977) grain sorghum requires more accumulated GDDs to reach the reproductive stage than corn, but fewer accumulated GDDs to reach physiological maturity than corn.

Dramatic differences were observed between 2018 and 2019 at Prosper, ND for sorghum attaining physiological maturity. In 2018, all genotypes, including hybrids, reached physiological maturity and sorghum plants completed their life cycle before the first fall frost. At Prosper in 2018, the growing season was ideal and the first seeding was on 22 May and continued at 7 d intervals. Soil and air temperatures were at the minimum adequate range for sorghum growth and development. However, in 2019 at Prosper, seeding was delayed until 29 May due to the cool and wet conditions (Figure 1, 4, and Table 5). Cloudy, cool, and wet conditions continued throughout the season. Only the open-pollinated genotypes at the first and second seeding date reached physiological maturity in 2019. The hybrids did not reach physiological maturity even in the first seeding date at Prosper in 2019.

At Carrington in 2018, the open-pollinated genotypes at the first and second seeding dates reached physiological maturity, but the hybrids reached 100% physiological maturity only when seeded at the first seeding date. Similar results were obtained in 2019 at Carrington where the beginning of the season influenced crop growth and development negatively.

At Oakes in 2018, the open-pollinated genotypes reached physiological maturity at the first and second seeding date and hybrids only for the first seeding date. However, in 2019 seeding was earlier compared with in 2018 and the hybrids and the open-pollinated genotypes reached physiological maturity at both the first and second seeding dates.

Schatz (1988) reported that sorghum in North Dakota still not have adequate growing season length for late planting because of limited heat unit accumulation even in normal years. The sorghum seeding window in North Dakota is extremely narrow at approximately 14 d. The greatest concern about grain sorghum production in North Dakota is still attaining physiological maturity before fall frost.

Physiological maturity is important regarding grain yield because physiological maturity date is positively correlated with grain yield because of temporal and metabolic efficiency on seed dry weight accumulation (Eastin et al., 1973; Gerik et al., 2003; Ciampitti et al., 2016; Roozeboom and Prasad, 2016; Subalakhshmi et al., 2019).

## 5.4. Morphological evaluations

### *5.4.1. Plant height*

The analysis of variance across environments indicated that the main effects of seeding date and genotype were significant for plant height. The seeding date by genotype interaction was not significant for plant height. The environment by seeding date and environment by genotype interactions were significant for plant height, but since environment is a random effect, they are not discussed (Table 16).

Although plant height is a genotypic trait, it is also affected by temperature and plant density during vegetative and reproductive phases. Averaged across genotypes and five environments, plant height was 134, 133, and 129-cm for the first, second, and third seeding dates, respectively (data not shown). Lowest plant height at the last seeding date may have been related to greater heat unit accumulations in a shorter time period. Similarly, Saini et al. (2018) reported that the highest mean plant height was obtained with earlier sorghum seeding dates.

Table 16. Combined analysis of variance and mean square values for plant height, panicle length, and lodging score for seeding date by genotype (gen) study conducted at several North Dakota environments (env) in 2018 and 2019.

| SOV | df† | Plant height | df‡ | Panicle length | df† | Lodging score |
|---|---|---|---|---|---|---|
| Environment | 4 | 9495* | 2 | 83.8 | 4 | 103.5 |
| Rep (Env) | 15 | 195 | 9 | 4.0 | 15 | 11.3 |
| Date | 2 | 986* | 2 | 55.5* | 2 | 1.5 |
| Env x date | 8 | 107 | 4 | 5.3 | 8 | 34.7* |
| Env x rep x date | 30 | 120* | 18 | 2.7 | 30 | 7.0* |
| Genotype | 5 | 3738* | 5 | 552.3* | 5 | 450.2* |
| Env x gen | 20 | 338* | 10 | 5.8 | 20 | 14.8* |
| Date x gen | 10 | 60 | 10 | 5.4 | 10 | 3.3 |
| Env x date x gen | 40 | 97* | 20 | 7.2* | 40 | 5.9 |
| Residual | 225 | 33 | 135 | 2.9 | 225 | 2.5 |
| CV, % | | 4.3 | | 7.3 | | 40.5 |

* Significant at $P \leq 0.05$ levels of probability.

† Carrington 2018, Carrington 2019, Oakes 2019, Prosper 2018, Prosper 2019.

‡ Oakes 2019, Prosper 2018, Prosper 2019.

The four open-pollinated genotypes were taller than the two hybrids (Table 17). In addition, the open-pollinated genotypes for both seeding dates, which reached physiological maturity were also taller. Hybrid genotypes were shorter than the open-pollinated genotypes regardless of seeding date or growing environment.

Table 17. Mean plant height, panicle length, and lodging score for six grain sorghum genotypes averaged across three seeding dates and several North Dakota environments in 2018 and 2019.

| | Plant height | Panicle length | Lodging score† |
|---|---|---|---|
| Genotype | --------------------cm-------------------- | | ---0-9--- |
| AG1401 | 119 | 27 | 0.5 |
| RS320W | 124 | 29 | 0.3 |
| PI574595 | 136 | 19 | 5.9 |
| SARE10 | 135 | 21 | 5.5 |
| SARE14 | 137 | 22 | 5.6 |
| SARE17 | 138 | 21 | 5.7 |
| LSD (0.05) | 7 | 1.3 | 1.5 |

† 0= no lodging, 9= 100% lodged

### *5.4.2. Panicle length*

The analysis of variance across environments indicated that both the main effect of seeding date and genotype affected panicle length, but not the seeding date by genotype interaction (Table 16). The open-pollinated genotypes had shorter panicle lengths compared with the hybrids. Hybrid RS320W had a longer panicle length compared with hybrid AG1401 (Table 17). Panicle shape can be classified into four groups: i) compact, ii) semi-compact, iii) semi-open, and iv) open. While genotype AG1401, RS320W, and PI574595 had compact panicles, genotype SARE10, SARE14, and SARE17 had semi-open panicles.

#### *5.4.3. Lodging score*

The main effect of lodging was significant for genotype, but the main effect of seeding date and the seeding date by genotype interaction were not significant (Table 16). In addition, environment by date, environment by genotype, and the environment by date by genotype interactions were significant for lodging, but since environment is a random effect, they are not discussed, but these interactions appear in the Table B.2. Open-pollinated genotypes PI574595, SARE10, SARE14, and SARE17 lodged severely compared with the commercial hybrids AG1401 and RS320W (Figure C.1). The lowest lodging score was observed for the hybrids because they had better stalk strength, greater stem diameter, and they possessed the stay-green trait. Stem diameter was not determined, but field observations indicated that the open-pollinated genotypes had thinner stalks than the hybrids. Shorter stalk height (Table 17) and greater observed stem diameter for the hybrids benefited lodging resistance for the hybrids compared with the open-pollinated genotypes.

High wind and snow loads are two major natural occurring lodging factors to cause and increase plant lodging (Bashford et al., 1976). Severe lodging was observed at Prosper after frost, icy rain, snow, and high winds (48 and 55.7 km $h^{-1}$) on 9 and 10 October in 2018. Stalk breakage at the peduncle was not observed at the Carrington and Prosper locations in both years. Larson and Maranville (1977) found that artificial lodging especially stalk breakage during the early dough stage interrupted translocation between leaves to the developing panicle and decreased photosynthetic efficiency and grain development. After the heavy, wet snow the bird net collapsed from the weight and pushed the sorghum plants down, resulting in stalk breakage in all plots on 15 October 2018 at Oakes but this did not cause translocation problems for photosynthate movement from leaves to the panicle. For this reason, lodging score data was not collected at Oakes in 2018. Larson and Maranville (1977) also observed that during the early dough stage stem breaking reduced sorghum test weight. At Oakes lodging was not observed in 2018, but severe lodging was observed in 2019. When severe lodging occurred in the open-pollinated genotypes, the hybrids were still standing. The hybrid lodging score was also low at Prosper 2018 and Oakes 2019. According to Bennett et al. (1990) insect damage (stem borer) and diseases (charcoal root rot and fusarium root and stalk rot) can cause severe lodging. For these reasons producers must consider potential for soil borne pathogens, environmental conditions necessary for pest development, and presence of pests. Yield improvement studies of grain sorghum targeted to increase panicle length and number of kernels panicle$^{-1}$ can result in thinner stems that are more susceptible to lodging. For this reason, plant breeders were focused on plant standability that is benefitted by shorter and thicker-stemmed types that have less grain yield loss because there is lower plant lodging (Bashford et al., 1976; Bennett et al., 1990).

Results clearly explain that the open-pollinated genotypes were more sensitive and negatively affected that the hybrids under unfavorable climatic conditions that delayed harvest and resulted in plant lodging. One of the most significant late-season yield-limiting factors was lodging for all the open-pollinated genotypes at the Prosper 2018 environment. According to Kutka (2011), open-pollinated genotypes may have high grain yield potential under favorable growing conditions, but stalk strength resulting in lodging is a major biological concern for open-pollinated genotypes.

Field observations show that lodging can cause grain losses at harvest especially when the crop is mature. When mature panicles strike the ground this may also causes kernels to shatter. Grain loss from shattering can also occur in sorghum when harvest is delayed. Yield losses can be high in the open-pollinated genotypes when harvest is delayed due to both plant lodging and seed shattering.

Grain losses may happen mechanically at harvest when sorghum becomes lodging severely (Larson and Maranville, 1977). A lowered grain header cutter bar height might help to reduce grain losses, but when sorghum panicles are on the ground combine headers cannot gather sorghum panicles into the combine for threshing (Allen and Hollingsworth, 1981). However, combine header adjustments and some pick up attachments on the combine can help to reduce yield losses caused by lodging (Allen and Hollingsworth, 1981; Bennett et al., 1990). Turnquist and Matter (1967) indicated that immediate grain sorghum harvest after physiological maturity reduces grain losses caused by plant lodging at the southern sorghum belt. However, high moisture content is a major problem in the northern United States such as South Dakota and North Dakota due to the extra cost for artificial drying that results in reduced profitability. Researchers found that stalk lifters attached to the combine cutter bar reduced grain losses in Brookings, SD, when plots were severely lodged after high wind and delayed harvest (4 and 17 October). Conventional header harvest loss was 3.5 times more than row harvester when harvested on 17 October and 2.6 times greater compared with row harvester units mounted on a conventional header in 1965 at Brookings, SD. At Brookings, SD, sorghum harvest on 17

October 1966, with a conventional header and row harvest units had grain losses of 34.8% and 9.7%, respectively.

### 5.5. Grain yield

The analysis of variance across environments indicated that seeding date and seeding date by genotype interaction were significant for grain yield (Table 18). The main effect of genotype was not significant for grain yield. The environment by seeding date, environment by genotype, and environment by seeding date by genotype interactions were significant. Since environment is a random effect these interactions are not discussed but are shown in the Table B.3.

Table 18. Combined analysis of variance and mean square values for grain yield for seeding date by genotype (gen) study conducted at six North Dakota environments (env) in 2018 and 2019.

| SOV | df† | Grain yield |
|---|---|---|
| Environment | 5 | 149418690* |
| Rep (Env) | 18 | 2793547* |
| Date | 2 | 94051128* |
| Env x date | 10 | 5302654* |
| Env x rep x date | 36 | 1439223* |
| Genotype | 5 | 1735856 |
| Env x gen | 25 | 5547953* |
| Date x gen | 10 | 5483997* |
| Env x date x gen | 50 | 1434521* |
| Residual | 270 | 381660 |
| CV, % | | 16.3 |

* Significant at $P \leq 0.05$ levels of probability.
† Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018, Prosper 2019.

Averaged across seeding dates, genotype grain yield ranged from 3563 to 4021 kg ha$^{-1}$ (Table 19). The main effect of seeding date shows differences among seeding dates. The highest grain yield was obtained with the first and second seeding dates. The last seeding produced the lowest grain yield compared with the first and second seedings (Table 19).

In general, hybrids produced the highest grain yield at the first seeding date. Similarly, several researchers reported the highest sorghum grain yield was obtained when sorghum was planted early in the season in Turkey, Ankara; St. John, KS; Columbia, MO; Bushland, TX; Iran, Tehran; Brazil, Sao Paulo; India, Gujarat; Elizabeth and Stoneville, MS, respectively (Emeklier and Koksoy, 1997; Martin and Vanderlip, 1997; Conley and Wiebold, 2003; Baumhardt et al., 2005; Safari and Sanavy, 2010; Zandonadi et al., 2017; Saini et al., 2018; Bruns, 2019).

In the second seeding date, all genotypes had similar grain yield. In the third seeding date, hybrid RS320W produced a similar grain yield to the open-pollinated genotypes. Hybrid AG1401 had the lowest grain yield at the third seeding date (Table 19).

Table 19. Mean grain yield interaction between genotypes and seeding dates averaged across six environments at Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | Date 1 | Date 2 | Date 3 | Genotype mean |
|---|---|---|---|---|
| Genotype | ---------------------------------kg $ha^{-1}$--------------------------------- | | | |
| AG1401 | 4935 | 3490 | 2265 | 3563 |
| RS320W | 5518 | 3769 | 2777 | 4021 |
| PI574595 | 4304 | 4214 | 3091 | 3870 |
| SARE10 | 4243 | 3991 | 3121 | 3785 |
| SARE14 | 4063 | 3997 | 3044 | 3701 |
| SARE17 | 4133 | 4065 | 3289 | 3829 |
| Date mean | 4533 | 3921 | 2931 | |
| $LSD_1$ (0.05) | 809 | | | |
| $LSD_2$ (0.05) | NS | | | |
| $LSD_3$ (0.05) | 971 | | | |
| $LSD_4$ (0.05) | 836 | | | |
| $LSD_5$ (0.05) | 1448 | | | |

$LSD_1$= to compare among dates mean at 0.05 level of significance.
$LSD_2$= to compare among genotypes mean at 0.05 level of significance.
$LSD_3$= to compare among genotypes within the same seeding date at 0.05 level of significance.
$LSD_4$= to compare same genotypes between different seeding date at 0.05 level of significance.
$LSD_5$= to compare among genotypes on different seeding date at 0.05 level of significance.

The lowest grain yield for hybrid AG1401 is associated with longer vegetative and reproductive phases that required greater accumulated heat units to reach physiological maturity. According to Martin and Vanderlip (1997), Can and Yoshida (1999), Conley and Wiebold (2003), and Martin and Vanderlip (2013) at late planting sorghum grain yield reduction is a certainty. This is primarily due to delayed plant development caused by cool, decreasing temperatures during grain filling that occur later in the growing season.

The environment by seeding date by genotype interaction was significant for grain yield because vegetative and reproductive phases were delayed due to cool and wet growing season at the beginning of the seedling stage. Adverse conditions were observed at the Carrington 2019 and Prosper 2019 environments. Hybrids at all seeding dates and the open-pollinated genotypes at the third seeding date failed to reach physiological maturity at the Prosper 2019 environment. For this reason, grain yield reduction was more severe at the Prosper 2019 environment compared with the Carrington 2019 environment.

At the Carrington 2018 environment, there was less grain yield due to less precipitation (Table 5). August and September were the most important two months for grain sorghum crops because grain sorghum plants were between at the 50% heading to grain filling stage at 2018 Carrington environment. According to Mastrorilli et al. (1995) and Assefa et al. (2010) the period between the boot stage until anthesis stage is the most water dependent and sensitive period for grain sorghum. Oakes 2018 and 2019 environments were irrigated and irrigation reduced the rainfall dependency on grain sorghum and enhanced grain yield compared with the dryland Carrington environments.

Larson and Maranville (1977) found that lodging yield reduction was 21% and 15% depending on environmental conditions. According to Assefa and Staggenborg (2010) dryland sorghum grain yield gains over time since 1957 are related to replacement of open-pollinated genotypes with hybrids. Hybrid advantages are numerous, mostly due to associated with soil water, nutrient response, pest and disease resistance (Assefa and Staggenborg, 2010), stalk strength, and improved biological and agronomic traits (Kutka, 2011) on hybrid performance compared with open-pollinated genotypes. Results show that lodging is a concerning yield-limiting factor for the early-maturity open-pollinated genotypes evaluated in this study when harvest is delayed and inclement weather occurs. This was the case at the Prosper 2018 environment where harvest was delayed by rain and lastly a snowstorm, which caused lodging for the taller, thinner-stemmed, open-pollinated genotypes. This situation may not happen every year, but the risk is too high to recommend commercial production with the open-pollinated genotypes used in this study.

## 5.6. Crop yield components

### *5.6.1. Panicle density, tiller density, and tillers per plant*

The analysis of variance across environments indicated that the seeding date, genotype and seeding date by genotype interaction were not significant for panicle density, tiller density, and tillers plant$^{-1}$ (Table 20). The environment by seeding date and environment by genotype interactions were significant for panicle density. The environment by genotype and environment by seeding date by genotype interactions were significant for tiller density. The environment by seeding date by genotype interactions was significant for tillers plant$^{-1}$ but since environment is a random effect, these interactions are not discussed.

Table 20. Combined analysis of variance and mean square values for panicle density, tiller density, and tillers plant$^{-1}$ for seeding date by genotype (gen) study conducted at two North Dakota environments (env) in 2018 and 2019.

| SOV | df† | Panicle density | Tiller density | Tillers plant$^{-1}$ |
|---|---|---|---|---|
| Environment | 1 | 1982* | 105 | 0.01 |
| Rep (Env) | 6 | 58* | 4 | 0.09* |
| Date | 2 | 40 | 12 | 0.05 |
| Env x date | 2 | 65* | 5 | 0.02 |
| Env x rep x date | 12 | 4 | 1 | 0.01 |
| Genotype | 5 | 17 | 45 | 0.28 |
| Env x gen | 5 | 49* | 25* | 0.07 |
| Date x gen | 10 | 4 | 2 | 0.02 |
| Env x date x gen | 10 | 3 | 2* | 0.03* |
| Residual | 90 | 4 | 1 | 0.01 |
| CV, % | | 11 | 22 | 33.5 |

* Significant at $P \leq 0.05$ levels of probability.

† Prosper 2018, Prosper 2019.

Panicle density, tiller density, and tillers plant$^{-1}$ were not affected by seeding date and genotype at the Prosper environments (Table 21). However, Bruns (2019) found that the average number of panicle ha$^{-1}$ was higher in May seedings and lowest in June seedings in the lower Mississippi River Valley. The number of panicles ha$^{-1}$ that reach physiological maturity is an important yield component for grain sorghum.

Table 21. Mean panicle density, tiller density, and tillers plant$^{-1}$ for six grain sorghum genotypes averaged across three seeding dates and two environments at Prosper, ND in 2018 and 2019.

| | Panicle density | Tiller density | Tillers plant$^{-1}$ |
|---|---|---|---|
| Genotype | ---------------panicle or tillers m$^{-2}$--------------- | | ----no.---- |
| AG1401 | 18.3 | 2.8 | 0.18 |
| RS320W | 16.4 | 2.3 | 0.17 |
| PI574595 | 18.2 | 4.4 | 0.32 |
| SARE10 | 17.2 | 4.5 | 0.32 |
| SARE14 | 18.6 | 6.1 | 0.46 |
| SARE17 | 18.1 | 3.7 | 0.26 |
| LSD (0.05) | NS | NS | NS |

$P \leq 0.05$ levels of probability.

### *5.6.2. Panicle yield*

The analysis of variance across environments indicated that the main effect of seeding date was significant for panicle yield (Table 22). However, the genotype main effect and the seeding date by genotype interaction were not significant for panicle yield. The environment by genotype interaction was significant, but since environment is a random effect it is not discussed.

Table 22. Combined analysis of variance and mean square values for panicle yield and kernel panicle$^{-1}$ for seeding date by genotype (gen) study conducted at three North Dakota environments (env) in 2018 and 2019.

| SOV | df† | Panicle yield | Kernel panicle$^{-1}$ |
|---|---|---|---|
| Environment | 2 | 34970.0* | 53601602* |
| Rep (Env) | 9 | 217.7* | 423764* |
| Date | 2 | 2360.0* | 2528007 |
| Env x date | 4 | 167.0 | 379673* |
| Env x rep x date | 18 | 31.0* | 69816* |
| Genotype | 5 | 317.6 | 3844038 |
| Env x gen | 10 | 916.4* | 3746680* |
| Date x gen | 10 | 137.3 | 355110* |
| Env x date x gen | 20 | 85.5 | 64761* |
| Residual | 135 | 9.9 | 27605 |
| CV, % | | 10.3 | 11.2 |

* Significant at $P \leq 0.05$ levels of probability.
† Oakes 2019, Prosper 2018, Prosper 2019.

All genotypes had similar panicle yield when averaged across environments and seeding dates. Mean panicle yields for the first (36 g panicle$^{-1}$) and second (31 g panicle$^{-1}$) seeding dates were similar, but panicle yield at the third seeding was lower (25 g panicle$^{-1}$) (data not shown). Panicle yield may have decreased for the third seeding date due to pollen sterility. Pollen sterility is a yield-limiting factor especially in northern climates due to poor seed set from cold temperature stress during anthesis and early seed set which would have occurred later in the season for the third seeding date (B. Schatz, 2018, personal communication).

Failure to reach physiological maturity during the late season does not allow the plant to reach full yield potential. This would be more problematic when later maturity genotypes are grown in cool, short season environments (Larson and Maranville, 1977; Rosenthal and Gerik, 1990). Frost occurrence before physiological maturity considerably reduces sorghum grain filling (Schatz et al., 1990; Martin and Vanderlip, 1997; Can and Yoshida, 1999; Pale et al., 2013).

### *5.6.3. Number of kernels per panicle*

The seeding date by genotype interaction was significant for number of kernels panicle$^{-1}$ (Table 22). Environment by date, environment by genotype, and environment by date by genotype interactions were significant, but since environment is a random effect, they are not discussed. Hybrids AG1401 and RS320W produced the highest number of kernels panicle$^{-1}$ at the first seeding date with each successive seeding date producing fewer kernels panicle$^{-1}$ (Table 23).

Table 23. Mean number of kernels panicle$^{-1}$ interaction between three seeding dates and six genotypes averaged across three North Dakota environments: Oakes 2019, Prosper 2018, and Prosper 2019.

| | Date 1 | Date 2 | Date 3 |
|---|---|---|---|
| Genotype | -----------------------no. kernels panicle$^{-1}$----------------------- | | |
| AG1401 | 2054 | 1764 | 1273 |
| RS320W | 2409 | 2095 | 1621 |
| PI574595 | 1303 | 1279 | 1000 |
| SARE10 | 1474 | 1449 | 1302 |
| SARE14 | 1272 | 1327 | 1147 |
| SARE17 | 1303 | 1313 | 1297 |
| $LSD_1$ (0.05) | 968 | | |
| $LSD_2$ (0.05) | 292 | | |
| $LSD_3$ (0.05) | 987 | | |

$LSD_1$= to compare among genotypes within the same seeding date at 0.05 level of significance.
$LSD_2$= to compare same genotypes between different seeding date at 0.05 level of significance.
$LSD_3$= to compare among genotypes on different seeding date at 0.05 level of significance.

Genotype PI574595 had the highest kernels panicle$^{-1}$ in the first and second seeding dates, but the lowest at the last seeding date, which suggests this genotype is not as early-maturing as the SARE lines. Further evidence supporting that the SARE genotypes are earlier maturing than PI574595 is the greater GDDs required for PI574595 to reach 50% anthesis compared with the SARE genotypes (Table 13). Genotypes SARE10, SARE14, and SARE17 had similar kernels panicle$^{-1}$ at each seeding date.

Baumhardt et al. (2005) developed the Sorkam Simulation Model on sorghum field performance trails conducted in Kansas. This model predicted that kernels panicle$^{-1}$ was higher for early-maturing cultivars compared with the medium- and late- maturing cultivars in their simulations. M'Khaitir and Vanderlip (1992) observed that when sorghum seeding date was delayed, the number of kernels panicle$^{-1}$ increased. Number of kernels panicle$^{-1}$ and 1000-kernel weight are useful to determine sorghum grain yield (Ciampitti et al., 2016). Tolk and Schwartz (2016) reported that 1000-kernel weight was more important than number of kernels panicle$^{-1}$ for sorghum yield when kernels are fully developed.

### *5.6.4. 1000-kernel weight*

The analysis of variance across environments indicated the main effect of seeding date and genotype were significant for 1000-kernel weight, but the interaction between seeding date and genotype was not significant for 1000-kernel weight (Table 24). The environment by date, environment by genotype, and environment by date by genotype interactions were significant, but since environment is a random effect, they are not discussed.

Table 24. Combined analysis of variance and mean square values for 1000-kernel weight and test weight for seeding date by genotype (gen) study conducted at six North Dakota environments (env) in 2018 and 2019.

| SOV | df† | 1000-kernel weight | Test weight |
|---|---|---|---|
| Environment | 5 | 1772.3* | 2684.1* |
| Rep (Env) | 18 | 4.0 | 32.0* |
| Date | 2 | 599.1* | 3497.3* |
| Env x date | 10 | 46.6* | 226.7* |
| Env x rep x date | 36 | 5.9* | 13.9 |
| Genotype | 5 | 1048.2* | 3312.7* |
| Env x gen | 25 | 20.3* | 185.1* |
| Date x gen | 10 | 5.8 | 111.0* |
| Env x date x gen | 50 | 5.0* | 23.4* |
| Residual | 270 | 2.5 | 14.9 |
| CV, % | | 8.7 | 7.4 |

* Significant at $P \leq 0.05$ levels of probability.

† Carrington 2018, Carrington 2019, Oakes 2018, Oakes 2019, Prosper 2018, Prosper 2019.

Table 25. Mean 1000-kernel weight for three seeding dates and six genotypes averaged across six environments at Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | 1000-kernel weight | | 1000-kernel weight |
|---|---|---|---|
| Genotype | -----------g----------- | Seeding date | -----------g----------- |
| AG1401 | 13 | Date 1 | 20 |
| RS320W | 14 | Date 2 | 18 |
| PI574595 | 21 | Date 3 | 16 |
| SARE10 | 19 | | |
| SARE14 | 20 | | |
| SARE17 | 21 | | |
| $LSD_1$ (0.05) | 1.8 | $LSD_2$ (0.05) | 1.5 |

$LSD_1$= to compare among seeding date means at 0.05 level of significance.
$LSD_2$= to compare among genotype means at 0.05 level of significance.

One-thousand kernel weight was the highest at the first seeding date and was reduced at each successive seeding date (Table 25). The open-pollinated genotypes PI574595, SARE14, and SARE17 had higher 1000-kernel weights compared with small seeded open-pollinated genotype SARE10 and the hybrids. This may be because they reached physiological maturity earlier. Although genotype PI574595 required more accumulated GDDs to reach 50% anthesis compared with the SARE lines (Table 13), it produced the heaviest 1000-kernel weight because it genetically appears to have larger seed compared with the other genotypes. Hybrids AG1401 and RS320W produced the lowest 1000-kernel weight.

Subalakhshmi et al. (2019) stated that 1000-kernel weight was positively correlated with sorghum grain yield indicating the importance of this yield component for final grain yield. Other researchers found that early-maturing genotypes have more consistent grain fill compared with mid- and late-maturing genotypes (Martin and Vanderlip, 1997; Conley and Wiebold, 2003). However, Emeklier and Koksoy (1997) observed in studies conducted in Ankara, Turkey, that the 20 April and 5 May seeding dates had the lowest 1000-kernel weight and the highest 1000-kernel weight was observed at the latest seeding date on 20 May. However, sorghum grain yield was higher for the 20 April compared with 5 May and 20 May seeding dates indicating number of kernels was more important for determining final grain yield than 1000-kernel weight.

One-thousand kernel weight is greatly influenced by unfavorable environmental conditions such as frost, drought, and heat that occur prior to physiological maturity. These factors can substantially reduce grain filling that result in reduced 1000-kernel weight (Schatz et al., 1990; Martin and Vanderlip, 1997; Can and Yoshida, 1999; Pale et al., 2013).

#### *5.6.5. Test weight*

The analysis of variance across environments indicated that test weight was significantly affected by the seeding date, genotype, and the seeding date by genotype interaction (Table 24). The genotype by seeding date interaction for test weight indicated that the hybrids responded differently than the open-pollinated genotypes as seeding date was delayed. Test weight decreased as seeding date was delayed for all genotypes but the reduction in test weight was greater for the hybrids compared with the open-pollinated genotypes. Hybrids AG1401 and RS320W test weight decreased 16 and 14 kg $hL^{-1}$, respectively, from seeding date 1 to seeding date 3. The open-pollinated genotypes decreased 9, 6, 7, and 7 kg $hL^{-1}$, for PI574595, SARE10, SARE14, and SARE17, respectively, from seeding date 1 to seeding date 3 (Table 26). The main effect of genotype indicated the open-pollinated genotypes all produced a test weight of 56 kg $hL^{-1}$. Hybrid AG1401 and RS320W produced test weights of 39 and 49 kg $hL^{-1}$, respectively (Table 26).

Table 26. Mean test weight interaction between six genotypes and three seeding dates averaged across six environments at Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| Genotype | Date 1 | Date 2 | Date 3 | Genotype mean |
|---|---|---|---|---|
| | ---------------kg $hL^{-1}$--------------- | | | |
| AG1401 | 47 | 40 | 31 | 39 |
| RS320W | 56 | 50 | 42 | 49 |
| PI574595 | 60 | 58 | 51 | 56 |
| SARE10 | 58 | 57 | 52 | 56 |
| SARE14 | 58 | 57 | 51 | 56 |
| SARE17 | 59 | 57 | 52 | 56 |
| Date mean | 56 | 53 | 47 | |
| $LSD_1$ (0.05) | 3.9 | | | |
| $LSD_2$ (0.05) | 4.6 | | | |
| $LSD_3$ (0.05) | 5.1 | | | |
| $LSD_4$ (0.05) | 4.4 | | | |
| $LSD_5$ (0.05) | 6.1 | | | |

$LSD_1$= to compare among seeding date means at 0.05 level of significance.
$LSD_2$= to compare among genotype means at 0.05 level of significance.
$LSD_3$= to compare among genotype within the same seeding date at 0.05 level of significance.
$LSD_4$= to compare same genotype between different seeding date at 0.05 level of significance.
$LSD_5$= to compare among genotype on different seeding date at 0.05 level of significance.

Other researchers found that early seeding results in higher test weight compared with late seeding, because cooler temperatures influenced test weight (Martin and Vanderlip, 1997; Conley and Wiebold, 2003). Emeklier and Koksoy (1997) and Zandonadi et al. (2017) reported that the highest test weight was obtained with the latest seeding date compared with early seeding. High test weight in late seeded sorghum can occur if there are sufficient heat units for the genotype grown to reach physiological maturity without incidence of frost or other stresses that might impact complete kernel fill.

Test weight was significant for the seeding date by genotype interaction while 1000-kernel weight was not significant for this interaction (Table 24). This difference occurred because test weight is usually related to grain quality and not correlated with yield, however, 1000-kernel weight is directly correlated grain yield (Deivasigamani and Swaminathan, 2018). According to the Buffo et al. (1998), test weight is mostly related with kernel shape, kernel moisture content, and foreign material in the seed lot. When kernels shrink at the end of the season because of early frost, kernels cannot fill completely with nutrients which results in smaller seed. Low endosperm and small seed particles become denser than irregular shaped and bigger seeds. A shortened grain filling period results in smaller seed reduces 1000-kernel weight but may not affect test weight because higher test weight does not represent higher grain yield (Buffo et al., 1998; Chiremba et al., 2011; Sipes and Vanderlip, 2013).

### 5.7. Percent bird damage

Percent bird damage was significant for seeding date, genotype, and the interactions between seeding date and genotype (Table 27). The environment by date interaction was significant, but since environment is a random effect, this is not discussed.

Observations indicate that resident granivorous birds did not have a feeding preference by genotype, but rather by sorghum growth stage. Birds preferred the soft dough stage for feeding. Bird feeding on sorghum was problematic at the Oakes 2018 and Oakes 2019 environments, but not at the Carrington and Prosper environments. The most serious damage was caused by field sparrow, chipping sparrow, grasshopper sparrow, and the clay-colored sparrow at the beginning of the soft dough stage when the sugar content of the kernel was maximum. Sparrows mashed and ate the developing grain endosperm (Figure C.6). However, rusty blackbird and red-winged blackbird tended to feed on kernels as a whole mature seed when in the hard dough stage. Bird damage was more severe in the early-maturity, open-pollinated genotypes than in the hybrids because the early-maturing genotypes reached the soft dough stage before the later maturity hybrids. At Oakes, in 2018, the first bird attack was observed on 20 August and a bird net was placed over the whole experiment on 24 August. At Oakes, in 2019, the first bird attack was on 15 August and the experiment was covered with a bird net on 21 August.

Table 27. Combined analysis of variance and mean square values for percent bird damage for seeding date by genotype (gen) study conducted at two North Dakota environments (env) in 2018 and 2019.

| SOV | df† | Bird damage |
|---|---|---|
| Environment | 1 | 1332 |
| Rep (Env) | 6 | 192 |
| Date | 2 | 18790* |
| Env x date | 2 | 971* |
| Env x rep x date | 12 | 188* |
| Genotype | 5 | 1595* |
| Env x gen | 5 | 54 |
| Date x gen | 10 | 1259* |
| Env x date x gen | 10 | 39 |
| Residual | 90 | 88 |
| CV, % | | 74 |

* Significant at $P \leq 0.05$ levels of probability.

† Oakes 2018, Oakes 2019.

Bird damage was also observed in some early-maturing, open-pollinated genotypes in the second seeding date before the netting was placed over the study, but bird damage was zero for the hybrid genotypes in the second and third seeding dates. Lack of bird feeding damage for the hybrid genotypes was due to their later maturity and delayed endosperm initiation. The open-pollinated genotypes did not have any bird damage in the third seeding date (Table 28). Bird damage severity averaged 49.8% for the open-pollinated genotypes for seeding date 1 compared with a 6.9% average for the hybrids where netting was not yet covering the study.

Table 28. Mean percent bird damage interaction between six genotypes and three seeding dates averaged across two environments at Oakes, ND in 2018 and 2019.

| | Date 1 | Date 2 | Date 3 | Genotype mean |
|---|---|---|---|---|
| Genotype | -----------------------------------% | ----------------------------------- | | |
| AG1401 | 7.5 | 0 | 0 | 2.5 |
| RS320W | 6.2 | 0 | 0 | 2.1 |
| PI574595 | 50.6 | 1.1 | 0.6 | 17.5 |
| SARE10 | 48.7 | 4.4 | 0.1 | 17.7 |
| SARE14 | 43.7 | 5.6 | 0 | 16.5 |
| SARE17 | 56.2 | 3.1 | 0.6 | 20.0 |
| Date mean | 35.52 | 2.37 | 0.23 | |
| $LSD_1$ (0.05) | 27.4 | | | |
| $LSD_2$ (0.05) | 5.4 | | | |
| $LSD_3$ (0.05) | 7.4 | | | |
| $LSD_4$ (0.05) | 15.5 | | | |
| $LSD_5$ (0.05) | 15.7 | | | |

$LSD_1$= to compare among seeding date means at 0.05 level of significance.
$LSD_2$= to compare among genotypes means at 0.05 level of significance.
$LSD_3$= to compare among genotypes within the same seeding date at 0.05 level of significance.
$LSD_4$= to compare same genotypes between different seeding date at 0.05 level of significance.
$LSD_5$= to compare among genotypes on different seeding date at 0.05 level of significance.

According to Tipton et al. (1970), bird damage is typically more serious than insect damage in Louisiana. Researchers also reported that bird damage severity can be as great as 80% grain loss. McMillan et al. (1972) reported, in Georgia, that bird damage severity was related to kernel tannin content and non-tannin genotypes were damaged up to 80%, but with tannin-containing sorghum varieties damage severity was 20%.

Bennett et al. (1990) explained that some cultural (cyanide guns, seeding and harvest date adjustments) and chemical (repellents) methods are available to reduce bird damage but they do not work satisfactorily and are not an effective deterrent. However, sorghum’s bitter tasting seed lowers bird damage because of tannin content of the kernel. Bullard and York (1985) showed that tannin imparts astringent palatability for birds. Tannin is present in the kernel before the soft dough stage but disappears when the kernel ripens. Tipton et al. (1970) found that even though grain sorghum soft and hard dough stages can prevent bird damage by using bird resistance high-tannin sorghum genotypes; granivorous birds still swallow whole, mature kernels regardless of tannin content.

Meyer (1973) reported the first sorghum bird damage at Oakes, ND, where damage ranged from 0% to 6% grain loss. Martin and Vanderlip (1997) found that bird damage severity may cause more than 50% grain losses with early seeding of early-maturing sorghum genotypes. Sparrows and blackbird species have been major pests during the past 10 years in North Dakota for sorghum, sunflower (*Helianthus annuus* L.), and corn and cause substantial yield losses (H. Eslinger, 2020, personal communication).

# 6. SUMMARY

Field research studies on grain sorghum were conducted at the Carrington Research Extension Center, the Robert Titus Research Farm at the Oakes Irrigation Research Site, and the Prosper off-station Research Site of North Dakota State University during the 2018 and 2019 field seasons to determine the influence of seeding date and genotype maturity interactions on grain sorghum performance in eastern North Dakota. Two commercial grain sorghum hybrids AG1401 and RS320W and four open-pollinated genotypes PI574595, SARE10, SARE14, and SARE17 were evaluated at three seeding dates. Seeding dates for eastern North Dakota were targeted at the third and last week of the May and the first week of the June to identify optimum dates. The objective of the study was to identify seeding date effects on grain yield and other trait responses for edible, white-seeded, early-maturing hybrid and open-pollinated sorghum genotypes when grown at several locations in eastern North Dakota.

The analysis of variance across environments indicated PLSE was generally lower than 50% for all genotypes when averaged across seeding dates. The hybrids required greater AGDD to reach both 50% and 100% heading and anthesis stages at base temperatures of 10ºC and 15ºC. Accumulated GDDs for physiological maturity at 10ºC was unique at each seeding date and was 1134, 1081, and 1038 GDDs for the first, second, and the third seeding dates, respectively. Mean plant height was 134-, 133-, and 129-cm for the first, second, and third seeding dates, respectively. Mean hybrid plant height was shorter; however, panicle length was longer than with the open-pollinated genotypes. All open-pollinated genotypes lodged severely compared with the two commercial hybrids at the Prosper 2018 environment due to a heavy snow and high wind. Lodging was incidental at the Carrington and Oakes environments in both years and only in a few plots at the Prosper 2019 environment. Averaged across genotype mean seeding date grain yield was 4533, 3921, and 2931 kg $ha^{-1}$ for the first, second, and third seeding dates, respectively. Averaged across seeding dates and environments mean genotype grain yield ranged from 3563 to 4021 kg $ha^{-1}$ averaged across seeding dates. In general, hybrids produced the highest grain yield at the first seeding date. Panicle density, tiller density, and tillers $plant^{-1}$ were not affected by seeding date and genotype at the Prosper environments which was the only environments where these traits were determined. All genotypes had similar panicle yield when averaged across environments and seeding dates. The mean panicle yield for the first (36 g $panicle^{-1}$) and second (31 g $panicle^{-1}$) seeding dates was similar, but panicle yield at the third seeding was lower (25 g $panicle^{-1}$). The mean 1000-kernel weight was 20, 18, 16 $g^{-1}$ for seeding dates 1, 2, 3, respectively, when averaged across genotypes and environments. The main effect of genotype indicated the open-pollinated genotypes all produced a test weight of 56 kg $hL^{-1}$. The hybrid AG1401 and RS320W produced test weights of 39 and 49 kg $hL^{-1}$, respectively. Averaged across genotypes and environments, percent bird damage severity averaged 49.8% for open-pollinated genotypes for seeding date 1 compared with a 6.9% average for the hybrids at the Oakes environments.

# 7. CONCLUSIONS

Shortness of the growing season and generally cool and often wet field conditions, with likelihood of early fall frosts, coupled with late-maturity cultivars, are the primary concerns farmers face with grain sorghum production in North Dakota. Successfully grain sorghum production starts with stand establishment, which is the first yield component for grain field crops. The recommendation would be to increase seeding rate by 35% to 50% to account for sorghum's higher seedling mortality as compared with wheat, corn, and soybean.

Seeding date determination is one of the most important management practices for successful crop production. This decision is influenced by several factors related to weather and field conditions that are variable from season to season. Seeding grain sorghum in North Dakota, should be done before mid-June with early-maturing genotypes to allow life cycle completion. Cool and wet conditions at the beginning of the growing season may cause slow crop development and reduced yield potential. Therefore, producers should select early-maturing genotypes for North Dakotas' short growing season because seasonal accumulated GDDs are not adequate for mid- and late- maturity genotypes to attain physiological maturity.

All crop yield component expressions are related to life-cycle completion, specific growth phases, and attaining physiological maturity. Although tillers have the potential for increasing panicles harvested per hectare and grain yield, the later maturity of tillers compared with the main stem panicle does not always allow tiller panicles to reach physiological maturity and contribute to grain yield. Tillers typically lag behind developmentally when compared with the main plant stem due to their later initiation of growth. Late-season grain losses associated with plant lodging may occur if stalk strength is weak as was observed with the open-pollinated genotypes in this study at the Prosper 2018 environment.

The open-pollinated genotypes reached physiological maturity earlier and produced moderate grain yield, but the risk of their susceptibility to plant lodging due to poor harvest conditions is too great for recommending production until stem strength is improved. The major pest problem was bird feeding damage on grain sorghum at the Oakes environments in both years. At the Oakes location farmers should select bird resistance, high tannin content grain sorghum genotypes for obtaining high grain yield. Covering grain sorghum fields with bird nets is not a practical solution to prevent damage from bird feeding on the field scale.

Optimum plant seeding date and early-maturing, lodging-resistance grain sorghum varieties would improve grain yield in eastern North Dakota. Previously screened high-yielding, open-pollinated genotypes with improved stem strength could provide early-maturity, open-pollinated white sorghum genotypes for North Dakota.

## REFERENCES


Allen R.R., and L.D. Hollingsworth. 1981. Combine header performance in lodged grain sorghum. Trans. ASAE 24(6):1426-1428. doi:10.13031/2013.34465

Antony, R.M., M.B. Kirkham, T.C. Todd, S.R. Bean, J.D. Wilson, P.R. Armstrong, E. Maghirang, and D.L. Brabec. 2019. Low temperature tolerance of maize and sorghum seedlings grown under the same environmental conditions. J. Crop Improv. 33(3):287-305. doi:10.1080/15427528.2019.1579139

AOSA (Association of Official Seed Analyst). 1993. Rules for testing seeds. J. Seed Technol. 16:3-113. Available at: https://www.jstor.org/stable/23432704?seq=1 (Verified 2 January 2020).

Assefa, Y., and S.A. Staggenborg. 2010. Grain sorghum yield with hybrid advancement and changes in agronomic practices from 1957 through 2008. Agron. J. 102:703-706. doi:10.2134/agronj2009.0314

Assefa, Y., S.A. Staggenborg, and V.P.V. Prasad. 2010. Grain sorghum water requirement and responses to drought stress: A review. Crop Manag. doi:10.1094/CM-2010-1109-01-RV

Assefa, Y., K. Roozeboom, C. Thomson, A. Schlegel, L. Stone, and J. Lingenfelser. 2014. Corn and grain sorghum comparison: all things considered. 1st ed. Press. Elsevier Academic Press. Waltham, MA 02451, USA.

Bashford, L.L., J.W. Maranville, S.A. Weeks, and R. Campbell. 1976. Mechanical properties affecting lodging of sorghum. Trans. ASAE 19(5):962-966. doi:10.13031/2013.36155

Baumhardt, R.L., J.A. Tolk, and S.R. Winter. 2005. Seeding practices and cultivar maturity effects on simulated dryland grain sorghum yield. Agron. J. 97:935-942. doi:10.2134/agronj2004.0087

Baumhardt, R.L., and T.A. Howell. 2006. Seeding practices, cultivar maturity, and irrigation effects on simulated dryland grain sorghum yield. Agron. J. 98:462-470. doi:10.2134/agronj2005.0156

Bennett, W.F., B.B. Tucker, A.B. Maunder. 1990. Modern grain sorghum production. 1st ed. Press. Iowa State Univ. Academic Press. Ames, IA 50011, USA.

Berti, M.T., S. Podder, S. Cabello, B. Andersen, D. Samarappuli, A. Peterson, and J.V. Anderson. 2018. Chilling-tolerant forage sorghum as a potential bioenergy feedstock in North Central USA. p. 127-132 *In* 26th European Biomass Conf. and Ex. Copenhagen, Denmark. 14-17 May 2018.

Bruns, H.A. 2019. Grain sorghum yield components as influenced by hybrid, seeding date, and irrigation. Agrosyst. Geosci. Environ. 2:180030. doi:10.2134/age2018.08.0030

Buffo, R.A., C.L. Weller, and A.M. Parkhurst. 1998. Relationships among grain sorghum quality factors. Cereal chem., 75(1):100-104. doi:10.1094/CCHEM.1998.75.1.100

Bullard, R.W., and J.O. York. 1985. Progress in plant breeding -1. Breeding for bird resistance in sorghum and maize. doi:10.1016/B978-0-407-00780-2.50012-6

Can, N.D., and T. Yoshida. 1999. Grain yield of sorghum cultivars in a double cropping system. Plant Prod. Sci. 2(2):121-124. doi:10.1626/pps.2.121

Chiremba, C., L.W. Rooney, and J.R.N. Taylor. 2011. Relationships between simple grain quality parameters for the estimation of sorghum and maize hardness in commercial hybrid cultivars. Cereal chem., 88(6):570-575. doi:10.1094/CCHEM-06-11-0078

Ciampitti, I.A., P.V.V. Prasad, A.J. Schlegel, L. Haag, R.W. Schnell, B. Arnall, and J. Lofton. 2016. Sorghum: State of the art and future perspectives. Genotype x environment x management interactions: US Sorghum cropping systems. doi:10.2134/agronmonogr58.2014.0067

Conley, S.P., and W.J. Wiebold. 2003. Grain sorghum response to planting date. Online. Crop Manag. doi:10.1094/CM-2003-0204-01-RS (Accessed 30 November, 2019).

Deckard, E.L., C.G. Messersmith, and J.L. Helm. 1994. Ext. Bull. No. 3. How cereal crops grow. Ext. Serv., North Dakota State Univ., Fargo, ND.

Deivasigamani, S., and C. Swaminathan. 2018. Evaluation of seed test weight on major field crops. Int. J. Res. Stud. Agric. Sci., 4(1):8-11. doi:10.20431/2454-6224.0401001

Eastin, J.D., J.H. Hultquist, and C.Y. Sullivan. 1973. Physiologic maturity in grain sorghum. Crop Sci., 13:175-178. doi:10.2135/cropsci1973.0011183X001300020008x

Emeklier, H.Y., and N.F. Koksoy. 1997. Effect of sowing time and plant density on yield components of sorghum (*Sorghum bicolor* (L.) Moench). J. Agric. Sci., 3:20-28.

Espinoza L., and J. Kelley. 2004. Grain sorghum production handbook. MP-297. Arkansas Coop. Ext. Serv., Univ. of Arkansas, Little Rock, AR.

FAO (Food and Agriculture Organization of the United Nations). 2019. Available at: http://www.fao.org/home/en/ (Verified 2 January 2020).

Franzen, D.W. 2018a. North Dakota fertilizer recommendation tables and equations. SF-882. Ext. Serv., North Dakota State Univ., Fargo, ND.

Franzen, D.W. 2018b. Soil sampling as a basis for fertilizer application. SF-990. Ext. Serv., North Dakota State Univ., Fargo, ND.

Gerik, T., B. Bean, and R.L. Vanderlip. 2003. Sorghum growth and development. C-687. Agric. Exp. Stn. and Coop. Ext. Serv., Texas A&M Univ., Amarillo, TX.

GIPSA (Grain Inspection, Packers and Stockyards Administration). United States Department of Agriculture. Inspecting Grain – Practical Procedures for Grain Handlers Guide. 2009. Washington, DC, USA. Available at: https://www.gipsa.usda.gov/fgis/publication/ref/primer.pdf (Verified 2 January 2020).

Ikley, J., M. Christoffers, C. Dalley, G. Endres, G. Gramig, K. Howatt, B. Jenks, C. Keene, M. Ostlie, T. Peters, A. Robinson, A. Thostenson, and H.H. Valenti. 2020. North Dakota Weed Control Guide. W253-20. Ext. Serv., North Dakota State Univ., Fargo, ND.

Kapanigowda, M.H., R. Perumal, R.M. Aiken, T.J. Herald, S.R. Bean, and C.R. Little. 2013. Analyses of sorghum [*Sorghum bicolor* (L.) Moench] lines and hybrids in response to early-season planting and cool conditions. Can. J. Plant Sci. 93:773-784. doi:10.4141/CJPS2012-311

Knodel, J., P. Beauzay, M. Boetel, T.J. Prochaska, and L. Lubenow. 2020. North Dakota Field Crop Insect Management Guide. E1143-20. Ext. Serv., North Dakota State Univ., Fargo, ND.

Knutson, A., E. Bynum, D. Kerns, P. Porter, S. Biles, and B. Reed. 2018. Managing Insect and Mite Pests of Texas Sorghum. ENTO-085 10/18. AgriLife Ext. Serv., Texas A&M Univ., College Station, TX.

Kutka, F. 2011. Open-pollinated vs. hybrid maize cultivars. Sustainability 3(9):1531-1554 doi:10.3390/su3091531

Larson, J.C., and J.W. Maranville. 1977. Alterations of yield, test weight, and protein in lodged grain sorghum. Agron. J. 69:629-630. doi:10.2134/agronj1977.00021962006900040027x

Levene, H. 1960. Robust tests for equality of variance. In contributions to probability and statistics: Essays in honor of Harold Hotelling, I. Olkin et al. eds., Stanford Univ. press, pp. 278-292.

Lofton, J., A. Zander, and C. Harris. 2019. Influence of hybrids on cold soil germination in grain sorghum. CR-2185. Oklahoma Coop. Ext. Serv., Oklahoma State Univ., Stillwater, OK.

M'Khaitir, Y.O., and R.L. Vanderlip. 1992. Grain sorghum and pearl millet response to date and rate of planting. Agron. J. 84:579-582. doi:10.2134/agronj1992.00021962008400040007x

Martin, V.L., and R.L. Vanderlip. 1997. Sorghum hybrid selection and planting management under moisture limiting conditions. J. Prod. Agric., 10:157-163. doi:10.2134/jpa1997.0157

Mastrorilli, M., N. Katerji, and G. Rana. 1995. Water efficiency and stress on grain sorghum at different reproductive stages. Agric. water manag. 28(1):23-24. doi:10.1016/0378-3774(95)01160-K

Maulana, F., and T.T. Tesso. 2013. Cold temperature episode at seedling and flowering stages reduces growth and yield components in sorghum. Crop Sci. 53(2):564-574. doi.10.2135/cropsci2011.12.0649

McMillian, W.W., B.R. Wiseman, R.E. Burns, H.B. Harris, and G.L. Greene. 1972. Bird resistance in diverse germplasm of sorghum. Agron. J. 64:821-822. doi:10.2134/agronj1972.00021962006400060036x

Meyer, D.W. 1973. 1971-1975 Oakes grain sorghum trials report. North Dakota Agric. Exp. Sta. Misc. Pub. 1973:40-45.

NDAWN (North Dakota Agricultural Weather Network). 2020. Growing degree day calculation in formula. Available at: https://ndawn.ndsu.nodak.edu/help-corn-growing-degree-days.html (Verified 2 January 2020).

Neild, R.E., and M.W. Seeley. 1977. Growing degree days predictions for corn and sorghum development and some applications to crop production in Nebraska. 280:12. Nebr. Agric. Exp. Stn. Res. Bull. No. 280, Univ. of Nebraska-Lincoln, Lincoln, NE

Neild, R.E. 1982. Temperature and rainfall influences on the phenology and yield of grain sorghum and maize: A comparison. Agr. Meteo. 27:79-88. doi:10.1016/0002-1571(82)90022-X

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi, J.A. Tolk, and T.A. Howell. 2014. Early and late maturing grain sorghum under variable climatic conditions in the Texas High Plains. Trans. ASABE 57(6):1583-1594. doi:10.13031/trans.57.10424

Pale, S., S.C. Mason, and T.D. Galusha. 2003. Planting time for early-season pearl millet and grain sorghum in Nebraska. Agron. J. 95:1047-1053. doi:10.2134/agronj2003.1047

Petersen, R.G. 1994. Agricultural Field Experiments. 1st ed. CRC Press. Boca Raton, FL, USA. https://doi.org/10.1201/9781482277371

Podder, S. 2019. Screening for forage sorghum genotypes with chilling tolerance. A Master's Thesis, North Dakota State Univ., Fargo, ND.

Rider, D.A. 2012. The Heteroptera (Hemiptera) of North Dakota I: Pentatomomorpha: Pentatomoidea. The Great Lakes Entomologist, The Michigan Entomological Society vol. 45, Nos. 3&4 Fall/Winter 2012. Available at: https://scholar.valpo.edu/tgle/vol45/iss2/13

Roozeboom, K.L., and P.V.V. Prasad. 2016. Sorghum: State of the art and future perspectives. Sorghum growth and development. doi:10.2134/agronmonogr58.2014.0062

Rosenthal W.D., R.L. Vanderlip, G.F. Arkin, and B.S. Jackson. 1989. SORKAM: a grain sorghum crop growth model. Texas Agric. Exp. Stn. MP-1699.

Rosenthal W.D., and T.J. Gerik. 1990. Application of a crop model to evaluate cultural practices and optimize dryland grain sorghum yield. J. Prod. Agric. 3:124-131. doi:10.2134/jpa1990.0124

Saeed, M., and C.A. Francis. 1984. Association of weather variables with genotype x environment interactions in grain sorghum. Crop Sci. 24(1):13-16. doi:10.2135/cropsci1984.0011183X002400010004x

Safari, M., M. Aghaalikhani, and S.A.M. Modares Sanavy. 2010. Effect of sowing date on phenology and morphological traits of three grain sorghum (*Sorghum bicolor* L.) cultivars. Iranian J. of Crop Sci. 12(4):452-466.

Saini, L.H., S.J. Trivedi, B.K. Davda, and A.K. Saini. 2018. Effect of sowing dates on growth, yield, and economics of sorghum (*Sorghum bicolor* L. Moench) genotypes. J Pharmacog. and Phytochem. 7(5):535-538.

SAS Institute 2019. The Statistical Analysis System software for Windows operating system. Release 9.4. SAS Institute Inc., Cary, NC, USA.

Schatz, B.G. 1988. Grain sorghum production as influenced by row spacing and plant population. A Master’s Thesis, North Dakota State Univ., Fargo, ND.

Schatz, B.G., A.A. Schneiter, and J.C. Gardner. 1990. Effect of plant density on grain sorghum production in North Dakota. Farm Res. 47(5):15-18.

Sipes, J.D., and R.L. Vanderlip. 2013. Improving marketability of low test weight sorghum grain frozen before maturity. J. Prod. Agric., 7(4):458-465. doi:10.2134/jpa1994.0458.

Subalakhshmi, V.K.I.S., B. Selvi, D. Kavithamani, and N. Vadivel. 2019. Relationship among grain yield and its component traits in sorghum (*Sorghum bicolor* (L.) Moench) germplasm accessions. J. Plant Breed., 10(2):446-450. doi:10.5958/0975-28X.2019.00057.7.

TCLO (The Cornell Lab of Ornithology). 2020. Sparrow and blackbird identifications. https://www.birds.cornell.edu (Verified 4 February 2020).

Tipton, K.W., E.H. Floyd, J.G. Marshall, and J.B. McDevitt. 1970. Resistance of certain grain sorghum hybrids to bird damage in Louisiana. Agron. J. 62:211-213. doi:10.2134/agronj1970.00021962006200020010x

Tolk, J.A., and R.C. Schwartz. 2016. Do more seeds per panicle improve grain sorghum yield? Crop Sci. 57(1):490-496. doi:10.2135/cropsci2016.04.0245.

Turnquist, P.K., and V.E. Matter. 1967. Header attachments help save grain sorghum at harvest. Ext. Bull. No. 542. Agric. Eng. Dept. Agric. Exp. Stn., South Dakota State Univ., Brookings, SD.

Vanderlip, R.L., and H.E. Reeves. 1972. Growth stages of sorghum (*Sorghum bicolor* (L.) Moench). Agron. J. 64:13-16. doi:10.2134/agronj1972.00021962006400010005x

Vanderlip, R.L. 1993. How a sorghum plant develops. S-3. Agric. Exp. Stn. and Coop. Ext. Serv., Kansas State Univ., Manhattan, KS.

Vanderlip, R.L. 1998. Grain sorghum production handbook. Growth and development of sorghum plant. C-687. Agric. Exp. Stn. and Coop. Ext. Serv., Kansas State Univ., Manhattan, KS.

Web Soil Survey (United States Department of Agriculture Natural Resources Conservation Service). 2019. Available at: http://www.websoilsurvey.sc.egov.usda.gov/App/HomePage/htm (Verified 2 January 2020).

Zandonadi, C.H.S, C.J.B. Albuquerque, R.S. De Freitas, A.D.M. De Paula, and M.A. Clemente. 2017. Agronomic characteristics and macronutrient export of grain sorghum hybrids from different sowing dates. Ciencia e Agrotecnologia 41(1):7-14. doi:10.1590/1413-70542017411018716

## APPENDIX A. HISTORY OF WHITE OPEN-POLLINATED GRAIN SORGHUM GENOTYPE SCREENING IN NORTH DAKOTA

Four white open-pollinated sorghum genotypes were selected from 106 genotypes screened for adaptation in North Dakota over a three-year period from 2015 to 2017. The selection process occurred in two phases with the first phase including 56 genotypes evaluated in 2015, a second phase including 50 different genotypes evaluated in 2016, and a seed increase phase for the superior genotypes in 2017. Selection criteria included high grain production, early-maturity, cold tolerance, black spot formation (physiological maturity), seed size, and no or low green seed. Former North Dakota Sustainable Agriculture Research and Education (SARE) coordinator and Dickinson Research Extension Center Assistant Director Dr. Frank Kutka was provided 56 open-pollinated, early-maturing and cold tolerant (when night time temperatures 7-10ºC) open-pollinated sorghum genotypes. These genotypes were bred in 1993 at the Hermiston Agricultural Research and Extension Center, Oregon, by retired small grains plant breeder Emeritus Professor Mathias Kolding who is from North Dakota.

These white sorghum genotypes were evaluated at Enderlin, Carrington, Dickinson, and Prosper, ND, in 2015. In 2016, Michael Ostlie and Burton Johnson evaluated 50 different open-pollinated white sorghum genotypes at the Carrington Research Extension Center and Prosper research site that were sourced from the Plant Genetic Resources Conservation Unit in Griffin, Georgia. In total there were 106 open-pollinated white grain sorghum genotypes evaluated from which 21 selections based on the previous criteria were grown for seed increase in 2017 at the Prosper, ND, location. Agronomic characters recorded during the growing season included plant emergence and stand, growth/vigor, heading date, anthesis date, physiological maturity date, number of tillers, panicle shape, plant height, plant lodging, grain yield, test weight, green seed, and 1000-kernel weight. After agronomic character screening, the four most promising genotypes moved forward to a seeding date and genotype study at the Carrington Research Extension Center, Oakes Irrigation Site, and Prosper Research Site in the 2018 and 2019 growing seasons.

The four white open-pollinated, early-maturing, and high-yielding genotypes were PI574595, SARE10, SARE14, and SARE17. Genotype PI574595 had compact panicles and other SARE lines had semi-open panicles. The two earliest-maturity white grain sorghum hybrids were AG1401 from Alta Seed Company, Irving, TX, and RS320W from Richardson Seed Company, Vega, TX. Both hybrids are white-seeded, edible, food-grade, had compact panicles, and have the stay-green trait. Hybrid AG1401 is a mid-early hybrid with good grain yield under stress conditions and RS320W an early-maturing white grain sorghum with good grain yield, high standability, and threshing ease.

## APPENDIX B. TABLES

Table B.1. Mean pure live seed emergence (PLSE) (%) of three seeding dates and six genotypes in six environments in Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | | Environment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carrington | | | Oakes | | | Prosper | | |
| | | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 |
| Year | Genotype | ---------- | ---------- | ---------- | ---------- | % | ---------- | ---------- | ---------- | ---------- |
| 2018 | AG1401 | 51 | 59 | 50 | 35 | 35 | 28 | 74 | 71 | 79 |
| | RS320W | 33 | 36 | 32 | 33 | 40 | 35 | 71 | 71 | 71 |
| | PI574595 | 46 | 50 | 44 | 29 | 34 | 40 | 64 | 71 | 67 |
| | SARE10 | 35 | 37 | 33 | 27 | 34 | 32 | 53 | 55 | 49 |
| | SARE14 | 55 | 41 | 42 | 23 | 39 | 32 | 59 | 61 | 58 |
| | SARE17 | 38 | 46 | 39 | 29 | 40 | 35 | 63 | 68 | 58 |
| 2019 | AG1401 | 35 | 19 | 17 | 55 | 47 | 41 | 69 | 64 | 64 |
| | RS320W | 34 | 20 | 21 | 43 | 51 | 39 | 64 | 51 | 53 |
| | PI574595 | 41 | 30 | 18 | 41 | 64 | 52 | 61 | 54 | 50 |
| | SARE10 | 45 | 20 | 18 | 41 | 64 | 48 | 53 | 49 | 44 |
| | SARE14 | 40 | 27 | 13 | 44 | 66 | 49 | 56 | 49 | 43 |
| | SARE17 | 47 | 28 | 20 | 55 | 60 | 51 | 59 | 53 | 52 |
| LSD (0.05) | | | | | | 9 | | | | |

Table B.2. Mean lodging score (0-9) of three seeding dates and six genotypes in five environments in Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | | Environment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carrington | | | Oakes | | | Prosper | | |
| | | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 |
| Year | Genotype | ------------------------------------ 0-9† ------------------------------------ | | | | | | | | |
| 2018 | AG1401 | 0 | 0 | 0 | ‡ | ‡ | ‡ | 0 | 0 | 0 |
| | RS320W | 0 | 0 | 0 | ‡ | ‡ | ‡ | 0 | 0 | 0 |
| | PI574595 | 7 | 7 | 3 | ‡ | ‡ | ‡ | 7 | 8 | 9 |
| | SARE10 | 6 | 6 | 6 | ‡ | ‡ | ‡ | 8 | 5 | 9 |
| | SARE14 | 7 | 7 | 6 | ‡ | ‡ | ‡ | 8 | 7 | 9 |
| | SARE17 | 6 | 6 | 4 | ‡ | ‡ | ‡ | 8 | 8 | 9 |
| 2019 | AG1401 | 1 | 2 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | RS320W | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | PI574595 | 5 | 5 | 5 | 4 | 8 | 8 | 6 | 5 | 1 |
| | SARE10 | 6 | 4 | 6 | 1 | 8 | 7 | 4 | 3 | 1 |
| | SARE14 | 7 | 4 | 5 | 4 | 6 | 7 | 3 | 2 | 1 |
| | SARE17 | 6 | 5 | 4 | 3 | 8 | 8 | 5 | 4 | 1 |
| LSD (0.05) | | | | | | 2.2 | | | | |

† 0= no lodging, 9= 100% lodged

‡ Lodging score data was not collected at Oakes 2018 due to artificial lodging of bird net.

Table B.3. Mean grain yield (kg $ha^{-1}$) of three seeding dates and six genotypes in six environments in Carrington, Oakes, and Prosper, ND in 2018 and 2019.

| | | Environment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carrington | | | Oakes | | | Prosper | | |
| | | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 | Date 1 | Date 2 | Date 3 |
| Year | Genotype | ---------- | ---------- | ---------- | ---------- | kg $ha^{-1}$ | ---------- | ---------- | ---------- | ---------- |
| 2018 | AG1401 | 4106 | 2623 | 1079 | 6919 | 5299 | 2720 | 6337 | 5581 | 4175 |
| | RS320W | 4186 | 2567 | 1406 | 8241 | 5809 | 3682 | 6722 | 5575 | 5150 |
| | PI574595 | 3852 | 3837 | 2938 | 5881 | 6582 | 4009 | 6303 | 5745 | 5356 |
| | SARE10 | 4216 | 3795 | 3491 | 5030 | 5765 | 3808 | 5655 | 5023 | 4654 |
| | SARE14 | 4431 | 3987 | 3508 | 4311 | 5589 | 3354 | 5132 | 4744 | 5108 |
| | SARE17 | 3983 | 4233 | 2962 | 4005 | 6499 | 3679 | 6250 | 5461 | 5934 |
| 2019 | AG1401 | 3506 | 1910 | 2096 | 7154 | 4985 | 3457 | 1590 | 541 | 65 |
| | RS320W | 4230 | 2312 | 2208 | 7165 | 5570 | 4124 | 2567 | 781 | 91 |
| | PI574595 | 2222 | 1951 | 1339 | 3746 | 4747 | 3928 | 3821 | 2424 | 974 |
| | SARE10 | 2581 | 1814 | 1091 | 3787 | 4476 | 4457 | 4188 | 3071 | 1227 |
| | SARE14 | 2785 | 2467 | 938 | 3974 | 4032 | 4129 | 3746 | 3161 | 1228 |
| | SARE17 | 3499 | 1997 | 1238 | 2964 | 3176 | 4479 | 4100 | 3024 | 1444 |
| LSD (0.05) | | | | | | 861 | | | | |

## APPENDIX C. FIGURES

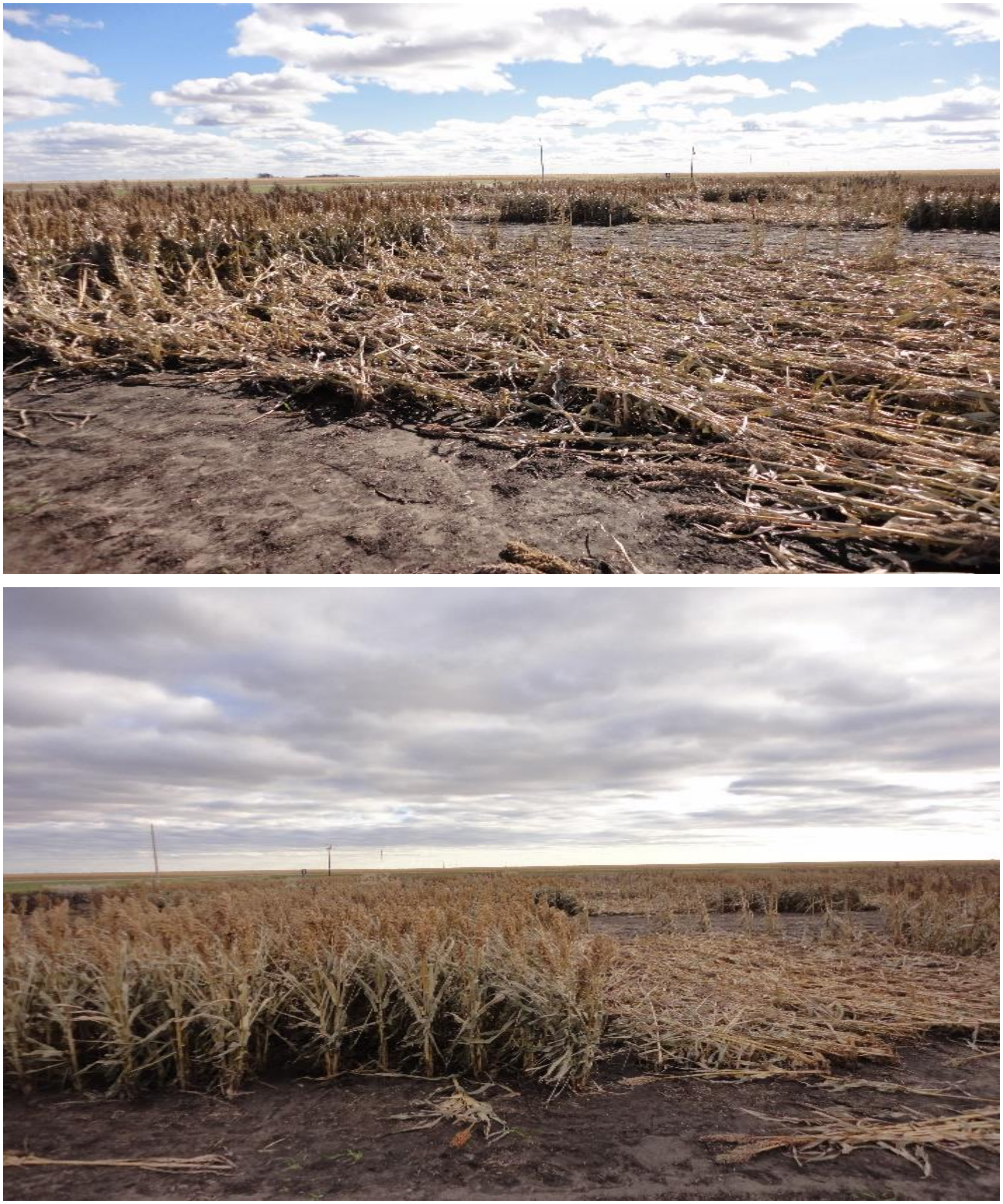


Figure C.1. After excessive rain, high wind velocity, and snowstorm, open-pollinated genotypes PI574595, SARE10, SARE14, and SARE17 lodged severely compared with the commercial hybrids AG1401 and RS320W at Prosper, ND, in 2018.

Figure C.2. Snow caused the bird netting to collapse onto the sorghum panicles pushing plants/panicles from 45 cm to ground surface at Oakes, ND, in 2018.


Figure C.3. A net with supports was installed over the sorghum plot at both Oakes environments to prevent further bird damage.

Figure C.4. Left figure shows Paraquat herbicide contact injury response on the open-pollinated genotype SARE17 leaf damage. Right figure shows that bacterial leaf spot on the hybrid AG1401 leaves at Prosper, ND, 2018.

Figure C.5. The most problematic pests were birds at Oakes, ND in 2018 and 2019. Top left field sparrow, top right chipping sparrow, middle left grasshopper sparrow, middle right clay-colored sparrow, bottom left rusty blackbird, bottom right red-winged blackbird (Courtesy of the Cornell Lab of Ornithology).

Figure C.6. Panicle and kernel damage on the open-pollinated genotype PI574595. Sparrows mashed and ate the developing grain endosperm at the beginning of the soft dough stage on grain sorghum at Oakes environments.

## APPENDIX D. MY GRAIN SORGHUM PRESENTATIONS

1) Location, seeding date, and genotype maturity interactions on grain sorghum performance in North Dakota. Oral presentation. 4th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 22 February 2018

2) Location, seeding date, and genotype maturity interactions on grain sorghum performance in North Dakota. Showcase display. 4th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 22 February 2018

3) Location, seeding date, and genotype maturity interactions on grain sorghum performance in North Dakota. Oral presentation. 2th Annual Graduate Student Council (GSC) Research Symposium, Fargo, ND. 6 April 2018.

4) Location, seeding date, and genotype maturity interactions on grain sorghum performance in North Dakota. Oral presentation. 1st Gamma Sigma Delta – NDSU Chapter Faculty and Student Symposium. Fargo, ND. 12 April 2018.

5) Seeding date and genotype maturity effect on grain sorghum performance in North Dakota. Poster presentation (Presented by Dr. Burton L. Johnson). 30st Association for the Advancement of Industrial Crops (AAIC) Annual Meeting. London, Ontario, Canada. 26 September 2018.

6) Sorghum production offers human health and agro-ecological benefits. Oral presentation. 5th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 21 February 2019

7) How seeding date effects on grain sorghum performance in North Dakota? Poster presentation. 5th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 21 February 2019

8) Grain sorghum can be a viable alternative crop for North Dakota. Showcase display. 5th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 21 February 2019

9) Seeding date effects on grain sorghum performance in North Dakota. Oral presentation. 35th Annual Plant Science Graduate Student Symposium. Fargo, ND. 16 March 2019.

10) Grain sorghum can be a viable alternative crop for North Dakota. Showcase display. 2019 North Dakota University System Legislative Showcase. Capitol Building, Bismarck, ND. 27 March 2019.

11) Seeding date effects on grain sorghum performance in North Dakota. Poster presentation. 2019 North Dakota University System Legislative Showcase. Capitol Building, Bismarck, ND. 27 March 2019.

12) Seeding date effects on grain sorghum performance in North Dakota. Poster presentation. 3th Annual Graduate Student Council (GSC) Research Symposium, Fargo, ND. 3 April 2019.

13) Seeding date and genotype maturity interactions on grain sorghum performance in North Dakota. Oral presentation. NDSU Experiment Station Oakes Irrigation Site Robert Titus Research Farm Field Day. Oakes, ND. 15 August 2019.

14) Seeding date effect on grain sorghum performance in North Dakota. Oral presentation. 31st Association for the Advancement of Industrial Crops (AAIC) Annual Meeting. Tucson, AZ. 11 September 2019.

15) Grain sorghum performance in North Dakota. Oral presentation. 2019 ASA-CSSA-SSSA International Annual Meeting. San Antonio, TX. 13 November 2019.

16) Seeding date and genotype effects on grain sorghum performance in North Dakota. Poster presentation. 2019 ASA-CSSA-SSSA International Annual Meeting. San Antonio, TX. 13 November 2019.

17) Grain sorghum yield response to genotype maturity and seeding date in North Dakota. Oral presentation. 4th Annual Graduate Student Council (GSC) Research Symposium, Fargo, ND. 21 November 2019.

18) Grain sorghum is becoming a new crop in North Dakota. Oral presentation. Gate City 759 Toastmaster International Weekly Meeting. Fargo, ND. 13 February 2020.

19) Grain sorghum is becoming a new crop in North Dakota. Oral presentation. 6th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 20 February 2020.

20) Sorghum: a nutritious new edible grain in North Dakota. Showcase display. 6th NDSU Graduate School 3-Minute Thesis Competition and Graduate Student Showcase. Fargo, ND. 20 February 2020.