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Is durum wheat amenable to an ultra-early seeding system and associated abiotic stress?

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Abstract

Ultra-early seeding provides several benefits for hexaploid wheat (*Triticum aestivum* L.), including an extended planting window, grain yield protection, enhancement and stability, earlier harvest, and improved weed competitiveness. However, a knowledge gap exists around whether durum wheat (*Triticum turgidum ssp. durum*) is also amenable to this practice. Thus, an experiment was conducted at four locations in Alberta and Saskatchewan, Canada, from 2022 to 2024. The treatment combinations consisted of five durum wheat cultivars, planted at six soil temperature triggers separated by 2˚C increments beginning at 0˚C through to 10˚C. Among the cultivars, irrespective of planting time, AAC Donlow, CDC Defy, and AAC Stronghold attained similar grain yields when averaged across all environments, which were superior to CDC Desire and Transcend. Planting at a soil temperature of 2˚C measured at the 5-cm soil depth generally resulted in higher grain yields and greater net returns. Moreover, a partial least squares regression-additive Main effects and multiplicative interaction analysis indicated that a 2˚C planting system was better adapted to warmer June and arid summer conditions, which suggests the system imparts enhanced heat and drought stress resilience. If planting was delayed—that is, ≥10˚C soil temperature—a yield drag was usually experienced. Grain protein concentration was not affected by the soil temperature trigger. Thus, commercially available durum cultivars are amenable to ultra-early seeding and optimized when planted at a soil temperature of 2˚C, which could increase returns by $CAD 134 ha^{-1}. Future studies will investigate durum responses when planted ultra-early versus dormant-plantings in fall, with variations to planting depth.

Abbreviations: aCV, adjusted coefficient of variation; AMMI, Additive Main effects and Multiplicative Interaction; CWAD, Canada Western Amber Durum; GDD, growing degree days; PLS, partial least squares.

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Plain Language Summary

This study investigated the potential of ultra-early seeding for Canada Western Amber Durum wheat production in the northern Great Plains. Five cultivars and six planting times, triggered when soil temperatures in the top 5 cm reached the target temperature (0°C, 2°C, 4°C, 6°C, 8°C, and 10°C), were evaluated to assess the feasibility and risks of ultra-early seeding of durum into cold soils. Our results indicated that grain yield was usually optimized when planted at a soil temperature of 2°C measured at the 5-cm soil depth. There was an indication of genotype differential as CDC Defy and Transcend appeared particularly well-adapted to colder soils, whereas Stronghold was insensitive to soil temperature at planting. Delayed planting, when the soil temperature was ≥10°C, resulted in lower yields and less stability. This study also highlighted the economic benefits of ultra-early seeding, with potential for growers to increase returns by $CAD 134 ha^{-1} when planting at the 2°C soil temperature compared to delayed planting.

1 | INTRODUCTION

Decisions around planting date can be an important factor influencing wheat (*Triticum aestivum* L.) production and yield potential; however, those decisions are seemingly influenced more by socio-economic or logistical considerations that overlook the implications for crop growth and development. For example, in southern Alberta, Canada, conventional wisdom assumed that as long as planting occurred by the crop insurance cut-off date, typically May 10, yield and yield potential would be protected. Toward the northern boundary of the wheat production region (Figure 1), the insurance cut-off planting date is later; in Saskatoon, Saskatchewan, Canada, for example, it is generally June 20 (Saskatchewan Crop Insurance Corporation, 2025). Furthermore, provincial jurisdictions established that the optimum soil temperature for wheat germination and seedling development is approximately 20°C (Government of Alberta, 1980). Our previous research challenged the traditional planting paradigm that adheres to a calendar date and conceptualized a shift to a prescriptive practice driven by soil temperature as the trigger to commence planting (Collier et al., 2024).

Early planting of spring wheat allows growers to capitalize on early-season soil moisture and growing degree days (GDD) while avoiding heat stress during anthesis, often resulting in higher and more consistent grain yields (Collier et al., 2021). Forster et al. (2017) observed that early planting of durum wheat (*Triticum turgidum ssp. durum*) maximized yields across various environmental conditions in North Dakota, regardless of cultivar. Jbir et al. (2022) also found that early planting increased spring durum wheat yield and reduced ergot incidence in semi-arid regions of North Dakota and Montana. Ultra-early seeding systems are pushing planting time even earlier into colder soils to enhance yield stability and mitigate climate-induced fluctuations. These systems leverage genetic × environment × management synergies to further optimize wheat production (Collier et al., 2024). Although the effectiveness of ultra-early seeding has been demonstrated for hexaploid wheat varieties (Collier et al., 2022), and is now a well-established practice in the northern Great Plains, its suitability for the Canada Western Amber Durum (CWAD) wheat market class remains uncertain.

As farming operations expand, wheat growers are increasingly exploring ultra-early seeding. This management strategy aims to protect or increase current grain yield and enhance the yield stability and resiliency in Canadian spring wheat growing systems against impending negative yield impacts of climate change (Collier et al., 2021, 2020). Previous work with hexaploid wheat classes indicated no additional risk associated with planting that occurred at soil temperatures of 0°C in the top 5 cm of the soil surface (Collier et al., 2022). In contrast, in certain environments, a yield drag was observed when planting occurred at soil temperatures ranging between 8°C and 10°C (Collier et al., 2020, 2021), suggesting that abiotic stress associated with colder soil conditions does not impede ultra-early planting strategies. In fact, previous research has identified a number of benefits associated with an ultra-early seeding system, such as an expanded planting window, increased grain yield, enhanced yield stability, earlier harvest, improved competitive ability against weeds, and more efficient equipment use. These positive responses were observed despite extreme ambient air temperatures below 0°C after planting, and seedling survival was greater for the earliest seeded treatment. Therefore, the successful establishment of durum in an ultra-early seeding system in the northern Great Plains may have the potential to increase yield compared to current practices, which largely adhere to a calendar date.

Recent advancements in cold-tolerant genetics could further enhance ultra-early seeding systems. These genetic improvements could potentially contribute to more consistent crop responses around variables such as establishment, with reports suggesting that photoperiod response may play a role (González et al., 2005). Lanning et al. (2012) observed that photoperiod-sensitive cultivars exhibited better adaptation to early planting dates, likely resulting from delayed transition from vegetative to reproductive growth, a well-known trigger of enhanced seedling cold tolerance (Mahfoozi et al., 2001). The vast majority of durum wheat cultivars grown in western Canada are photoperiod sensitive, and this highlights the potential for leveraging genetics to optimize crop establishment under varying conditions.

Despite the success of an ultra-early seeding system in hexaploid wheat classes, the adaptiveness of commercially available durum cultivars to this practice has yet to be explored. As such, our objective was to assess the feasibility of and risks associated with ultra-early seeding of durum wheat into cold soils.

Core Ideas

- Yield of durum was first optimized when seeded at 2°C soil temperature at a 5-cm depth.
- A significant downward linear yield trend was observed as soil temperature increased from 2°C to 10°C.
- Benefits of planting durum ultra-early at a 0–4°C soil temperature included an earlier harvest.
- Net returns increased when planting at a 2°C soil temperature (+$CAD 134 ha^{-1}) compared to 10°C.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The experiment was conducted in the northern Great Plains from 2022 to 2024. In 2022, the sites included "Lethbridge Dry (LethDry)" and "FarmingSmarter (FS)" in Lethbridge, Alberta, as well as locations in Indian Head, Saskatoon, and Swift Current, Saskatchewan (Table 1). In 2023 and 2024, the sites were "LethDry," "Lethbridge Irrigated (LethIrr)", and FS in Lethbridge, AB, in addition to sites in Indian Head, Saskatoon, and Swift Current, Saskatchewan. LethDry, Indian Head, Saskatoon, and Swift Current represent rain-fed sites. The annual precipitation across these sites ranged from 180.7 to 418.1 mm (Figure 2). Mean annual air temperatures varied between 1.4°C and 8.0°C across the sites, with monthly average air temperatures spanning from −19.4°C to 21.7°C (Figure 2a). The FS site received 190.5, 228.6, and 113.0 mm of irrigation water in 2022, 2023, and 2024, respectively, while LethIrr received an additional 102.0 and 59.0 mm of irrigation water in 2023 and 2024, respectively, supplementing the growing season precipitation (Figure 2b). In 2022, LethDry, FS, Indian Head, and Saskatoon sites, and in 2023 and 2024, LethDry, LethIrr, Indian Head, and Saskatoon sites were previously planted with canola (*Brassica napus* L.). Wheat was utilized as the preceding crop in Swift Current in 2022 and 2024, and field pea (*Pisum sativum* L.) and canola were preceding crops at the FS site in 2023 and 2024, respectively.

2.2 | Seeding operations and experimental procedures

The experiment consisted of a factorial randomized complete block arrangement of 30 total treatments with four replicates. Treatment combinations consisted of five durum wheat cultivars and six planting times dictated by soil temperature triggers. The first planting was triggered when soils reached 0°C at a 5-cm depth, with the subsequent five plantings completed at 2°C intervals up to soil temperatures of 10°C, regardless of calendar date. Planting triggers were activated once the targeted soil temperature was first observed from a soil temperature monitor when performed around 10:00 a.m., and planting commenced immediately after, regardless of subsequent changes to soil temperature. The soil temperature was determined using an Omega handheld anemometer (Model HHF81) with an external temperature probe (Model 88311) (Omega Sensing Solutions ULC). The soil temperature in the top 5 cm was measured at multiple spots within the experimental area to obtain an average value. This instrument and measurement protocol used in this study can be readily adopted by farmers for on-farm soil temperature monitoring to drive decisions of when to plant. The durum cultivars used for this experiment are AAC Donlow (Government of Canada, 2019), CDC Desire (Pozniak, 2013), CDC Defy (Pozniak et al., 2020), AAC Stronghold (Ruan et al., 2019), and Transcend (Singh et al., 2012).

Planting equipment varied across locations. Lethbridge utilized a low-disturbance drill designed and built at Agriculture and Agri-Food Canada Lethbridge Research Centre. This drill features eight ConservaPak knife openers (Model CP129, Vale Industries) spaced 24 cm apart, and each followed by independent spring-tensioned rubberized packer wheels, Morris seed cups (Morris Industries Ltd.), a hydraulic seed calibration and product control system from Raven (Raven Industries Inc.), and an air product delivery system from Valmar (Valmar Air Inc.) (Beres et al., 2023). Similar drills were

TABLE 1 Site summary and post-planting air temperature extremes and cumulative freezing events.

Location	Latitude/longitude	30-Year average yearly precipitation[a] (mm)	Actual precipitation (mm)	Earliest planting date	Number of days with air temperature below (0°C)	Lowest air temperature recorded after planting (0°C)
FS		380				
2022	49°41′N/112°44′W		560	Feb 14, 2022	66	−29.1
2023	49°41′N/112°44′W		212	Apr 12, 2023	14	−7.8
2024	49°41′N/112°44′W		379+irrigation	Mar 19, 2024	26	−18.0
LethDry		380				
2022	49 40′N/112 45′W		357	Feb 9, 2022	69	−29.1
2023	49 40′N/112 45′W		212	Apr 17, 23	9	−7.8
2024	49 40′N/112 45′W		379	Mar 18, 2024	26	−18.0
LethIrr						
2023	49°43′N/112°42′W		314	Apr 17, 2023	9	−7.8
2024	49°43′N/112°42′W		438	Apr 10, 24	10	−9.8
Indian head		428				
2022	50°31′N/103°41′W		408	May 4, 2022	3	−0.8
2023	50°31′N/103°41′W		227	May 3, 2023	4	−1.8
2024	50°33′N/103°40′W		407	Apr 8, 2024	23	−8.3
Saskatoon		340				
2022	52°9′N/106°32′W		209	Apr 19, 2022	13	−7.5
2023	52°9′N/106°32′W		232	Apr 24, 23	4	−1.7
2024	52°9′N/106°32′W		342	Apr 19, 24	7	−8.3
Swift current		392				
2022	50°15′N/107°43′W		274	Mar 28, 22	31	−13.2
2024	50°15′N/107°44′W		265	Apr 9, 2024	12	−8.3

Note: FS, LethDry, and LethIrr represent Farming Smarter, Lethbridge Dry, and Lethbridge Irrigated, respectively.
[a]1981–2010 average yearly precipitation accumulation.

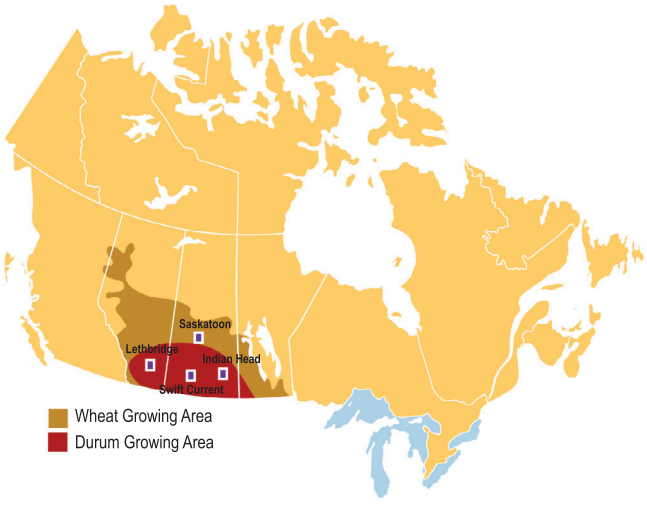


FIGURE 1 Durum wheat production regions in Canada and experimental locations across the Canadian Prairies.

utilized at Saskatoon and Indian Head; however, the Indian Head drill was 3.7 m wide with openers spaced 30 cm apart. The opener depth for these drills is controlled by lowering or raising the frame of the drill. Fine adjustments to the separation distance between seed and fertilizer were made by adjusting the seed tube of the opener. The FS site used a Wintersteiger plot seeder (Wintersteiger Holding AG) equipped with Bourgault openers (F.P. Bourgault Tillage Tools Ltd.) spaced 24 cm apart. In Swift Current, a Fabro Hoe drill (Fabro Ltd.) equipped with eight "C"-shanks supporting Atom Jet side band openers (Atom-Jet Agriculture) at 25 cm spacing was employed. Seeding rates were calibrated to 400 seeds m^{-2}, with a target plant density of approximately 250–300 plants m^{-2}. No pre-plant herbicides were applied, as weeds are generally absent at the time of ultra-early seeding (Beres et al., 2025). In-crop herbicide applications were conducted when the average crop growth was at the three- to five-leaf stage in the spring. Herbicide selection was based on the site-specific weed spectrum and infestation level, and, when required, products were applied at full label rates. Herbicide applications were made using motorized sprayers calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure (Collier et al., 2020).

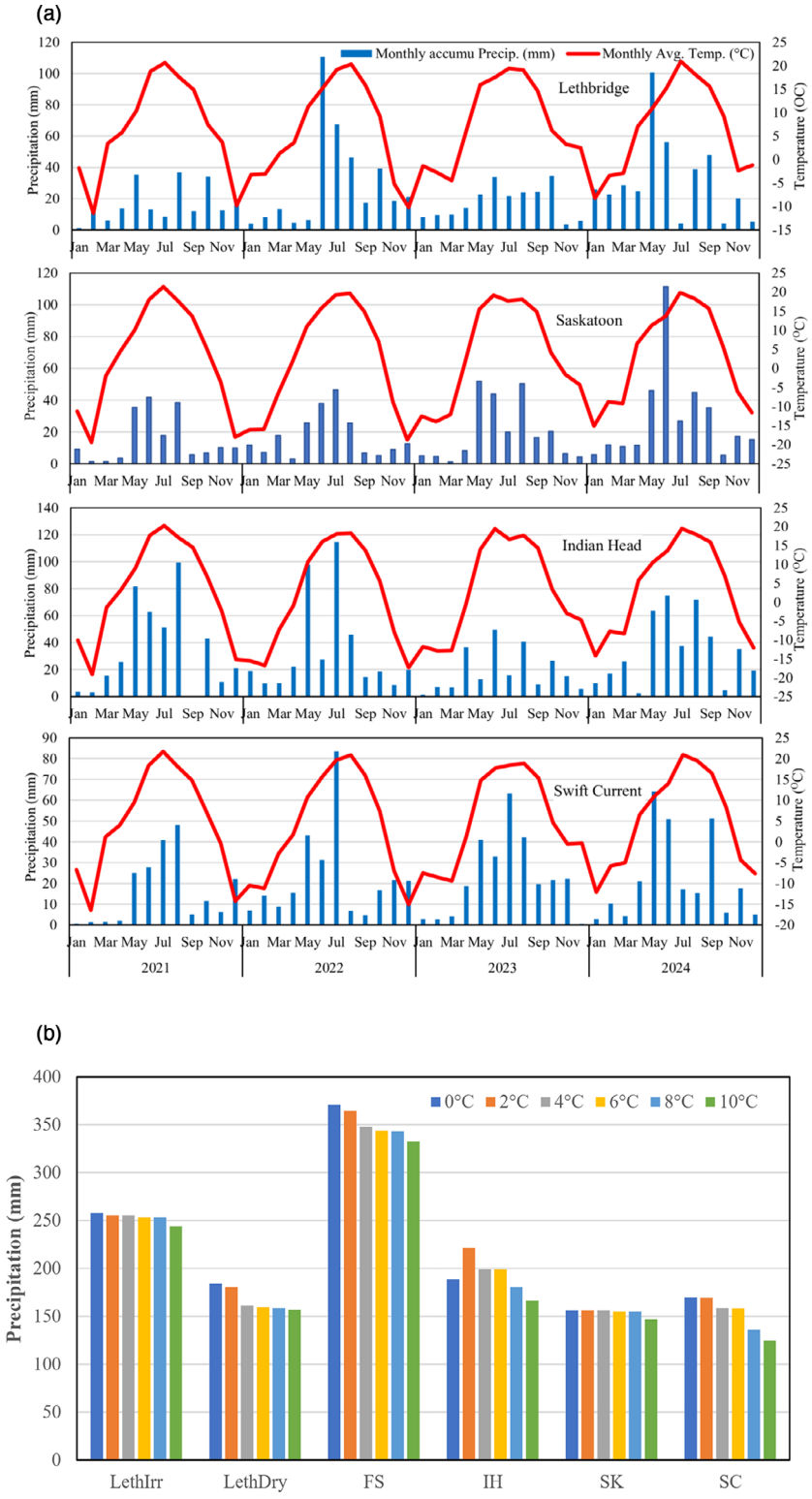


FIGURE 2 (a) Monthly average temperature and total precipitation at Lethbridge, Alberta, and Saskatoon, Swift Current, and Indian Head, Saskatchewan, in 2021, 2022, 2023, and 2024. (b) Precipitation accumulated from planting to harvest for each planting time dictated by soil temperature trigger in 2022, 2023, and 2024, with supplemental irrigation water included for the LethIrr and FS sites. LethIrr, LethDry, FS, IH, SK, and SC represent Lethbridge Irrigated, Lethbridge Dry, Farming Smarter, Indian Head, Saskatoon, and Swift Current, respectively.

2.3 | Data collection

The emergence date was recorded when plants transitioned from the first to the second and third leaf stages, allowing late-germinating plants, due to uneven seed size, soil moisture, and soil compaction, to fully emerge from the soil surface. Plant counts were conducted at the three-leaf stage, and plants in half-meter-long in rows 2, 3, 5, and 6 were recorded and averaged to obtain plants per square meter. Heads were counted near physiological maturity from the two 1-m rows marked before tillering for plant density in each plot. The number of heads was divided by the number of plants in the same

area to calculate the number of heads per plant. Plant height was measured at physiological maturity. Anthesis and maturity dates were recorded on the days of onset of anthesis and physiological maturity, respectively. Days from planting to emergence (hereafter referred to as days to emergence), to anthesis (hereafter referred to as days to anthesis), and to maturity (hereafter referred to as days to maturity), and days from anthesis to maturity (hereafter referred to as anthesis to maturity) were calculated. The plots were harvested using Wintersteiger plot combine (Wintersteiger Holding AG) at "LethIrr," "LethDry," "FS," Indian Head, and Swift Current, while a Zürn 150 (Zürn Harvesting GmbH & Co.) was used at Saskatoon. Grain yield (Mg ha^{-1}) was calculated and adjusted to 13.5% moisture. A two-kg sub-sample was retained to measure seed mass (g 1000 $kernels^{-1}$) and grain bulk density (kg hL^{-1}). Whole grain protein concentration was determined from the same sub-sample using near-infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc.).

A simple economic analysis was conducted based on grain yield and CWAD price. The net return was calculated as follows:

$$NR = Y \times P_c - W_s \times P_s$$

where NR is net return ($CAD ha^{-1}), Y is grain yield (Mg ha^{-1}), P_c is the averaged price of CWAD commodity in both Alberta and Saskatchewan in 2022–2024 (sourced from Government of Alberta: https://economicdashboard.alberta.ca/dashboard/wheat-price/ and Government of Saskatchewan: https://dashboard.saskatchewan.ca/agriculture/grain-and-specialty-crop-prices/wheat), W_s is the weight of seed (Mg ha^{-1}) and P_s is the average price of seeds. These equations were modified based on the methods of other agronomic studies (Fast et al., 2023).

2.4 | Statistical analyses

Univariate mixed model analyses for all variables were conducted using the MIXED and GLIMMIX procedures of SAS (Littell et al., 2006; SAS Institute, 2023). The replicate effect was treated as random, while environment (combinations of location and among), cultivar, and soil temperature trigger effects were considered fixed. However, data from Indian Head 2022 were excluded from the analysis due to missing data for the first planting. A heavy late-spring storm caused snow accumulation and drifting across the site, which resulted in waterlogging and plot damage. Homogeneity of error variance was assessed using the UNIVARIATE procedure, revealing heterogeneous residual variances among environments. To address this, a preliminary PROC MIXED analysis was conducted with heterogeneous residual variances modeled to estimate starting covariance parameter values. These estimates were then utilized in a subsequent PROC GLIMMIX analysis via the PARMS statement (SAS Institute, 2023). The model fit criterion, AICc (corrected Akaike's information), confirmed the benefit of modeling residual variance heterogeneity among environments. Heterogeneity was addressed using the REPEATED statement for PROC MIXED and the RANDOM statement for PROC GLIMMIX. In the PROC GLIMMIX analyses, a Gaussian error distribution was assumed, and the treatment and environment by treatment effects were considered significant if the associated p-value was ≤ 0.05. Since some effects were not significant, but their associated contrasts showed significance, an unprotected F-test was employed to evaluate the significance of all variables to avoid a Type II error (Barnette & McLean, 1998). Mean separation tests were performed using Fisher's least significant difference (LSD). Due to missing data, the LSD for all the phenological parameters was not estimated. Therefore, all possible (unadjusted) pairwise comparisons for both cultivar and planting time treatments were conducted with the *diff* option for the LSMEANS statement. Letters indicating significant differences between treatments for the phenological parameters were assigned based on the p-values from each pairwise comparison.

To explore treatment responses and variability for grain yield, a grouping methodology originally developed by Francis and Kannenberg (1978) was modified. The coefficient of variation (CV) used in the methodology of Francis and Kannenberg (1978) was replaced by an adjusted CV (aCV) as proposed by Döring and Reckling (2018). This modification involved estimating the mean and aCV for each treatment combination across years and replicates. Subsequently, the means were plotted against the aCV and used to classify the biplot data into four quadrants: high mean and high stability (Group I), high mean and low stability (Group II), low mean and low stability (Group III), and low mean and high stability (Group IV).

A multivariate partial least squares (PLS) regression combined with additive main effects and multiplicative interaction (AMMI) methods was used to explore treatment by environment interactions for crop yield in relation to weather-related variables (Crossa et al., 2015). The results from this analysis were summarized in a biplot. The factorial combinations of the applied treatments were combined into one treatment. Treatment least-squares means were estimated separately for each environment and saved for further analysis using PROC MIXED (SAS Institute, 2023) with replicates as a random effect and treatments as a fixed effect. A residual matrix (AMMI model approach) was estimated from the preceding least-squares means using a PROC GLM (SAS Institute, 2023) model that included environment and treatment main effects. Weather data included precipitation, average air temperature, GDD, and drought monitor data. Drought monitor

(Dm) data were derived from https://open.canada.ca/data/en/dataset/292646-cd-619f-4200-afb1-8b2c52f984a2. The Dm data are produced monthly by the Canadian Drought Monitor. It is developed from NDVI, streamflow values, Palmer Drought Index, and other drought indicators. Data are classified as no drought (0), abnormally dry (1), moderate drought (2), severe drought (3), extreme drought (4), and exceptional drought (5). The residual matrix for PROC GLM and the weather data set were separately standardized to a mean of 0 and a standard deviation of 1 using PROC STANDARD (SAS Institute, 2023). The two standardized data sets were merged and then subjected to PROC PLS (SAS Institute, 2023) analysis. Residual matrix data were considered as responses, and weather data were considered as explanatory variables for the analysis. PROC PLS statement method option was set to *pls*, algorithm option was set to *svd*, and latent variables maximum option was set to 3. Scores and xloading and yloading estimates were recovered and modified from the PLS output for the first two latent variables (dimensions). PROC IML (SAS Institute, 2023) was used to prepare/format scores for plotting the first two dimensions. Scores for each environment and treatment y-loading value were plotted for the first two dimensions. Weather variable xloading estimates were plotted as vectors emanating from the origin.

The PLS biplot interpretation is similar to that for AMMI biplot. The closer a treatment or environment point is to origin (0 scores for both latent variables), the more stable the treatment is across environments or the environment across treatments (Kuang et al., 2014). Ultimately, the Euclidean distance a point is from the origin can be interpreted as a measure of instability. Treatment and environment, coincidentally further from the origin, indicate treatment adapted to the conditions of a particular environment, which would be considered a positive interaction. A negative interaction occurs when treatments and environments are relatively far apart from each other within the ordination space and not close to the origin of the biplot. Weather vectors located at the same or opposite ends of the ordination space, where adaptation is observed, indicate the weather conditions driving the adaptation.

3 | RESULTS AND DISCUSSION

3.1 | Responses of grain yield and quality to ultra-early seeding

Differential responses among the five tested cultivars were observed for grain yield, quality, and agronomic parameters, but not for head density, when an unprotected *F* test was used (Tables 2 and 3). Soil temperature trigger influenced grain yield, plant stand, head per plant, and plant height. Orthogonal contrast analysis indicated a marginally significant linear effect of soil temperature trigger on grain yield (Table 2). CDC Defy, AAC Donlow, and AAC Stronghold achieved similar yields averaged across all environments, outperforming CDC Desire and Transcend. In cultivar performance tests conducted by the breeders, CDC Defy (Pozniak et al., 2020), AAC Stronghold (Ruan et al., 2019), and Transcend (Singh et al., 2012) yielded 10%, 5%, and 2.8% more than the check, Strongfield, respectively, while CDC Desire (Pozniak, 2013) exhibited a yield comparable to Strongfield under conventional growing conditions. According to its cultivar description, AAC Donlow yielded 10% higher in Saskatchewan and 11.1% higher in Alberta compared with Strongfield (https://canterra.com/resources/products/AAC_Donlow_2023.pdf?utm_source=chatgpt.com). The yield differential response of these cultivars under an ultra-early seeding system was similar to that observed under conventional conditions. With respect to soil temperature triggers, planting that occurred when the top 5 cm of soil reached a temperature of 2°C resulted in the highest yield; the 0°C and 4°C–8°C plantings attained a comparable yield to the 2°C planting (Table 2). When the planting was delayed to ≥10°C soil temperature, a significant yield drag was observed compared to the 2°C planting. A downward trend in grain yield response to soil temperature triggers from 2°C planting to 10°C planting was apparent (Figure 3). Across all the environments, a grain yield increase of 6.6% was observed for the 2°C planting compared to the 10°C planting, suggesting that higher grain yield attainment is associated with ultra-early seeding. This observation aligns with the results by Collier et al. (2020), who reported a similar yield response to soil temperature triggers, with the highest grain yield obtained when Canada Western Red Spring (CWRS) wheat was planted at a soil temperature trigger of 2°C. Similarly, in another study, Collier et al. (2021) reported that planting CWRS wheat as soon as feasible after soil temperatures reach 0°C, and prior to soils reaching 7.5°C–10°C, increased grain yield and stability compared to the planting practices based on the calendar date. Some growers may have concerns about low viable plant stands when adopting ultra-early seeding for durum production because durum usually has weaker vigor relative to spring bread wheat (Zubaidi et al., 1999). In fact, despite extreme conditions that followed plantings as early as February 9 and as many as 69 days post-planting with ambient temperatures below 0°C, survivability and plant establishment were similar to the latest planting for all cultivars (Tables 1, 2, and 4).

The highest grain yields were attained at the 2°C planting for CDC Defy and CDC Desire, at the 4°C planting for AAC Donlow, and at 0°C and 4°C for Transcend (Table 3). All cultivars displayed a yield reduction when planting was delayed to soil temperatures of 10°C in all environments. In general, the number of heads per plant declined with delayed planting. However, seed mass remained largely consistent, indicating

TABLE 2 Responses of grain yield, quality, and agronomic parameters to the main effects of G (cultivar) and M (planting based on soil temperature trigger).

	Grain yield (Mg ha^{-1})	Seed mass (g 1000 kernel^{-1})	Plant stand (plant m^{-2})	Head density (head m^{-2})	Heads per plant	Plant height (cm)	Protein concentration (g kg^{-1})	Grain bulk density (kg hL^{-1})
Cultivar								
AAC Donlow	4.69a	42.3b	189.6b	325.3	1.95abc	82.7c	146.1b	78.6c
CDC Defy	4.62ab	40.6c	202.3a	337.2	1.89c	87.2b	140.7c	79.3a
CDC Desire	4.51b	40.5c	187.8b	330.3	2.02ab	83.9c	146.9b	78.7bc
AAC Stronghold	4.68a	43.4a	184.3b	325.5	1.99abc	79.8d	147.4b	79.3a
Transcend	4.50b	41.6b	184.8b	325.3	2.04a	89.1a	151.1a	78.9bc
LSD$_{0.05}$	0.15	0.6	12.2	12.9	0.13	1.3	2.4	0.3
[a]**Planting time**								
0°C	4.65ab	41.8	180ab	333.5	2.21a	81.6c	145.7	78.8
2°C	4.68a	42.0	174.3b	323.1	2.25a	82.3c	146	79
4°C	4.66ab	41.7	185.5ab	337.4	2.09ab	84.3b	145.8	79.1
6°C	4.64ab	41.9	200.4a	329.7	1.76b	85.6ab	146.4	79.1
8°C	4.58ab	41.4	205.4a	331.5	1.76b	86.0ab	148	78.9
10°C	4.39b	41.2	193.3ab	317	1.78b	87.3a	147	78.8
LSD$_{0.05}$	0.28	0.76	26.2	27.7	0.36	1.9	3.1	0.6
Linear	0.059*	0.049*	0.029*	0.429	<0.001***	<0.0001***	0.174	0.982
Quadratic	0.160	0.296	0.510	0.434	0.639	0.561	0.909	0.189

[a]Planting time is dictated by soil temperature trigger. Different letters within columns after the means indicate significant differences between treatments.
* and *** denote significant effects at $p \leq 0.05$ and 0.001, respectively. The data from Indian Head 2022 were excluded from the analysis.
Abbreviation: LSD, least significant difference.

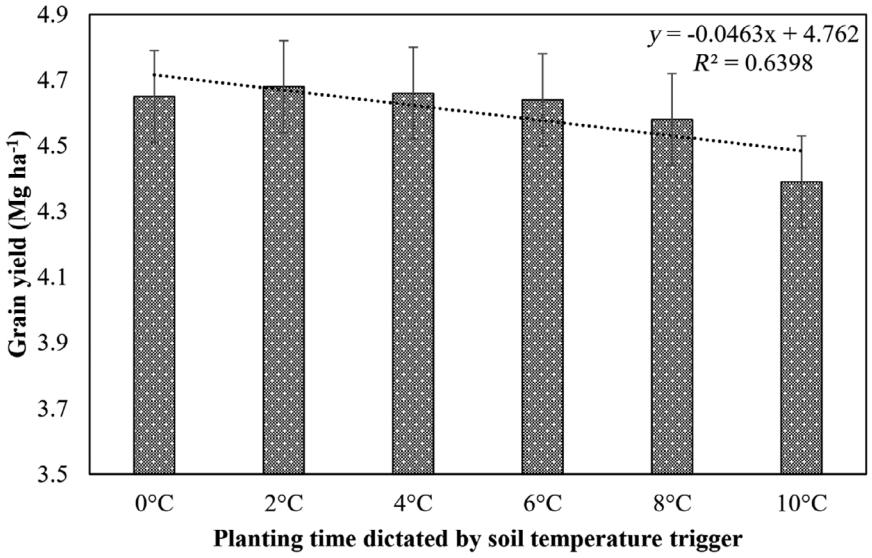


FIGURE 3 Grain yield responses to prescriptive planting time dictated by soil temperature triggers, averaged over all locations in 2022–2024 (excludes Indian Head 2022).

that the reduction in yield was primarily due to a decrease in the number of seeds per plant. Conversely, the grain yield of AAC Stronghold did not vary significantly among soil temperature triggers, suggesting it was less sensitive to variations in soil temperature at planting compared to other cultivars. Haddad et al. (2016) noted that late-planted durum wheat in semi-arid Algerian environment typically experiences a yield drag due to the exposure to abiotic stresses, such as water deficit and high temperature at critical growth stages. The downward trend observed with later plantings is likely

TABLE 3 Responses of grain yield, quality, and agronomic parameters to the interaction of G (cultivar) × E (cold soils across all site-years) × M (planting based on soil temperature trigger).

		Planting time dictated by soil temperature trigger									
	Cultivar	0°C	2°C	4°C	6°C	8°C	10°C	$LSD_{0.05}$	*p*-values	Linear	Quadratic
Grain yield	AAC Donlow	4.76ab	4.68ab	4.78a	4.74ab	4.66ab	4.48b	0.30	0.370	0.095	0.213
(Mg ha^{-1})	CDC Defy	4.65ab	4.75a	4.68a	4.67a	4.62ab	4.37b	0.30	0.184	0.045*	0.098
	CDC Desire	4.51ab	4.63a	4.53ab	4.58ab	4.46ab	4.32b	0.30	0.401	0.113	0.169
	AAC Stronghold	4.73	4.75	4.74	4.67	4.70	4.51	0.30	0.614	0.146	0.369
	Transcend	4.57a	4.56a	4.57a	4.55ab	4.46ab	4.27b	0.30	0.284	0.044*	0.189
Seed mass	AAC Donlow	42.3ab	42.8a	42.7a	42.3ab	42.0ab	41.5b	1.00	0.109	0.022	0.079
(g 1000 $kernel^{-1}$)	CDC Defy	40.4	40.5	40.5	41.1	40.4	40.9	1.00	0.668	0.336	0.895
	CDC Desire	40.7	40.6	40.5	40.5	40.1	40.3	1.00	0.883	0.247	0.868
	AAC Stronghold	43.7a	43.8a	43.2ab	43.7a	43.3ab	42.6b	1.00	0.207	0.045*	0.322
	Transcend	42.1a	42.1a	41.8a	42.0a	41.2ab	40.8b	1.00	0.043*	0.003**	0.220
Plant stand	AAC Donlow	182.6	177.1	183.9	201.3	202.3	190.4	27.8	0.367	0.118	0.549
(plant m^{-2})	CDC Defy	191.7ab	188.9b	196.0ab	211.1ab	218.1a	208.3ab	27.8	0.226	0.029*	0.700
	CDC Desire	179.2ab	167.9b	187.2ab	201.1a	200.2a	191.2ab	27.8	0.152	0.044*	0.451
	AAC Stronghold	174.5ab	172.0b	183.2ab	192.1ab	201.5a	182.8ab	27.8	0.296	0.100	0.334
	Transcend	171.9b	165.5b	177.1b	196.3ab	204.6a	193.7ab	27.8	0.039*	0.004**	0.700
Head density	AAC Donlow	334.2	317.9	328.2	327.8	323.5	320.3	30.4	0.912	0.562	0.946
(head m^{-2})	CDC Defy	340.7	335.9	347.9	339.0	336.8	322.5	30.4	0.693	0.289	0.296
	CDC Desire	329.2	330.4	334.5	335.9	335.2	316.6	30.4	0.803	0.602	0.237
	Stronghold	333.8	312.1	338.0	320.5	338.1	310.6	30.4	0.233	0.542	0.530
	Transcend	329.9	319.0	338.4	325.3	324.0	315.0	30.4	0.705	0.428	0.464
Heads per plant	AAC Donlow	2.21a	2.13ab	2.09	1.74c	1.73c	1.79bc	0.37	0.027*	0.002**	0.517
	CDC Defy	2.14a	2.17a	2.01ab	1.70b	1.65b	1.67b	0.37	0.008**	<0.001***	0.771
	CDC Desire	2.21a	2.40a	2.06ab	1.79b	1.83b	1.81b	0.37	0.005**	<0.001***	0.720
	AAC Stronghold	2.22a	2.19a	2.11ab	1.79b	1.82b	1.79b	0.37	0.039*	0.002**	0.719
	Transcend	2.28a	2.38a	2.20ab	1.77c	1.75c	1.87bc	0.37	0.001***	<0.001***	0.558
Plant height	AAC Donlow	80.0c	80.5c	82.6bc	84.0ab	84.1ab	84.9a	2.34	<0.001***	<0.001***	0.418
(cm)	CDC Defy	83.5c	83.3c	86.9b	89.3a	89.0ab	91.0a	2.34	<0.001***	<0.001***	0.538
	CDC Desire	81.5c	82.9bc	83.1bc	84.4ab	85.1ab	86.2a	2.34	0.002**	<0.001***	0.951
	AAC Stronghold	77.8c	77.8c	79.8bc	80.2b	81.0ab	82.5a	2.34	<0.001***	<0.001***	0.682
	Transcend	85.1c	87.2c	89.2bc	90.3ab	90.7ab	92.0a	2.34	<0.001***	<0.001***	0.170
Protein concentration	AAC Donlow	145.3	145.5	144.9	146.5	148.4	146.1	3.7	0.486	0.209	0.827
(g kg^{-1})	CDC Defy	140.6	140.2	140.0	140.1	142.3	141.0	3.7	0.838	0.478	0.654
	CDC Desire	145.9	146.6	146.5	146.0	148.6	148.1	3.7	0.605	0.142	0.693
	AAC Stronghold	147.4	146.4	147.7	146.8	148.6	147.6	3.7	0.885	0.531	0.860
	Transcend	149.5	151.1	149.6	152.4	152.2	152.0	3.7	0.455	0.100	0.748
Grain bulk density	AAC Donlow	78.4	78.5	78.8	78.7	78.6	78.3	0.7	0.772	0.901	0.142
(kg hL^{-1})	CDC Defy	79.1	79.4	79.4	79.5	79.2	79.4	0.7	0.846	0.690	0.419

(Continues)

TABLE 3 (Continued)

	Planting time dictated by soil temperature trigger									
	Cultivar	**0˚C**	**2˚C**	**4˚C**	**6˚C**	**8˚C**	**10˚C**	**$LSD_{0.05}$**	***p*-values**	**Linear**	**Quadratic**
	CDC Desire	78.6	78.7	78.8	78.8	78.6	78.8	0.7	0.986	0.726	0.704
	AAC Stronghold	79.2	79.3	79.5	79.4	79.3	79.2	0.7	0.960	0.967	0.349
	Transcend	78.6ab	78.9ab	79.1a	79.1a	78.9ab	78.5b	0.7	0.315	0.629	0.021

Note: Different letters within rows after the means indicate significant differences between treatments.
*, **, and *** denote significant effects at $p \leq 0.05$, 0.01, and 0.001, respectively. The data from Indian Head 2022 were excluded from the analysis.
Abbreviation: LSD, least significant difference.

TABLE 4 Responses of phenological parameters to the main effects of G (cultivar) and M (planting times based on soil temperature trigger).

	Days to emergence	**Days to anthesis**	**Days to maturity**	**Days from emergence to anthesis**	**Days from anthesis to maturity**	**Anthesis date (Julian)**	**Maturity date (Julian)**
Cultivar							
AAC Donlow	17.5bc	72.8ab	110.0b	54.0a	36.4c	188a	226b
CDC Defy	17.2c	71.7c	109.6bc	53.2c	37.3ab	186b	225c
CDC Desire	17.9a	72.5b	108.9c	53.4bc	35.7d	188a	225c
AAC Stronghold	17.6ab	73.0a	111.2a	54.0a	37.4a	188a	227a
Transcend	17.9a	73.0a	110.3b	53.8ab	36.7bc	188a	226b
[a]**Planting time**							
0˚C	27.2a	86.9a	126.0a	58.0a	38.0a	183e	222e
2˚C	22.0b	80.2b	118.9b	57.1ab	38.0a	184e	224de
4˚C	18.4c	73.9c	111.5c	55.0b	37.1ab	186d	225 cd
6˚C	16.7c	69.5 cd	106.6d	51.8c	36.7bc	188c	226bc
8˚C	14.1d	66.6d	102.3d	51.5c	35.2c	191b	228b
10˚C	11.5e	61.5e	97.2e	49.3d	35.2c	193a	230a
	p-values						
	<0.001***	<0.001***	<0.001***	0.009**	<0.001***	<0.001***	<0.001***
	<0.001***	<0.001***	<0.001***	<0.001***	0.001***	<0.001***	<0.001***
Linear	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Quadratic	0.906	0.408	0.376	0.900	0.753	0.255	0.207

[a]Planting time is dictated by soil temperature trigger. Different letters within columns after the means indicate significant differences between treatments. The letters were assigned based on the *p*-values from each pairwise comparison in the LSMEANS statement.
, and * denote significant effects at $p \leq 0.01$, and 0.001, respectively. The data from Indian Head 2022 were excluded from the analysis.

attributable to sensitivity to abiotic stress such as heat and drought stress, as crop growth and development are not completed before the onset of terminal drought in semi-arid prairie locations.

Figure 4 illustrated that AAC Donlow seeded at soil temperatures of 0˚C, 4˚C, 6˚C, and 8˚C, and AAC Stronghold seeded at soil temperatures of 0˚C, 4˚C, and 8˚C, consistently attained higher-than-average yields with stable results. CDC Defy achieved above-average yields at 0˚C–6˚C, although only the 6˚C planting exhibited high stability. CDC Desire attained above-average yields only at 2˚C, but with high variability. Transcend consistently produced inferior grain yield compared to the other cultivars, except for CDC Desire, which, as an early-maturing cultivar, has a lower yield potential due to its lower growing degree-day requirement. AAC Donlow, CDC Defy, CDC Desire, and AAC Stronghold seeded at 2˚C soil temperatures all produced above-average yields but displayed lower than average stability, suggesting that durum may be somewhat more sensitive to ultra-early planting and associated site-year variation than to 4˚C and 8˚C plantings. The low-yielding cultivar, Transcend, seeded at 2˚C also produced higher yield compared with other planting times. Overall, the grain yield of all cultivars was protected at the coldest planting temperature trigger and trended lower

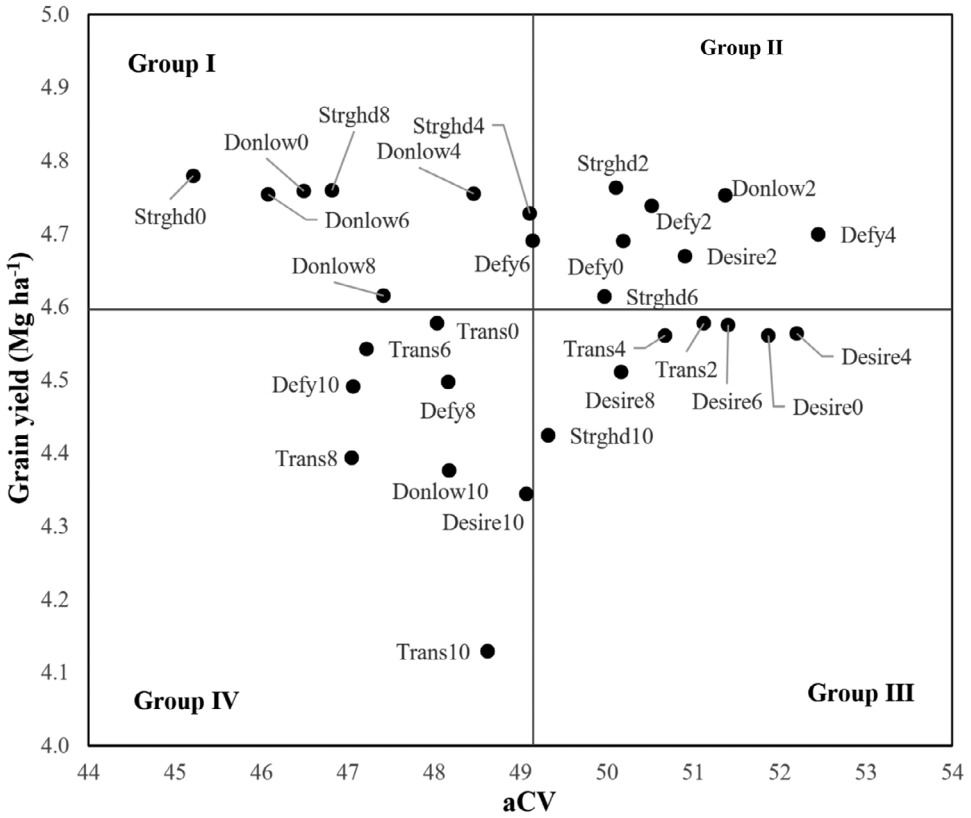


FIGURE 4 Biplots summarizing grain yield versus adjusted coefficient of variation (aCV) for cultivar by soil temperature trigger interactions. Donlow, Defy, Desire, Strghd, and Trans represent cultivars of AAC Donlow, CDC Defy, CDC Desire, AAC Stronghold, and Transcend, respectively. 0, 2, 4, 6, 8, and 10 after cultivar name are soil temperature triggers of 0˚C, 2˚C, 4˚C, 6˚C, 8˚C, and 10˚C, respectively.

when planted at 10˚C, supporting the linear downward trend illustrated in Figure 3. This parallels responses of hexaploid wheat classes reported by Collier et al. (2022), who observed that all western Canadian hexaploid wheat classes exhibited improved grain yield stability (lower adjusted CV values) and optimal grain yield when planted ultra-early at 2˚C soil temperature compared to the 8˚C soil temperature.

In 2023, all sites experienced cooler pre-planting conditions, less precipitation during the summer months, and a warmer June (Figure 5). In contrast, the 2024 sites were characterized by a warmer winter, a wetter spring, less drought stress, and, to a lesser extent, a cooler June with fewer GDDs. Overall, temperature, GDD, drought stress, and spring precipitation were the most influential weather variables across all sites.

The 2˚C planting treatments were primarily positioned on the left side of the ordination space (Figure 5). Planting time treatments associated with CDC Desire were oriented mainly toward the top and right, while those of AAC Donlow were located at the bottom. The 0˚C planting treatments were generally positioned in the lower right quadrant, except for CDC Desire. Meanwhile, the 4˚C–8˚C plantings were positioned closer to the origin on the right side of the ordination space. CDC Desire exhibited better adaptation to warmer and more stressful growing conditions, particularly when seeded at a soil temperature of 10˚C, which could be a consequence of an early maturity trait that facilitated completion of the critical growth period. The 2˚C planting for all the cultivars was adapted to a warmer June, cooler pre-planting weather conditions, and reduced summer precipitation. The 4˚C–8˚C plantings did not align with specific weather conditions. However, the 0˚C plantings for AAC Donlow, CDC Defy, AAC Stronghold, and Transcend performed better in environments with a warmer winter, wetter spring, less drought stress, and, to a lesser extent, a cooler June with lower GDDs.

Protein concentration responses followed the order: Transcend > AAC Stronghold = CDC Desire = AAC Donlow > CDC Defy (Table 2). Soil temperature trigger did not affect grain protein concentration in any of the cultivars (Tables 2 and 3). Grain protein concentration responses differed from Collier et al. (2021), who reported that delayed planting resulted in a linear increase in spring wheat protein concentration, likely reflecting the inverse relationship between yield and protein concentration. However, when the 2022 and 2023 data were analyzed together, we observed that delayed planting increased grain protein concentration (data not shown). The lack of grain protein concentration responses

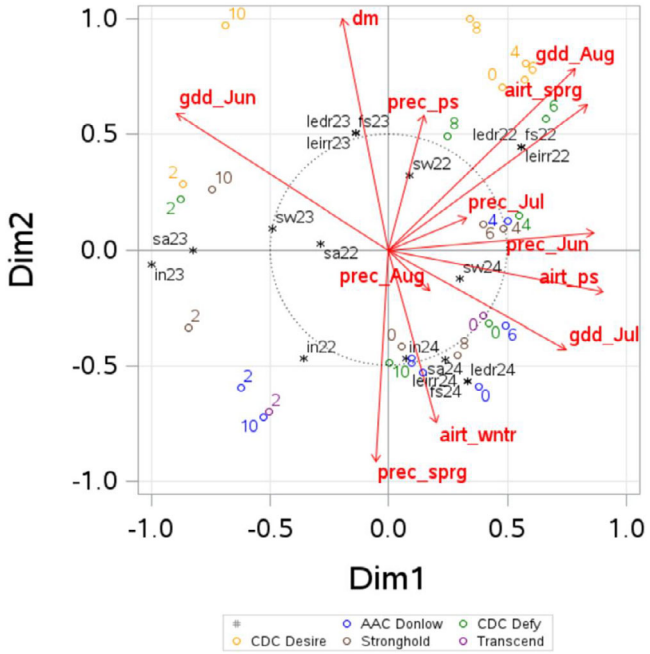


FIGURE 5 Partial least squares (PLS)-Additive Main effects and Multiplicative Interaction (AMMI) biplots for the five cultivars and six planting times triggered by soil temperatures. Leirr, ledr, FS, Sa, In, and Sw represent:Lethbridge Irrigated," "Lethbridge Dry," "Farming Smarter," Saskatoon, Indian Head, and Swift Current, respectively. Numbers 22, 23, and 24 are growing seasons 2022, 2023, and 2024, respectively. Drought monitor (Dm), growing degree days (GDD), precip and airt denote average drought stress of May–August, growing degree days, precipitation, and air temperature, respectively. PS after Prec and AirT stand for pre-planting (September–December of the previous year). Wntr represent average of the winter months (January and February). Sprg denote average of the spring months (March–May). 0, 2, 4, 6, 8, and 10 are soil temperature triggers of 0°C, 2°C, 4°C, 6°C, 8°C, and 10°C, respectively.

to soil temperature triggers could be attributed to the site-year variation (data not shown).

Lodging is a common issue in cereal production that can significantly impact yield and quality. Fischer and Stapper (1987) reported that culm lodging can decrease grain yield by 7%–35%, with the most significant losses occurring within the first 20 days after anthesis. Berry et al. (2004) noted that lodging can reduce yield by up to 80% and is associated with several negative outcomes, including reduced grain quality, increased drying costs, and delayed harvest. Lodging has also been positively correlated with plant height (Navabi et al., 2006). In this study, plant height increased linearly as planting time was delayed to a soil temperature of 10°C, irrespective of cultivar selection (Tables 2 and 3), which was inconsistent with Collier et al. (2021), who reported no significant effect of soil temperature trigger on plant height. When planting was delayed to a soil temperature of 10°C, plant height increased compared to the 0°C planting by 4.9 cm in AAC Donlow, 6.5 cm in CDC Defy, 4.7 cm in CDC Desire, 4.7 cm in AAC Stronghold, and 4.9 cm in Transcend. These results suggest that ultra-early seeding may help reduce the risk of lodging, providing further benefits over delayed planting at soil temperatures ≥10°C.

3.2 | Responses of phenological parameters to ultra-early seeding

The intervals between the durum growth developmental phases consistently decreased as planting was delayed (Table 4). Across various growing environments, plantings at 0°C, 2°C, 4°C, 6°C, and 8°C required 16, 11, 7, 5, and 3 more days, respectively, to emerge compared to the 10°C planting. Furthermore, the interval from emergence to anthesis and from anthesis to maturity was, on average, 8 and 3 days, respectively, longer for the first two soil temperature triggers compared to the 10°C planting (Table 4). In a study by Collier et al. (2021), it was observed that the interval from anthesis to maturity was 4 and 3 days longer for spring wheat planted at soil temperatures of 0°C–2.5°C and 5°C, respectively, relative to a soil temperature of 10°C.

Interestingly, plantings at 0°C, 2°C, and 4°C flowered 10, 9, and 7 days earlier and matured 8, 6, and 5 days earlier than the planting at 10°C (Table 4), resulting in an intangible benefit of earlier harvests without a yield penalty. Wheeler et al. (1996) observed that prolonged exposure to temperatures above 31°C for five consecutive days before anthesis reduced seed set in winter wheat, consequently lowering the number of seeds per spike. Shifting planting times earlier allows wheat to progress through floret initiation, anthesis, and grain fill during cooler temperatures early in the growing season (Collier et al., 2024). Using LethDry as an example, in 2022, the 0°C, 2°C, and 4°C plantings experienced 1 day of maximum air temperature exceeding 31°C during the critical period spanning 10 days before and after anthesis, while 10°C planting experienced 3 such days. In 2023, the 0°C planting again experienced 1 day, whereas the 2°C and 4°C plantings encountered 3 days each, and the 10°C planting faced 4 days of extreme heat. In 2024, the corresponding days were 0, 0, 1, and 5 for the 0°C, 2°C, 4°C, and 10°C planting, respectively. The average anthesis dates for 0°C, 2°C, 4°C, 6°C, 8°C, and 10°C were June 21, June 24, June 25, June 28, and July 3, respectively. Across the experimental years, maximum air temperatures exceeded 31°C on 10 days in June and 27 days in July. Therefore, ultra-early plantings successfully shifted the critical growth period out of the heat and temperature stress in July, thereby protecting and at times enhancing grain yields.

3.3 | Economic considerations

Net returns in response to cultivar followed the order: AAC Donlow ≥ AAC Stronghold ≥ CDC Defy > Transcend ≥ CDC Desire (Figure 6). Plantings at 2°C soil temperature

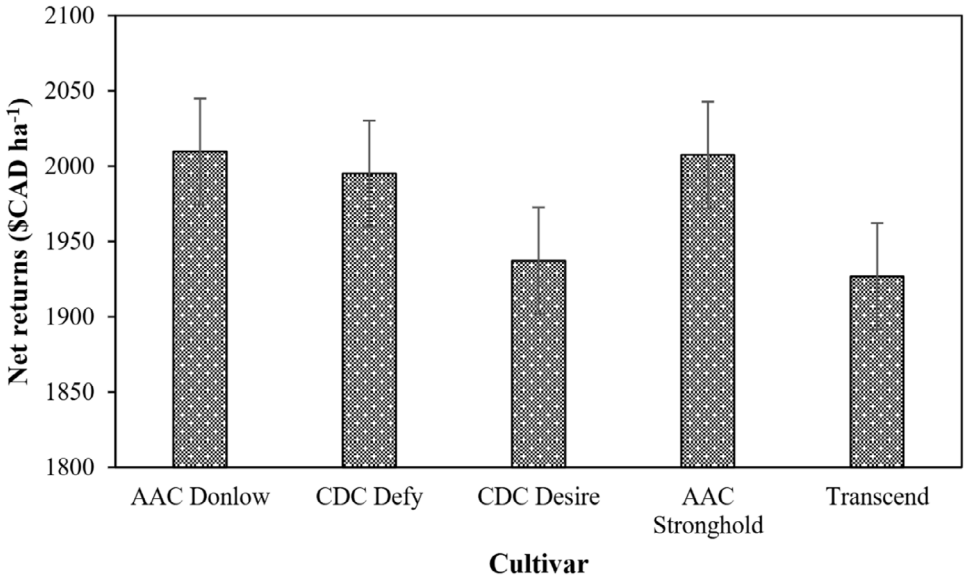


FIGURE 6 Net return by cultivar. Error bars represent the least significant difference (LSD; $p = 0.05$)

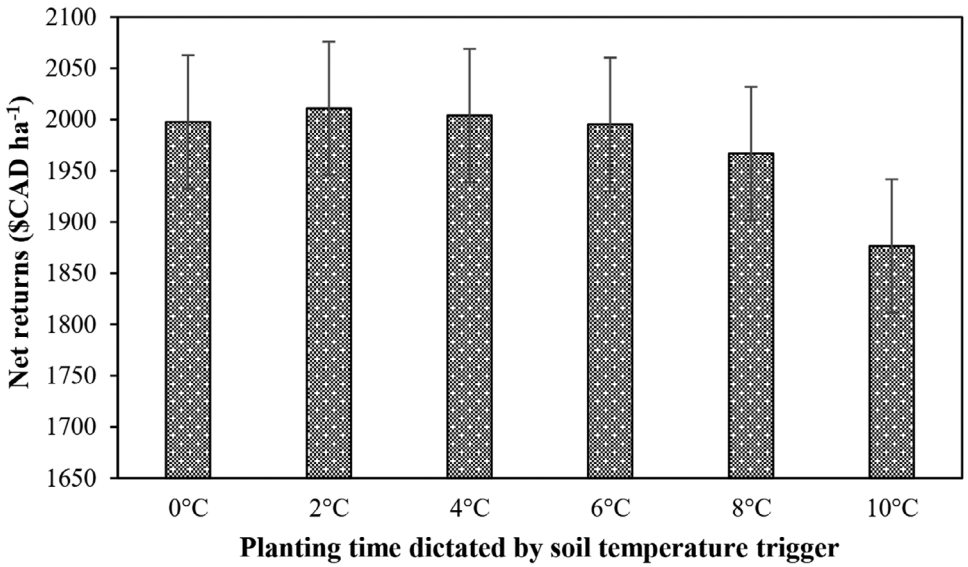


FIGURE 7 Net return by planting time as dictated by soil temperature trigger. Error bars represent the LSD ($p = 0.05$).

resulted in marginally significantly higher net returns than planting at 10˚C, while plantings at 0˚C, 4˚C, 6˚C, and 8˚C provided intermediate net returns (Figure 7). Specifically, plantings at 2˚C achieved $CAD 134 ha^{-1} higher net returns than those at 10˚C. In terms of cultivar by planting time interactions, CDC Defy seeded at 2˚C soil temperature resulted in the highest net returns, followed by AAC Donlow seeded at 4˚C (data not shown). In this study, all other production costs, including fertilizer, pesticides, equipment, and fuel, were assumed to be consistent across cultivars and planting times. Therefore, net returns were calculated based on seed price, seed volume, grain yield, and the durum commodity price specific to each trial year. Protein premiums were not included in the analysis, as they vary by year, region, market conditions, and purchasing companies and are unlikely to alter the overall economic trends as stated in Fast et al. (2023). In this study, no pre-plant herbicide was applied. Consequently, herbicide costs were lower than in the conventional system, representing an additional benefit of adopting the ultra-early system. For the 2025–2026 season, the area seeded to durum is forecast at 2.5 million ha (http://agriculture.canada.ca/sites/default/files/documents/2025-01/Canada_Outlook_for_Principal_Field_Crops_202501.pdf and Figure 1). Based on the increased net returns observed in this study, planting durum before soil temperature reaches ≥10˚C, rather than following conventional recommendations

or adhering to an arbitrary calendar date, could generate an estimated additional $323 million in revenue for growers in Canada if all were able to adopt the strategy in the durum production region.

4 | CONCLUSIONS

Although there have been anecdotal concerns from industry and academia that durum may be sensitive to the cold abiotic stress associated with an ultra-early seeding system, our results suggest that ultra-early seeding has no detrimental effect on grain yield and quality parameters of commercially available durum cultivars. Planting durum wheat as early as when the top 5 cm soil temperatures reached 2°C consistently resulted in high and often stable grain yield. In contrast, delayed plantings, particularly when soil temperature is 10°C, were associated with lower yield stability and inferior yield in most scenarios. Irrespective of soil temperature triggers, AC Donlow, CDC Defy, and AAC Stronghold attained higher grain yield compared to CDC Desire and Transcend across all environments. Additionally, our research suggests that growers can protect or even improve profit margins by adopting ultra-early seeding systems. In this study, when averaged across all locations (https://economicdashboard.alberta.ca/dashboard/wheat-price/#Product:Durum%20wheat), a $CAD 134 ha^{-1} increase in net returns was achieved with 2°C seeding systems compared to delayed planting when the soil temperature has reached 10°C. This presents a compelling economic incentive for growers to adopt ultra-early seeding practices, and, contrary to purported expectations, factors such as cold soils, related abiotic stress, and even post-emergent frost/snow events did not impede the success of ultra-early seeding. This is not to say the practice can be adopted in every field in every year across the prairies, given that field conditions may prevent access with seeding equipment. However, the frequency of years facilitating ultra-early seeding is substantial and would include all of the durum production area (2.5 M hectares) in Canada (Figure 1).

AUTHOR CONTRIBUTIONS

Zhijie Wang: Data curation; investigation; validation; writing—original draft. **Curtis Pozniak**: Investigation; methodology; writing—review and editing. **Yuefeng Ruan**: Investigation; methodology; writing—review and editing. **Kui Liu**: Investigation; methodology; writing—review and editing. **Chris Willenborg**: Investigation; methodology; writing—review and editing. **William May**: Investigation; methodology; writing—review and editing. **Ken Coles**: Investigation. **Brian L. Beres**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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