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Authors: Collier, Graham R.S., Spaner, Dean M., Hall, Linda M., Graf, Robert J., and Beres, Brian L.

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Fall-applied residual herbicides improve broadleaf weed management in ultra-early wheat (*Triticum aestivum* L.) production systems on the northern Great Plains

Graham R.S. Collier[a], **Dean M. Spaner**[a], **Linda M. Hall**[a], **Robert J. Graf**[b], **and Brian L. Beres**[a,b]

[a]Department of Agricultural, Food and Nutritional Science , 410 Agriculture/Forestry Centre, University of Alberta, Edmonton, AB T6G 2P5, Canada; [b]Lethbridge Research and Development Centre, Agriculture and Agri-Food Canada, 5403 1st Avenue South, Lethbridge, AB T1J 4B1, Canada

Corresponding authors: **Graham R.S. Collier** (email: gcollier@ualberta.ca); **Brian L. Beres** (email: brian.beres@canada.ca)

Abstract

Ultra-early spring wheat (*Triticum aestivum* L.) planting systems based on soil temperature on the northern Great Plains have lower overall variability in grain yield, and can increase grain yield relative to current calendar date-based spring wheat planting systems used in the region. However, ultra-early planting when soils are cold (2 °C), and resulting early crop emergence, precludes most foliar pre-seeding weed control options. Field trials were conducted at three sites in western Canada from 2017 to 2019 to evaluate the crop safety, broadleaf weed efficacy, and growing system stability resulting from the inclusion of fall applications of soil-applied residual herbicides prior to planting wheat ultra-early the following spring. Flumioxazin (protoporphyrinogen oxidase inhibitor; Weed Science Society of America (WSSA) group 14) and pyroxasulfone (very long chain fatty acid synthesis inhibitor; WSSA group 15) were applied alone and in combination at multiple rates in the late fall prior to ground freeze. The following spring, hexaploid spring wheat was planted ultra-early, based on a soil temperature trigger of 2 °C, and later, triggered by a soil temperature of 8 °C. When planting was completed ultra-early, grain yield was greater, and variability of grain yield was lower. Herbicide treatments increased broadleaf weed control, and in some environments further increased grain yield and reduced grain yield variability without resulting in phytotoxicity. The ability to safely incorporate fall-applied residual herbicides into ultra-early spring wheat planting systems provides an option for growers to adopt ultra-early planting without negatively impacting weed management on their farms.

Key words: wheat, yield, stability, ultra-early, agronomy

Résumé

Les méthodes de culture du blé de printemps (*Triticum aestivum* L.) ultra précoce qui s'appuient sur la température du sol dans les grandes plaines du nord de l'Amérique stabilisent le rendement grainier et peuvent l'accroître comparativement à celui obtenu avec les méthodes régionales reposant sur le calendrier. Quoi qu'il en soit, semer du blé ultra précoce sur un sol froid (2 °C), avec la levée hâtive qui en résulte, interdit la plupart des méthodes foliaires de lutte contre les mauvaises herbes qui précèdent les semailles. De 2017 à 2019, les auteurs ont procédé à des essais sur le terrain à trois sites dans l'ouest du Canada pour évaluer le degré de protection de la culture, l'efficacité des dicotylédones et la stabilité du régime agricole, consécutivement à l'application automnale d'herbicides rémanents au sol avant la plantation du blé, le printemps suivant. Dans cette optique, ils ont épandu de la flumioxazine (inhibiteur de la protoporphyrinogène oxydase, un herbicide du groupe 14 selon la Weed Science Society of America) et du pyroxasulfone (inhibiteur de la synthèse des acides gras à très longue chaîne, un herbicide du groupe 15) seuls ou ensemble, à divers taux, à la fin de l'automne, avant que le sol gèle. Le printemps suivant, le blé hexaploïde a été semé très tôt, soit dès que la température du sol a atteint 2 °C. La germination est survenue par la suite, lorsque le sol s'est réchauffé à 8 °C. Des semailles très hâtives accroissent le rendement grainier, qui varie moins. Les herbicides assurent une meilleure lutte contre les dicotylédones et, à certains endroits, ont augmenté encore plus le rendement, tout en réduisant sa variabilité, sans qu'il y ait phytotoxicité pour autant. Pouvoir appliquer un herbicide rémanent au régime cultural du blé de printemps ultra précoce à l'automne sans qu'on mette en danger ce dernier ajoute une option aux céréaliculteurs qui souhaiteraient adopter de telles variétés sans que cela entrave la lutte contre les mauvaises herbes. [Traduit par la Rédaction]

Mots-clés : blé, rendement, stabilité, ultra précoce, agronomie

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Introduction

Grain production on the northern Great Plains is partially limited by regional environmental conditions primarily characterized by short frost-free growing periods and high average daily temperatures during sensitive wheat (*Triticum aestivum* L.) reproductive growth stages (Lanning et al. 2010; He et al. 2012; Thomas and Graf 2014; Iqbal et al. 2016; Fatima et al. 2020). Wheat grain production in the region has increased by 38% from 1961–1970 to 2008–2017, despite a decrease in planted area of 31% over the same period (Statistics Canada 2021). Hatfield and Beres (2019) reported an average increase in realized on-farm wheat grain yield of 0.6 kg ha^{-1} year^{-1} from 1960 to 2017; however, an average increase in grain yield potential, the maximum attainable grain yield in an unconstrained environment, of 0.9 kg ha^{-1} year^{-1} was reported over the same period. Previous studies in similar wheat growing regions around the world have reported that shifting spring wheat planting earlier in the growing season resulted in greater grain yield and could potentially reduce the gap between realized and potential grain yields (Kirkegaard et al. 2015; Hunt et al. 2018; Beres et al. 2020). Collier et al. (2020) evaluated ultra-early planting of wheat on the northern Great Plains of North America and identified soil temperatures from 2 °C to 6 °C as indicators of the optimum time for planting spring wheat to achieve the greatest grain yield and grain yield stability on the northern Great Plains. Collier et al. (2021) defined grain yield stability as a measure of the variability in grain yield resulting from a particular treatment level, and growing system stability as the overall grain yield stability resulting from multiple applied agronomic management tactics. Collier et al. (2021) reported that the growing system stability of ultra-early wheat growing systems could be enhanced by combining early planting with optimum seeding rates of not less than 400 viable seeds m^{-2}.

Wheat planted at traditional timings later in the growing season relies on pre-seeding weed control, followed by in-crop herbicide applications to manage weed competition. Ultra-early wheat planting systems as described by Collier et al. (2020, 2021, 2022) necessitate planting prior to the emergence of most weeds, while soil temperatures are cold (prior to 6 °C). Early crop emergence resulting from ultra-early planting increases the competitiveness of the crop with weeds that emerge later in the growing season; however, it also negates the use of a foliar pre-emergent or pre-plant herbicides (Clements et al. 1929; Harker and O'Donovan 2013). Fall-applied soil residual herbicides are used successfully in other crops in western Canada to control early-emerging weeds and maintain low weed pressure during critical weed-free periods (Jha and Kumar 2017; Johnson et al. 2018). Weed control benefits of mechanical planting operations may be negated by ultra-early planting systems due to the absence of emerged weeds at planting. Subsequently, ultra-early planting may stimulate weed emergence via early spring soil disturbance (Geddes and Gulden 2017).

Flumioxazin and pyroxasulfone can be applied in the fall or spring prior to planting spring wheat to supplement or replace pre-seeding herbicide applications (Anonymous 2020). For effective activity, pyroxasulfone and flumioxazin require moisture after application to transition the active ingredients from the surface of the soil into soil water solution where they become available for plant uptake (Westra et al. 2015; Eason et al. 2022). Both flumioxazin and pyroxasulfone have low leaching potential and are primarily degraded in the soil by microbial activity that is temperature and moisture dependent (Shaner 2014; Nash 2016). These herbicides effectively form a layer of active ingredients in the soil that weed species must germinate in, infiltrate with roots, or grow through to emerge (Westra et al. 2015; Eason et al. 2022). When combined, the two separate modes of action of flumioxazin and pyroxasulfone can act sequentially on the same weed species, reducing selection for resistance (Beckie 2006; Beckie and Reboud 2009; Beckie and Harker 2017). On the northern Great Plains, fall application of these active ingredients promotes the movement of the herbicides into soil water solution when snow cover ablation occurs in the spring. Weed control with fall applications can be more consistent than with spring applications, which are dependent on precipitation after application. Fall applications of these herbicides on the northern Great Plains made after soil temperatures, and subsequently microbial activity, have decreased, and do not result in significant degradation of active ingredients in the soil prior to weed emergence the following spring (Cessna et al. 2017; Anonymous 2020).

This study evaluated grain yield, growing system stability, spring wheat tolerance, and weed control when flumioxazin and pyroxasulfone were applied to soil alone, and in combination, at multiple rates in the fall prior to ultra-early spring wheat planting the following spring.

Materials and methods

Site description, experimental design, determination of planting time using soil temperature triggers, and herbicide treatments

This study was conducted at three sites in western Canada in each of 2017 and 2018 and one site in 2019 for a total of seven environments (Table 1). Additional information regarding location, soil characteristics, and precipitation at each site is included in Table 1. The treatment structure of the experiment consisted of 18 total treatments arranged in a factorial randomized complete block design with four blocks. The treatment combinations consisted of two planting dates and nine herbicide treatments (Table 2). Each plot was 2 m wide and 6 m long; 1 m of untreated area was retained between each plot to negate any risk of treatment overlap and maintain an untreated area between each plot to allow the verification of weed population uniformity. Herbicide applications were made to the full width of each 2 m plot and extended 50 cm before and after each plot to ensure even soil application through the entire plot area.

The herbicide treatments, which included seven herbicide treatments, an untreated check, and a weed-free check treatment, were applied at each trial location the fall before ultra-early spring planting occurred. Applications of flumioxazin,

Table 1. Growing season descriptions, post-seeding air temperature extremes, and cumulative freezing events recorded at each environment (location × year).

Location	Latitude/longitude	Agroecological region	Soil zone, texture	Soil organic matter (%)	pH	Average yearly precipitation* (mm)	Year	Actual precipitation (mm year^{-1})	Earliest seeding date†	Number of days with air temperature below 0 °C after initial seeding date	Lowest air temperature recorded after seeding (°C)
Edmonton, AB	53°33′N 113°29′W	Parkland	Black, loam	9.5	5.9	446	2017	416	7 April	14	−6.1
							2018	391	27 April	1	−1.2
Lethbridge, AB	49°41′N 112°50′W	Western Prairies	Dark brown, clay loam	4.6	8.0	380	2017	249	20 March	17	−7.6
							2018	284	23 April	2	−1.2
							2019	253	2 April	16	−6.9
Scott, SK	52°21′N 108°49′W	Western Prairies	Dark brown, clay loam	2.9	6.0	366	2017	300	31 March	27	−9.4
							2018	257	24 April	5	−3.1

Note: Site-specific soil data are gathered from on-site soil analyses. Average and actual precipitation data for Edmonton, Alberta (University of Alberta) and Lethbridge, Alberta (Agriculture and Agri-food Canada Lethbridge Research and Development Center) sites provided by Alberta Agriculture, Forestry and Rural Economic Development, Alberta Climate Information Service (ACIS; https://acis.alberta.ca). Average and actual precipitation data for Scott, Saskatchewan (Agriculture and Agri-food Canada Scott Research Farm) sites provided by Environment and Climate Change Canada, Historical Data, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html.

*1981–2010 average yearly precipitation accumulation.

†Based on 2 °C soil temperature trigger date.

Table 2. Herbicide treatment descriptions.

Treatment	Common name	Trade name	Formulation concentration and type	Applied rates (gai ha^{-1})	In-crop application	Manufacturer/distributor
1	Weed-free check	–	–	–	–	–
2	Untreated Check	–	–	–	–	–
3	Flumioxazin	Valtera™ Herbicide	51% WDG	70	–	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary, AB.
4	Flumioxazin	Valtera™ Herbicide	51% WDG	105	–	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary, AB.
5	Pyroxasulfone	Pyroxasulfone 85 WG Herbicide	85% WDG	125	–	K-I Chemical U.S.A. Inc., Durham, NC. Distributed by multiple companies*
6	Pyroxasulfone	Pyroxasulfone 85 WG Herbicide	85% WDG	150	–	K-I Chemical U.S.A. Inc., Durham, NC. Distributed by multiple companies*
7	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	160	–	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary, AB.
8	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	240	–	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary, AB.
9	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	240	1.25 L ha^{-1} Enforcer® M Herbicide 480 gai L^{-1}	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary, AB.

Note: (WDG) Water dispersible granule formulation. Valtera Herbicide and Fierce Herbicide are no longer commercially available as WDG formulations; both herbicides have been replaced by liquid suspension concentrate formulations.

*Pyroxasulfone is available in western Canada in combinations with other active ingredients, including flumioxazin, carfentrazone, sulfentrazone, and saflufenacil.

pyroxasulfone, and flumioxazin + pyroxasulfone were done after soil temperatures had dropped below 10 °C, generally after 15 October, and all applications were made prior to the ground freezing. Applications were completed using a motorized sprayer calibrated to deliver a carrier volume of 100 L ha^{-1} at 275 kPa. Flumioxazin and pyroxasulfone were each applied at two rates according to the Health Canada Pest Management Regulatory Agency (PMRA)-approved labels for flumioxazin (Valtera™ Herbicide) and pyroxasulfone (Pyroxasulfone 85 WG Herbicide) (Table 2). A combination of flumioxazin and pyroxasulfone (flumioxazin + pyroxasulfone) was also applied at two rates as per the PMRA-approved label (Fierce™ Herbicide) (Table 2). One herbicide treatment consisted of the lower application rate of flumioxazin + pyroxasulfone in the fall, followed by a post-emergent foliar herbicide treatment applied during the following growing season (Table 2). Additional information regarding herbicide formulations, active ingredient manufacturers, and rate structures is included in Table 2.

The following spring, soil temperatures were determined using an Omega™ TPD42 soil temperature probe (Omega Environmental, St-Eustache, QC, Canada) at a 5 cm depth at 10:00 AM each day leading up to planting. The initial planting date was triggered when soil temperatures first reached 2 °C and the second planting date was triggered when soils first reached 8 °C. To more readily identify any effect of soil-applied residual herbicide activity on spring wheat survival, phytotoxicity, and grain yield, the wheat line “LQ1299A”, as described in Collier et al. (2020, 2021), was planted at a suboptimal sowing density of 200 viable seeds m^{-2}. Previous studies completed by Collier et al. (2021) indicated that optimal seeding rates increased ultra-early wheat growing system stability and thus, if used in this study, could have served to mask potential negative effects of herbicide applications combined with suboptimal growing conditions.

The post-emergent foliar herbicide application required in treatment nine was applied between wheat development stages Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) scale 12–22. The same post-emergent foliar herbicide was used at each location: Enforcer® M Herbicide consisting of 80 g acid equivalent L^{-1} fluroxypyr, 200 g active ingredient L^{-1} bromoxynil, and 200 g acid equivalent L^{-1} MCPA ester (Nufarm Agriculture Inc., Calgary, AB, Canada) was applied at 1.25 L ha^{-1} (Table 2). Applications of the post-emergent treatment were completed using a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa.

Planting operations and nutrient management

Planting equipment varied between locations, but remained similar to the low-disturbance drill built at Agriculture and Agri-Food Canada Lethbridge, which utilizes eight ConservaPak™ knife openers (Model CP129, Vale Industries, Indian Head, SK, Canada) spaced 24 cm apart, and each followed by independent spring-tensioned rubberized packer wheels, Morris™ seed cups (Morris Industries Ltd., Saskatoon, SK, Canada), a hydraulic seed calibration and product control system from Raven™ (Raven Industries Inc., Sioux Falls, SD, USA), and an air product delivery system from Valmar™ (Valmar Air Inc., Elie, MB, Canada). Low-disturbance seeding systems are required for planting after soil-applied fall applications of flumioxazin and pyroxasulfone. Planting systems that result in the movement of soil out of the seed row at planting can remove the soil containing the herbicide layer, thus creating an area in the seed row where no herbicide is present. The drills used in this study planted each plot with a single pass, eight-row wide and resulted in less than 30% soil disturbance, defined by a seed bed utilization value of 30% or less. Seed bed utilization was calculated as follows: seed row opener width, divided by seed row width, multiplied by 100%.

Macronutrient fertilizer (N, P, K, and S) was applied based on 0–15 and 15–60 cm soil test results and recommendations based on grain yield targets appropriate for each location; these soil tests were also used to determine soil organic matter and soil pH at each site (Western Ag Labs PRS® soil test system, Saskatoon, SK, Canada). When required, nutrients were applied as urea nitrogen (46–0–0–0), monoammonium phosphate (11–52–0–0) (Koch Fertilizer, LLC, Wichita, KS, USA), potassium chloride (0–0–60) (The Mosaic Company, Tampa, FL, USA), and ammonium sulphate (21–0–0–24) (Yara Canada, Regina, SK, Canada). Fertilizer granules were incorporated as a band below and to the side of the seed row at planting. Wheat seeds were treated with a fungicide seed treatment (Raxil PRO—tebuconazole 3.0 g active ingredient L^{-1} + prothioconazole 15.4 g active ingredient L^{-1} + metalaxyl 6.2 g active ingredient L^{-1} [Bayer CropScience Canada Inc., Calgary, AB, Canada]) to control seed and soil-borne diseases.

Data collection

Similar to Collier et al. (2021), days to emergence was recorded when an estimated 50% of seedlings had emerged in a plot based on daily visual assessments. Crop anthesis was determined as days from planting date when an estimated 50% of the heads in a plot first extruded anthers based on daily visual assessment. Maturity was defined as physiological maturity and recorded as the days from planting to kernel moisture content in the lower third of the heads being below 40%. The period of time between emergence and maturity was broken into three subsegments, all reported in days: emergence to anthesis, anthesis to maturity, and emergence to maturity. This is necessary to investigate differential lengths of growth periods between planting dates and herbicide treatments and remove the confounding effect of increased days to emergence often observed with ultra-early planting dates (Collier et al. 2020, 2021).

Plant counts were completed between BBCH 20 to BBCH 49. Two 1 m-long areas of the second and third rows, and second and third last rows of each plot were counted and used to calculate the number of viable plants per 6 m row. Phytotoxicity of herbicide treatments was evaluated visually 14 and 21 days after each plot reached 50% emergence. Visual ratings for general phytotoxicity were assigned to each plot, taking into account any chlorosis, plant height reduction, reduced vigor, or biomass reduction. Phytotoxicity ratings were completed on a scale of 0%–100%, with 0% meaning no visual symptoms and 100% meaning complete plant death. Broadleaf weed control was evaluated at 21, 35, 49, and 63 days after initial crop emergence for each plot using a similar 0%–100% scale, where 0% was no visual effect on weed control and 100% indicated no broadleaf weeds present in the plot. Visual broadleaf weed control was considered as a combination of absence of individuals versus the untreated check and versus the untreated space between each plot, decreases in biomass resulting from stunted growth, and presence of chlorotic and (or) necrotic tissue. All visual ratings were completed based on the Canadian Weed Science Society visual rating scales for herbicide efficacy and phytotoxicity (CWSS 2018).

A one-time plant development stage assessment was completed using the Haun wheat development scale after plots had reached a minimum development stage of 4.+ (fifth leaf extending) (Haun 1973). Twenty plants from each plot, regardless of planting date, were evaluated and the average Haun scale stage was reported for each plot on the same day to determine absolute differences in plant development stage between herbicide and planting date treatments. Lodging was assessed on a 1–9 scale with 1 indicating an upright, erect canopy structure and 9 indicating complete lodging (data not shown).

Each plot was harvested in its entirety with a Wintersteiger Nurserymaster Elite plot combine (Wintersteiger AG, Salt Lake City, UT, USA) or a similar combine, all equipped with a straight cut header, crop lifters, and pickup reel. Grain samples from each whole plot were weighed after they were dried and corrected to 14% grain moisture content, and then used to calculate total grain yield ha^{-1} (Mg ha^{-1}). A two kg subsample from each plot was retained to complete assessments of grain bulk density (kg hL^{-1}) and seed mass (from 500 seeds). Grain protein content was determined using near-infrared reflectance spectroscopy for each subsample (Foss Decater GrainSpec, Foss Food Technology Inc., Eden Prairie, MN, USA) (Irvine et al. 2013).

Statistical analyses

The UNIVARIATE procedure in SAS version 9.4 (Cary, NC, USA) was used to test data for normality and identify outlier observations resulting from any measurement or recording error. These observations were removed prior to completing combined analyses across sites. A mixed model analysis of variance was used to perform a combined analysis of all environments (location × year combinations) using the MIXED procedure in SAS (Littell et al. 2006; SAS Institute 2018). Environment, replication within environment, and additional interactions with environment were considered random effects, while treatment effects (soil temperature at planting and herbicide treatment) and interactions were considered fixed and significant if $P \leq 0.05$ (Steel et al. 1997). Treatment means were generated using the LSMEANS statement in SAS to generate marginal means of the fixed effects (SAS Institute 2018).

Error variances between environments were found to be heterogeneous using Akaike's information criterion. Variance heterogeneity was modeled for all analyses by using the RANDOM statement in the MIXED procedure with the GROUP option set to environment, which allowed variation in covariance parameters by environment (SAS Institute 2018). The Satterthwaite approximation was used for degrees of freedom. Environments were then grouped and analyzed based on latitude, with sites north of 51°N latitude (four environments) and south of 51°N latitude (three environments) being analyzed together due to environmental similarities including the rate of spring snow cover ablation, and the rate of soil temperature increase. These two factors influenced the date of first planting in each environment and the length of time between planting dates at each environment (Table 1). A similar grouping was used in the study completed by Collier et al. (2020).

A biplot grouping methodology originally developed by Francis and Kannenberg (1978) was modified and used to evaluate grain yield and growing system stability as well as weed control consistency. The methodology developed by Döring and Reckling (2018) was used to generate an adjusted coefficient of variation (aCV) that was substituted for the traditional coefficient of variation (CV) used by Francis and Kannenberg (1978). The use of an aCV rather than a CV accounts for data conforming to Taylor's power law where the value of the CV is dependent on the yield or weed control and will tend to decrease relative to increases in yield or weed control (Taylor 1961; Döring et al. 2015). The mean and standard deviation for each treatment combination were estimated using the GLM procedure in SAS and then used to calculate the CV for each treatment combination. The aCV for each treatment combination was then calculated based on the procedure of Döring and Reckling (2018). The aCV was then plotted on the horizontal biplot axis, and the treatment mean on the vertical biplot axis. The average aCV and mean for the treatment combinations were used to group the data into four quadrants: (Group I) high mean grain yield or weed control and low variability, (Group II) high mean grain yield or weed control and high variability, (Group III) low mean grain yield or weed control and high variability, and (Group IV) low mean grain yield or weed control and low variability. In this manner, biplots can be used to visualize growing system stability and weed control consistency with either grain yield or weed control plotted on the vertical axis and the aCV plotted on the horizontal axis.

Results

Environmental conditions

Cold temperatures and freezing events after planting (ambient air temperature less than 0 °C) were most extreme for all locations in the 2017 planting season relative to the 2018 and 2019 planting seasons. The earliest soil temperature triggered planting at each location occurred in 2017. Respective initial planting dates were 20 March, 31 March, and 7 April for Lethbridge, AB, Scott, SK, and Edmonton, AB, respectively (Table 1). The spring of 2018 had prolonged cold conditions resulting in late snow cover ablation at all sites; as a result, the first planting date at all sites fell between 23 April and 27 April. In 2019, the initial planting date at the Lethbridge, AB site was 2 April.

Each site recorded ambient air temperatures below 0 °C after planting. The Scott, SK site in 2017 recorded the most nights with temperatures below freezing after planting, and the lowest temperature recorded after planting, with 27 nights where the ambient air temperature dropped below freezing and one night where temperatures reached −9.4 °C (Table 1). In 2017, the Lethbridge, AB site recorded 17 nights where the ambient air temperature dropped below freezing after planting, the most severe being −7.6 °C, and the Edmonton, AB site recorded 14 nights with ambient air temperatures below freezing, the most severe of which was −6.1 °C (Table 1).

In 2018, planting began later than in 2017 at all sites. Later than normal disappearance of snow cover meant frozen soils experienced longer day length and greater light intensity, thus warming quickly and uniformly across sites in western Canada. Initial planting occurred on 23, 24, and 27 April at Lethbridge, AB, Scott, SK, and Edmonton, AB, respectively, and each site recorded relatively few days with ambient air temperatures dropping below zero after planting. The lowest air temperatures reached after the initial planting were −1.2 °C at the Edmonton, AB and Lethbridge, AB sites and −3.1 °C at the Scott, SK site. In 2019, in Lethbridge, AB the first planting was completed on 2 April, and 16 subsequent nights had ambient air temperatures drop below freezing after the initial planting, the lowest being −6.9 °C (Table 1).

All seven environments received less precipitation than their 30-year averages. In 2017 and 2019, the Lethbridge, AB site had the greatest precipitation deficit, receiving 66% and 67% of the sites' 30-year average level of precipitation, respectively. In the 2018, growing season at the Scott, SK site was most affected by below average precipitation, receiving 70% of the sites' 30-year average precipitation (Table 1).

Crop establishment and development

Wheat planted at ultra-early planting dates emerged slower than wheat planted at later, more traditional planting dates. Wheat required an additional 10.3 and 8.0 days to emerge when planted ultra-early at sites north and south of 51°N latitude, respectively (Table 3). Despite slower emergence, ultra-early planted wheat always emerged, reached anthesis, and matured earlier than the later planted treatments (data not shown). At sites north of 51°N latitude, the duration of the emergence to anthesis, anthesis to maturity, and emergence to maturity periods was greater for the ultra-early planting date than the later planting date. At sites south of 51°N latitude, only the emergence to anthesis period was significantly longer for the ultra-early planting date than the

Table 3. Least-squares means for crop emergence, growth periods, and plant counts for ultra-early seeded wheat and residual fall herbicide applications at sites north and south of 51°N latitude.

	Days to emergence	Emergence to anthesis period (days)	Anthesis to maturity period (days)	Emergence to maturity period (days)	Plant count (plants 6 m row^{-1})
Sites north of 51°N latitude ($n = 4$)					
Planting trigger					
2 °C soil temperature	24.0	50.5	41.7	92.4	231
8 °C soil temperature	13.7	48.7	39.6	88.5	245
F test	***	***	***	***	NS
$\text{LSD}_{0.05}$	4.9	0.6	1.0	1.3	
Herbicide treatment					
Weed-free check	19.0	49.7	41.3	91.4	234
Untreated check	18.8	49.6	40.2	90.1	236
Flumioxazin 70 gai ha^{-1}	18.8	49.6	40.4	90.0	228
Flumioxazin 105 gai ha^{-1}	19.5	49.6	40.5	90.3	237
Pyroxasulfone 125 gai ha^{-1}	18.9	49.9	40.3	90.4	239
Pyroxasulfone 150 gai ha^{-1}	18.9	49.8	40.8	90.6	236
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	18.2	49.4	40.6	90.2	243
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	19.0	49.0	41.0	90.1	241
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	18.8	49.6	40.8	90.7	244
F test	NS	NS	NS	NS	NS
$\text{LSD}_{0.05}$					
Planting trigger × herbicide	NS	NS	NS	NS	NS
Sites south of 51°N latitude ($n = 3$)					
Planting trigger					
2 °C soil temperature	22.6	55.3	35.6	90.9	232
8 °C soil temperature	14.6	53.2	36.6	89.8	196
F test	***	***	NS	NS	*
$\text{LSD}_{0.05}$	2.0	0.6			30
Herbicide treatment					
Weed-free check	18.5	54.2	36.3	90.4	205
Untreated check	18.6	53.7	36.6	90.3	219
Flumioxazin 70 gai ha^{-1}	18.3	54.5	35.9	90.5	223
Flumioxazin 105 gai ha^{-1}	18.4	54.5	36.2	90.7	207
Pyroxasulfone 125 gai ha^{-1}	18.7	54.4	36.5	90.9	207
Pyroxasulfone 150 gai ha^{-1}	19.1	53.8	36.3	90.1	204
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	18.5	53.9	36.2	90.1	222
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	18.8	54.3	35.5	89.8	220
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	18.5	54.7	35.6	90.3	218
F test	NS	NS	NS	NS	NS
$\text{LSD}_{0.05}$					
Planting trigger × herbicide	NS	NS	*	NS	NS

Note: (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. ($\text{LSD}_{0.05}$) Least significant difference at $P < 0.05$.

later planting date (Table 3). None of the herbicide treatments had an effect on the length of the growth periods of wheat in this study regardless of geographic location. There was a significant interaction between herbicide and planting date for the anthesis to maturity period at sites south of 51°N latitude; all treatments (except pyroxasulfone at 125 and 150 gai ha^{-1}) required numerically fewer days to progress from anthesis to maturity at the ultra-early planting date. Pyroxasulfone 125 and 150 gai ha^{-1} treatments required a numerically longer time to progress from anthesis to maturity when planted ultra-early. This longer grain-fill period did not lead to increased grain production.

Plant establishment and survival were not affected by herbicide treatment at any location (Table 3). Planting date had no effect on wheat populations at sites north of 51°N latitude (Table 3). At sites located south of 51°N latitude, ultra-early planting resulted in greater wheat establishment and survival than the later planting time (Table 3). There was no negative effect on plant survivability of planting at ultra-early timings.

Relative development stages between planting dates and herbicide treatments were evaluated using a single Haun stage evaluation. No herbicide treatment at any location resulted in a difference in Haun scale rating relative to the untreated check or weed-free check, indicating no delays in development as a result of herbicide treatment (Tables 4 and 5). At the sites north of 51°N latitude, there was a difference in plant stage at the time of evaluation with the early planting averaging a Haun stage of 6.4 and the later planting averaging 5.4 (Table 4). At the sites south of 51°N latitude, the two planting dates no longer exhibited a differential in plant stages at the time of evaluation.

Spring wheat herbicide tolerance and weed control

Herbicide applications did not result in negative effects on plant density, visible phytotoxicity, or delayed growth (Tables 3–5). No variation in phytotoxicity from the untreated check or weed-free check was present with any herbicide treatment, and overall phytotoxicity was negligible with values between 1% and 2% at 14 days after wheat emergence and between 0% and 2% at 21 days after wheat emergence (Tables 4 and 5).

Broadleaf weed control was evaluated at four timings: 21, 35, 49, and 63 days after the crop emerged. At sites south of 51°N latitude, planting date did not affect weed control, while at sites north of 51°N latitude greater weed control was observed with the late planting time for the final three weed control evaluations (Tables 4 and 5). All herbicide treatments provided a weed control benefit over the untreated check at all environments and evaluation timings. Weed control was generally greatest at the earliest evaluation timing, and lowest at the latest evaluation timing. The exception to this was the flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop herbicide application treatment at sites north of 51°N latitude where weed control was greater at the later evaluations in response to the post-emergent herbicide application (Table 4). Overall herbicide efficacy was lower and more variable at sites north of 51°N latitude than sites south of 51°N latitude (Tables 4 and 5, Figs. 1A and 1B). Individual herbicide treatment effectiveness varied between sites north and south of 51°N latitude as well. Greater separation between individual herbicide treatments based mainly on active ingredient load occurred at sites north of 51°N latitude, while performance between treatments remained more similar at sites south of 51°N latitude (Tables 4 and 5). In general, treatments with either flumioxazin alone or pyroxasulfone alone performed similar to one another. Flumioxazin + pyroxasulfone and flumioxazin + pyroxasulfone with a post-emergent herbicide application tended to be the highest performing treatments for broadleaf weed efficacy (Tables 4 and 5).

The most consistent weed control 63 days after emergence occurred at the sites north of 51°N latitude when flumioxazin 105 gai ha^{-1}, flumioxazin + pyroxasulfone 160 gai ha^{-1}, flumioxazin + pyroxasulfone 240 gai ha^{-1}, or flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application treatments were applied. Weed control in the later planted plots tended to be more consistent than the early planted treatments (Figs. 1A and 1C). In sites located south of 51°N latitude, the most consistent weed control at 63 days after emergence occurred when flumioxazin 105 gai ha^{-1}, pyroxasulfone 150 gai ha^{-1}, flumioxazin + pyroxasulfone 160 gai ha^{-1}, flumioxazin + pyroxasulfone 240 gai ha^{-1}, or flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application was applied (Figs. 1B and 1D). At the sites south of 51°N latitude, there was a trend toward more consistent weed control when herbicides were combined with ultra-early planting.

Grain yield and grain quality

Ultra-early planting had no effect on grain protein content regardless of location. Grain yield was significantly higher when wheat was planted at the initial 2 °C soil temperature trigger at sites south of 51°N latitude; grain yield at sites north of 51°N latitude did not change as a result of soil temperature triggered planting date. Grain test weight (bulk density) and grain kernel weight were greater at sites south of 51°N latitude when wheat was planted earlier, and greater at sites north of 51°N latitude when planted at the later soil temperature trigger (Table 6).

Herbicide treatment had no effect on grain yield, grain protein concentration, or kernel weight at sites south of 51°N latitude (Table 6). Grain test weight was affected by the combination of fall-applied flumioxazin + pyroxasulfone with a post-emergent application of herbicide, leading to an increase in test weight over the weed-free check, while both rates of flumioxazin + pyroxasulfone and the higher application rate of pyroxasulfone resulted in a decrease in grain test weight (Table 6). A significant interaction was present between planting trigger and herbicide treatment at sites south of 51°N latitude; this was a result of a greater decrease in grain test weight at later planting times relative to early planting when the active ingredient pyroxasulfone was present in the herbicide treatment (Table 6).

At sites north of 51°N latitude, herbicide treatment did not affect grain protein concentration or grain test weight. Grain yield for all herbicide treatments was equal to the grain yield of the weed-free check, and multiple herbicide

Table 4. Least-squares means for crop phytotoxicity, crop uniformity, and broadleaf weed control in ultra-early seeded wheat with residual fall herbicide applications north of 51°N latitude.

	Phytotoxicity (%) 14 DAE	Phytotoxicity (%) 21 DAE	Haun Growth stage assessment	Broadleaf weed control (%) 21 DAE	Broadleaf weed control (%) 35 DAE	Broadleaf weed control (%) 49 DAE	Broadleaf weed control (%) 63 DAE
Sites north of 51°N latitude ($n = 4$)							
Planting trigger							
2 °C soil temperature	1	0	6.4	74	71	71	68
8 °C soil temperature	1	1	5.7	79	77	79	76
F test	NS	NS	**	NS	*	**	**
$\mathrm{LSD}_{0.05}$			0.1		5	5	5
Herbicide treatment							
Weed-free check	2	0	6.0	100	100	100	100
Untreated check	1	0	6.1	0	0	0	0
Flumioxazin 70 gai ha^{-1}	1	0	6.1	83	76	77	71
Flumioxazin 105 gai ha^{-1}	1	1	6.0	86	79	84	78
Pyroxasulfone 125 gai ha^{-1}	1	1	6.1	79	75	75	69
Pyroxasulfone 150 gai ha^{-1}	1	1	6.1	83	77	77	70
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	1	1	6.1	83	81	85	81
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	1	0	6.1	89	87	87	84
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	2	1	6.0	86	89	92	96
F test	NS	NS	NS	***	***	***	***
$\mathrm{LSD}_{0.05}$				8	8	6	6
Planting trigger × herbicide	NS	NS	NS	NS	NS	NS	NS

Note: (DAE) Days after crop emergence. (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. ($\mathrm{LSD}_{0.05}$) Least significant difference at $P < 0.05$.

treatments resulted in a greater grain yield than the untreated check. The weed-free check produced more grains than the untreated check (Table 6). Grain thousand kernel weight was also greater for the weed-free check than the untreated check. There were no herbicide treatments that resulted in a grain kernel weight reduction relative to the untreated check; several herbicide treatments resulted in increased grain kernel weight similar to the weed-free check (Table 6).

In sites north of 51°N latitude, where planting date did not significantly affect grain yield, the biplot representing grain yield stability of the growing system shows few trends regarding planting date (Fig. 2A). However, the biplot clearly illustrates that lowest grain yield occurred in the untreated check for both planting dates. For sites south of 51°N latitude where grain yield was significantly higher when ultra-early seeding occurred, the biplot for grain yield stability clearly illustrates that ultra-early planting increased yield and growing system stability. Furthermore, the use of fall-applied residual herbicides combined with ultra-early planting tended to increase growing system stability of ultra-early planted treatments (Fig. 2B).

Discussion

Ultra-early wheat growing system

Spring wheat planted ultra-early at sites located south of 51°N latitude in this study exhibited increases in grain yield and a marked increase in growing system stability. Ultra-early planting at sites south of 51°N latitude resulted in a grain yield increase of 0.45 Mg ha^{-1}, an 18% increase relative to delaying planting until soil reached 8 °C. Using an average wheat grain value of \$261.00 Mg^{-1} (September 2015 to December 2021 average southern Alberta price for CWRS wheat, 13.5% protein content), a grower would expect a gross economic benefit of \$117.45 ha^{-1} by shifting to an ultra-early planting date (Alberta Wheat Commission 2021). Greater grain yield at sites south of 51°N latitude resulting from ultra-early seeding can be attributed to increased plant populations, earlier access to spring soil moisture, drought

Table 5. Least-squares means for crop phytotoxicity, crop uniformity, and broadleaf weed control in ultra-early seeded wheat with residual fall herbicide applications south of 51°N latitude.

	Phytotoxicity (%) 14 DAE	Phytotoxicity (%) 21 DAE	Haun growth stage assessment	Broadleaf weed control (%) 21 DAE	Broadleaf weed control (%) 35 DAE	Broadleaf weed control (%) 49 DAE	Broadleaf weed control (%) 63 DAE
Sites south of 51°N latitude (*n* = 3)							
Planting trigger							
2 °C soil temperature	2	2	4.8	85	82	80	75
8 °C soil temperature	2	2	4.7	85	82	80	74
F test	NS	NS	NS	NS	NS	NS	NS
LSD$_{0.05}$							
Herbicide treatment							
Weed-free check	2	2	4.6	100	100	100	100
Untreated check	2	2	4.8	0	0	0	0
Flumioxazin 70 gai ha^{-1}	2	2	4.7	94	90	88	77
Flumioxazin 105 gai ha^{-1}	2	2	4.6	94	91	88	78
Pyroxasulfone 125 gai ha^{-1}	2	2	5.0	95	89	86	81
Pyroxasulfone 150 gai ha^{-1}	2	2	4.8	96	91	89	83
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	2	2	4.8	96	91	88	85
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	2	2	4.7	98	94	93	85
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	2	2	4.7	94	91	90	83
F test	NS	NS	NS	***	***	***	***
LSD$_{0.05}$				3	5	5	7
Planting trigger × herbicide	NS	NS	NS	NS	NS	NS	NS

Note: (DAE) Days after crop emergence. (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. (LSD$_{0.05}$) Least significant difference at $P < 0.05$.

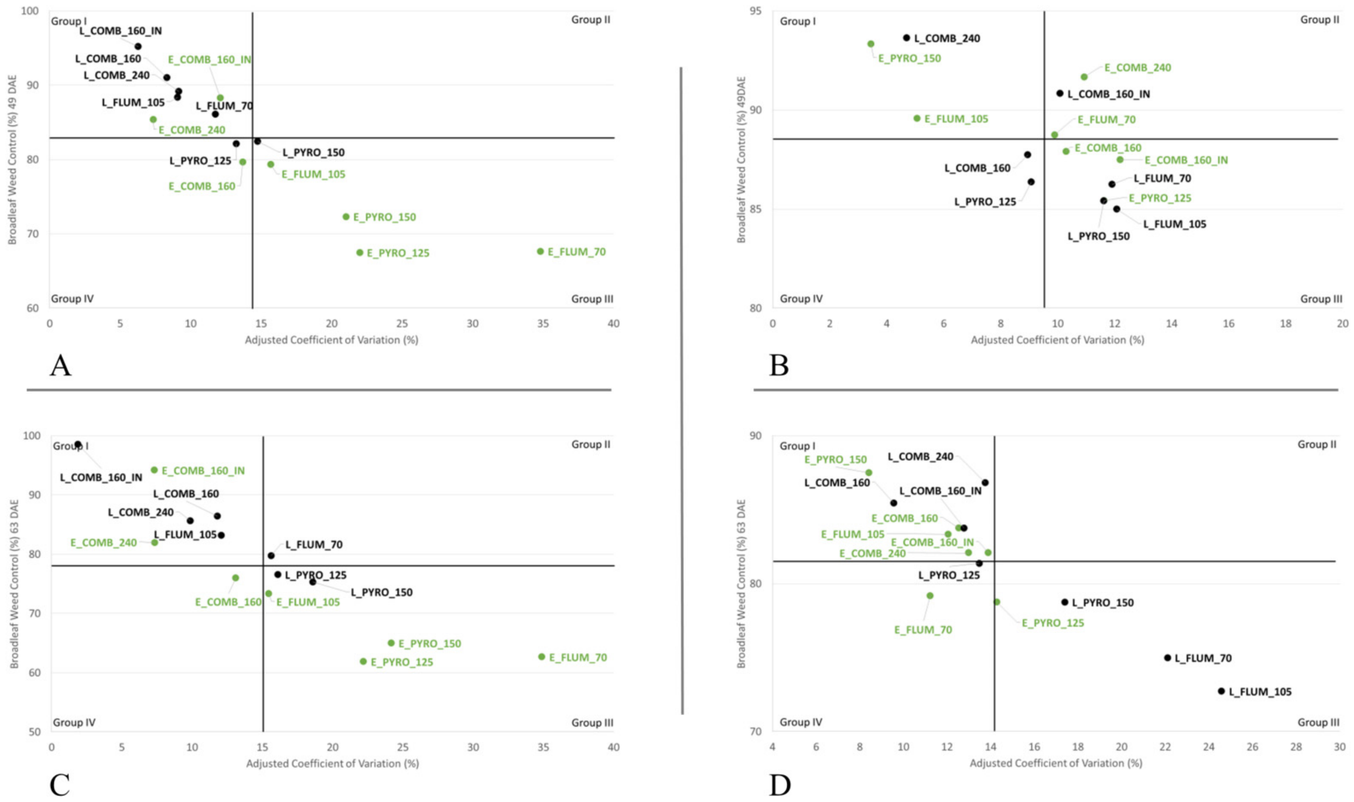
and heat stress avoidance, and a longer vegetative growth period similar to the reports of Kirkegaard et al. (2015), Hunt et al. (2018), and Collier et al. (2021).

At sites north of 51°N latitude, there was no grain yield difference between ultra-early and later planted wheat and little differential in growing system stability. This result varies from similar studies conducted by Collier et al. (2020), who reported similar yields between ultra-early and later planting dates, but an increase in growing system stability when planting occurred ultra-early. Collier et al. (2021) reported that using optimal wheat seeding rates of 400 viable seeds m^{-2} or more increased growing system stability of ultra-early wheat growing systems. The incongruity between studies at sites north of 51°N latitude may be attributed to the suboptimal seeding rate of 200 viable seeds m^{-2} used in this study versus the seeding rate of 400 viable seeds m^{-2} used in the study completed by Collier et al. (2020).

Spring wheat tolerance to fall-applied soil residual herbicides

Selectivity in wheat for pyroxasulfone and flumioxazin is dependent on the ability of wheat to quickly metabolize and detoxify the herbicidally active form(s) of each active ingredient (Niekamp et al. 1999; Tanetani et al. 2013). Due to primary reliance on plant metabolism to complete detoxification, crop safety could be influenced by environmental conditions that reduce plant metabolism. Cold temperatures and saturated soils, both conditions that are commonly encountered by wheat planted ultra-early, can limit the ability of plants to metabolize herbicides (Niekamp et al. 1999; Tanetani et al. 2013; Jha and Kumar 2017). Additionally, we have reported that wheat planted ultra-early takes longer to emerge than later planted wheat, meaning that imbibition and initial growth stages are occurring over a longer period of time and are occurring in soil treated with residual herbicides (Collier et al. 2020, 2021). In this respect, ultra-early wheat planting systems potentially carry a greater risk of herbicide damage from soil-applied residual herbicides than traditional wheat growing systems. In our study, however, soil-applied residual herbicide treatments did not impact wheat emergence, and plant density, or alter phenology in any environment. The absence of crop response to fall-applied residual herbicide use, and the lack of any trends of increasing injury with increased herbicide dose, indicates that the crop

Fig. 1. Biplot summarizing average broadleaf weed control means versus adjusted coefficient of variation (aCV) for each planting date and herbicide treatment at 49 days after emergence (DAE) for (A) sites north of 51°N latitude and (B) sites south of 51°N latitude and at 63 DAE for (C) sites north of 51°N latitude and (D) sites south of 51°N latitude.
Abbreviations are as follows: (I) The first letter represents the planting date (E—ultra-early planting triggered at a soil temperature of 2 °C. L—later planting triggered at a soil temperature of 8 °C.) (II) The next letters denote the herbicide treatment (UTC—untreated check. WFC—weed-free check. FLUM—flumioxazin. PYRO—pyroxasulfone. COMB—flumioxazin + pyroxasulfone.) (III) The next numbers, if present, represent the amount of active ingredient in the treatment in gai ha^{-1}. (IV) The final letters (IN), if present, represent the presence of an in-crop herbicide application. Colours are a visual representation of planting date: green—ultra-early, black—later planting. Grouping categories are divided by a vertical line representing the mean aCV and a horizontal line representing the mean grain yield: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.



selectivity of pyroxasulfone and flumioxazin is broad enough to support the safe use of these herbicides in the fall prior to ultra-early planting of wheat the following spring.

Herbicide efficacy and consistency

Extended residual weed control varied between sites located north of 51°N latitude and sites south of 51°N latitude. Overall weed control was greater at the sites south of 51°N latitude. At the sites north of 51°N latitude, at later planting dates early weed escapes were partially controlled by the planting operation that resulted in improved weed control. Variation in soil organic matter, soil moisture, and soil pH values influence the level of adsorption of herbicide to soil colloids, and as such, more active ingredients would be expected to be in soil water solution and available for plant uptake in the soils at sites south of 51°N (Table 1) (Mahoney et al. 2014; Westra et al. 2015; Eason et al. 2022). Subsequently, the greater availability of herbicide in soil water solution at sites south of 51°N latitude likely accounts for improved weed control relative to sites north of 51°N latitude.

The individual active ingredient treatments, flumioxazin 70 gai ha^{-1}, flumioxazin 105 gai ha^{-1}, pyroxasulfone 125 gai ha^{-1}, and pyroxasulfone 150 gai ha^{-1}, performed similar to one another at locations north and south of 51°N latitude. Generally, the combination of both active ingredients, flumioxazin + pyroxasulfone 160 gai ha^{-1}, and flumioxazin + pyroxasulfone 240 gai ha^{-1} provided more consistent weed control longer into the growing season than the individual active ingredient treatments.

The main mechanism of herbicide breakdown in soil for both pyroxasulfone and flumioxazin is microbial degradation. Therefore, the amount of herbicide in the soil available for plant uptake decreases with time (Shaner 2014). This manifests visually as weed control reductions over time; later emerging weed flushes may be less effectively controlled. This effect is evident in all sites in this study as overall weed control decreased for all herbicide treatments from the 21 days after emergence evaluation to the 63 days after emergence evaluation, with the exception of the flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application treatment at

Table 6. Least-squares means for grain yield and grain quality parameters for ultra-early seeded wheat and residual fall herbicide applications at sites north and south of 51°N latitude.

	Yield (Mg ha^{-1})	Protein (%)	Test weight (kg hL^{-1})	Thousand kernel weight (g)
Sites north of 51°N latitude (*n* = 4)				
Planting trigger				
2 °C soil temperature	4.17	11.6	81.7	31.4
8 °C soil temperature	4.27	11.2	82.7	31.9
F test	NS	NS	***	*
LSD$_{0.05}$			0.5	0.5
Herbicide treatment				
Weed-free check	4.26	11.4	82.5	32.3
Untreated check	4.01	11.3	82.1	31.0
Flumioxazin 70 gai ha^{-1}	4.28	11.3	82.3	31.5
Flumioxazin 105 gai ha^{-1}	4.19	11.4	82.2	31.1
Pyroxasulfone 125 gai ha^{-1}	4.34	11.4	82.0	32.0
Pyroxasulfone 150 gai ha^{-1}	4.19	11.4	82.0	31.7
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	4.15	11.5	82.0	31.3
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	4.26	11.5	82.1	32.0
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	4.30	11.5	82.5	32.2
F test	*	NS	NS	**
LSD$_{0.05}$	0.19			0.8
Planting trigger × herbicide	NS	NS	NS	NS
Sites south of 51°N latitude (*n* = 3)				
Planting trigger				
2 °C soil temperature	2.97	12.5	77.0	29.2
8 °C soil temperature	2.52	12.6	75.9	28.2
F Test	**	NS	**	*
LSD$_{0.05}$	0.24		0.7	0.9
Herbicide treatment				
Weed-free check	2.72	12.6	76.4	28.3
Untreated check	2.70	12.4	76.5	28.4
Flumioxazin 70 gai ha^{-1}	2.86	12.3	76.6	28.7
Flumioxazin 105 gai ha^{-1}	2.83	12.4	76.9	29.1
Pyroxasulfone 125 gai ha^{-1}	2.63	12.4	76.6	28.8
Pyroxasulfone 150 gai ha^{-1}	2.73	12.6	76.3	28.7
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	2.75	12.6	76.0	28.3
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	2.67	12.8	76.0	28.6
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + in-crop broadleaf herbicide application	2.82	12.4	77.0	29.1
F test	NS	NS	*	NS
LSD$_{0.05}$			0.6	
Planting trigger × herbicide	NS	NS	*	NS

Note: (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. (LSD$_{0.05}$) Least significant difference at $P < 0.05$.

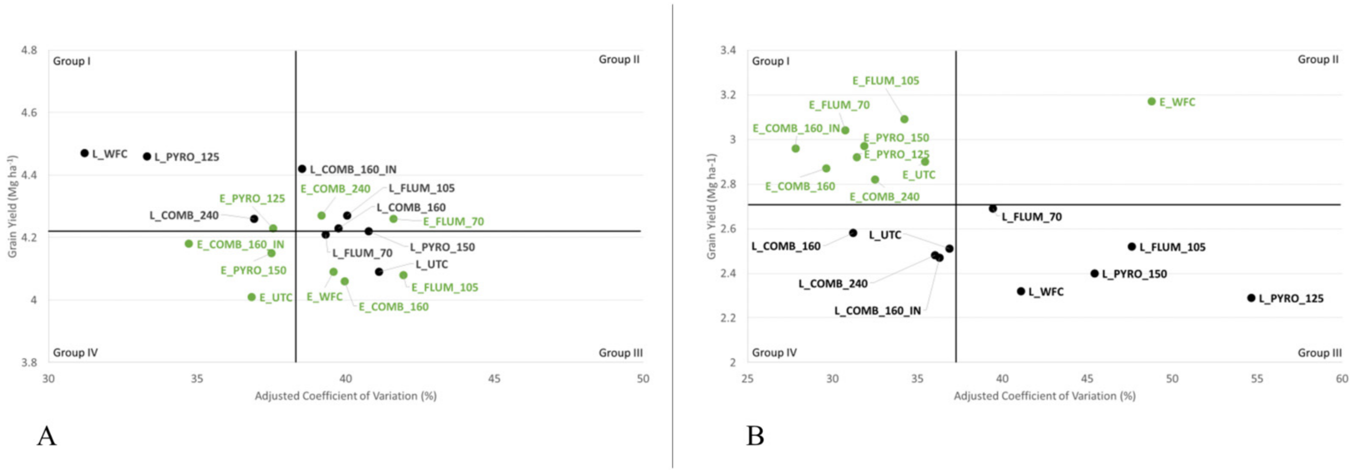


Fig. 2. Biplot summarizing grain yield means versus adjusted coefficient of variation (aCV) for each planting date and herbicide treatment at sites (A) north of 51°N latitude and (B) south of 51°N latitude.
Abbreviations are as follows: (I) The first letter represents the planting date (E—ultra-early planting triggered at a soil temperature of 2 °C. L—later planting triggered at a soil temperature of 8 °C.) (II) The next letters denote the herbicide treatment (UTC—untreated check. WFC—weed-free check. FLUM—flumioxazin. PYRO—pyroxasulfone. COMB—flumioxazin + pyroxasulfone.) (III) The next numbers, if present, represent the amount of active ingredient in the treatment in gai ha^{-1}. (IV) The final letters (IN), if present, represent the presence of an in-crop herbicide application. Colours are a visual representation of planting date: green—ultra-early, black—later planting. Grouping categories are divided by a vertical line representing the mean aCV and a horizontal line representing the mean grain yield: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

sites north of 51°N latitude. The use of fall-applied residual herbicides in ultra-early wheat growing systems successfully replaced spring burndown applications for early-season weed control; however, our study suggests that in-crop weed control remains necessary to reduce weed seed load into the soil seedbank.

Conclusions

The implementation of an ultra-early wheat planting system improves overall growing system stability and grain yield on the northern Great Plains but negates the use of foliar herbicides to remove weeds prior to planting, or prior to the emergence of the crop. Fall-applied residual herbicide use can allow producers to adopt ultra-early wheat planting without sacrificing early-season weed control opportunities. Our results demonstrated that a weed management program in ultra-early planted wheat growing systems can safely include fall applications of flumioxazin, pyroxasulfone, and combinations of flumioxazin and pyroxasulfone to manage weeds emerging the following spring. By combining early planting, optimal seeding rates, a competitive cultivar, and soil-applied residual herbicides as components of ultra-early wheat growing systems, grain yield, grain yield stability, and integrated weed management can be optimized.

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Data availability

Data generated or analyzed during this study are available from the corresponding authors upon reasonable request.

Author information

Author ORCIDs

Graham R.S. Collier https://orcid.org/0000-0001-8012-3016
Dean M. Spaner https://orcid.org/0000-0002-2088-5104

Author notes

Brian Beres served as an Editor in Chief at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Andrew McKenzie-Gopsill.

Author contributions

GRSC, primary corresponding author. Co-developed and conceptualized the hypotheses and field experiments. Used project for partial fulfilment of PhD thesis requirements at the University of Alberta. Analyzed data and prepared manuscript. Participated in meetings and presented findings at conferences, field days, and grower meetings.

BLB, co-investigator/corresponding author. Co-developed and conceptualized the hypotheses and field experiments. Identified and recruited collaborators, PhD student, and led workshops to finalize proposal. Participated in meetings and presented findings at conferences, field days, and grower meetings. Co-supervises GRSC.

RJG, co-investigator. Developed cold-tolerant lines used for field experiments. Reviewed and edited manuscript.

LMH, co-investigator. Co-developed and conceptualized the hypotheses and field experiments. Reviewed and edited manuscript.

DMS, principal investigator responsible for the field experimentation at the Edmonton sites. Co-supervisor of GRSC. Reviewed and edited manuscript and mentored manuscript preparation and statistical analyses.

Competing interests

Graham R.S. Collier is an employee and shareholder of Nufarm Agriculture Inc. Nufarm Agriculture Inc. distributes products containing the active ingredients pyroxasulfone and flumioxazin.

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