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Authors: Mangin, Amy, Brûlé-Babel, Anita, Flaten, Don, Wiersma, Jochum, and Lawley, Yvonne

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Canopy management: the balance between lodging risk and nitrogen use for spring wheat production in the Canadian Prairies

Amy Mangin ^a, Anita Brûlé-Babel^a, Don Flaten^b, Jochum Wiersma^c, and Yvonne Lawley^a

^aDepartment of Plant Science, University of Manitoba, d222 Agriculture Building, 66 Dafoe Road, Winnipeg, MB R3T 2N2, Canada;

^bDepartment of Soil Science, University of Manitoba, 362 Ellis Building, 13 Freedman Crescent, Winnipeg, MB R3T 2N2, Canada;

^cNorthwest Research and Outreach Center, 2900 University Ave., Crookston, MN 56716, USA

Corresponding author: Amy Mangin (email: ummangia@myumanitoba.ca)

Abstract

Lodging risk in spring wheat has grown with the introduction of high-yielding cultivars that require high nitrogen (N) inputs to optimize grain yield and protein content. Canopy management (CM) strategies have been used to reduce lodging risk. However, the short growing season and unpredictable moisture supply may limit the use of these strategies in the Canadian Prairies. The objective of this study was to quantify the ability of agronomic practices to modify the early season crop canopy, and hence lodging risk, and to determine how these practices influence N use and final grain N yield. Split-plot field trials were established at four site-years (SYs) in Manitoba to evaluate CM strategies including three plant densities, a split N fertilizer application, and the application of chlormequat chloride (CCC) on canopy size (dry matter (DM) and height at anthesis), N uptake and remobilization, lodging and stalk strength, grain yield, protein, and grain N yield on the cultivar AAC Brandon. Precipitation was low during this study (64%–78% of long-term average (LTA)), resulting in modest yields and low lodging pressure. However, low plant density (PD), split N, and CCC applications all showed potential to reduce lodging risk without reducing grain yield or protein concentration. Split N and plant growth regulator (PGR) applications increased final grain N yield by 11.2% and 2.4%, respectively. Therefore, CM practices have potential in the Canadian Prairies to reduce lodging risk without compromising grain N, but results should be validated in higher precipitation environments and across additional cultivars and growing regions of western Canada.

Key words: wheat, nitrogen, plant density, canopy management, plant growth regulator, lodging

Résumé

Les risques de verse chez le blé de printemps se sont accrus avec l'introduction de cultivars à haut rendement dont on optimise le rendement et la teneur en protéines par un apport important d'engrais azoté (N). Pour atténuer ce risque, les producteurs recourent à la gestion du feuillage. Cependant, la brièveté de la période végétative et une teneur en eau imprévisible dans le sol pourraient restreindre le recours à une telle stratégie dans les Prairies canadiennes. Les auteurs voulaient déterminer dans quelle mesure les pratiques agricoles permettraient de modifier la densité du feuillage, donc les risques de verse, en début de saison et établir comment de telles pratiques influent sur l'utilisation du N et la concentration finale de cet élément dans le grain. Pour cela, ils ont procédé à des essais en tiroir sur le terrain pendant quatre années-sites, au Manitoba. Les méthodes de gestion du feuillage examinées comprenaient trois densités de feuillage, l'application fractionnée de N et l'application de chlorure de chlorméquat (CC). Les chercheurs ont évalué l'incidence de ces stratégies sur l'abondance du feuillage (poids sec et hauteur à l'anthèse) du cultivar AAC Brandon, l'absorption et la relocalisation du N, la verse et la longueur de la tige, le rendement grainier, la concentration de protéines et le rendement en N du grain. Comme il n'a guère plu pendant l'étude (64 à 78 % de la moyenne à long terme), le rendement était modeste et la pression engendrée par la verse, relativement faible. Néanmoins, un peuplement de faible densité, l'application fractionnée de N et celle de CC sont autant de mesures susceptibles d'atténuer les risques de verse sans que le rendement grainier ou la teneur en protéines du grain en souffrent. L'application fractionnée de N et celle d'un régulateur de croissance ont respectivement augmenté le rendement en N final du grain de 11,2 et de 2,4 %. Les auteurs en concluent que la gestion du feuillage pourrait réduire les risques de verse

dans les Prairies canadiennes sans diminuer la teneur en N du grain, mais ces conclusions devront être confirmées lors de précipitations plus abondantes et avec d'autres cultivars ainsi que dans des zones de culture différentes de l'Ouest canadien. [Traduit par la Rédaction]

Mots-clés : blé, azote, densité de peuplement, gestion du feuillage, régulateur de croissance, verse

1. Introduction

The release of spring wheat cultivars with high-yield potential has increased concerns about lodging in the Canadian Prairies. High-yielding cultivars require high N inputs to meet yield and protein concentration targets, additionally, high yields are associated with heavy spikes, which increase lodging risk (Berry 2019). The occurrence of lodging is unpredictable, but when it occurs, grain yield and quality may be reduced, and harvest operations can be challenging (Berry 2019). Lodging is defined as the displacement of a plant from the vertical position as a result of stem breakage or bending (stem lodging) or the rotation of the crop from the root cone (root lodging). When leverage on a plant, or individual stem, exceeds stem or root anchorage strength, lodging will occur. Leverage placed on the stem and root is largely influenced by combinations of precipitation, wind, and agronomic management of individual fields, making lodging extremely difficult to predict (Baker et al. 1998, 2014; Berry et al. 2000). Introduction of semidwarfing genes reduced lodging incidence because shorter crop canopies reduce plant leverage (Berry et al. 2003b; Baker et al. 2014). However, with higher yield potential and increasing severe weather events, semidwarfing genes alone are not sufficient to control lodging in the Canadian Prairies (Cogato et al. 2019; MASC 2020). Therefore, alternate strategies need to be explored.

Canopy management (CM), the manipulation of the crop canopy through agronomic management, is commonly used to reduce lodging risk in high-yielding wheat growing areas across the world (Berry et al. 2000; Peake et al. 2016; Wu et al. 2019; Mizuta et al. 2020). Reductions in early-season vegetative growth have direct and indirect effects on the crop's susceptibility to lodging. Tall and heavy canopies intercept more wind and rain, which increases leverage and lodging risk compared with short, light canopies (Berry et al. 2000). Additionally, increased early-season vegetative growth results in shading within the canopy, which alters the quantity and quality of light intercepted by the crop (Sparkes and King 2008). As a result, stems elongate quicker, producing weaker stems, and potentially smaller rooting systems that are more likely to lodge. Peake et al. (2016) demonstrated a positive linear relationship between lodging occurrence and crop biomass at anthesis and between lodging occurrence and leaf area index (LAI), also measured at anthesis ($R^2 = 0.9385$ and 0.7271 , respectively), which could be used to predict lodging risk.

CM strategies targeted at reducing early season vegetative biomass will be adopted only if there are negligible risks to grain yield and protein content. Reduced plant densities, split N fertilizer applications, and plant growth regulator (PGR) applications are agronomic practices that have been reported to reduce lodging risk while maintaining yield (Berry et al. 2000; Peake et al. 2016; Wu et al. 2019; Mizuta et al. 2020). Lower

plant densities in wheat have been shown to reduce lodging risk by increasing both stem and root anchorage strength, without sacrificing grain yield (Berry et al. 2000; Zheng et al. 2017). When a portion of N fertilizer was delayed until after stem elongation, shading within the canopy was reduced early in the season and as a result stem strength was increased, compared with when applied entirely at planting (Wu et al. 2019). This strategy also had the added benefit of increasing grain protein content and producing similar grain yields. The PGR chlormequat chloride (CCC) is a tool available to farmers to manage lodging risk by reducing stem length, through inhibition of the gibberelic biosynthesis pathway (Rademacher 2000).

The efficacies of these practices to reduce early-season vegetative growth specifically for reductions in lodging risk have not been tested in dryland spring wheat production in the Canadian prairies. The short-growing season and unpredictable moisture supply in this region are presumed to limit the ability of CM strategies to reduce lodging risk without having detrimental effects on grain yield, protein content, or grain N yield. Canadian Western Red Spring (CWRS) wheat is known globally for high protein content and milling quality and farmers are paid a premium for producing grain that meets these standards (Canadian Grain Commission 2019). Therefore, any management practices that have negative effects on grain N content and protein concentration are unlikely to be adopted, even if grain yield levels remain high.

Reductions in the crop's vegetative growth may alter the crop's ability to accumulate and store N early in the growing season, thereby reducing available N for grain N-yield production (Brasire et al. 2019). Wheat accumulates N in vegetative tissue from emergence to anthesis (Zadoks GS10-GS60) (Zadoks et al. 1974), which is remobilized to the developing grain during the grain fill period (Zadoks GS60-GS90) (McMullan et al. 1988; Kong et al. 2016). Remobilized N from vegetative tissue is a major source of grain N, and as a result, grain protein concentration, an important grain quality parameter in CWRS wheat (Barbottin et al. 2005; Kong et al. 2016). Nitrogen can also be taken up postanthesis, during the grain fill period, to increase final grain N. However, postanthesis N uptake is heavily reliant on soil moisture availability during the postanthesis period, which is highly variable in dryland wheat production in the Canadian prairies (Malhi et al. 2006). Therefore, N accumulated in vegetative tissue early in the growing season is a reliable source of N for the developing grain that is less dependent on late-season growing conditions. As a result, reducing early-season vegetative biomass to lower lodging risk may make the crop more reliant on postanthesis N uptake to meet grain protein quality requirements, increasing marketing risk for the farmer.

The ability of CM practices and their interactions to reduce lodging risk and affect N accumulation and remobilization from vegetative tissue has yet to be explored in CWRS wheat production in the Canadian Prairies. Therefore, the objectives of this study were to:

1. Determine the effect of plant density (PD), split N application, and application of CCC on early-season CWRS wheat vegetative growth and lodging risk.
2. Determine how canopy biomass alterations, through agronomic management, influence crop N uptake and remobilization for grain N yield in CWRS wheat.

2. Materials and methods

2.1 Site descriptions and agronomic management

Field trials were conducted during the 2018 and 2019 growing seasons at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB, and in a commercial field near Manitou, MB for a total of four site-years (SYs; Car18, Car19, Man18, and Man19). For all trials, soil was sampled at 0–15, 15–60, and 60–120 cm depths to determine residual soil nutrient levels in the spring before planting (Table 1). Growing season precipitation and temperature data were collected using WatchDog 2700 series weather stations (Spectrum Technologies, Aurora, IL, USA) located at each field site from April to September (Fig. 1).

The cultivar AAC Brandon falls into the CWRS market class and was chosen for this study as it has been widely adopted across Manitoba, being grown on 90% of the spring wheat acres in 2017 and 2018 (MASC 2020). AAC Brandon is a semidwarf variety with a very good lodging resistance and disease resistance package (Cuthbert et al. 2016). Seed was treated with Raxil Pro fungicide (Bayer CropScience Canada) (tebuconazole (3.0 g L⁻¹), prothioconazole (15.4 g L⁻¹), and metalaxyl (6.2 g L⁻¹)) at a rate of 325 mL product per 100 kg seed weight. Seeding rates were calculated to target desired PD treatments using 1000-seed weight, germination percentage, and an assumed 15% seedling mortality. Seeding was completed using an 8-row small plot-forced air seeder with 20.3 cm row spacing and knife openers, with midrow-banding capabilities (R-Tech Industries Ltd.). A seeding depth of 2.5–3.0 cm was targeted with midrow-banded N fertilizer applied at approximately the 6 cm depth. Seed-placed phosphorus was applied as monoammonium phosphate (11–52-0) at a rate of 19.6 kg P₂O₅ ha⁻¹ across the entire trial area at each location. Herbicides were applied as necessary to keep the crop as weed-free as possible and varied between trial locations based on weed spectrum and pressure during the growing season. Twinline (BASF Canada) containing pyraclostrobin (130 g L⁻¹) and metconazole (80 g L⁻¹) was applied at 494 mL ha⁻¹ at all sites to control leaf diseases at flag leaf timing (Zadoks GS39). The fungicide ProSaroXTR (prothioconazole (125 g L⁻¹) and tebuconazole (125 g L⁻¹) was applied to reduce incidence and severity of Fusarium head blight at anthesis (Zadoks GS60) at all SYs. Dates

of major field operations for individual SYs are presented in Table 1.

2.2 Treatments and experimental design

The trial was designed as a split-plot with four blocks at each SY. PD was the main plot factor, and three treatments were to target low (150 plants m⁻²), medium (250 plants m⁻²), and high (350 plants m⁻²) plant densities. The medium PD is the current provincial recommendation for spring wheat production in Manitoba (Manitoba Agriculture 2020). The low PD was included as a CM strategy to reduce lodging risk (Berry et al. 2000). The high PD was included to reflect the current trend in Manitoba to use high PD to promote uniformity across fields.

The split-plot factor was a combination of N fertilizer application timing and CCC application for a total of four treatments. Two N fertilizers were included, all of the N applied at seeding and the second was a split N application. The total amount of fertilizer N was (156 kg N ha⁻¹) for both treatments, based on previous research evaluating N requirements for high-yielding spring wheat in Manitoba (Mangin and Flaten 2018). The first N treatment represented the common practice in Manitoba of applying all N fertilizers for the growing season at planting using midrow banders and conventional urea. The second N treatment was a split application, with half (78 kg N ha⁻¹) of the N applied at planting, midrow banded as conventional urea, and the second half applied at the flag leaf timing (Zadoks GS39), broadcast on the soil surface as SUPERU® (Koch Fertilizer). SUPERU® was used to reduce volatilization risk of in season applied N. Both N treatments were tested in combination with and without the PGR CCC, trade name Manipulator™620 (Belchim Canada). The PGR was applied to the canopy at the onset of stem elongation (Zadoks GS31–32) at 1.8 L ha⁻¹ using a CO₂ backpack sprayer with 100 L ha⁻¹ water volume and flat fan nozzles.

2.3 Data collection

Plots were 8 m long with designated areas for destructive and nondestructive sampling. Plant densities were determined by taking the mean of four plant counts, collected at the 2–3 leaf stage, from 1 m of row in rows 3 and 4 at the front of each plot and 1 m of row in rows 5 and 6 from the back of each plot. Canopy height was recorded from each plot at the soft dough stage (Zadoks GS85), approximately 2 weeks after anthesis for each plot. Distance from the soil surface to the spike tip (excluding awns) was measured from five randomly selected locations within the plot and averaged for each plot. LAI was measured using an ACCUPAR LP-80 Meter (METER Group, Inc., USA) at flag leaf (GS39) from five randomly selected locations in each plot and averaged to quantify canopy density for each plot.

The front 1.5 m and back 1.5 m of each plot was used for destructive sampling to quantify above-ground biomass and N uptake at anthesis (Zadoks GS65) and maturity (Zadoks GS89). Samples from 0.5 m of row length were cut at ground level from rows 4 or 5 in the destructive sampling area; the

Table 1. Characteristics of each SY including location, year, residue, soil residual nutrients, soil organic matter (SOM), and dates of key field operations.

	Site-year				
	Car18	Car19	Man18	Man19	
Location	Carman, MB	Carman, MB	Manitou, MB	Manitou, MB	
Year	2018	2019	2018	2019	
Latitude	49.496 611° N,	49.500 878° N,	49.087 722° N,	49.080 626° N,	
Longitude	98.040 352° W	98.030 846° W	98.501 826° W	98.515 924° W	
Residue type	Soybean	Canola	Canola	Canola	
Spring soil samples	Depth (cm)				
NO ₃ -N (kg ha ⁻¹)	0–120	72.5	84.9	96.9	73.0
Olsen P (mg kg ⁻¹)	0–15	8.0	13.5	9.8	25.0
K (mg kg ⁻¹)	0–15	270.0	389.0	314.0	370.5
S (kg ha ⁻¹)	0–60	242.6	117.0	119.9	105.9
SOM (%)	0–15	5.6	5.3	7.1	5.7
Soil texture	Sandy clay loam	Sandy clay loam	Clay loam	Sandy clay loam	
Field operations and treatment applications					
Seeding	7 May 2018	26 April 2019	29 April 2018	7 May 2019	
Plant growth regulator application	9 June 2018	5 June 2019	7 June 2018	14 June 2019	
Split N application	21 June 2018	20 June 2019	18 June 2018	26 June 2019	
Harvest	14 August 2018	8 August 2019	15 August 2018	23 August 2019	

Note: In crop N fertilizer treatments applied at the flag leaf growth stage with the first application made at seeding.

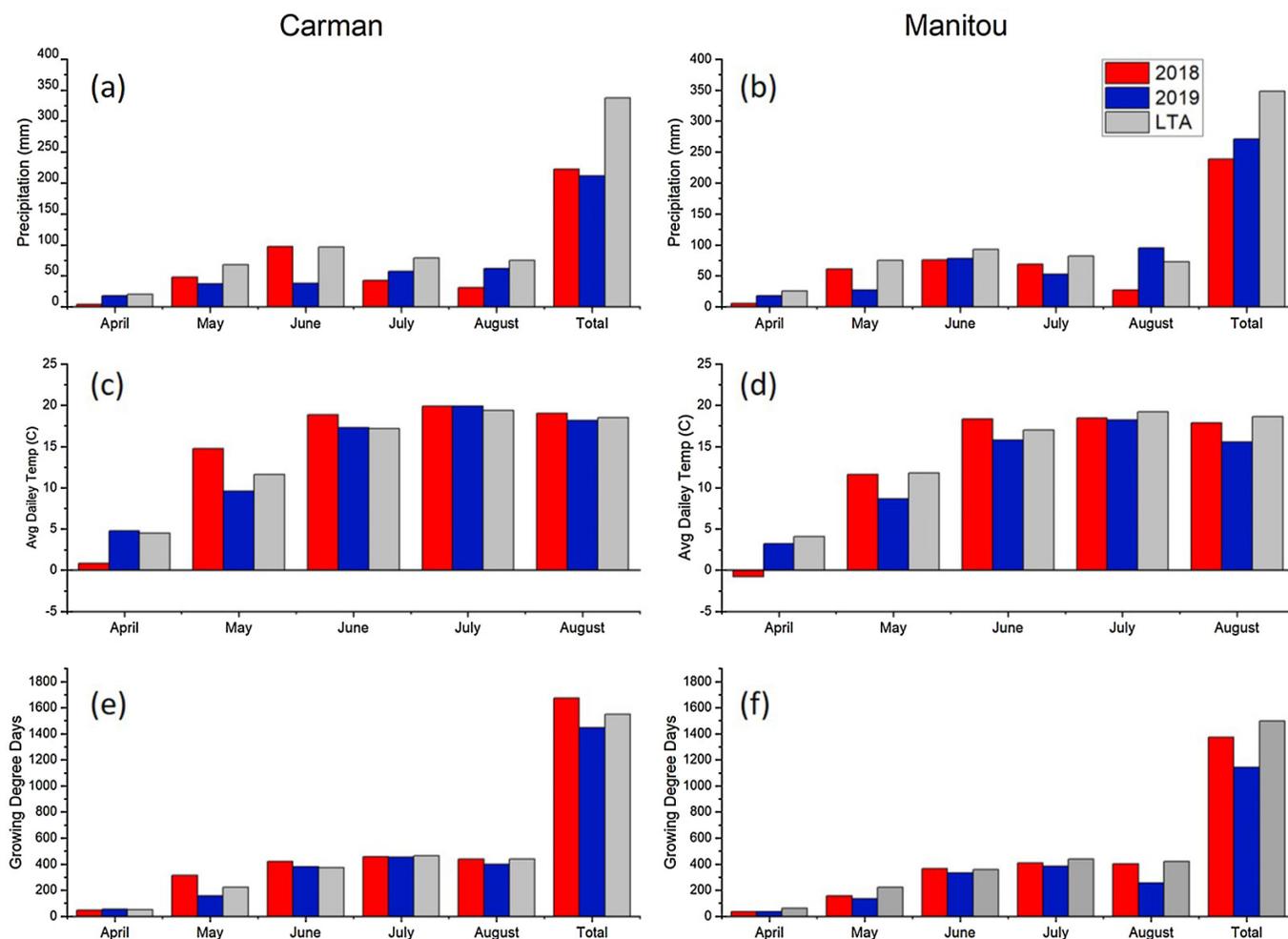
first sample was taken at GS65 when 50% of the spikes in the entire plot area were at anthesis and the second sample was taken at GS89 when 50% of the peduncles had lost green colouration. Samples were divided into leaf lamina, stem (stem + leaf sheath), and spikes, before being oven-dried at 80 °C for 24 h. Oven-dried samples of each plant part were weighed, leaf and stem tissue samples were summed together to determine vegetative dry matter (DM) and all plant parts summed to determine total above-ground DM for each sampling time. The ratios of leaf to total DM and the ratio of stem to total DM was calculated by dividing the stem or leaf DM by the total DM. Samples were then finely ground (1 mm) using a cyclone mill, and a subsample was sent to AGVISE laboratories (Northwood, ND, USA) for total N analysis by Dumas combustion (Matejovic 1995). Nitrogen content of each plant part at anthesis and maturity was then determined by multiplying the DM by total N concentration. Total above-ground N uptake was calculated at each sampling time by summing the N content of all three plant parts for each plot. Post-anthesis N uptake in the above-ground tissue was calculated by subtracting N uptake at anthesis (GS65) from N uptake at maturity (GS89) for each plot. Vegetative N remobilization (NRm) during the grain fill period was calculated by subtracting N content at maturity (GS89) in the vegetative tissue (stem, leaf sheath, and leaf) from the N content at anthesis (GS65) in similar tissue.

Lodging was rated for each plot to quantify natural lodging during the growing season after any major storm event, at anthesis (GS65), and maturity (GS89). Visual lodging ratings were taken by multiplying the % of the plot lodged (0%–100%)

by the severity of the lodging (1–9 scale). To quantify lodging risk in the absence of lodging, stalk strength was measured at anthesis (GS65) and maturity (GS89) from the centre rows at two locations for each plot using a Stalker push force meter manufactured at the Marchetto Lab at the University of Minnesota (Heuschele et al. 2019; Heuschele et al. 2020). Stalk strength was measured by pushing on 1.2 m of row length from rows 2 and 7 at half the plant height and recording the resistance force of the plant when it was pushed 45 degrees from the vertical position. Previous studies found a good relationship between stalk strength and natural lodging occurrence in spring and winter wheat (Berry et al. 2003a; Wiersma et al. 2007).

The middle 5 m of plot was used for nondestructive in-season sampling and was harvested at maturity for grain yield and N determination. Rows 1 and 8 were removed using a weed trimmer before harvest to minimize edge effects. The remaining six rows were straight cut harvested using a small plot combine (8-XP Kincaid SRES, Haven, KS, USA). The grain samples collected from each plot were cleaned using a vibratory sieve seed cleaner (C.C. King & Company, 2 mm sieve) and moisture content was determined using the GAC 2500-INTL Grain Analysis Computer (Dickey-John, Auburn, IL, USA). Grain yield and protein content were corrected to 13.5% moisture. A subsample of grain from each plot was oven-dried and finely ground (1 mm) using the cyclone mill (Retsch TWISTER, Haan, Germany) before being sent to AGVISE laboratories for total N analysis by Dumas combustion. Grain N yield was calculated for each plot by multiplying grain yield by grain N concentration. Milling protein content for each

Fig. 1. Monthly growing season (April–August) precipitation, average daily temperature, and growing degree days (GDD) for 2018 and 2019 at Carman (a,c,e) and Manitou (b,d,f) compared with the 30-year long-term average (LTA) (1988–2018).



plot was calculated by multiplying total N concentration by the factor of 5.7 (Williams et al. 1998).

2.4 Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS version 9.4 (SAS Institute 2001) with SY, PD, N timing, PGR, and their interactions as fixed factors. Random factors in the model included block nested within SY and the interaction of block with planting density to account for the split plot arrangement at each SY. Significant main plot effects and interactions between model effects ($p < 0.05$) were determined using an analysis of variance (ANOVA). Assumptions for ANOVA analysis were completed using PROC UNIVARIATE to test normality of the residual and the homogeneity of variance was examined visually. Means grouping were determined for significant effects using Tukey's HSD ($p < 0.05$). When interactions were significant the SLICE function in PROC MIXED was used to determine means groupings within individual main effects of interest. The PROC CORR procedure of SAS was used to determine the cor-

relations among plot means of response variables across all SYs.

3. Results and discussion

3.1 Growing season conditions

Overall, during the growing season, precipitation was 64%–78% of the LTA of the four SYs where the trials were conducted (Fig. 1). However, the pattern of precipitation differed between the 2 years; in 2018 early-season precipitation (May/June) was similar to LTA, with late-season precipitation being much lower for both Carman (July/August) and Manitou (August). In 2019, May precipitation was low at Manitou and both May and June precipitation were low for Carman, with July and August precipitation being similar to the LTA for both locations. Daily average temperatures were higher than the LTA in May and June at both locations in 2018, particularly at Carman. July and August temperatures similar to the LTA in 2018. In 2019, both Carman and Manitoba locations had temperatures lower than the LTA for the month of May.

Temperatures were similar to the LTA for the remainder of the 2019 season in Carman. In Manitou in 2019, average temperatures in June and July were similar to the LTA and lower than the LTA in August. The Carman 2018 SY had greater GDD compared the LTA due to high temperature in the month of May, alternatively in 2019 the Carman SY experienced lower GDDs in May leading to slightly lower growing season GDD compared with the LTA. In Manitou, the amount of GDD accumulated in 2018 was similar to the LTA, with 2019 having reduced GDDs, due to cool temperatures in August. In general, 2018 growing season was wetter and warmer than 2019 resulting in more favorable growing conditions for Carman and Manitou 2018 SYs.

3.2 Grain yield

ANOVA indicated significant effects of SY, the interaction of SY with PD ($SY \times PD$), and the main effect of PGR for grain yield (Table 2). Car18 and Man18 had significantly higher yields than Car19 and Man19 (Table 3). At both SYs in 2018, there was generally more early-season precipitation (May/June) and a greater number of GDD (April–Aug) compared with the 2019 SYs (Fig. 1), which likely led to higher yields in the 2018 SYs compared with the 2019 SYs.

At Car18, the high PD treatment resulted in 357 and 429 kg ha⁻¹ higher grain yield compared with the low and medium plant densities, respectively. There was no effect of PD on grain yield at the other three SYs (Table S1). A large number of factors contribute to the response of spring wheat grain yield to seeding rate, including genetic diversity in tillering potential, environmental conditions, and resources available to the crop (Mehring 2016; Bastos et al. 2020). Increasing PD does not consistently result in increased grain yield, but when grain yield is increased, it is commonly a result of increased spikes per hectare (Faris and De Pauw 1980; Bastos et al. 2020). Car18 accumulated a higher amount of GDDs than the LTA in May due to above normal temperatures, when the spring wheat was tillering. As a result, plants moved quickly through the tillering growth stage, which did not allow for the medium and low plant densities at Car18 to produce similar spike densities as the high PD treatment, allowing for a yield advantage through increased spike density in the high PD treatments (Table S2).

PGR application significantly increased yield by 158 kg ha⁻¹ (3%) across all other treatment factors in this experiment (Table 3). Yield responses to CCC applications are variable, with other experiments in wheat reporting no yield response (Clark and Fedak 1977; Cox and Otis 1989; Peake et al. 2020) and even yield reductions due to CCC applications (Rajala et al. 2002; Zhang et al. 2017). There was no significant change to grain yield when N fertilizer was applied as a split N application compared applying all N at planting (Tables S2 and S3).

3.3 Canopy structure

Agronomic practices have potential to reduce lodging risk in spring wheat by manipulating the canopy structure, which includes reductions in early season biomass and height of the canopy. When resources are abundant, the crop may pro-

duce unnecessary vegetative growth which increases stem and plant leverage caused by wind and rain interception, while decreasing the quantity and quality of light intercepted by the canopy, which reduces stem anchorage and strength (Berry et al. 2000; Sparkes and King 2008).

3.3.1 DM at anthesis

Total above-ground DM and vegetative DM at anthesis were not significantly influenced by SY, but the ratio of leaf to total DM and stem to total DM at anthesis varied significantly across SYs (Table 2). The two 2018 SYs had a significantly higher ratio of leaf to total DM compared with the two 2019 SYs, which followed the same trend as grain yield at each SY (Table 3). The ratio of stem to total DM was highest for Car19 (0.48), followed by Man19 (0.45) and Car18 (0.45), and lastly Man18 (0.44). This was likely due in part to the height differences between SYs. Car18 and Man18 had the overall shortest canopy heights (72.2 and 72.3 cm, respectively) corresponding to the low stem DM at these sites (data not shown).

ANOVA indicated that there was no significant influence of PD on total DM, vegetative DM, or the ratio of leaf to total DM (Table 2). However, there was a significant interaction of PD with SY for total DM, and vegetative DM. Man18 was the only SY where there was a significant effect of PD on total DM. Man18 and Car19 had significant effects of PD on vegetative DM at anthesis (Table 4). At Man18, low PD resulted in the largest total DM at anthesis (5100 kg ha⁻¹) and the high PD producing the smallest total DM (4440 kg ha⁻¹). For vegetative DM, there was a similar trend at Man18, where low PD resulted in higher vegetative DM (3743 kg ha⁻¹) compared with the medium (3463 kg ha⁻¹) and high (3277 kg ha⁻¹) plant densities. In contrast, at Car19 the high PD resulted in the highest vegetative DM (3645 kg ha⁻¹), and the low PD treatment produced the lowest vegetative DM (3330 kg ha⁻¹) (Table 4). This may be accounted for by the exceptionally low precipitation in May/June at the Car19 SY (Fig. 1).

There was a significant effect of PD on the ratio of stem to total DM (Table 2). When averaged across all other model factors, the high PD treatment had a small, but significantly higher ratio of stem to total DM (0.46) compared with both the medium (0.45) and low (0.45) PD treatments (Table 3). It was expected that low PD treatments would have had a higher stem to total DM ratio, because the low PD treatment did not reduce total spike density (Table S2). Mizuta et al. (2020) reported that reducing planting density from 400 to 200 seeds m⁻² caused an increase in dry weight per unit length of stem tissue; however, this effect was not observed in our study when examining the stem to total DM ratio.

The main effect of NT was not significant for any of the anthesis DM measurements, but there was a significant interaction between SY and NT for both total DM and vegetative DM (Table 2). At three out of the four SYs, the split N applications tended to reduce total DM at anthesis (Table 4). However, this reduction in DM was only significant at Car19 where total DM was reduced by 400 kg ha⁻¹ or 8% and vegetative DM was reduced by 319 kg ha⁻¹ or 9% (Table 4). Reduced early-season biomass is expected when N is applied as a split application because early-season N availability is lower, which will limit

Table 2. ANOVA for main effects of SY, PD, N application timing (NT), PGR, and their interactions for grain yield, protein content, and grain nitrogen (N) yield, canopy structure measurements (total anthesis DM, vegetative anthesis DM (leaf + stem), the ratio of leaf and stem DM to total DM, canopy height, LAI), N uptake and remobilization, lodging risk measurements (visual lodging rating, stalk strength measured at anthesis and maturity), maturity rating (days to anthesis (DTA)) and grain fill duration (GFD).

Sources of variation	df	Response variable																
		Grain yield	Protein content	Grain N yield	Anthesis dry matter				Canopy height	LAI	N uptake		N remobilization	DTA	GFD	Lodging	Stalk strength	
					Total	Vegetative	Leaf: total	Stem: total			Preanthesis	Postanthesis					Anthesis	Maturity
Site-year (SY)	3	***	ns	***	ns	ns	***	***	*	ns	*	***	***	***	***	n/a	*	***
Plant density (PD)	2	ns	ns	ns	ns	ns	ns	**	*	**	***	ns	***	***	***	*	*	***
SY × PD	6	*	ns	ns	***	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
Nitrogen timing (NT)	1	ns	***	***	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
SY × NT	3	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	***	n/a	ns	ns
PD × NT	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY × PD × NT	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
Plant growth regulator (PGR)	1	***	ns	*	ns	*	***	***	***	ns	ns	ns	ns	*	ns	***	ns	ns
SY × PGR	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
PD × PGR	2	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns
SY × PD × PGR	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
NT × PGR	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY × NT × PGR	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	n/a	ns	ns
PD × NT × PGR	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	***	ns	ns	ns	ns	ns
SY × PD × NT × PGR	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns

Note: LAI was measured at only the two 2019 environments due to equipment constraints. Due to a lack of natural lodging occurrence lodging rating were recorded for only one environment in 2019 (Man19) after a heavy rainfall event, n/a, not available. *Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significant at the 0.001 probability level. ns, nonsignificant.

Table 3. Least-squared means for the influence of main effects of SY, PD, NT, and PGR on grain yield and canopy structure response variables including PD, total DM at anthesis, vegetative (leaf + stem), the ratio of leaf to total DM at anthesis, the ratio of stem to total DM at anthesis, canopy height, and LAI.

	Grain yield (kg ha ⁻¹)	Plant density (plants m ⁻²)	Anthesis dry matter			Canopy height (cm)	LAI	
			Total (kg ha ⁻¹)	Vegetative	Leaf: total			Stem: total
Site-year								
Car18	5821a	192b	4660	3375	0.28a	0.45bc	72.2b	
Car19	4592b	245a	4820	3497	0.25b	0.48a	76.2a	1.98
Man18	5361a	212ab	4760	3495	0.30a	0.44c	72.3ab	
Man19	4638b	203b	4980	3536	0.26b	0.45b	73.5ab	2.10
Plant density								
Low	5108	134c	4860	3491	0.27	0.45b	74.7a	1.85b
Med	5068	213b	4810	3470	0.27	0.45b	73.3ab	2.11ab
High	5133	292a	4750	3466	0.27	0.46a	72.8b	2.17a
Nitrogen timing								
Planting	5121	215	4870	3536	0.27	0.45	73.7	2.14a
Split	5085	211	4740	3415	0.27	0.45	73.4	1.95b
Plant growth regulator								
Untreated	5024b	212	4880	3553a	0.26b	0.46a	75.3a	2.02
CCC	5182a	214	4730	3397b	0.27a	0.44b	71.8b	2.06

Note: Within columns, and main effects, means followed by the same letter are not significantly different at the 0.05 probability level as determined by Tukey HSD; absence of letters indicates no significant differences within columns. LAI was measured only at Man19 and Car19 environments due to equipment constraints. CCC, Chlormequat chloride.

Table 4. Least-squared means of the interactions of SY with PD and SY with NT for total and vegetative (leaf + stem) DM at anthesis.

	Site-year			
	Car18	Car19	Man18	Man19
	Total dry matter			
	kg ha⁻¹			
Plant density				
Low	4510	4620	5100a	5190
Med	4650	4870	4740ab	4970
High	4820	4970	4440b	4770
Nitrogen timing				
Planting	4500	5020a	4850	5100
Split	4830	4620b	4670	4850
	Vegetative dry matter			
	kg ha⁻¹			
Plant density				
Low	3551	3330b	3743a	3684
Med	3369	3517ab	3463ab	3532
High	3204	3645a	3277b	3391
Nitrogen timing				
Planting	3479	3657a	3601	3615
Split	3271	3338b	3389	3456

Note: Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level as determined by Tukey HSD; absence of letters indicates no significant differences within columns.

excessive vegetative growth (Peake et al. 2016; Wu et al. 2019; Mizuta et al. 2020).

The application of CCC as a PGR significantly reduced the vegetative DM by 156 kg ha⁻¹ or 4% when averaged across all other treatment factors (Tables 2 and 3). This was expected due to the influence of PGR applications on stem elongation. Additionally, there was a significant interaction of PGR and PD for total DM at anthesis (Table 2). The application of CCC significantly reduced total DM at anthesis from 4980 to 4630 kg ha⁻¹ the medium PD (Table S3). High PD treatments had a similar trend as the medium density, but this was not significant at $p = 0.05$. At low densities, PGR application did not reduce total DM. This was likely driven by differences in stem tissue DM. This interaction between PGR and PD was not observed in canopy height measurements as PGR reduced height similarly for all plant densities (Table 2). This indicates that the reduction in DM from a PGR application is not solely due to reductions in stem length. Crops grown under low plant densities have more tillers per plant than under high plant densities (Slafer 2007). At low plant densities, tillers emerged and developed after the main stem, which delayed DTA, compared with higher plant densities (Table 5). The increased days of vegetative growth, as indicated by DTA, observed with low plant densities may have contributed to additional DM accumulation, offsetting DM reductions resulting from reduced height when a PGR is applied.

The application of CCC had a significant effect on vegetative DM, the ratio of leaf to total DM and the ratio of stem to total DM at anthesis (Table 2). By reducing the canopy height, the application of CCC also reduced vegetative DM by 4.4% and reduced the ratio of the total DM that was stem tissue by 3.8% and increased the ratio of DM that was leaf tissue by

4.3% (Table 3). There was also a significant effect of the two-way interaction between PD and PGR for total DM at anthesis (Table 2). Total DM at anthesis was significantly reduced from 4980 to 4630 kg ha⁻¹ (7%) when CCC was applied on the medium PD treatment (Table S3). There were no significant differences in total DM for the low or high plant densities when CCC was applied (Table S3).

3.3.2 Canopy height

Overall canopy height was shorter than expected due to the dry growing season conditions experienced in this study (Fig. 1). The average canopy height significantly varied across SYs ranging from 72.2 cm at Car18 to 76.2 cm at Car19 (Table 3), which is 5–9 cm lower than the reported average plant height for the cultivar AAC Brandon (Manitoba Seed Growers' Association Inc. et al. 2020). The ANOVA also indicated that canopy height was significantly influenced by the main effects of PD and PGR (Table 2). Plant height was slightly higher at the low PD (74.7 cm) compared with plant height at the high PD (72.8 cm) (Table 3). Mehring (2016) reported a significant interaction of cultivar and seeding rate when testing the canopy height response to increased seeding rate on 12 spring wheat cultivars. Positive, negative, and neutral responses of canopy height were observed with an increased seeding rate.

PGR applications target reductions in canopy height. In this experiment, the application of CCC reduced stem height by 3.5 cm when averaged across all SYs and other treatment factors (Table 3). Height decreases with a PGR application were small due to the already short canopy, but they were consistent across all SYs, plant densities, and NTs. There was no influence of NT on canopy height (Tables 2 and 5).

Table 5. Least-squared means for main effects of SY, PD, NT, and PGR on grain N yield, preanthesis N uptake, % of total N uptake as preanthesis uptake, postanthesis N uptake, % of total uptake as postanthesis uptake, NRm during the grain fill period, DTA, and GFD.

	N uptake							
	Grain N yield	Preanthesis		Postanthesis		NRm (kg N ha ⁻¹)	DTA (days)	GFD (days)
		kg N ha ⁻¹	%	kg N ha ⁻¹	%			
Site-year								
Car18	145a	138	57	103a	43	81ab	43.6d	32.6ab
Car19	116c	128	70	56b	30	71b	48.6a	31.1b
Man18	132b	147	64	83a	36	87a	47.4b	33.9a
Man19	115c	134	72	51b	28	73b	44.5c	31.3b
Plant density								
Low	128	142a	66	73	34	82a	46.9a	32.7a
Med	126	137ab	66	70	34	78ab	45.8b	32.1ab
High	127	132b	64	75	36	73b	45.4c	31.7b
N application timing								
Planting	125b	139	67	70	33	80	46.0	32.1
Split	139a	134	63	77	37	76	46.1	32.3
PGR								
Untreated	125b	138	65	73	35	79	45.9b	32.1
CCC	128a	136	65	73	35	77	46.1a	32.3

Note: Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level as determined by Tukey HSD; absence of letters indicates no significant differences within columns.

3.3.3 Leaf area index

LAI is a measure of the leaf area per unit of ground area and is an indicator of the crop's ability to intercept the photosynthetically active radiation and can be used as an indirect estimate of shading within the canopy (Nielsen et al. 2012). LAI was only measured in 2019 due to equipment limitations. There were no significant differences in LAI measured at flag leaf among the 2019 SYs but the ANOVA indicated a significant effect of both PD and N timing on LAI (Table 2). The LAI increased from 1.85 to 2.17 from low to high PD when measured at flag leaf (GS39) (Table 3), indicating that higher plant densities may lead to increased shading within the canopy. Early season shading within the canopy has been reported to reduce stem strength of wheat, and as a result, increase lodging risk (Sparkes and King 2008). Alternatively, Peake et al. (2016) did not observe any LAI differences between high and low plant densities in winter wheat when LAI was measured at anthesis but did observe higher LAI with increased PD when measurements were collected earlier in the season at stem elongation.

Split N application also significantly lowered LA by 9% compared with when N was applied entirely at planting (Tables 2 and 3). By reducing the amount of N early in the season, the split N treatment reduced early season canopy growth, but this did not lead to yield reductions in the dry environmental conditions of this study (Table 3). However, previous work conducted in Manitoba without major moisture limitation, also did not detect a yield reduction by withholding a portion of N until the flag leaf growth stage (Mangin and Flaten 2018). Additionally, other research has demonstrated that delaying a portion of N fertilizer to later in the season decreased

canopy size without yield penalties (Berry et al. 2000; Wu et al. 2019; Mizuta et al. 2020). There was no influence on LAI of the PGR application or its interactions with other treatments (Table 2).

Reductions in canopy size have been reported to reduce lodging risk, but with reduced vegetative biomass, the amount of N accumulated and stored within the plant during the preanthesis growth stages may be reduced, having detrimental effects on the crop's ability to later remobilize N to the grain.

3.4 Grain protein concentration and grain nitrogen yield

The timing of N fertilizer application was the only factor that had a significant effect on grain protein concentration in this experiment (Table 2). On average, grain protein increased from 13.9% to 14.5% when application of half of the N fertilizer was delayed to the flag leaf growth stage (Table S1). Split N applications provide N to the crop during the later growth stages, allowing for late-season uptake and consequently increased protein concentration (Bogard et al. 2010). With the split N application, the increase in grain protein concentration, without a corresponding decrease in grain yield, led to a significant increase in grain N yield from 125 to 139 kg N ha⁻¹ (Table 5).

Grain N yield (kg N ha⁻¹) is a fundamental measure of how much N is present in the grain on an area basis and represents N without the confounding effect of the interaction between yield and protein concentration. In addition to N timing, the ANOVA indicated significant treatment effects of SY and PGR

on grain N yield (Table 2). Car18 had the highest grain N yield with 145 kg N ha⁻¹, followed by Man18 with 132 kg N ha⁻¹, both of which were significantly higher than Car 19 (116 kg N ha⁻¹) and Man19 (115 kg N ha⁻¹) (Table 5). These differences in grain N yield across SYs corresponded to the differences in yield across SYs, as average grain protein concentrations were similar at all SYs (Table S1).

The application of the PGR CCC had a small, but significant, positive influence on grain N yield (3 kg N ha⁻¹) (Table 5). This small increase could be a result of the small, but insignificant, increase in grain yield when a PGR was applied (Table 3). There were no significant effects of PD or its interactions with NT or PGR on grain protein content or grain N content in this experiment (Table 2).

3.5 N uptake and remobilization

3.5.1 Preanthesis N uptake

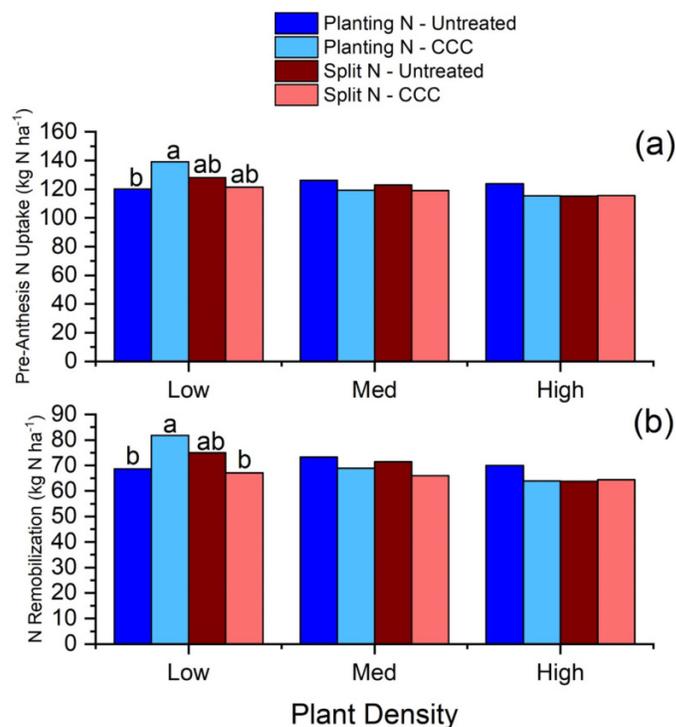
Nitrogen measured at anthesis in the above-ground tissue indicates the amount of N available for remobilization to the spike during the grain fill period (Pask et al. 2012). Gaju et al. (2014) and Pask (2009) suggested that to improve grain N yield and N use efficiency of wheat, increased N uptake prior to anthesis for remobilization during the grain fill period should be targeted. In this experiment, preanthesis N uptake was significantly influenced by SY, PD, and the three-way interaction of PD × NT × PGR (Table 2). As PD increased from low to high, there was a reduction in the preanthesis N uptake from 142 to 132 kg N ha⁻¹ (Table 5). There was a significant ($p > 0.0001$) correlation between vegetative DM at anthesis and N uptake at anthesis ($r = 0.82$) (Table S4), indicating that any reduction in biomass prior to anthesis will also likely reduce preanthesis N uptake.

The three-way interaction was attributed to higher preanthesis N uptake with the low PD, when a PGR was applied, and N was applied entirely at planting compared with the same N treatment when no PGR was applied (Fig. 2a). There were no differences in preanthesis N uptake at the medium or high plant densities. This corresponded with the increased leaf DM when a PGR was applied at the low PD to spring applied N (Fig. S1), indicating that the relationship between DM and N uptake at anthesis was driven by leaf DM accumulation. This suggests that when there are large amounts of tillering, such as with low plant densities, the application of CCC has a different influence on DM accumulation and N uptake than at higher plant densities.

3.5.2 Vegetative remobilization

The amount of N that is remobilized from the vegetative tissue into the grain is directly proportional to the amount of N taken up and stored in vegetative tissue during the preanthesis growth stages (Barbottin et al. 2005; Pan et al. 2006; Pask et al. 2012; Kong et al. 2016). There was a significant ($p < 0.0001$) correlation between preanthesis N uptake and N remobilized from the vegetative tissue (leaf lamina, leaf sheath, and stem) during this experiment ($r = 0.92$) (Table S4). As a result, any treatment which had higher preanthesis N uptake would also have higher NRm, which held true for both the main effect of PD (Table 5) and the three-way PD × N × PGR interaction (Figs. 2a–2b). Low planting densities had the highest amount of remobilization while high densities had the lowest (Table 5). Within, the low planting density, when all N fertilizers were applied at planting, the PGR treatment had greater remobilization due to the increased preanthesis N uptake at anthesis (Fig. 2a). This interaction was consistent across preanthesis N uptake and NRm (Table 2), indicating that more work is needed to explain what is driving this interaction.

Fig. 2. Interaction of low (target 150 plants m⁻²), medium (target 250 plants m⁻²), and high (target 350 plants m⁻²) plant densities with PGR application and N fertilizer application timing for (a) preanthesis N uptake and (b) NRm during the grain fill period. Bars with similar letters within each PD treatment indicate no significant difference at the 0.05 probability level.



There was also a significant effect of SY on the total amount of N remobilized during the grain fill period (Table 2). Man18 remobilized the largest amount of N during the grain fill period (87 kg N ha⁻¹), followed by Car18 (81 kg N ha⁻¹), Man19 (73 kg N ha⁻¹), and Car19 (71 kg N ha⁻¹) (Table 5). There was a similar trend in preanthesis N uptake between the four SYs; however, there were no significant differences between them. This variation in remobilization between SYs can be attributed to the compound effect of preanthesis N uptake paired with differences in GFD (Table 5). The SYs with longer GFD had more NRm. For example, Man18 had the longest GFD (33.9 days) and also the largest amount of NRm, while Car19 had the shortest GFD (31.1 days) and also the lowest amount of NRm. There was a significant ($p < 0.0001$) correla-

Table 6. Least-squared means for the interaction of SY, NT, and PGR application on postanthesis N uptake.

N timing	PGR	Site-year (kg N ha ⁻¹)			
		Car18	Car19	Man18	Man19
Planting	Untreated	101.6	49.3ab	86.0ab	54.4
	CCC	103.7	41.5b	65.4b	54.5
Split	Untreated	100.8	55.3ab	80.9ab	55.2
	CCC	103.0	73.9a	104.6a	36.9

Note: Within columns and interactions, means followed by the same letter are not significantly different at the 0.05 probability level as determined by Tukey's HSD; absence of letters indicates no significant differences within columns.

tion between GFD and NRm ($r = 0.39$) (Table S4). Remobilization of N from vegetative tissues and alterations in NRm are likely to have an influence on final grain protein and grain N yield of the crop. There was a positive correlation between NRm and grain N yield ($p < 0.0001$, $r = 0.43$), but there was no significant relationship between grain protein content and NRm because the influence of yield is not accounted for when looking at protein content alone. A second source of N for the developing grain is N that is taken up from the soil after anthesis during the grain fill period and this is prioritized to the grain for grain N content (Barbottin et al. 2005).

3.5.3 Postanthesis N uptake

Nitrogen uptake from the soil is influenced substantially by soil moisture availability and N availability, which can be unpredictable during the postanthesis period in dryland wheat production across western Canada. This could explain the significant effect of SY on postanthesis N uptake in this experiment (Table 2). Averaged across all treatments 103 kg N ha⁻¹ was taken up at Car18 during the postanthesis period; this was statistically similar to the 83 kg N ha⁻¹ taken up at Man18 (Table 5). These SYs both had larger postanthesis N uptake compared with Car19 (56 kg N ha⁻¹) and Man19 (51 kg N ha⁻¹). The differences in postanthesis uptake between SYs may be due to differences in plant available soil moisture to facilitate crop uptake and potential mineralization of organic N from the soil during the growing season (Fig. 1).

There was a three-way interaction between SY \times NT \times PGR for postanthesis N uptake (Table 2). In Car19 and Man18, postanthesis uptake was significantly increased when N fertilizer application was split and CCC was applied (Table 6). There was no significant difference between N treatments when CCC was not applied, nor between any treatments at Car18 and Man19. The application of a PGR may have facilitated late-season N uptake at the Car19 and Man18 SYs. Although not measured the application of a PGR may have led to reallocation of resources to the root system allowing for increased N uptake. Additionally, PGR application significantly increased DTA by 0.2 days, which could have allowed for a greater development of the root system, influencing N capture efficiency (Table 5). In this experiment, PGR application did not increase GFD (anthesis to maturity), indicating that the length of the postanthesis period was not causing this increase in N uptake with PGR application. There is currently very little literature exploring the relationship between a PGR application and the response of the rooting sys-

tem to PGRs due to the difficulty in quantifying the below ground portion of the plant.

There was no benefit to the split N application on postanthesis N uptake at Car18 and Man19 (Table 6). This indicates that late-season soil N supply was sufficient when N was applied entirely at planting for these SYs. In-season losses of N from seeding to flag leaf at these SYs were probably very small due to dry conditions. Additionally, low soil moisture during the grain fill period likely reduced the crop's ability to take advantage of additional N provided late in the season and resulted in little benefit to split N application (Barbottin et al. 2005).

The amount of N taken up postanthesis had a positive correlation with final grain N yield ($p < 0.0001$, $r = 0.39$) (Table S4). This indicates the importance of both vegetative NRm and postanthesis N uptake for grain N-yield production, with 57%–72% of N taken up preanthesis and 28%–43% taken up postanthesis in this study (Table 5). However, postanthesis uptake of N can be extremely variable depending on growing season conditions, as observed by the large variation in postanthesis uptake across SYs in this study (51–103 kg N ha⁻¹) (Table 5). Nitrogen taken up earlier in the season, stored in the vegetative tissue, and remobilized to the grain is a much more reliable and consistent source of N for the developing grain and ranged from 71 to 87 kg N ha⁻¹ (Table 5). Sufficient soil moisture in the spring for early-season N uptake is much more predictable due to soil moisture recharge by previous fall precipitation and spring snowmelt in western Canada.

3.6 Lodging risk

3.6.1 Lodging ratings

CM through reduced seeding rates, split N fertilizer applications, and PGR applications have been shown to decrease lodging risk by reducing leverage placed on stems and (or) by increasing stem and anchorage strength (Berry et al. 2000; Sparkes and King 2008; Wu et al. 2019; Mizuta et al. 2020). At all SYs of this experiment, conditions were drier than normal (Figs. 1A–1B), resulting in short crop canopies with very little lodging pressure (Table 7). However, there was one small lodging event at Man19 after a heavy rainfall on 31 July 2019. At Man19, PD, PGR, and PD*PGR had a significant effect on lodging ratings (Table 2). Low plant densities had negligible amounts of lodging, but lodging increased as the PD increased to medium and high (Table 7). Averaged across

Table 7. Least-squared means for the main effects of SY, PD, NT, and PGR on lodging ratings and stalk strength measured at anthesis and maturity.

		Lodging rating (0–9 scale)	Stalk strength (newtons)	
			Anthesis	Maturity
Site-year	Car18	n/a	n/a	12.36a
	Car19	n/a	3.24a	5.07b
	Man18	n/a	n/a	13.23a
	Man19	0.73	2.53b	6.09b
Plant density	Low	0.05b	3.10ab	10.11a
	Med	0.83ab	3.18a	9.19b
	High	1.29a	2.37b	8.27c
N timing	Planting	0.75	2.66	9.11
	Split	0.70	3.11	9.27
PGR	Untreated	1.17a	2.68	8.86
	CCC	0.28b	3.09	9.52

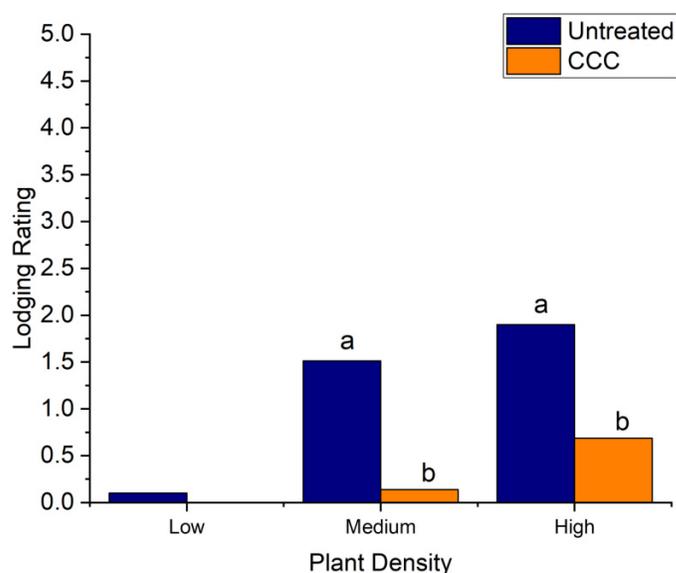
Note: Lodging ratings were taken only at Man19 environment due to very low natural occurrence of lodging at all other environments. Lodging ratings were calculated by multiplying the lodging severity (0–9 scale) by the % of the plot lodged. Stalk strength at anthesis was measured only at the two 2019 environments due to equipment limitations. Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level as determined by Tukey HSD; absence of letters indicates no significant differences within columns

all other treatments, the application of CCC significantly reduced lodging ratings from 1.17 to 0.28 (Table 7). The ANOVA also indicated a significant interaction of PD with PGR, which revealed that when lodging did occur, at high and medium plant densities, PGR applications significantly reduced lodging (Fig. 3). However, when there were very low levels of lodging in the low plant densities, there was no difference in lodging occurrence (Fig. 3). These results, although limited by low lodging pressure, indicate that the application of a PGR is a valuable in season tool to reduce lodging when high-lodging risk conditions are present and management practices such as high plant densities and high N fertilizer rates are used.

3.6.2 Stalk strength

Stalk strength measurements were taken to quantify the risk of crop canopy lodging and reduce the reliance on natural lodging for treatment differentiation. Even with low levels of lodging that occurred during this experiment a significant negative relationship ($p = 0.0011$, $r = -0.29$) between lodging ratings and stalk strength measurements at maturity was observed (Table S4). As expected, stalk strength was higher at maturity than anthesis (Table 7). At anthesis, the crop has just finished a rapid stem elongation phase and during the grain fill period a wheat crop deposits structural compounds that thicken stem cell walls and strengthen the stem, allowing for support of the developing grain (Jung et al. 1993). At both growth stages, the only factors that resulted in significant effects on stalk strength were SY and PD (Table 2). At anthesis, plants at Car19 had significantly higher stalk strength than Man19 (Table 7). At maturity, Car18 and Man18 had significantly stronger stalks than Car19 and Man19 (Table 7).

Fig. 3. Interaction of the plant densities (low (target 150 plant m^{-2}), med (target 250 plants m^{-2}), and high (target 350 plants m^{-2})) and a PGR application for visual lodging ratings at the Man19 SY lodging ratings were calculated by multiplying the lodging severity (1–9 scale) by the % of the plot lodged. Bars with different letters within each PD treatment indicate significant differences at the 0.05 probability level; absence of letters indicates no significant differences between columns.



At both growth stages, stalk strength was lower for high plant densities and increased as PD was reduced (Table 7). Reduced lodging and increased stalk strength with low plant densities is very well-documented (Fischer and Stapper 1987;

Webster and Jackson 1993; Berry et al. 2000, 2004; Whaley et al. 2000; Mizuta et al. 2020). Lower seeding rates increase tillering of each plant, increasing crown roots and size of the structural root plate. Additionally, decreased shading early in the growing season with low plant densities results in increased stem diameter, increased wall thickness, greater number of vascular bundles, lignin and cellulose content, and increased dry weight per unit length, resulting in increased stem strength (Berry et al. 2000; Whaley et al. 2000; Tripathi et al. 2003; Peng et al. 2014; Zheng et al. 2017).

Nitrogen fertilizer application timing and PGR applications did not have a significant effect on stalk strength at either time during this experiment (Table 2). However, there was a trend for both split N and PGR applications to increase stalk strength (Table 7). Other studies have found that delaying a portion of N to later in the season has proven to reduce canopy size and, in turn, increase the crop's ability to resist lodging (Wu et al. 2019). Decreased lodging and improved stalk strength associated with split N applications result from decreased shading early in the season, similar to that of reduced plants density (Peake et al. 2016; Wu et al. 2019; Mizuta et al. 2020). PGRs have been reported to increase stem diameter, increase degree of stem filling and stem wall width, all of which could lead to increased stalk strength and decrease lodging risk (Berry et al. 2000; Zhang et al. 2017).

Unfortunately, there was not enough natural lodging to allow for an accurate estimation of the relationships between DM at anthesis with lodging. With the conditions experienced in this experiment, the only relationship between early-season DM and stalk strength at anthesis was a weak negative relationship ($p = 0.0436$, $r = -0.20$) (Table S4). To get a better estimation of the relationships between lodging, stalk strength and canopy size, a larger-sample size would be required across a wider range of environmental conditions with varying lodging pressure.

4. Overall discussion and conclusions

Low seeding rates, PGR applications, and splitting fertilizer N all showed potential to manage the crop canopy and reduce lodging risk in spring wheat grown in western Canada. However, there was a general lack of lodging and lower than expected yields obtained during this study due to hot and dry environmental conditions. Canopy size, measured by above-ground DM at anthesis and canopy height, showed inconsistent treatment responses, depending on the response variable. It is possible that DM was measured too late in the season to capture vegetative differences in early-season canopy size that could result in potential-lodging differences between treatments (Sparkes and King 2008). DM samples taken at stem elongation (GS31–32) may have provided a better relationship with lodging risk compared with DM sampled at anthesis (GS65). LAI measurements indicated that high plant densities and N fertilizer applied entirely at planting consistently increased canopy leaf area, regardless of all other treatment factors, even though DM measurements were rarely impacted. Due to the low incidence of natural lodging during this experiment, reliable estimates of the relationship between canopy size and lodging could not be obtained. Further

investigation is warranted as stalk strength measurements suggested that the CM strategies of low plant densities, split N, and PGR application may reduce lodging occurrence in environments more favorable to lodging.

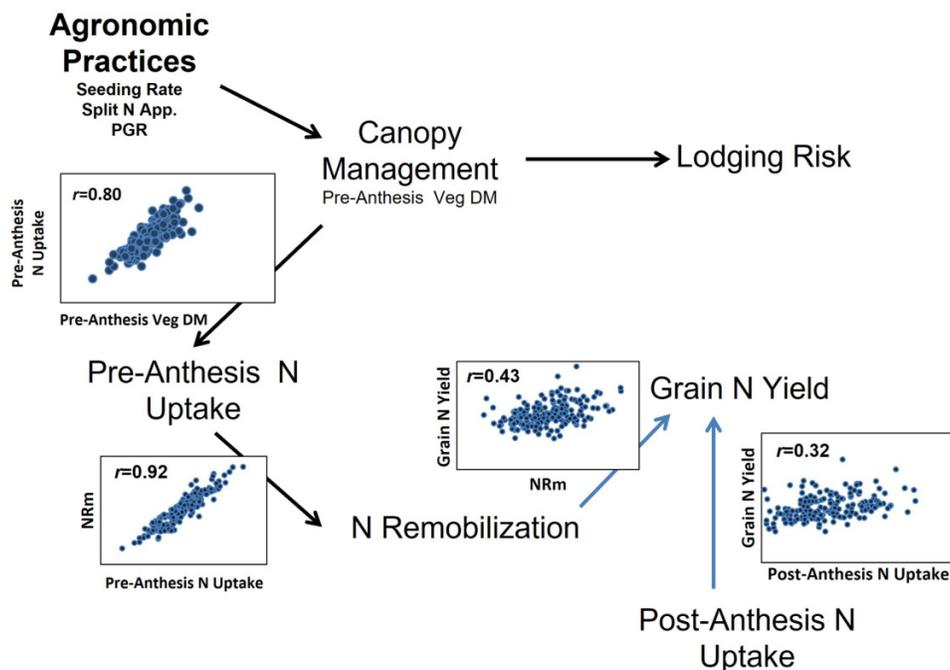
Vegetative DM at anthesis was highly correlated to pre-anthesis N uptake, which then influenced NRm during the grain fill period. This relationship is visualized in Fig. 4. The amount of N provided to the grain from NRm during the grain fill period (72–87 kg N ha⁻¹) was similar to the amount of N from postanthesis uptake (51–103 kg N ha⁻¹), indicating the importance of both N sources for grain N. However, the variability in postanthesis N uptake was much larger than that of N uptake at anthesis and remobilization. This indicates that N taken up early in the growing season, when moisture is typically plentiful in western Canada, and then later remobilized to the grain, is the most reliable source of grain N. In comparison, N taken up from the soil during the grain fill period relies heavily on growing season precipitation. When canopy size is reduced in the preanthesis period, the capacity of the crop to store N is reduced; therefore, making the crop more dependent on late-season N uptake for grain N yield and protein content. However, in this experiment, when modest yields (4592–5821 kg ha⁻¹) were achieved, grain N yield and protein content were not reduced with these CM strategies, as postanthesis N uptake was substantial at all SYs ranging from 28% to 36% of total N uptake during the growing season.

With the modest yields achieved in this experiment, there were no detrimental effects of reducing early season canopy size through CM treatments (low PD, split N, PGR application) on grain yield, grain protein concentration, or grain N yield. Additionally, PGR applications and split N fertilizer applications both increased final grain N yield by 2.4% and 11.2%, respectively. Increases in grain N yield attributed to the split N fertilizer application compared with when N was applied entirely at planting, were a result of increased grain protein concentrations (from 13.9% to 14.5%), rather than increases in yield. PGR applications increased grain N yield by increasing grain yield, with no significant effect on protein concentration. However, CWRS wheat is marketed based on yield and grain protein concentrations rather than grain N yield. As a result, the driving factor-influencing grain N yield increases will result in differing profitability of a crop, depending on protein premiums available in any given year and market.

This study indicated that CM strategies such as reduced PD, application of the PGR CCC, and split application of N have potential to reduce lodging risk, with low risk of reducing crop yield or grain protein concentration in the Canadian Prairies. However, reducing early season vegetative biomass may come with additional risks that were not explored in this research. The early season crop may be at a competitive disadvantage to weeds, which would affect weed management programs. Additionally, low plant densities, resulting in increased tillers per plant can lead to nonuniform anthesis timings between spikes, making the timing for fusarium head blight fungicide application and harvest timing difficult.

Results from this study should be validated in higher-yielding environments and across additional cultivars and growing regions of western Canada. AAC Brandon was the

Fig. 4. Conceptual diagram for relationships between DM, N uptake at anthesis, NRm, lodging, and grain N yield, including Pearson correlation coefficients (r) between variables. Due to the lack of lodging pressure during the experiment, the measured relationship between canopy management and lodging risk is unknown.



only cultivar used in this experiment. AAC Brandon is a semidwarf cultivar and may respond differently to PGRs, N management and plant densities compared with other CWSR cultivars. Lastly, even though dry conditions were experienced in this study, on average, the black soil zone of Manitoba has high growing season moisture compared with many other CWSR wheat growing regions of the Canadian Prairies, which will typically facilitate more late-season N uptake. In regions of the western Prairies that typically receive lower levels of growing season precipitation, reducing crop canopy size through CM strategies such as low plant densities, split N, and PGR applications may limit early N uptake and grain N yield due to lower N availability within the plant for remobilization to the developing grain.

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Author information

Author ORCIDs

Amy Mangin <https://orcid.org/0000-0002-7318-0108>

Author contributions

AM: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing—original draft. AB-B: Formal analysis, Methodology, Supervision, Writing—review and editing. DF: Conceptualization, Funding acquisition, Methodology, Writing—review and editing. JJW: Methodology, Writing—review and editing. YL: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing—review & editing.

Competing interests

The authors declare there are no competing interests.

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Supplementary material

Supplementary data are available with the article at <https://doi.org/10.1139/CJPS-2021-0287>.

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