

**Agronomic practices to minimize lodging risk while maximizing yield and protein potential
of spring wheat in the eastern Canadian Prairies**

by

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ABSTRACT

Mangin, Amy R., Ph.D., University of Manitoba June 2022. Agronomic practices to minimize lodging risk while maximizing yield and protein potential of spring wheat in the eastern Canadian Prairies. Ph.D. Co-Supervisors: Dr. Yvonne Lawley and Dr. Anita Brûlé-Babel.

Spring wheat is one of the most economically important crops grown on the Canadian prairies. Improvements in genetics and agronomy have resulted in higher yields obtained by producers, but have introduced challenges such as maintaining grain protein content and managing increased lodging risk. The objectives of this thesis research were to evaluate the effect of agronomic management practices such as N management, plant density, plant growth regulator (PGR) application and their interactions on spring wheat lodging risk, grain yield and protein content of spring wheat in the eastern Canadian prairies. This was done through two small plot field trials in south central Manitoba during the 2018 and 2019 growing seasons using cultivars common to, and widely grown across Manitoba. Early season N availability was critical for the development of yield components and allowed the crop to buffer against dry environmental conditions to produce grain protein. However, increased lodging risk associated with application of large amounts of N early in the season needs to be balanced with lodging management strategies. Low plant densities (150 plants m⁻²) and PGR applications improved the crop's ability to resist lodging in this research. The lowest plant densities tested (150 plants m⁻²) allowed the crop to better resist both root and shoot lodging through increases in stem and anchorage strength and stem flexibility indicators compared to the highest densities tested (350 plants m⁻²). Low plant densities are often associated with decreased early season competitive ability against weeds and more variable crop maturity, neither of which are desirable. Therefore, the ability of PGRs to reduce lodging risk, through increased stem strength and reduced leverage, provides a critical tool for lodging management in spring wheat in regions with high yield potential and lodging pressure. Flexibility of application and yield increases, even in the absence of lodging, through increased kernels per spike, support a wide adoption of this technology as yields are likely to continue to rise in the future across the Canadian Prairies.

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FOREWORD

The thesis includes an introduction, literature review and five research chapters followed by general discussion and conclusions. The research chapters contain work conducted at the University of Manitoba from January 2018 to January 2020. The research chapters are written in the format of *Agronomy Journal* and follow the guidelines defined by the Faculty of Graduate Studies and the Department of Plant Science, University of Manitoba, Winnipeg, MB, CA. In 2022, chapters 3 and 4 were published in *Agronomy Journal*, chapter 5 has been published in *Canadian Journal of Plant Science* and chapter 7 is accepted for publication to *Agronomy Journal*.

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CHAPTER 1. INTRODUCTION

Modern spring wheat cultivars capable of yielding higher than in the past are being grown widely across the Canadian prairies. With these cultivars comes a new set of challenges to manage the agronomic, economic, and environmental risks associated with higher input requirements. Spring wheat grown across the Canadian prairies is known worldwide for exceptional milling quality (Cereals Canada et al. 2019). As yields rise, this quality can only be achieved by increasing nitrogen (N) availability to the crop. The efficiency of the fertilizer to produce yield and protein decreases with higher N fertilizer application (Barraclough et al. 2010; Hawkesford & Riche 2020). Lower N use efficiency can lead to higher environmental losses and reduce return on fertilizer investment. Current N management practices that apply conventional urea, a form of N prone to losses, entirely before, or at, planting can lead to lower N use efficiency. Improved fertilizer and application technologies such as enhanced efficiency fertilizers and in-season fertilizer applications have increased the N management options available to producers (Hawkesford 2014).

The occurrence of lodging is highly dependent on environmental conditions and can be widespread across wheat growing regions of the Prairies. Lodging reduces yield and quality of the crop (Berry 2018). The application of high rates of N fertilizer, paired with high yields increases lodging risk for spring wheat production on the Prairies. Agronomic management strategies can be used to reduce lodging risk, while maximizing grain yield and protein (Berry et al. 2004).

Two different forms of lodging can occur in wheat fields: stem lodging and root lodging. Plant morphology and stem structural composition determines lodging risk of the plant. The plant characteristics most influential for root and shoot lodging are not necessarily the same, and agronomic management practices are thought to influence these plant characteristics differently (Berry et al. 2004). Therefore, there is a need to determine the most effective agronomic management strategy or combination of strategies that manipulate plant morphology to decrease lodging risk while maximizing resource partitioning to the developing grain.

Agronomic management practices that have had the largest influence on lodging risk in winter wheat in European studies include nitrogen management, plant density reductions and the use of plant growth regulators (PGRs) (Berry et al. 2000). Although these strategies are not new

to Canadian wheat production, their influence on lodging risk needs to be investigated for dryland spring wheat production, particularly in the eastern Canadian Prairies where moisture supplies are often sufficient for high yields with increased lodging risk. The short growing season with unpredictable environmental conditions in the Canadian prairies, compared to other high-yielding wheat growing regions of the world, will likely lead to region-specific lodging risk management considerations to ensure grain yield and protein levels are not compromised.

1.1 Overall Thesis Objective

The overall objectives of this thesis were to determine how agronomic management through N management, plant density, PGR application and their interactions influence spring wheat lodging risk, grain yield and protein content of spring wheat.

1.2 Specific Thesis Objectives

The specific objectives of the research were:

- To evaluate the ability of agronomic management practices, such as N fertilization strategies and PGR applications, to maximize grain yield in the eastern Canadian Prairies (Chapter 3).
- To determine which yield components affect grain yield response of current high-yielding spring wheat cultivars grown under intensive agronomic management practices (Chapter 3).
- To determine the potential of the PGR chlormequat chloride and N fertilization strategies to reduce lodging risk of spring wheat (Chapter 3).
- To determine N uptake, accumulation, and remobilization patterns of high-yielding spring wheat cultivars and how these patterns are influenced by agronomic practices such as N management and PGR application (Chapter 4).
- Measure the N use efficiencies for grain N production by spring wheat and potential for improvement through agronomic management in the eastern Canadian Prairies. (Chapter 4)
- Determine the effect of plant density, split N application, and application of CCC on early-season CWRS wheat vegetative growth and lodging risk (Chapter 5).

- Determine how canopy biomass alterations, through agronomic management, influence crop N uptake and remobilization for grain N yield in CWRS wheat (Chapter 5).
- Determine the ability of spring wheat management (PGR, cultivar selection, N management, and planting density) to decrease leverage and increase stem and anchorage strength (Chapter 6).
- Determine the effect of PGR application on lodging risk when used in combination with cultivars, N management and planting densities commonly used in western Canadian wheat production (Chapter 6).
- Demonstrate the potential of a new push force meter to evaluate the influence of agronomic management practices such as plant density, N application timing, and PGR applications on both stem and root lodging (Chapter 7).
- To identify which stem elasticity measurements (displacement, energy, power) have potential to differentiate between agronomic practices when measured at anthesis and maturity in wheat (Chapter 7).

CHAPTER 2. LITERATURE REVIEW

2.1 Spring Wheat Production in Western Canada

In 2020, Canadian farmers produced 25.8 million metric tonnes of spring wheat, 98% of which was produced on 7.1 million hectares in the prairie provinces of Alberta (35%), Saskatchewan (45%) and Manitoba (18%) (Statistics Canada 2020). Canadian wheat is grouped into classes based on properties that influence end use including, protein concentration, kernel hardness, gluten strength and kernel colour (Canadian Grain Commission 2019). In western Canada there are nine milling classes of wheat, with Canadian Western Red Spring (CWRS) accounting for 60% of annual spring wheat production in 2019 on the Prairies due to its excellent protein strength, milling characteristics, and flour and end-use quality (Cereals Canada et al. 2019).

Spring wheat yields across western Canada are higher than ever due to improved genetics and the adoption of improved agronomic management practices. Thomas and Graf (2014) used data collected from provincial seed guides and on farm yields from the Manitoba Management Plan Plus program to estimate that from 1991 to 2013 yield increased by 1.4% per year across western Canada with contributions from genetics and management. When evaluating wheat yields in cultivars released from 1885 to 2012, Iqbal et al. (2016) concluded that genetics contributed to a yield increase rate of 0.28% per year for CWRS cultivars. Even with higher yields being achieved, there is still a considerable yield gap between spring wheat yield potential and actual yields attained. Chapagain and Good (2015) quantified a 24% yield gap related to management and a 18% yield gap related to improper variety selection for rainfed spring wheat in Alberta, Canada.

The higher the yield potential, the higher the input requirements, especially fertilizer, to achieve high yields and quality. The majority of the spring wheat grown in western Canada is in dryland production (Statistics Canada 2020), with unpredictable moisture supply during the growing season. This makes it difficult to predict the seasonal yield potential and efficiency of crop inputs and may increase the agronomic, economic, and environmental risks of production.

2.2. Yield Components

The final yield of a spring wheat crop is made up of four yield components, plant density, spikes per plant, kernels per spike and kernel weight. Each yield component is determined at different times during the growing season and will be dependent on the resources and environmental conditions, or stresses, present when they are being determined (Slafer 2007). All yield components affect final crop yields. However, the level of plasticity of each component varies. Kernel weight has a low level of plasticity and will only account for small changes in yield, while plant density and spikes per plant are highly plastic and may be responsible for large variations in yield (Slafer et al. 2014).

2.2.1 Plant Density

Plant density is determined largely on the seeding rate chosen by farmers, seed germination percentage of the seed lot used, and mortality. The recommended target plant density to maximize production in Manitoba is 250 plants m⁻² (Manitoba Agriculture and Resource Development 2018). Seed mortality and optimum seeding rates for individual farm operations are based on planting methods, spring fertilizer applications, and environmental conditions (Bastos et al. 2020; Mehring et al. 2020).

Some cultivars will have higher mortality levels regardless of germination percentage, likely due to genotype specific responses to stresses. Gent et al. (1997) quantified differences in mortality base on whether a cultivar was a dwarf (61%), semi-dwarf (48%), or tall (39%) genotype. Variation in mortality has also been reported within semi-dwarf cultivars due to sensitivity to seeding depth (Robbins 2009). The semi-dwarfing alleles *Rht-B1b* and *Rht-D1b* are both known to reduce coleoptile length, and as a result have high mortality with deeper seeding depth, compared to *Rht8* semi-dwarfs that do not reduce coleoptile length (Robbins 2009).

The effect of plant density on final grain yield is largely determined by specific environmental conditions during a growing season. Mehring (2016) reported that seeding rate for maximum yield increased as average yield in an environment decreased, and vice versa. Additionally, this relationship can be cultivar specific. For example, as seeding rate increased, yield decreased in high yielding environments only for cultivars with weak stem strength, when environmental conditions were conducive for lodging (Mehring 2016). Tillering capacity of a

specific cultivar is also an important factor for determining how plant density will influence final grain yield. Stanley et al. (2020) developed a decision tree for selecting the optimum seeding rate of hard red spring wheat based on straw strength, estimated yield potential in an environment, and tillering capacity of a cultivar.

2.2.2. Spikes per Plant

Spikes per plant is a key yield component which is determined by tiller initiation, development, and survival as the crop matures (Slafer 2007). Tillers are initiated and emerge continuously until resources become limited, or the plant encounters unfavorable environmental conditions, resulting in tiller mortality. Tillers are produced from the 3-leaf to jointing growth stage (GS31) (Zadoks et al. 1974) in an exponential pattern until resources become limited, and then tillers die in the reverse order of emergence until the period immediately before anthesis (GS60) when no new tillers are formed (Slafer et al. 2014). This highlights the ability of spring wheat to compensate for plant density and adjust the number of spikes per plant to match resources available during the early growing season (Slafer et al. 2015). Genotypic variation in tillering is present among cultivars of hard red spring wheat which leads to differences in tiller production and survivability (Hucl and Baker 1989; Mehring et al. 2020; Stanley et al. 2020)

Mehring (2016) reported a range of spikes per plant from 2.06 to 2.64 when evaluating tillering potential across a wide range of modern hard red spring wheat cultivars. With current management practices, tillers may contribute a large portion to final grain yield in wheat. In North Dakota, under growing conditions similar to Manitoba, Otteson et al. (2008) determined that 53-56%, 31-33%, 10-12% and 2% of yield was accounted for by the main spike, first tiller, second tiller and third tiller, respectively. A study conducted in Saskatchewan, using older cultivars and cultivation practices reported 67% of total grain yield was produced by the main stem and first two tillers (Hucl and Baker 1989).

Agronomic management practices such as nitrogen (N) fertilization and plant growth regulator (PGR) applications have potential to influence the final number of spikes per plant in spring wheat. If N fertilizer is limited, or withheld, during the pre-anthesis growth stages, lower tiller production and survivability have been reported, leading to fewer final spikes per plant (Strong 1982; Mossedaq and Smith 1994; Borghi 1999; Weisz et al. 2001; Montemurro et al. 2007; Otteson et al. 2007, 2008). Application of gibberellin (GA) inhibitor PGRs have been

reported to increase the final number of spikes per plant in cereals by increasing tiller survival (Waddington and Cartwright 1988; Craufurd and Cartwright 1989).

2.2.3. Kernels Per Spike

The number of kernels per spike is determined by the number of spikelets and florets initiated, and floret survival within each spikelet (Slafer 2007). Floret initiation takes place from approximately the 3-leaf (GS13) to jointing (GS31) growth stages, by producing 6-12 floret primordia per spikelet. Floret survival is very low with only 20-30% of total florets continuing development during the stem elongation (GS31-39) growth stage due to resource limitations (water and assimilates) (Slafer et al. 2014). Entz and Fowler (1988) reported that environmental conditions from the 2-leaf (GS12) to anthesis (GS60) growth stages in winter wheat were critical for kernels per spike development in the Canadian Prairies. More specifically, Fischer and Stockman (1980) reported that resource limitation through shading of the crop 10-13 days pre-anthesis resulted in the biggest reductions in kernel number per spike. An increase in photosynthetic radiation has been shown to have a positive relationship to kernel number per spike, while high temperatures during anthesis had a negative relationship with final kernel number per spike, when water and nutrient supply was ample (Slafer et al. 2014).

Similar to spikes per plant, any management practice that influences availability or allocation of resources to the plant during the critical period of kernel development will influence the final number of kernels set per spike. Very low N fertilization rates, as well as withholding a large portion of N fertilizer until after flowering, have been shown to reduce kernel number per spike (Otterson et al. 2007). The application of PGRs targets a reduction in stem elongation, which coincides with the timing of floret death (Kirby 1988). When a PGR reduces stem elongation, resources that would have been allocated to stem elongation may be reallocated to the developing spike, increasing floret survivability, and final number of kernels per spike (Peltonen-Sainio and Rajala 2001).

2.2.4. Kernel Weight

Kernel weight is typically the least plastic of all yield components, with alterations only resulting in minor yield changes (Sadras and Slafer 2012). Silva et al. (2020) tested 21 winter wheat cultivars under two management intensities and determined that kernel weight explained

only 6% of the variation in yield among yield components. Kernel weight is a product of carpel size, determined largely in the pre-anthesis stage, and kernel fill, determined during the grain fill period from anthesis to maturity (Calderini et al. 2001; Entz and Fowler 1988; Xie et al. 2015). Unfavorable conditions during the grain fill period, such as high temperatures and low moisture supply have the ability to reduce final kernel weight (Wiegand and Cuellar 1981; Altenbach et al. 2003; Slafer et al. 2014). There are genetic variations in kernel weight among cultivars, with kernel weight being a more heritable trait than kernel number (Slafer et al. 2014). Wang et al. (2003) evaluated differences between cultivars registered between 1994 - 1997 and cultivars registered between 1960 – 1969 and determined that increased kernel weight in new cultivars was due to an increase in rate of grain fill, allowing for greater assimilate accumulation during the grain fill period.

There is typically a negative relationship between kernel weight and number of kernels per spike, leading to low kernel weights when high kernel numbers per spike are achieved. Lower kernel weight associated with higher kernel number per spike could be a product of increased seed set of tertiary and quaternary florets that produced smaller kernels (Slafer 2007). Alternatively, resource competition when a high number of kernels are set could also influence this relationship. Slafer (2007) states that resource competition immediately after anthesis, when the number of endosperm cells is being determined, or when carpel size is being determined a few days before anthesis, are most important for the negative relationship between kernel number and kernel size.

The influence of agronomic management on kernel weight is inconsistent in the literature, but was commonly accounted for through the negative relationship with kernel number per spike. Studies have reported no change in kernel weight as N fertilizer rates change (Tariq Jan and Khan 2000), or a decrease in kernel weight when increases in N rates result in yield increases (Otterson et al. 2007). Otterson et al. (2007) observed no differences in kernel weight with in-season N fertilizer applications when N was applied at a suboptimal rate, but kernel weight increased at high N rates with late split N applications.

2.3. Nitrogen Use in Spring Wheat

Nitrogen fertilizer is the largest annual input cost for spring wheat crop production, as large amounts of N are required to produce high yields with grain protein concentrations suitable for milling. This large investment prompts continued interest to maximize N use efficiency (NUE) to produce grain N yield, especially because as N fertilizer application rates increase, the efficiency of use is decreased (Foulkes et al. 2009; Barraclough et al. 2010; Brasier et al. 2019). The NUE of wheat is composed of two major processes. The first is the crop's ability to take up N (residual or fertilizer) from the soil, and the second is the ability of the plant to allocate that N towards grain N either directly or through remobilization. Both processes are largely influenced by genetics, management, and environmental conditions (Hawkesford and Riche 2020).

2.3.1. Nitrogen Uptake

Nitrogen is taken up from the soil by spring wheat using mass flow and diffusion into the rooting system. Therefore, the amount of N taken up at any time during the growing season will depend heavily on soil moisture supplies, N availability in the soil, and the crop's rooting system (Barbottin et al. 2005; Foulkes et al. 2009). Rooting traits that are critical for improving N capture from the soil include root axis number, rooting depth, root density, and root longevity during the post-anthesis period (Foulkes et al. 2009).

Wheat has the ability to take up N during the entire growing season, but there are stages when N is taken up more rapidly. In winter wheat, 17% of the total N uptake occurred from planting to tillering (GS00-20), 82% occurred from tillering to heading (GS20-50), and less than 2% was taken up from heading to maturity (GS50-87) (McGuire et al. 1998). This low level of N uptake during the post anthesis growth stages agrees with many other studies in winter wheat that reported on average 0 to 30% of total N uptake occurred during this period (Pask et al. 2012; Barraclough et al. 2014; Brasier et al. 2019; De Oliveira Silva et al. 2021). Malhi et al. (2006) determined that the maximum rate of N uptake for spring wheat in western Canada was between the tillering and stem elongation (GS20-30) growth stages, while the maximum amount of N uptake during the season was reached at anthesis (GS60), with negligible uptake after anthesis. When comparing different cultivars of hard red spring wheat in western Canada, Wang et al. (2003) also reported maximum N uptake at the anthesis growth stage (GS60) in two out of three testing years, with less than 10% of total uptake occurring after anthesis in the third testing year.

In contrast, Przednowek (2003) reported that on average 23% of the total crop N uptake occurred during the post-anthesis growth stages in the black soil zone of Manitoba.

The total amount of N taken up during the post anthesis growth stage is dependent on genotype and N fertilization (Wang et al. 2003; Kichey et al. 2007; Barraclough et al. 2014). When very high rates of N fertilizer are applied at planting, or when additional N fertilizer is applied during the growing season, increasing the availability of soil N available to the crop during the post-anthesis growth stage, late season uptake commonly will increase compared to when modest N rates are applied entirely at planting (Kichey et al. 2007; Pask et al. 2012; Barraclough et al. 2014). The ability of the crop to take up N post-anthesis is desirable, as it has been shown to allow for increased grain protein concentrations without a reduction in yield that is typically seen with the negative grain yield/protein relationship (Bogard et al. 2010; Hawkesford 2012; Barraclough et al. 2014). The deviation from the common negative relationship is thought to be due to N being allocated directly to the developing grain. However, if by increasing the post-anthesis uptake, pre-anthesis uptake is reduced, as reported across some cultivars, high levels of post-anthesis uptake may be negatively associated with grain yield, as early season N uptake is a main driver of grain yield (Gaju et al. 2014).

2.3.2. Nitrogen Assimilation

When N was not limited for uptake, on average across 20 cultivars of wheat grown in the UK, 189 kg N ha⁻¹ was taken up in the above ground portion of the plant prior to anthesis (Barraclough et al. 2014). Of that 189 kg N ha⁻¹, the leaf blades accounted for 35% of the N, leaf sheath 14%, true stem 28% and spike 23%. Foulkes et al. (2011) did a similar evaluation and determined that 35% of the above ground N at anthesis was in the leaf blades, and 30% was in the true stem with the remaining 35% divided between the leaf sheath and spike (not differentiated). When N was insufficient, a higher percentage of N was allocated to the spike compared to other plant parts, indicating the spike was the primary sink for N over the leaf and stem (Gaju et al. 2014).

When N is taken up during the pre-anthesis growth stages, it is assimilated into vegetative tissue and used for photosynthesis, primarily as Rubisco, or as a structural protein within supporting tissue and vascular connections (Foulkes et al. 2009). Nitrogen can also be stored in the vegetative tissue, particularly the true stem, as reserve N, that doesn't appear to serve an

immediate function, but can be remobilized during the grain fill period to the spike (Foulkes et al. 2009; Pask et al. 2012; Barraclough et al. 2014).

Pask et al. (2012) defined and quantified where each pool of N was located at the anthesis growth stage in wheat. Photosynthetic N was primarily located in leaf blades and sheaths (91%), with only 7% located in the spike and 2% in the true stem. The photosynthetic N was entirely remobilized to the spike during the grain fill period. Structural N was defined as the amount of N remaining in the vegetative tissue at maturity. The true stem accounted for 33% of the total structural N, with 27%, 25%, and 15% allocated to the spikes, leaf blades and sheaths, respectively. The reserve N was defined as the total N subtracted from the functional N (photosynthetic N plus reserve N). The true stem accounted for 48% of the total reserve N, while the spike had 25%, leaf blade 15%, and leaf sheath 13%. There was also indication that as stem length was increased, the total amount and portion of reserve N in the true stem was increased, indicating that internode length may be related to reserve N storage (Pask et al. 2012). Nitrogen that is present in vegetative tissue at anthesis is an important source of N for grain N if the plant has the ability to remobilize and transport the N to the developing grain to synthesize grain proteins. Remobilization and transport of N is reliant on where and how the N is assimilated within the vegetative tissue. Gaju et al. (2014) concluded that genetic selections should target increased leaf N accumulation prior to anthesis to optimize N utilization and grain N in future cultivars. Wang et al. (2003) reported that advances in cultivar development resulted in more efficient N remobilization by the crop during grain fill, rather than more efficient uptake of N from the soil.

2.3.3. Nitrogen Remobilization

The proportion of total grain N attributed to N remobilized from vegetative tissue can range from 40 – 90% (Kichey et al. 2007; Kong et al. 2016). This portion is likely underestimated because calculations are done using the N budget method, which doesn't account for N remobilized from the root system, or any N that may have been replaced by N absorbed during the post-anthesis period (Kichey et al. 2007). However, Critchley (2001) and Wang et al. (2003) concluded that leaves and stems are the most important sources of remobilized N, with roots and chaff contributing a much smaller amount. It was thought that N stored as reserve N in vegetative tissue was remobilized before photosynthetic N, as canopy green area and

photosynthetic rate were not reduced in the early post-anthesis growth stages, while total N content in the vegetative tissue was being reduced (Pask et al. 2012). Typically, a lower percentage of N is remobilized from tissue with a higher proportion of structural N, such as the true stem, than other plant tissues (Pask et al. 2012). Nitrogen remobilization efficiency ranges from 75-80% for the leaf blade, 18-61% for the leaf sheath, 20–73% for the true stem, 47% for the roots, and 16-56% for the chaff (Kichey et al. 2007; Pask et al. 2012; Kong et al. 2016).

The start of N remobilization is triggered by the N demand of developing grain, and then the rate and total amount of remobilization is thought to be regulated by source (N available for grain fill) and sink (number of kernels) relationships (Kong et al. 2016). The amount of N accumulated by the plant in the pre-anthesis growth stage has a highly positive correlation with the total amount of N remobilized during the grain fill period (Kichey et al. 2007; Pask et al. 2012; Gaju et al. 2014). Kichey et al. (2007) reported a highly significant ($P < 0.05$) linear relationship between N uptake at anthesis and N remobilization during the grain fill period ($R^2 = 0.99$). Pask et al. (2012) observed that N remobilization was driven by N supply in vegetative tissue up to an upper limit of 1.1–1.2 mg N grain⁻¹, after which the process seemed to be sink limited.

There are a number of factors that influence the rate and total amount of remobilization during the grain fill period. The amount of N that the crop takes up during the post-anthesis period has been shown to alter remobilization. Gaju et al. (2014) reported a negative correlation between post-anthesis N uptake and N remobilization from both the leaf lamina ($r = -0.75$ to -0.79) and the true stem ($r = -0.63$ to -0.80). This agreed with other studies, indicating that N taken up post-anthesis may be preferentially transported to the spike to meet N demand of the grain (Bogard et al. 2010; Pask et al. 2012; Kong et al. 2016). Due to this relationship, any environmental condition that reduces the crops' ability to take up N post-anthesis has been shown to increase N remobilization. For example, low soil moisture and soil N availability during grain fill have increased N remobilization efficiency by up to 13% in wheat (Barbottin et al. 2005; Kong et al. 2016). Plant stress from high temperatures during the grain fill period was shown to reduce total N remobilization, primarily by reducing the grain fill duration; however, the rate of remobilization during that time was increased (Kong et al. 2016). Duration of grain fill is commonly positively related to increased total N remobilization within a plant; therefore,

any factors that are known to increase grain fill duration, such as high N fertilization or fungicide applications, increase total N remobilization (Hawkesford 2012).

There is strong evidence that genotypic variation exists for a crop's ability to accumulate and remobilize N during the season (Barbottin et al. 2005; Foulkes et al. 2009; Hawkesford 2012). Foulkes et al. (2009) demonstrated that between cultivars, regardless of N fertilization rate or environment, the range of N remobilization efficiency in the above ground tissue was 52 – 92%. This could be indirectly due to cultivars' differences in maturity and resistance to diseases and lodging. When disease and/or lodging incidence are high, the ability of the crop to translocate N is reduced (Barbottin et al. 2005). When there were no differences in disease pressure or lodging during the grain fill period, differences in remobilization between cultivars were often small and total remobilization could be estimated with the same linear equation ($=4.13 + (\text{N uptake at anthesis} \times 0.76)$, $R^2=0.97$).

2.4. Lodging

Lodging is defined as the displacement of the plant from the vertical position (Berry et al. 2004). Lodging commonly occurs later in the season after stem elongation and during grain fill. The most severe yield losses occur when lodging takes place between anthesis and the beginning of grain fill (Fischer and Stapper 1987). Berry and Spink (2012) developed a model to predict yield loss from lodging and determined that lodging at 90 degrees from vertical at the milk stage (GS75) would result in a 61% yield loss. In extreme cases, up to 80% of entire field yields have been lost due to lodging (Berry 2004). Yield loss from lodging can be a result of reduced assimilation and translocation of resources, increased respiration, increased disease susceptibility, and difficulties collecting the crop during combining operations (Berry et al. 2004). Lodging can also result in reduced kernel and test weight, and increase the risk of sprouted grain (Berry et al. 2004; Acreche and Slafer 2011).

Lodging risk in a particular year is influenced by a very complex set of factors, which include weather, soil moisture levels, topography, pest pressure, cultivar selection, and management (Berry et al. 2004). As a result, differences in lodging can occur on several scales, including between regions, between farms, and between or within fields. Furthermore, two types of lodging can occur in wheat; stem and root lodging which are not necessarily caused by the

same factors. Additionally, plant characteristics that help the plant resist stem lodging seem to be opposite to those that help resist root lodging (Farquhar and Meyer-Phillips 2001).

2.4.1 Stem Lodging

Stem lodging occurs when the leverage on an individual stem from wind and rain exceeds the stem strength, resulting in bending or breaking of the lower internodes (Berry et al. 2004). The amount of leverage placed on the stem by wind and rain events is influenced by plant morphological characteristics. Tall, dense canopies are more likely to intercept wind and rain, therefore, increasing the leverage (Berry et al. 2007).

Stem strength, the ability of the stem to resist being bent or broken, is also largely dependent on the crop's morphological characteristics and structural composition. Parametric analysis from models developed to predict lodging determined that the crop parameters most influential for stem lodging included stem height, stem diameter and wall width, and stem composition (Baker et al. 1998; Berry et al. 2003). The quantity, as well as arrangement, of stem structural fiber components, including lignin, cellulose, and hemi-cellulose, and non-structural carbohydrates can have an influence on stem strength (Jung et al. 1993; Wang et al. 2012; Peng et al. 2014; Nguyen et al. 2016). Analysis of spring wheat varieties from registration trials using Fourier transform infrared resonance (FTIR) spectroscopy identified that cellulose content, rather than lignin content, had the strongest relationship to a cultivar's ability to resist lodging (Wang et al. 2012). It has been suggested that the arrangement and interactions between structural components of stem walls may have a greater influence on stem strength and the ability to resist lodging than the absolute concentration of the individual compounds. However, preferential arrangements and interactions have not been fully defined (Knapp et al. 1987; Wiersma et al. 2011).

2.4.2. Root Lodging

Root lodging occurs when the wind and rain induced leverage exerted on the entire plant exceeds the anchorage strength and the plant rotates at its windward edge, resulting in the displacement of an entire plant rather than independent stems (Crook and Ennos 1993; Crook et al. 1994). Unlike stem lodging, root lodging is highly dependent on soil conditions such as moisture content, clay content, and soil compaction (Baker et al. 1998). As soil moisture and

clay content increase, soil strength is reduced greatly, making the crop more prone to root lodging. In contrast, compaction increases soil strength, reducing root lodging occurrence. Baker (1998) observed that the occurrence of precipitation had a stronger relationship with root lodging than the amount of precipitation, with root lodging occurring with as little as 4 mm of precipitation. A wind tunnel experiment showed that once soil was saturated, root lodging could occur very quickly (less 5 minutes), with relatively low wind speeds of only 8 m s^{-1} and gusts of 10 m s^{-1} (Sterling et al. 2003a).

The main plant characteristics that influenced anchorage strength in wheat included the width and depth of the structural rooting area (Crook and Ennos 1993; Baker et al. 1998; Berry et al. 2007). The structural rooting area is defined by the parts of the crown root that are surrounded by a rhizosheath and have an outer ring of lignified tissue in addition to the lignified central stele in the roots (Crook et al. 1994; Berry et al. 2000, 2007). The structural rooting width and depth were directly related to the number of tillers per plant. As tillers per plant increased, the number of crown roots increased (Whaley et al. 2000).

2.4.3. Lodging Management

There are a number of methods that can be used to management lodging. The crop canopy characteristics that are most responsible for the crop's ability to resist lodging may respond differently to management practices (Berry et al. 2000).

2.4.3.1. Cultivar Selection

Cultivar selection is the most common management strategy used to manage lodging in cereals. During the 1960s and 1970s there was a large shift to the incorporation of semi-dwarfing genes into spring wheat varieties to reduce height, and as a result, reduce lodging potential (Berry et al. 2004). Semi-dwarfing genes can be categorized based on their sensitivity to gibberellin (GA), with *Rht-B1* and *Rht-D1* being insensitive and *Rht8* being sensitive (Robbins 2009). A screen of 82 spring wheat varieties registered in Canada determined that eight had the *Rht-B1b* and 13 had the *Rht-D1b* dwarfing alleles (Chen et al. 2016). Height reductions that occur in response to the GA insensitive dwarfing genes result in decreased stem length due to reductions in stem elongation (Robbins 2009). By shortening stems and reducing lodging risk, cultivars with semi-dwarfing alleles often have the added benefit of being higher yielding

because of their higher harvest index and ability to respond positively to higher rates of N fertilizer by being less prone to lodging (Gent and Kiyomoto 1997; Robbins 2009).

Among cultivars that have a similar semi-dwarfing allele, there is genetic variation in plant height and other plant characteristics that will result in differences in lodging resistance in the field. Genetic variation has been reported for stem diameter, stem wall width, root plate width and depth, tillering potential, internode length, and degree of filling (Kelbert et al. 2004; Otteson et al. 2007; Chen et al. 2016; Piñera-Chavez et al. 2016).

2.4.3.2 Plant Growth Regulators

Plant growth regulators (PGR) are synthetic compounds, which are used in cereal production, to reduce plant height, and as a result, have been reported to reduce lodging in fields by up to 70% (Rademacher 2015). This is mainly achieved by reducing cell elongation, but also by decreasing the rate of cell division which can reduce spring wheat height by 0 – 40% (Berry et al. 2004; Matysiak 2006; Rademacher 2015; Zhang et al. 2017). Plant growth regulators can be classified into two main groups: inhibitors of GA biosynthesis, and ethylene-releasing compounds. However, GA inhibitors are the most commonly used PGRs in western Canadian cereal production. Among the inhibitors of GA biosynthesis in cereal crops, chlormequat chloride (CCC), mepiquat chloride and trinexapac-ethyl (TXP) are most commonly used. Chlormequat chloride blocks the early steps of GA metabolism, whereas trinexapac-ethyl blocks a later step in the GA biosynthesis pathway (Rademacher 2000a). Gibberellin inhibitors such CCC and TXP are foliar-applied during the growing season, usually at the beginning of stem elongation for cereal crops. Because GA inhibiting PGRs act on a hormonal system, they can influence a wide range of plant morphological characteristics that can affect lodging resistance, in addition to plant height, grain yield and quality.

There are contrasting reports of the response of cereal tillering patterns to the application of GA inhibitors. A number of studies showed increased tiller production and survival with the application of CCC at stem elongation (Craufurd and Cartwright 1989; Whaley et al. 2000; Peltonen-Sainio and Rajala 2001). This increase in tiller production may be due to an indirect relationship of the GA inhibitor with photoperiod response, therefore making plants behave as though they are experiencing short-day conditions and reducing apical dominance (Craufurd and Cartwright 1989). The indirect influence of GA inhibitors on levels of other plant growth

hormones, such as auxins and cytokinins, that have a major role in apical dominance, may also play a large role in the effect of GA inhibitors on tillering (Evans 1984; Ma and Smith 1991, 1992; Harrison and Kaufman 2013). Alternatively, Cox and Otis (1989) did not see an increase in tiller production or survival in winter wheat with the application of CCC in a two-year research study. Similarly, CCC applied at the onset of stem elongation (GS31) or as a double application at stem elongation (GS31) and flag leaf (GS39) did not influence winter wheat tiller production (Berry et al. 2000).

Plant characteristics that are directly related to stem strength such as stem diameter, stem wall width and structural fibre content can also be altered with the application of a GA inhibiting PGR. Stem strength, when measured with breakage tests, commonly reveal increased stem strength with PGR applications (Crook and Ennos 1995). When measured in the field with a push force device at the soft dough stage, stem strength was 20% greater than the control when TXP was applied at the highest rate of 250 g ai ha⁻¹, but was not significantly different from the control when lower application rates (62.5 – 125 g ai ha⁻¹) of TXP were applied (Wiersma et al. 2011). Zhang et al. (2017) observed increased breakage strength of stem internode segments with applications of TXP and CCC to spring wheat varieties. In contrast, applications of CCC have also resulted in decreased strength of the stems (Crook and Ennos 1993; Berry et al. 2000).

Responses to individual factors that have potential to increase stem strength are variable. The influence of CCC application on stem diameter and wall width was variable and ranged from no significant difference to a highly significant increase with application (Crook and Ennos 1993; Berry et al. 2000; Zhang et al. 2017). Zhang et al. (2017) evaluated CCC and TXP applications across six Canadian spring wheat varieties in a greenhouse study and observed increased stem diameter, stem wall width and therefore, degree of stem filling, with all PGR applications, regardless of cultivar. Degree of stem filling was attributed to increased proportions of sclerenchyma and parenchyma tissue in stems. Additionally, measurement of cell size and number in stem walls revealed that plants treated with a GA inhibitor had a greater number of cells that were shorter by 37.6 - 52.3% and wider by 11.3 – 22.7% compared to cells in the untreated plants stem walls.

Alterations of stem structural composition in response to applications of GA inhibitors have been reported in only a small number of studies, even though GA's are known to stimulate

differentiation in fibre cells (Rademacher 2000b). Zhang et al. (2017) reported increased lignin content in wheat stems treated with the PGRs CCC and TXP. A high rate (250 g ai ha⁻¹) of TXP applied to spring wheat increased concentrations of acid detergent lignin by 12.8% compared to the low rate of TXP (92.3 g ai ha⁻¹), but neither application rate was significantly different than the untreated control (Wiersma et al. 2011). In contrast, a number of studies have shown no significant responses of structural fiber content to PGR application (Clark and Fedak 1977; Knapp et al. 1987). This has led to the hypothesis that the increases in stem strength from GA inhibiting PGRs are likely due to changes in the interactions and arrangement of the structural fiber components, rather than the absolute amounts. (Clark and Fedak 1977). An increased proportion of sclerenchyma and parenchyma tissues, the degree of stem filling, and the number of total cells in an analysis of stem cross sections was reported as a response to PGR applications (Zhang et al. 2017).

Structural rooting width and depth response to plant growth regulator application has been measured in only a very limited number of studies. The application of CCC has not been shown to alter structural root width or depth at maturity (Crook and Ennos 1995; Berry et al. 2000), even though Crook and Ennos (1995) observed an increase in total crown root number with CCC application in wheat. Many other studies have reported effects of PGRs on cereal root growth, but these usually either include the distal roots, that play no role in anchorage, or report effects during early growth stages that are not maintained until maturity, and therefore, do not influence lodging resistance (De et al. 1982; Steen and Wunsche 1990; Rajala and Peltonen-Sainio 2001, 2002).

The responses of yield to GA inhibitor application are very inconsistent in the absence of lodging. Yields have been reported as unchanged (Clark and Fedak 1977; Cox and Otis 1989), increased (Waddington and Cartwright 1988; Rajala et al. 2002; Matysiak 2006), and decreased (Rajala and Peltonen-Sainio 2002; Zhang et al. 2017) with the application of GA-inhibiting PGR. When yield increases do occur in response to PGR application, they have been attributed to an increased number of kernels per spike (Matysiak 2006). Early application before, or at the beginning, of stem elongation may increase kernel number per spike by initiating more spikelets and florets per spike. In contrast, applications later in the stem elongation phase may be due to

decreased abortion of spikelets and florets as the application would be after the double ridges stage when spikelet differentiation occurs (Craufurd and Cartwright 1989; Rajala 2003).

2.4.3.2. Nitrogen Fertilization

It is well documented that high rates of N fertilizer will increase lodging risk of a cereal crop. Lodging risk increases with N application rates through increased plant height (or stem length), decreased stem diameter and wall width, excessive above ground foliar growth and reduced stem and root strength (Mulder 1954; Kasperbauer and Karlen 1986; Ayoub et al. 1993; Crook and Ennos 1995; Berry et al. 2000). This has led to alternative N management strategies that allow for high rates of N fertilizer to be applied without increasing lodging risk.

Delaying the application or availability of a portion of N fertilizer until after stem elongation can reduce lodging risk in cereals without sacrificing grain yield or protein. Ayoub et al. (1993) reported reduced lodging occurrence when N was applied as a split application (60% plantings and 40% heading), compared to when applied entirely at planting at one out of four environments tested.

By reducing the portion of N applied at, or before, planting, early season vegetative growth is reduced. This can decrease shading within the canopy, which alters the quality and quantity of light within the canopy (Berry et al. 2000; Sparkes and King 2008; Wu et al. 2019; Mizuta et al. 2020). There is evidence that as shading within the canopy is reduced, stem strength is increased due to slower stem elongation that allows for increased stem diameter, stem wall width and deposition of lignin in stem tissue (Berry et al. 2000; Sparkes and King 2008; Mizuta et al. 2020). Additionally, high rates of N applied early in the season promote tall dense canopies that intercept more wind and rain, which increases leverage placed on the crop, an effect that can be partially mitigated with delayed N application (Mulder 1954; Berry et al. 2000; Mizuta et al. 2020).

Delaying the timing of N availability during the growing season, whether through split N applications or controlled-release fertilizers, comes with risk in dryland production due to unpredictability of in-season precipitation to facilitate N uptake and yield production (Holzapfel et al. 2007). However, if precipitation is not limited during the growing season, there is

commonly no negative impact on yield and there are often positive impacts for grain protein when N availability is delayed (Karamanos et al. 2004; McKenzie et al. 2006; Grant et al. 2012).

2.4.3.3. Plant Density

Reduced plant densities have been reported to increase the crop's ability to resist lodging during the growing season by increasing both stalk and anchorage strength (Faris and De Pauw 1980; Berry et al. 2000; Tripathi et al. 2003; Zheng et al. 2017). Similar to reducing the N fertilizer early in the growing season, low plant densities can reduce shading and competition for light, resulting in stronger stem development (Berry et al. 2000; Zheng et al. 2017). Zheng et al. (2017) reported increases in stem wall diameter, stem wall width and lignification in sclerenchyma and vascular bundles in response to reduced plant densities in spring wheat. The abundance of sclerenchyma cells in the cortex and vascular bundles increased, resulting in a more compact arrangement of cells in plant stems grown in a low plant density compared to high plant density.

In response to early season shading, anchorage strength may be reduced due to increased partitioning of assimilates to the shoot rather than root. This can lead to reduced root development in high plant densities compared to low plant densities (Kasperbauer and Karlen 1986). It is widely known that as plant density decreases, tiller production per plant increases in wheat (Berry et al. 2000, 2004; Whaley et al. 2000). Structural rooting spread and depth were directly related to the number of tillers per plant. As tillers per plant increased, the number of crown roots increased (Whaley et al. 2000). Berry et al. (2000) reported that reducing plant density from 400 plants m⁻² to 200 plants m⁻² increased anchorage strength by 50%, which was accounted for by increased root number, thicker roots, and a wider, deeper structural rooting area. The increased number of tillers per plant with low plant densities will increase the total leverage placed on the plant by wind and rain; however, the better anchorage strength in low plant densities is great enough to compensate for the increased leverage and provides further resistance to lodging (Berry et al. 2000, 2004; Sterling et al. 2003b)

CHAPTER 3. MAXIMIZING SPRING WHEAT PRODUCTIVITY IN THE EASTERN CANADIAN PRAIRIES I. YIELD, YIELD COMPONENTS, AND LODGING RISK

3.1 Abstract

Spring wheat yields across the Canadian prairies are rising; however, a yield gap remains between average yield and yield potential, which can be explored further under Prairie conditions. The high rates of nitrogen (N) fertilizer required for current high-yielding cultivars may increase lodging risk, adding to this yield gap. The objectives of this study were to determine the influence of intensive management through N fertilization and plant growth regulator (PGR) application, on grain yield, yield components, and their relationships, in addition to lodging risk. Field trials were conducted at two locations in 2018 and 2019 in Manitoba, CA to evaluate three high-yielding spring wheat cultivars, three N management strategies, and the application of a PGR. Kernels per spike had the strongest overall linear relationship with grain yield ($r^2=0.47$), while the response of spikes per plant was highly related to yield response with alterations in N and PGR management practices ($r^2=0.98$). Splitting N fertilizer applications showed potential to reduce lodging risk of spring wheat, while maintaining yield and increasing protein. PGR applications reduced lodging and increased grain yield by 91 kg ha⁻¹ mainly through increases in kernels per spike. To achieve consistent yield increases, management practices should maximize early season N availability to target increases in spikes per plant and kernels per spike; thus a PGR application may be required to balance increased lodging risk.

3.2. Introduction

Wheat accounts for approximately 35% of the total Canadian cropland in annual production each year and 77% of that wheat area is spring wheat (Statistics Canada 2020). Over the past 20 years, average hard red spring wheat yields in the eastern Canadian Prairies have risen by over 59% (from 2513 to 4245 kg ha⁻¹) and are continuing to rise (MASC 2020). Even with these increases in wheat yield, there is still approximately a 20% yield gap between regional average yields and regional yield potential in western Canada (Chapagain and Good 2015). Examination of the influence that intensive high-yielding management practices have on individual yield components, as well as the relationships between yield and yield components, could help to close the yield gap.

Wheat grain yield consists of four components, plant density, spikes per plant, kernels per spike and kernel weight (Wang et al. 2003; Slafer et al. 2014). Plant density is primarily driven by seeding rate, but final plant density achieved is also influenced by growing season conditions such as moisture and pest pressure (Mehring et al. 2020). Wheat will compensate for low plant stands by producing additional stems per plant, called tillers, to capitalize on resources and space available (Bastos et al. 2020). Tiller development begins at the three-leaf stage and continues exponentially until stem elongation, or when resources become limited (Slafer et al. 2015b). From stem elongation to anthesis, a portion of tillers die in the reverse order of emergence until the final spike-bearing tiller number is set based on resource availability and environmental conditions. (Slafer et al. 2015b; Tilley et al. 2019). In similar growing conditions to the eastern Canadian Prairies, Mehring (2016) reported a range of spikes per plant from 2.06 to 2.64 when evaluating tillering potential across a wide range of modern hard red spring wheat cultivars.

Kernel number per spike has a large influence on final grain yield. For any specific cultivar, the number of kernels set per spike is closely related to resources available to the plant from the beginning of stem elongation to anthesis (Fisher 1985; Slafer et al. 2014). Slafer et al. (2015b) supported this finding with reports of reduced kernel number only when the crop was resource limited after the stem elongation phase and there was no influence on kernels set per spike with resource reductions at earlier growth stages. Kernel weight accounts for a much smaller proportion of variability in grain yield compared to kernel number per spike (Slafer et al. 2014). Although, similar to kernel number per spike, kernel weight varies with cultivar, but

within a cultivar, changes are usually accounted for by environmental conditions (Slafer et al. 2014; Lollato and Edwards 2015). Conditions between heading and anthesis, as well as during grain fill, are critical for kernel weight determination (Calderini et al. 2001; Entz and Fowler 1988). High temperatures and inadequate moisture during grain fill have been reported to reduce kernel weight (Wiegand and Cuellar 1981; Slafer et al. 2014). A negative relationship between kernel weight and kernel number has been reported. This relationship is strongest when comparing across cultivars and is weaker when comparing across environments (Slafer et al. 2014, 2015b). An increased number of smaller kernels being set in distal florets or increased resource competition between kernels while kernel size and weight are being determined are driving this negative relationship (Calderini et al. 2001; Slafer et al. 2014, 2015b). The negative relationship between kernels number and kernel weight may be overcome in response to genetics, agronomic management, and the growing season environment (Slafer et al. 2014, 2015b). Agronomic management practices can alter the duration and timing of growth stages and resource availability to the crop during the growing season. As a result, it is not likely that all management practices influence grain yield through similar yield components (Slafer et al. 2015a). Further yield increases of current cultivars may be achieved by understanding which yield components are contributing to yield responses from intensive management practices.

Current spring wheat cultivars grown across western Canada are achieving much higher yields than in the past (Thomas and Graf 2014), and as a result, high rates of nitrogen fertilizer are required to maximize productivity, while risks of lodging and N losses are increased (Berry et al. 2004; Lollato and Edwards 2015). A recent study in Manitoba demonstrated that 30 kg N ha⁻¹ of combined soil residual N and applied N fertilizer were required per kilogram of grain yield to optimized economic levels of grain yield and protein (Mangin and Flaten 2018). Due to the short growing season, nitrogen (N) fertilizer is primarily applied prior to or at planting in the eastern Canadian Prairies, even though the period of rapid uptake doesn't begin until the stem elongation phase (Malhi et al. 2006). This strategy leaves N fertilizer vulnerable to losses in the early growing season and promotes unnecessary early season vegetative growth which can increase lodging risk through shading effects (Berry et al. 2004).

Withholding a portion of N fertilizer until the crop is established may reduce N losses, increase final grain protein concentrations, reduce shading effects, and allow for adjustments in

total N rates based on crop establishment and current growing season conditions (Berry et al. 2004; Strong 1982; Karamanos et al. 2004). A major limitation of this strategy is the uncertainty of growing season precipitation to facilitate crop N uptake when N is applied in crop during the short spring wheat growing season of the Canadian Prairies. Research in the dark brown soil zone of Saskatchewan demonstrated the risk of delaying a portion of N fertilizer into the growing season in years when yields were reduced due to low in-season precipitation (Holzapfel et al. 2007). Controlled release nitrogen products applied at planting are an alternative strategy to in-season N applications. They are used to limit N fertilizer losses when large amounts of N fertilizer are applied in advance of crop requirements by only releasing N to the soil for uptake when soil moisture and temperature conditions are favorable for crop growth, in theory, matching N supply with crop demand to reduce losses and maximize uptake (Shoji et al. 2001).

Lodging is the displacement of a crop from the vertical position that typically occurs after stem elongation when kernels are filling (Berry et al. 2004). Many factors influence lodging risk including environmental conditions, topography, soil type, cultivar, management practices, and diseases (Berry et al. 2004). When lodging occurs, there is reduced carbon assimilation by the canopy, decreased translocation of resources to the spike for grain fill, and increased susceptibility to pests and disease (Berry et al. 2004). This results in grain yield reductions of 10-40% and up to 80% in extreme cases. Yield loss is greatest when lodging occurs at anthesis or early grain fill (Rademacher 2016). Grain quality can be compromised by lodging through decreases in kernel weight, protein content, milling and baking quality and increased mycotoxin presence. Harvest operations can be impacted when lodging occurs with up to a 50% reduction in harvesting speeds and increased grain drying requirements (Berry et al. 2004; Berry and Spink 2012; Rademacher 2016).

Plant growth regulator (PGR) application is currently the only tool that growers have available to manage lodging risk in-season, in response to the growing season conditions. Plant growth regulators are foliar-applied synthetic compounds that decrease stem length by reducing stem cell elongation and the rate of cell division (Berry et al. 2000; Rademacher 2000). Inhibitors of gibberellin biosynthesis, such as chlormequat chloride (CCC) and trinexipac-ethyl (TXP), are the most widespread PGR's used in cereals across western Canada. Gibberellin inhibitors are applied at the onset of stem elongation resulting in a shorter canopy which reduces

the leverage exerted on the canopy by wind and precipitation to decrease lodging risk (Berry et al. 2000). The influence of a PGR application on lodging occurrence is not solely associated with reduced canopy height, as even when the canopy has been shortened, there are not always reductions in lodging during the growing season (Knapp et al. 1987). Additionally, there have been reports of decreased lodging occurrence with the application of a gibberellin inhibitor when little or no canopy height reductions were seen (Sterling et al. 2003). This would support the concept that stalk strength can be increased with a gibberellin inhibitor application, but results of this effect in the literature are extremely inconsistent and at present the mechanisms of stalk strength increases are unknown (Berry et al. 2000).

With the current genetics, producers across the Canadian prairies are targeting higher spring wheat yields than ever before. This is especially true in the eastern Prairies that has historically had more precipitation to support higher yields. As a result, N fertilization requirements have grown, increasing production risks and the need for management practices that mitigate the agronomic, economic, and environmental risks without sacrificing grain yield. To allow for further increases in yield, this study aimed to evaluate the influence of intensive management practices on individual yield components and lodging risk under eastern Prairie growing conditions in Manitoba. The specific objectives of our study were to (1) evaluate the ability of agronomic management practices, such as N fertilization strategies and PGR applications, to maximize grain yield in the eastern Canadian Prairies; (2) determine which yield components are driving grain yield response of current high-yielding spring wheat cultivars grown under intensive agronomic management practices; and (3) determine the potential of the PGR chlormequat chloride and N fertilization strategies to reduce lodging risk of spring wheat.

3.3. Materials and Methods

3.3.1 Site Descriptions and Agronomic Management

Field experiments were established on conventional tillage fields in 2018 and 2019 at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB and in a commercial field near Manitou, MB. Soils were sampled at 0-15, 15-60, and 60-120 cm depths for characterization of residual soil nutrient levels and texture in the spring before planting at each location (Table 3.1). Daily weather data (precipitation, maximum and minimum temperature)

from seeding to harvest were collected using a WatchDog 2700 series weather station (Spectrum Technologies, Aurora, IL, USA) located at each experimental site.

Seeding rate was calculated for each spring wheat cultivar to target the recommended plant density of 250 plants per m² (Manitoba Agriculture 2020) using kernel weight, germination percentage, and a 15 percent mortality factor. Certified seed was treated with tebuconazole (3.0 g L⁻¹), prothioconazole (15.4 g L⁻¹) and metalaxyl (6.2 g L⁻¹) formulated as Raxil Pro fungicide (Bayer CropScience Canada) at a rate of 325 mL product per 100 kg seed weight. Seeding was completed using an 8-row small plot air seeder with 20.3 cm row spacing and knife openers, and midrow fertilizer banding capabilities. Seed-placed phosphorus fertilizer was applied as mono-ammonium phosphate (11-52-0) at a rate of 19.6 kg P ha⁻¹ across all plots 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. Pyraclostrobin (130 g L⁻¹) and metconazole (80 g L⁻¹) fungicides formulated as Twinline (BASF Canada) were applied at the flag leaf stage (GS39) (Zadoks et al. 1974) at 494 mL ha⁻¹ at all sites to control leaf diseases (Zadoks et al. 1974). The fungicide Prosaro-XTR, prothioconazole (125 g L⁻¹) and tebuconazole (125 g L⁻¹), was also applied at anthesis (GS60) at all locations to control Fusarium head blight. Dates of field operations for individual trial locations are presented in Table 3.1.

Table 3.1. Characteristics of each experimental site-year; location, year, previous crop, spring soil residual nutrients (nitrate-N (NO₃-N), Olsen phosphorus (P), potassium (K), sulfur (S) and soil organic matter (SOM)), soil texture and dates of key field operations (seeding, plant growth regulator (PGR) application, in-season split N application and harvest)

			Site-year			
			Carman18	Carman19	Manitou18	Manitou19
Location			Carman, MB	Carman, MB	Manitou, MB	Manitou, MB
Year			2018	2019	2018	2019
Latitude, Longitude			49.496611°N, 98.040352°W	49.500878°N, 98.030846°W	49.087722°N, 98.501826°W	49.080626°N, 98.515924°W
Previous Crop			Soybean	Canola	Canola	Canola
<i>Spring Soil Samples</i>		<i>Depth</i>				
NO ₃ -N	(kg ha ⁻¹)	0 – 60 cm	43	78	67	63
Olsen P	(mg kg ⁻¹)	0 – 15 cm	8	7	10	22
K	(mg kg ⁻¹)	0 – 15 cm	136	384	369	386
S	(kg ha ⁻¹)	0 – 60 cm	78	155	179	119
SOM	(%)	0 – 15 cm	3	5.9	7.3	6.7
Texture			Sandy Loam	Sandy Clay Loam	Clay Loam	Clay Loam
<i>Field Operations</i>						
Seeding [†]			May 7, 2018	April 26, 2019	April 29, 2018	May 7, 2019
PGR Application			June 9, 2018	June 5, 2019	June 7, 2018	June 14, 2019
Split N Application			June 21, 2018	June 20, 2019	June 18, 2018	June 26, 2019
Harvest			August 14, 2018	August 8, 2019	August 15, 2018	August 23, 2019

[†]N fertilizer applied at the time of planting, other than the portion of N applied in-season in the split N application

3.3.2 Treatments and Experimental Design

A four-replicate split-split plot design randomized as a Randomized Complete Block Design was used for each experiment. Spring wheat cultivar was the main plot factor, N fertilization was the sub-plot factor and PGR application was the sub-sub-plot factor (Table 3.2). The three high-yielding cultivars tested included AAC Brandon (Canadian Western Hard Red, CWRS), AAC Cameron (CWRS), and Prosper (Canadian Northern Hard Red, CNHR) (Canadian Grain Commission 2019). Cultivars were chosen based on current production levels in Manitoba, class and lodging risks. AAC Brandon has been widely adopted across Manitoba and was grown on 90% of spring wheat acres in 2017 and 2018 (MASC 2020). It is a semi-dwarf cultivar known for producing high yields and protein contents, while maintaining good resistance to lodging and fusarium head blight (Cuthbert et al. 2016; Manitoba Seed Growers' Association Inc. et al. 2020). AAC Cameron is a newly introduced cultivar to Manitoba and is similar to AAC Brandon for yield potential and protein content, but AAC Cameron is a tall cultivar with a slightly higher lodging risk (Fox et al. 2017; Manitoba Seed Growers' Association Inc. et al. 2020). Prosper was developed at North Dakota State University and has extremely high yield potential with a lower grain protein content than either AAC Brandon or AAC Cameron (Table 3.2). Prosper is a semi-dwarf cultivar with a lodging rating similar to AAC Cameron (Mergoum et al. 2013; Manitoba Seed Growers' Association Inc. et al. 2020). All cultivars included had similar days to maturity of 101, 100, and 100 days for AAC Brandon, AAC Cameron, and Prosper, respectively (Manitoba Seed Growers' Association Inc. et al. 2020).

The sub-plot factor in this experiment was N fertilizer management. Five N treatments were included: a zero N check plot, a standard practice reflective of current N fertilization practices for high-yielding spring wheat in the eastern Canadian Prairies, and three different N management strategies (rate, source, and timing) (Table 3.2). Nitrogen management strategies were chosen for their potential to reduce risks of lodging and N loss through limiting excess early season N to reduce shading effects (Berry et al. 2004; Sparkes and King 2007).

Table 3.2. List of treatments included in split-split plot experiment with a main plot of cultivar (AAC Brandon, AAC Cameron, and Prosper), sub-plot of nitrogen (N) management (check, reduced rate, standard, Environmentally Smart Nitrogen (ESN™) Blend, and a Split N Application, and sub-sub plot of the application of the plant growth regulator (PGR) chlormequat chloride (CCC).

Main Plot – Cultivar					
	<i>Wheat Class</i> [†]	<i>Yield</i> [‡]	<i>Grain Protein</i> [‡]	<i>Height</i> [‡]	<i>Lodging Rating</i> [‡]
		kg ha ⁻¹	%	cm	
AAC Brandon	CWRS	70	14.3	81	VG
AAC Cameron	CWRS	74	13.9	94	G
Prosper	CNHR	82	12.9	84	G
Sub Plot – N Management					
	<i>Total N Rate</i>	<i>App. Timing</i>	<i>N Source</i>		
Check	0				
Reduced Rate	78 kg N ha ⁻¹	Seeding	Urea		
Standard	156 kg N ha ⁻¹	Seeding	Urea		
ESN Blend	112 + 44 kg N ha ⁻¹	Seeding	ESN + Urea		
Split N App.	78 + 78 kg N ha ⁻¹	Seeding + Flag Leaf	Urea + SuperU		
Sub-Sub Plot – PGR					
	<i>Product</i>	<i>App. Timing</i>	<i>Rate</i>		
- CCC					
+ CCC	Manipulator	Stem Elongation [§]	1.8 L ha ⁻¹		

[†] Canadian wheat classification, CWRS; Canadian western red spring, CNHR; Canadian northern hard red

[‡] Yield, Protein, Height, and Lodging rating from Manitoba Variety Evaluation Trials summarized in Manitoba Seed Growers' Association Inc. et al. (2020), VG; Very good, G; Good.

[§] Zadoks growth stage 31, first node detectable and 1 cm above tillering node

The standard practice consisted of a high rate of N (156 kg N ha⁻¹), applied as conventional urea, midrow banded at planting. The reduced rate strategy was 78 kg N ha⁻¹ applied as conventional urea midrow banded at planting. The reduced rate strategy was included to demonstrate the potential trade-off between a modest N fertilizer rate to reduce lodging risk and an aggressive N fertilizer rate to maximize yield and protein.

Nitrogen source was evaluated using a blend of Environmentally Smart Nitrogen™ (ESN), a polymer-coated urea and conventional urea at the same total rate as that standard N

fertilizer treatment (156 kg N ha^{-1}) applied using midrow banders at planting (112 kg N ha^{-1} as ESN: 44 kg N ha^{-1} as urea). Split N application was tested by applying an overall rate that was similar to the standard practice, but the application was divided equally between planting and flag leaf growth stages. At planting 78 kg N ha^{-1} of N fertilizer was applied as conventional urea using midrow banders; the remaining 78 kg N ha^{-1} was broadcast on the soil surface as SuperU™ (Koch Fertilizer) at flag leaf timing (GS 39). Due to unpredictable precipitation during the growing season SuperU™, urea with NBPT (urease inhibitor) and DCD (nitrification inhibitor) added as stabilizers, was used as the fertilizer source for the in-season portion of the split application treatments to minimize the risk of N losses.

A sub-sub plot factor included in the experiment was the addition, or absence, of the PGR, CCC, applied to all combinations of cultivars and N treatments. This formulation of CCC, trade name Manipulator™620 (Belchim Canada), was applied at the onset of stem elongation (GS31) at 1.8 L ha^{-1} . CCC was applied as a foliar application to the canopy using a four nozzle, 2-meter-wide CO₂ backpack sprayer with 100 L ha^{-1} water volume at 207 kPa and AIXR TeeJet flat fan nozzles.

3.3.3 Data Collection

Individual plots were 1.63 m wide by 8 m long for a total plot area of 13.04 m^2 . All data were collected from the center four rows at least 1 m inward from the front and back of each plot. Plant counts were taken at the three-leaf stage (GS13) from 1 m row lengths at four different locations within each plot. Plant count areas were flagged and the same area in each plot was revisited at soft dough stage (GS85) for spike counts. Spikes per plant were calculated by dividing number of spikes by number of plants for each sample area. Due to a data collection error, plant count data from Manitou 2018 were excluded.

Before grain yield was harvested, the two outer rows of each plot were trimmed, as well as 1 m from the front and back of each to avoid edge effects for a total harvested area of approximately 6 m^2 . Grain samples to measure yield were collected from each plot using a small plot combine. Before being weighed, grain samples from each plot were cleaned using a vibratory sieve seed cleaner (C.C. King & Company, 2 mm sieve). Moisture content was measured for each plot grain sample using the GAC 2500-INTL Grain Analysis Computer (Dickey-John, Auburn, IL, USA) and grain yields were corrected to 13.5% moisture content.

Kernel weight was determined by calculating the mean weight of three counts of 250 seeds per plot and then converted to kernel weight per 1000 kernels. Kernel number per hectare was calculated by dividing grain yield of each plot by average weight per kernel. Kernel number per hectare was then divided by spike density per hectare to calculate kernels per spike.

Canopy height was measured on a per plot basis two weeks after anthesis by taking the mean of five randomly placed measurements of plant height from ground level to the top of the spike excluding awns. Date of anthesis was recorded for each plot when 50% of the spikes within the plot reached flowering and date of maturity was recorded when 50% of the spikes within a plot had lost green coloration in the peduncle. Grain fill duration was calculated by subtracting days to anthesis from days to maturity for each plot.

Lodging ratings were taken from each plot by multiplying the percent of the area of the plot lodged (0-100%) by the severity of the lodging, using a 1 - 9 scale, with 1 being a slight lean and 9 being completely flat. To quantify lodging risk, stalk strength measurements were taken at anthesis and maturity from the center rows at two locations for each plot. Stalk strength push force measurements were taken by pushing on 1.2 m of row length at half the plant height and recording the resistance force of the plants when rotated 45 degrees from the vertical position (Heuschele et al. 2019). Similar response data has shown a good relationship to winter and spring wheat natural lodging occurrence in the literature (Berry et al. 2003; Wiersma et al. 2007). These data were collected using the Stalker, a stalk strength meter manufactured by the Marchetto Lab at the University of Minnesota (Heuschele et al. 2019).

3.3.4 Statistical Analysis

Data were analyzed using PROC MIXED procedure of SAS version 9.4 (Statistical Analysis System 2001) with site-year, cultivar, N, and PGR and their interactions as fixed factors in the model. Random factors in the model included block nested within site-year and the interaction of block with cultivar and block with cultivar and nitrogen to account for the split-split plot arrangement at each site-year. 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 residual and the homogeneity of variance was examined visually. Variation associated with each model factor for each response variable was calculated by partitioning the total type 3 sums of squares,

allowing us to determine the relative contribution of each model factor to the overall variability of response (Brown 2008). Means groupings were determined for significant effects using Tukey's Honest Significant Difference (HSD) to a probability of 5% ($p < 0.05$). Significant interactions of interest were explored using the SLICE statement in PROC MIXED to determine means groupings within factors at a 95% confidence level. To align and focus the discussion on the study objectives, the main effects of site-year and cultivar are not discussed in detail unless there are significant interactions with N management or PGR.

Linear regression analysis was completed in PROC REG to examine the relationships between grain yield and yield components using data collected from each plot. To determine if the relationships between yield components and grain yield were consistent across the main model effects in this study (site-year, cultivar, N management, PGR) mixed model linear regression in PROC GLIMMIX was used for analysis of covariance. If the analysis of covariance indicated a significant interaction with a model effect, linear regression in PROC REG was completed for each treatment in that model effect individually.

The yield and yield component response of all combinations of N Management and PGR treatments compared to the standard N treatment without a PGR application, was calculated using means across site-years and cultivars. Linear regressions analysis in PROC REG was then used to examine which yield component responses had the strongest relationship with grain yield response due to management practices regardless of cultivar and site-year.

3.4. Results and Discussion

3.4.1 Grain Yield

Analysis of variance of grain yield indicated a highly significant effect of site-year (Table 3.3), which accounted for the largest percent of variability (41%) in grain yield of the response variables tested (Figure 3.1). The highest average yields of 5590 and 4869 kg ha⁻¹ occurred at Carman18 and Manitou18, respectively (Table 3.4). Grain yields achieved in this experiment were slightly higher than the commercial on-farm spring wheat yields reported for each site's local municipality during the 2018 and 2019 growing seasons (MASC 2020). However, growing conditions across Manitoba were drier than normal in both 2018 and 2019 with only 51%, 49%, 69% and 78% of the 30-year long term average growing season (Apr 1 to Sept 1) precipitation at

Carman18, Carman19, Manitou18, and Manitou19 experimental locations, respectively (Figure 3.2).

The main effect of cultivar was highly significant in the ANOVA of grain yield (Table 3.3). The cultivars AAC Brandon and Prosper produced similar mean yields across all treatments (4899 and 4964 kg ha⁻¹, respectively), while AAC Cameron had a significantly lower grain yield (4513 kg ha⁻¹) (Table 3.4). The cultivar ranking for yield in this study agreed with rankings reported in cultivar descriptions from the Manitoba variety evaluation trials (Table 3.2).

Mean grain yield was 1015 kg ha⁻¹ higher when the high rate of N was applied, in the standard fertilizer treatment, compared to the zero N check (Table 3.4). However, there were no significant differences in grain yield within the N treatments where N fertilizer was applied, even though the reduced N rate tended to produce lower yield than the three full rate treatments (Table 3.4). Grain protein content responded to higher rates of N, increasing 1.3% from the check treatment to the reduced rate treatment, and an additional 1.2% to the high rate of N applied in the standard treatment (Table 3.4). When the high rate of fertilizer was applied as a split application between seeding and flag leaf growth stages, grain yield was similar and grain protein content was increased by 0.5%, compared to when a similar N rate was applied entirely at planting (Table 3.4). There was no effect on grain yield or protein content when N fertilizer was applied as an ESN blend at planting compared to entirely as urea in the standard treatment (Table 3.4).

Table 3.3. Analysis of variance for the main effects of site-year (SY), cultivar (C), nitrogen (N) management, plant growth regulator (PGR), and their interactions for grain yield, yield components (plant density, spikes per plant, kernels per spike, kernel weight, canopy height, stalk strength measured at anthesis and maturity, and visual lodging rating. Bolded values indicate significance at 95% confidence level.

Sources of Variation	df	Response Variable									
		Grain Yield	Grain Protein	Plant Density	Spikes per plant	Kernels		Canopy Height	Stalk Strength		Lodging Ratings [‡]
						per Spike	Kernel Weight		Anthesis [†]	Maturity	
Site-year (SY)	3	<.0001	0.1001	0.1614	0.0796	<.0001	0.0078	0.0014	0.6644	<.0001	
Cultivar (C)	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0052	0.6213	0.6645
SY x C	6	0.0689	0.3371	0.1923	0.0105	0.0215	0.0888	0.0138	0.7068	0.216	
Nitrogen (N)	4	<.0001	<.0001	0.5429	<.0001	0.0017	0.4988	<.0001	0.0018	<.0001	<.0001
SY x N	12	0.1658	0.0418	0.9466	0.7691	0.1253	0.0019	0.2926	0.5428	0.7766	
C x N	8	0.4463	0.1414	0.1715	0.6679	0.4796	0.4145	0.2066	0.9357	0.7358	0.0375
SY x C x N	24	0.5436	0.0395	0.3858	0.0893	0.1042	0.0247	0.6474	0.7384	0.8144	
Plant Growth Regulator (PGR)	1	0.0005	0.0003	0.2308	0.0778	0.0089	0.0005	<.0001	0.0008	0.9186	<.0001
SY x PGR	3	0.0073	0.9329	0.0644	0.0487	0.8334	0.6637	<.0001	0.9716	0.135	
C x PGR	2	0.9234	0.6312	0.1336	0.8174	0.2508	0.3268	<.0001	0.8908	0.9491	0.3158
SY x C x PGR	6	0.7496	1	0.6968	0.5592	0.9185	0.3074	0.1284	0.5911	0.6922	
N x PGR	4	0.8474	0.6201	0.0779	0.4143	0.2791	0.6351	0.1329	0.5447	0.5121	0.0004
SY x N x PGR	12	0.2209	0.9755	0.5294	0.9212	0.8944	0.9945	0.4049	0.9002	0.3989	
C x N x PGR	8	0.6619	0.7239	0.7526	0.5021	0.318	0.707	0.8127	0.6193	0.6068	0.8152
SY x C x N x PGR	24	0.9559	0.7678	0.8994	0.4786	0.7864	0.2171	0.9341	0.0711	0.9434	
CV (%)		17	10	16	22	17	7	11	50	43	128

[†] Stalk strength was measured only at the two 2019 site-years due to equipment constraints

[‡] Due to a lack of lodging occurrence lodging ratings were recorded for only one site-year, Manitou19, after a heavy precipitation event

Table 3.4. Least squares means for yield and yield components for the main effects of site-year, cultivar, nitrogen (N) management and plant growth regulator application (PGR) application of chlormequat chloride (CCC).

Main Effects	Grain Yield	Grain Protein Content	Plant Density [†]	Spikes per Plant	Kernels per Spike	Kernel Weight g 1000 kernels ⁻¹
	kg ha ⁻¹	%	m ⁻²			
<i>Site-year</i>						
Carman18	5590 a	12.8	220	2.1	35.9 a	34.7 b
Carman19	4110 d	13.0	213	2.0	27.7 b	35.8 ab
Manitou18	4969 b	13.3	n/a	n/a	35.6 a	34.6 b
Manitou19	4499 c	12.8	196	2.4	28.1 b	36.6 a
<i>Cultivar</i>						
AAC Brandon	4899 a	13.3a	234 a	2.0 b	33.2 a	34.0 c
AAC Cameron	4513 b	13.2a	215 a	1.9 b	31.2 b	35.6 b
Prosper	4964 a	12.4b	180 b	2.6 a	31.0 b	36.4 a
<i>N Management§</i>						
Check	4032 b	11.1d	207	1.8 b	30.9 c	35.5
Reduced Rate	4830 a	12.4c	209	2.2 a	31.4 bc	35.6
Standard	5047 a	13.6b	212	2.3 a	32.2 ab	35.0
ESN Blend	5034 a	13.6b	211	2.3 a	32.7 a	35.1
Split App.	5015 a	14.1a	210	2.3 a	31.9 abc	35.4
<i>PGR</i>						
- CCC	4746 b	13.1a	211	2.1	31.4 b	36.5 a
+ CCC	4837 a	12.9b	209	2.2	32.2 a	35.0 b

[†] Due to a data collection error, Manitou18 plant density and spikes per plant data are excluded.
n/a = not available.

[‡] Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

[§] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

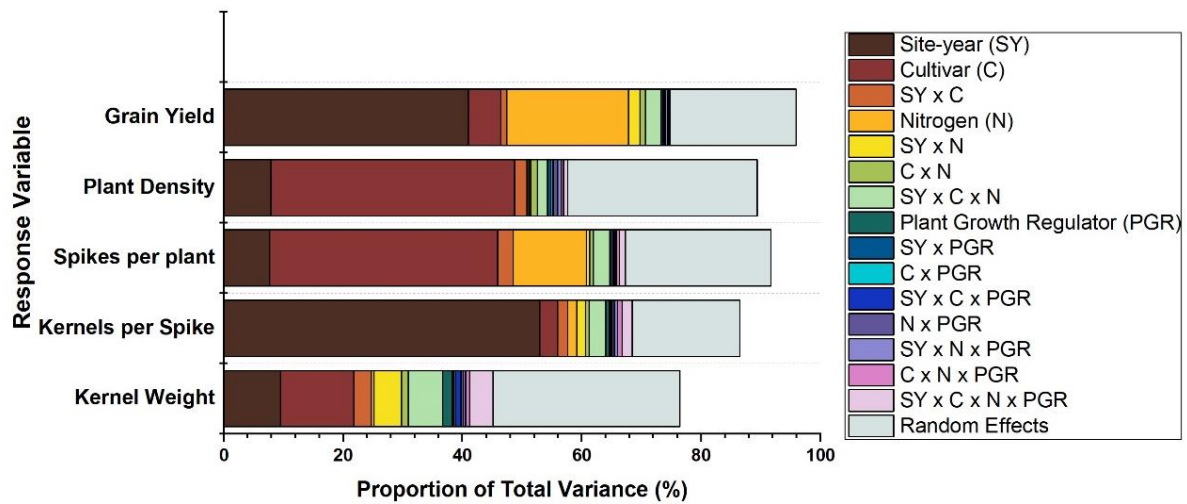


Figure 3.1. Proportion of total variance allocated to main effects and their interactions for each response variable calculated by partitioning the total type 3 sums of squares for each response variable. Proportion of variation accounted for by the residual is indicated by the difference between the maximum extent of each stack of bars and 100%.

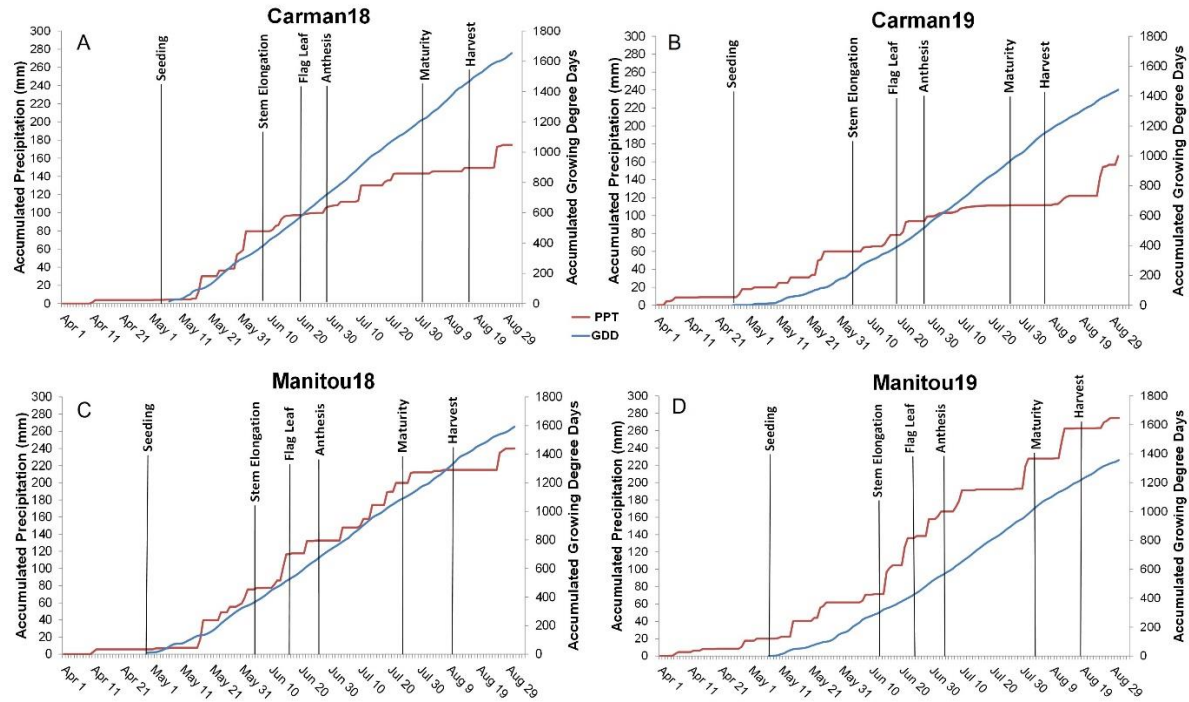


Figure 3.2. Growing season accumulated precipitation (starting April 1) and growing degree days (starting at seeding) for Carman18, Carman 19, Manitou18 and Manitou19. Seeding, harvest and the average growth stages for each site-year is indicated by vertical lines.

Mangin and Flaten (2018) reported that current high-yielding spring wheat cultivars grown in Manitoba required approximately 180 kg N ha^{-1} (pre-plant residual $\text{NO}_3\text{-N}$ plus fertilizer) to produce 5380 kg ha^{-1} grain yield and reach economic optimum yield and protein levels. With dry growing conditions across all site-years resulting in yields ranging from 4110 to 5590 kg ha^{-1} , it is not surprising that the 78 kg N ha^{-1} applied in the reduced rate treatment when paired with residual N levels ($43\text{--}78 \text{ kg ha}^{-1}$, Table 3.1) was sufficient to maximize grain yield in this study.

Yield increases from ESN blend and split N applications compared to the standard N treatment would have been expected if environmental conditions were more conducive to N losses, i.e., wet conditions, unlike the dry growing seasons experienced during this trial (Figure 3.2). There have been inconsistent reports of the efficacy of ESN to increase grain yield across western Canada due to interactions with environmental conditions. Grant et al. (2012) compared

ESN and ESN/urea blends to applications of 100% urea on spring wheat yield at five locations across the prairies and reported occasional yield increases with ESN blends only in the moist ecoregions of the Boreal transition and Aspen parkland. Therefore, the use of ESN as an alternative N fertilizer source is likely to be economical only in very specific growing season conditions when the risk of N losses is high.

The portion of N fertilizer applied at seeding for the split N application (78 kg N ha^{-1}), when paired with residual soil N, was sufficient for yields achieved in this experiment, as observed in the reduced rate treatment. Therefore, yields were not limited by withholding a portion of N until the flag leaf stage. Split applications of N are used to match the timing of N uptake with N supply in the soil to reduce N losses before crop uptake. In addition, split applications can increase the availability of N for crop uptake during the later stages of crop growth for grain protein increases as well as yield (Bogard et al. 2010). To facilitate N uptake of late season surface applied fertilizer, precipitation must occur shortly after application, or there is potential for the N to be stranded on the soil surface and provide no benefit to production (Karamanos et al. 2004; Holzapfel et al. 2007). In this experiment surface stranding of the fertilizer may only have been an issue at Carman18 where only 2.6 mm of precipitation occurred between the flag leaf and anthesis growth stages. All other site-years received over 15 mm of precipitation in the same period (Figure 3.2).

The application of a PGR and the interaction of PGR with site-year had significant effects on grain yield (Table 3.3), although they both accounted for only a very small proportion of the variability in grain yield (0.3%) (Figure 3.1). Averaged across all site-years, PGR applications increased grain yield by 91 kg ha^{-1} . The significant interaction of PGR with site-year was due to large increases at Carman18 (206 kg ha^{-1}) and Manitou18 (155 kg N ha^{-1}) the two highest yielding site-years, and modest increases at Carman19 (21 kg N ha^{-1}) and Manitou19 (14 kg ha^{-1}). If greater lodging pressure had occurred in this study, differences in grain yield between PGR treated and untreated treatments would likely have been larger, as reduced stem elongation may have protected the crop from lodging induced yield losses. Reports on the influence of CCC application on wheat yield are inconsistent. Commonly, no yield increases are reported (Clark and Fedak 1977; Caldwell and Starratt 1987; Cox and Otis 1989), while occasionally small yield increases (Humphries et al. 1965; Green 1986; Rajala et al. 2002), or even reduced grain yield in

a greenhouse environment, have been reported (Zhang et al. 2017). However, there has been little research focused on CCC application to high-yielding spring wheat cultivars grown under dryland conditions in the Canadian Prairies. The results of this study suggest that yield increases with a PGR application could also increase as higher yields are achieved, more reflective of a typical Manitoba growing season, even in the absence of lodging.

3.4.2 Yield Components

3.4.2.1 Site-year

Analysis of variance indicated that the site-year had a significant effect on the yield components kernels per spike and kernel weight, with no effect on plant density or spikes per plant (Table 3.3). Site-year accounted for 52% of the variation in kernels per spike in this study, more than all of the other fixed effects combined (Figure 3.1). Kernels per spike were highest at Carman18 and Manitou18, and lowest at Manitou19, and Carman19 (Table 3.4). Kernel weight was greatest at Manitou19 and Carman19 (36.2 and 35.8 g 1000 kernels⁻¹, respectively) and lowest at Carman18 and Manitou18 (34.7 and 34.6 g 1000 kernels⁻¹, respectively). Correlations between DTA, GFD and DTM and yield components were very inconstant in this study (Appendix Table A1).

3.4.2.2 Cultivar

Cultivar was the only significant factor in the ANOVA for plant density (Table 3.3). AAC Brandon had the highest plant density (234 plants m⁻²), followed by AAC Cameron (215 plants m⁻²), and Prosper (180 plants m⁻²) (Table 3.4). The difference in plant density due to cultivar was surprising, as seeding rates were adjusted based on each individual cultivar's seed lot germination percentage and seed weights, to target the same plant density. Spring conditions were dry across most site-years in this experiment which led to slow and uneven emergence patterns. Potentially, the cultivar Prosper wasn't as suited to handle these harsh spring conditions, or the seed lots (different seed lots used in 2018 and 2019) used in this study had reduced seedling vigour, increasing mortality, compared to AAC Brandon and AAC Cameron. Differential mortality across cultivars due to growing season conditions is common with spring wheat (Otteson et al. 2007; Mehring 2016). The differences in plant density between cultivars resulted in a significant effect of cultivar on spikes per plant (Table 3.3). Prosper had a significantly larger number of spikes per plant (2.6) compared to AAC Brandon (2.0) and AAC

Cameron (1.9) (Table 3.4). The significant interaction of cultivar by site-year for spikes per plant accounted for only 2.6% of the variation in spike per plant and was due to the magnitude of the cultivar response at each site-year, as the trend was similar at all site-years (data not shown).

Kernels per spike was significantly influenced by cultivar as well as the interaction of cultivar with site-year in this study (Table 3.3). Across all sites, AAC Brandon had the largest number of kernels per spike (33.2) compared to both AAC Cameron (31.2) and Prosper (31.0) (Table 3.4). The interaction of cultivar with site-year for kernels per spike accounted for a small amount of variability (Figure 3.1) and was due to differences in magnitude of this response across cultivars, with a similar ranking of cultivars at each site-year (data not shown). Kernel weight was also significantly influenced by the main effect of cultivar, which accounted for the greatest source of variation (12%) for kernel weight in this experiment (Table 3.3, Figure 3.1). Prosper had the largest kernel weight (36.4 g 1000 kernels⁻¹), followed by AAC Cameron (35.6 g 1000 kernels⁻¹), and lastly AAC Brandon (34.0 g 1000 kernels⁻¹).

3.4.2.3 Nitrogen Management

Nitrogen management did not have an effect on plant density in this experiment, while its effect on spikes per plant was significant (Table 3.3). There were no significant differences between all treatments with N fertilizer applied, all of which had increased spikes per plant compared to the check treatment (Table 3.4). It is likely that all applied N fertilizer treatments provided sufficient N early in the season when the number of spikes per plant was being determined. When early season N (seeding to heading) is limited, reductions in spikes per plant have been reported due to reductions in tiller production and increased tiller mortality (Weisz et al. 2001; Slafer 2007; Ayoub et al. 1994; Otteson et al. 2008).

Kernels per spike was also significantly influenced by N management in this experiment, although this effect only accounted for 1.6% of the total variation (Table 3.3, Figure 3.1). The number of kernels per spike significantly increased from 30.9 in the check treatment (no N fertilizer applied) to 32.2 and 32.7 when the high rate of N was applied in both the standard management treatment and the ESN blend, respectively (Table 3.4). There was no significant difference in kernels per spike across any of the N management treatments that applied a high rate of N (standard, ESN Blend, and split N). However, the split N application was not significantly different from the check or reduced rate treatment (Table 3.4). Early N supply from

stem elongation to anthesis is important for kernels per spike determination (Slafer 2007) and flag leaf N application might be too late to correct N limitations and influence kernels set in dryland wheat production. Nitrogen limitations during the growing season are known to reduce the number of kernels per spike by reducing floret initiation and survival per spikelet and an overall reduction in spikelets per spike (Ferrante et al. 2020).

The main effect of N management did not have a significant influence on kernel weight; however, the ANOVA indicated a significant two-way interaction between N management and site-year as well as the three-way interaction of N management, cultivar and site-year (Table 3.3). At Carman18, kernel weight was highest in the check treatment and standard treatment of a high rate of N applied as urea at seeding, both of which were significantly greater than the split N application (Table 3.5). Alternatively, at Manitou18 the split N application had the greatest kernel weight of all N management treatments (Table 3.5). Both Carman18 and Manitou18 had a high number of kernels per spike (Table 3.4), but precipitation between the flag leaf and anthesis growth stages was 15 mm at Manitou18 and only 2.6 mm at Carman19 (Figure 3.2). This precipitation at Manitou18 immediately after N application likely facilitated N uptake by the plant, allowing for an increase in N capture compared to Carman18, highlighting the dependency of this strategy on environmental conditions. There were no significant differences in kernel weight between N management treatments at Carman19 or Manitou19 (Table 3.5). This may be because N availability at these sites was sufficient for the low kernel numbers at these sites. The three-way interaction between N management, cultivar and site-year, revealed that the magnitude of kernel weight response, within each site-year, was dependent on cultivar, with the cultivar AAC Cameron being the most responsive to kernel weight changes (data not shown).

Table 3.5. Least squares means of the two-way interaction between nitrogen (N) management and site-year for kernel weight.

N Management [†]	Site-year			
	Carman18	Carman19	Manitou18	Manitou19
	g 1000 kernels ⁻¹			
Check	36.2 a [‡]	35.8	34.4 ab	35.5
Reduced Rate	34.1 bc	36.0	35.2 ab	37.2
Standard	35.3 ab	35.3	34.2 ab	35.2
ESN Blend	34.1 bc	35.9	33.9 b	36.7
Split App.	33.9 c	36.0	35.4 a	36.4

[†]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

[‡]Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

3.4.2.4 Plant Growth Regulator

The main effect of PGR did not influence spikes per plant in this experiment, but the interaction of PGR and site-year was significant (Table 3.3). At Carman19, CCC application significantly increased the average spikes per plant from 2.05 to 2.17, an effect that was not observed at any other site-year. This interaction accounted for only 0.4% of the variation in spikes per plant. Increases in final spikes per plant have been reported with CCC application by increased tiller production and survival (Humphries et al. 1965; Waddington and Cartwright 1988; Craufurd and Cartwright 1989; Steen and Wunsche 1990; Peltonen and Peltonen-Sainio 1997). Rademacher (2000) summarized that increases in tillering with gibberellin inhibitor application could be due to retardation of apical dominance by changes in response to daylight or inhibition of biosynthesis and transport of auxins responsible for apical dominance, as well as simply changes in assimilate production and nutrient availability. The potential of environmental factors to influence response of spikes per plant to PGR application has not been explored in the literature. Alternatively, CCC applications at stem elongation have been reported to have no influence on tiller production in winter wheat (Cox and Otis 1989; Berry et al. 2000).

The number of kernels per spike was significantly increased from 31.4 to 32.3 with the application of a PGR, when averaged across all site-years, cultivars, and N managements (Table 3.4). Increases in kernel number per spike have been reported for both of the common gibberellin inhibiting PGRs, trinexipac-ethyl (Matysiak 2006) and CCC (Humphries et al. 1965; Craufurd and Cartwright 1989). This could be due to resource reallocation to the developing spike when stem elongation is reduced by a PGR application. The number of kernels per spike are being determined during the stem elongation phase; therefore, any additional resources available during this time can drive increases in final kernel number per spike (Slafer et al. 2014). Due to the application timing of CCC at stem elongation (GS31), which is after the double ridges stage, any increases in kernel number are likely due to reduced floret abortion rather than increases in spikelets or florets (Craufurd and Cartwright 1989; Slafer et al. 2015b). A similar mechanism is thought to increase kernel number per spike when shoot length is reduced by dwarfing genes in spring wheat, increasing fertility of distal florets within spikelets (Butler et al. 2005).

PGR application significantly reduced kernel weight by 1.5 g 1000 kernels⁻¹ across all site-years, cultivars, and N treatments (Table 3.4). The cause for this reduction in kernel weight is likely linked to the increased kernel number per spike when a PGR was applied (Table 3.4). When more kernels are set per spike there is increased seed set of tertiary and quaternary florets that produced smaller kernels. Resource competition between kernels when a high number of kernels are set could also be influencing this relationship (Slafer 2007). Alternatively, Rajala and Peltonen-Sainio (2002) reported a 500 kg ha⁻¹ yield decrease when CCC was applied at stem elongation that was due to reduced kernel size in the absence of kernel number increases. This is evidence that kernel weight reductions with PGR application are not solely due to a negative relationship with kernel number, but instead by reducing shoot length there may be less assimilates stored in vegetative stem tissue available for remobilization during the grain fill period.

3.4.3 Relationships Between Yield and Yield Components

Linear regression and analysis of covariance provided an understanding of the relationships between yield and yield components. There was a small range in plant densities across this study and no significant linear relationship was observed between plant density and grain yield when regression was completed across all site-years and treatments (Table 3.6).

However, analysis of co-variance revealed that there was a site-year effect on the relationship of yield and plant density (Table 3.7). There was a significant negative linear relationship between plant density and grain yield at Carman19, which was not true at the other three environments (Figure 3.3). At Carman19 there was exceptionally low precipitation from seeding to the flag leaf growth stage (Figure 3.2). As a result, plant density increased intraspecific competition for limited resources and resulted in a yield penalty (Satorre 1999). The interaction of the relationship between plant density and grain yield with environmental conditions is important to understand, as it will have direct effects on how management practices that alter plant density influence grain yield. Bastos et al. (2020) determined that as attainable yield increases across environmental conditions, the agronomic optimum seeding rates decrease for wheat. There was no significant influence of cultivar, N management, or PGR on the overall relationship between plant density and yield in this study (Table 3.7).

Table 3.6. Linear regression between grain yield and yield components using data from individual plots, for all combinations of site-years, cultivar, nitrogen management and plant growth regulator applications. Bolded values indicate significance at 95% confidence level.

Y	X	<i>p</i>-value	Slope	Intercept	<i>r</i>²
Yield	Plant Density	0.3443			
Yield	Spikes per Plant	0.0002	11.4666	45.54343	0.14
Yield	Kernels per Spike	<0.0001	1.72334	16.43894	0.48
Yield	Kernel Weight	0.0155	-1.36046	119.3778	0.04

Table 3.7. Analysis of covariance between yield components (plant density, spikes per plant, kernels per spike and kernel weight) and grain yield with the main model effects of site-year, cultivar, nitrogen (N) management, and plant growth regulator (PGR) application. Bolded values indicate significance at 95% confidence level.

Y	X	Covariate			
		Site-year	Cultivar	N Management	PGR
		<i>p</i> -value			
Yield	Plant Density	0.0490	0.9051	0.8908	0.8453
Yield	Spikes per Plant	0.8991	0.0037	0.7633	0.5075
Yield	Kernels per Spike	0.7916	0.9668	0.4304	0.7536
Yield	Kernel Weight	0.0055	0.9397	0.0342	0.0925

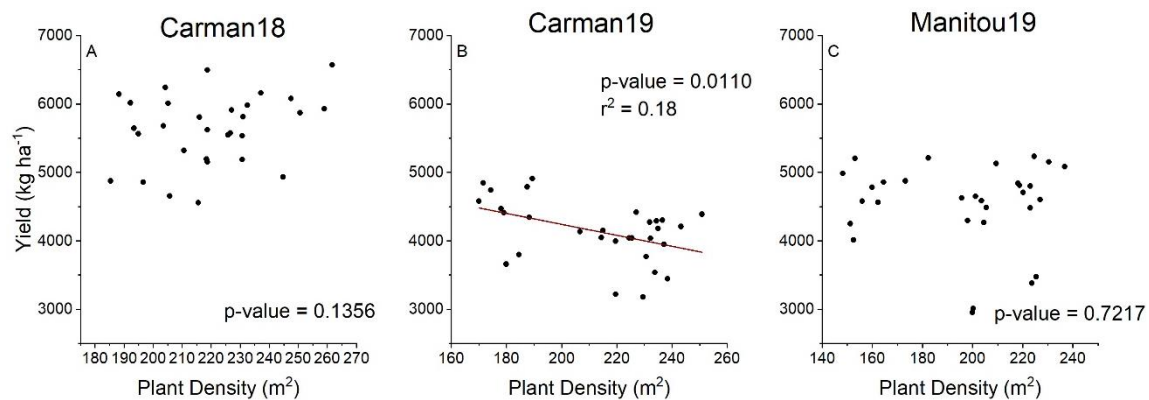


Figure 3.3. Linear regression between plant density and grain yield at Carman18 (A), Carman19 (B), and Manitou19 (C), for all combinations of cultivar, nitrogen management and plant growth regulator application.

Spikes per plant had a significant positive relationship with grain yield when combined across all treatment factors (Table 3.6). This relationship was similar at all site-years and with all N management and PGR treatments, but there was a significant interaction with cultivar (Table 3.7). The cultivar Prosper had no significant relationship between spikes per plant and grain

yield, while grain yield of AAC Brandon and AAC Cameron increased with increases in spikes per plant (Figure 3.4). This may have been due to the lower plant density of Prosper, leading to an overall higher number of spikes per plant compared to the two other cultivars (Table 3.4).

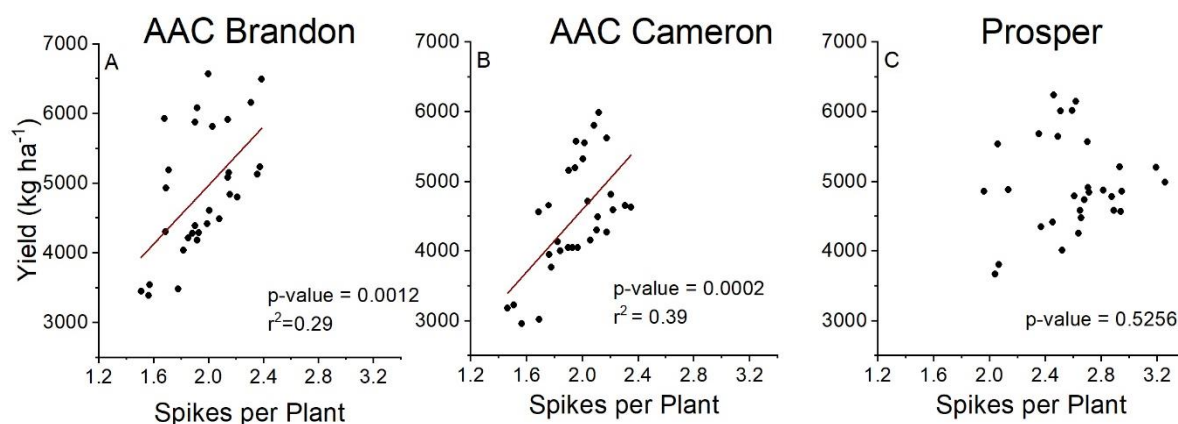


Figure 3.4. Linear regression between spikes per plant and grain yield for the cultivars AAC Brandon (A), AAC Cameron (B), and Prosper (C), for all combinations of site-year, nitrogen management and plant growth regulator application

Kernels per spike was the yield component with the strongest linear relationship with grain yield in this study (Table 3.6). As kernels per spike increased, grain yield also increased, and this relationship was consistent across site-years, cultivars, N management and PGR application with no significant model interactions in the analysis of covariance (Table 3.7).

Overall, kernel weight had a significant negative relationship with grain yield (Table 3.6); however, this relationship was not consistent across site-years or N management treatments (Table 3.7). The relationship between kernel weight and grain yield was negative at Carman18, positive at Man18, and there was no significant relationship at Carman19 or Manitou19 (Figure 3.5). Carman18 and Manitou18 both had the highest yields and kernels per spike in this study (Table 3.4), but Manitou18 had nearly double the precipitation as Carman18 from the flag leaf growth stage to physiological maturity (Figure 3.2). This makes it likely that resource availability during these growth stages was driving the relationships between kernel weight and

grain yield at these sites. Slafer (2007) states that resource competition between kernels within a spike has the greatest influence on kernel weight just before and immediately after anthesis, when number of endosperm cells and carpel size are being determined. This indicates that future yield gains may be possible through kernel weight increases by management; however, the yield response will be highly variable depending on growing season conditions.

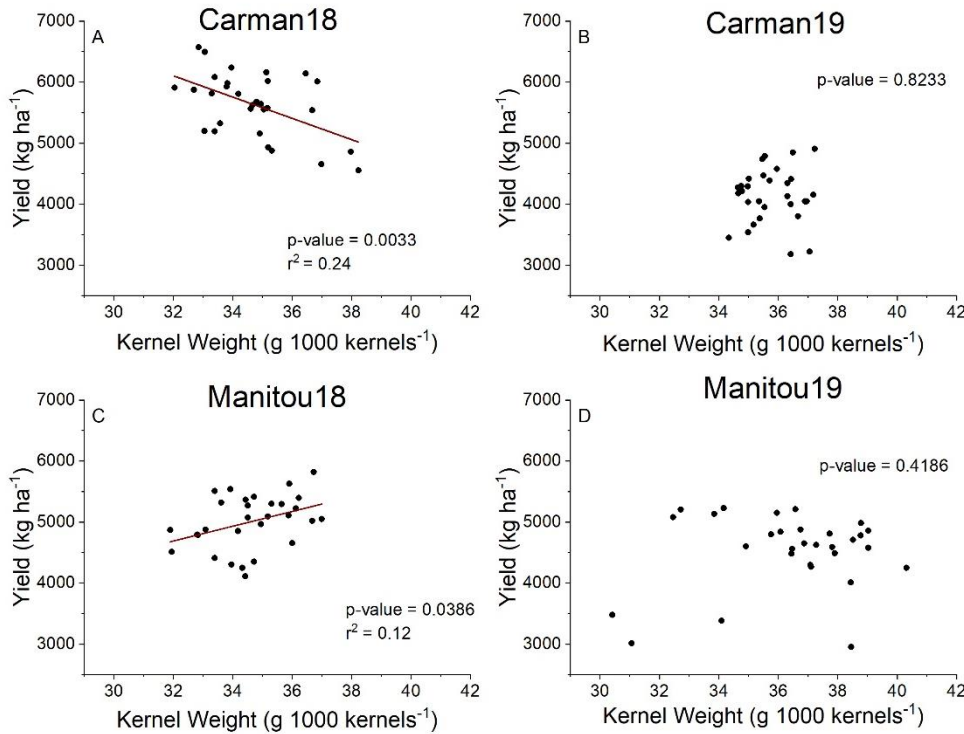


Figure 3.5. Linear regression between kernel weight and grain yield at Carman18 (A), Carman19 (B), Manitou18 (C), and Manitou19 (D), for all combinations of cultivar, nitrogen management, and PGR application.

There was no significant relationship between grain yield and kernel weight for the zero N check treatment, or when a high rate of N was applied in the spring at planting, regardless of the N source (Figure 3.6). When a low rate of N was applied at planting, in the reduced rate treatment, and the split N treatment, there was a significant negative relationship between grain yield and kernel weight (Figure 3.6). This indicates that the low rate of early season N did not

provide sufficient N to maximize kernel weight when high yields were achieved. It is assumed that the in-season application of N at the flag leaf growth stage did not have enough time to be taken up by the plant and increase N available to the spike when kernel size and weight were being determined. The dependence of the relationship between kernel weight and grain yield by N management demonstrates the importance of N availability early in the season to avoid reductions in kernel weight when high kernel numbers are set.

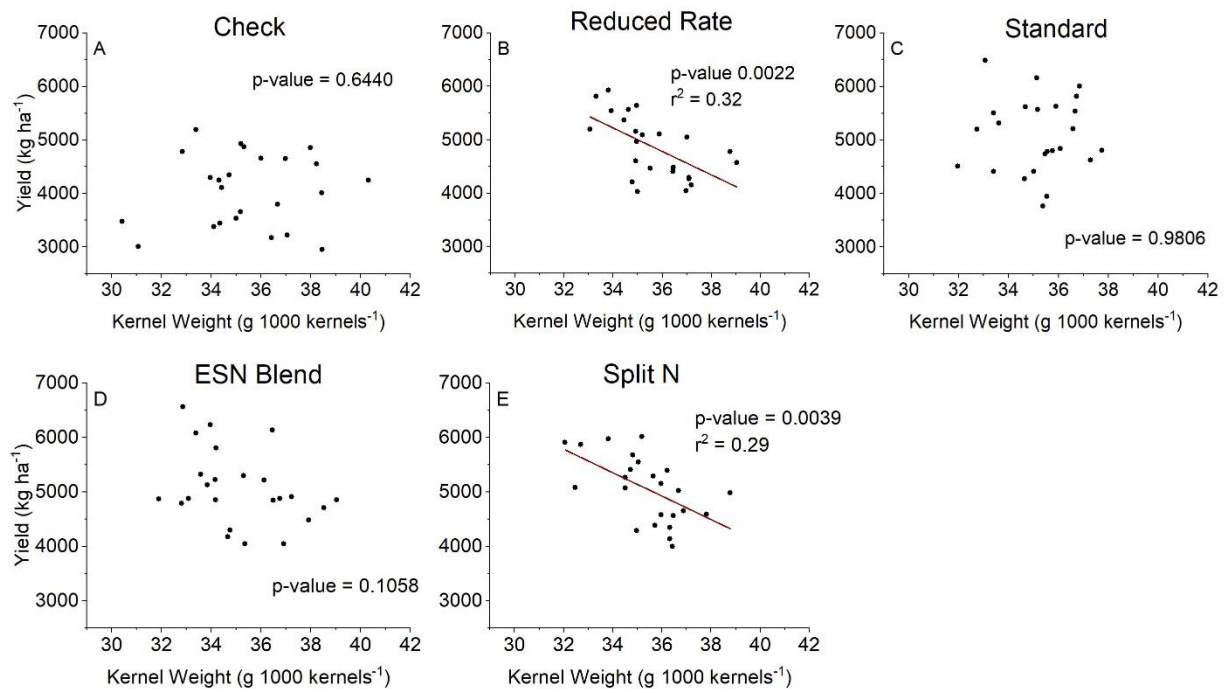


Figure 3.6. Linear regression between kernel weight and grain yield for individual nitrogen (N) management treatments of check (A), reduced rate (B), standard (C), ESN Blend (D) and split N, for all combinations of environment, cultivar, and plant growth regulator application. Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM

The changes to yield and yield components by management practices (N and PGR combinations), relative to the standard N treatment without a PGR applied, allowed for determination of which yield components are driving grain yield response when averaged across cultivars and site-years. There was a very strong positive linear relationship between the responses of spikes per plant and yield ($r^2=0.98$) (Figure 3.7). Additionally, kernels per spike and grain yield responses also had a significant positive relationship ($r^2=0.40$). Neither responses of plant density nor kernel weight had a significant relationship with yield response (Figure 3.7).

Kernels per spike had the most consistent relationship with grain yield across site-years, cultivars, N management and PGR applications. Although, when looking at how changes in yield components are influencing yield response in regard to only management (N and PGR), we saw that when these management practices lead to changes in spikes per plant, it resulted in a highly predictable positive relationship with yield response, more so than kernels per spike (Figure 3.7). This indicates that management practices targeting increased spikes per plant have the greatest potential to consistently increased grain yields. Yield and yield components responses to management were very modest in this study due to environmental conditions. It would be valuable to examine this relationship when responses are larger among management practices to better understand the range of these relationships.

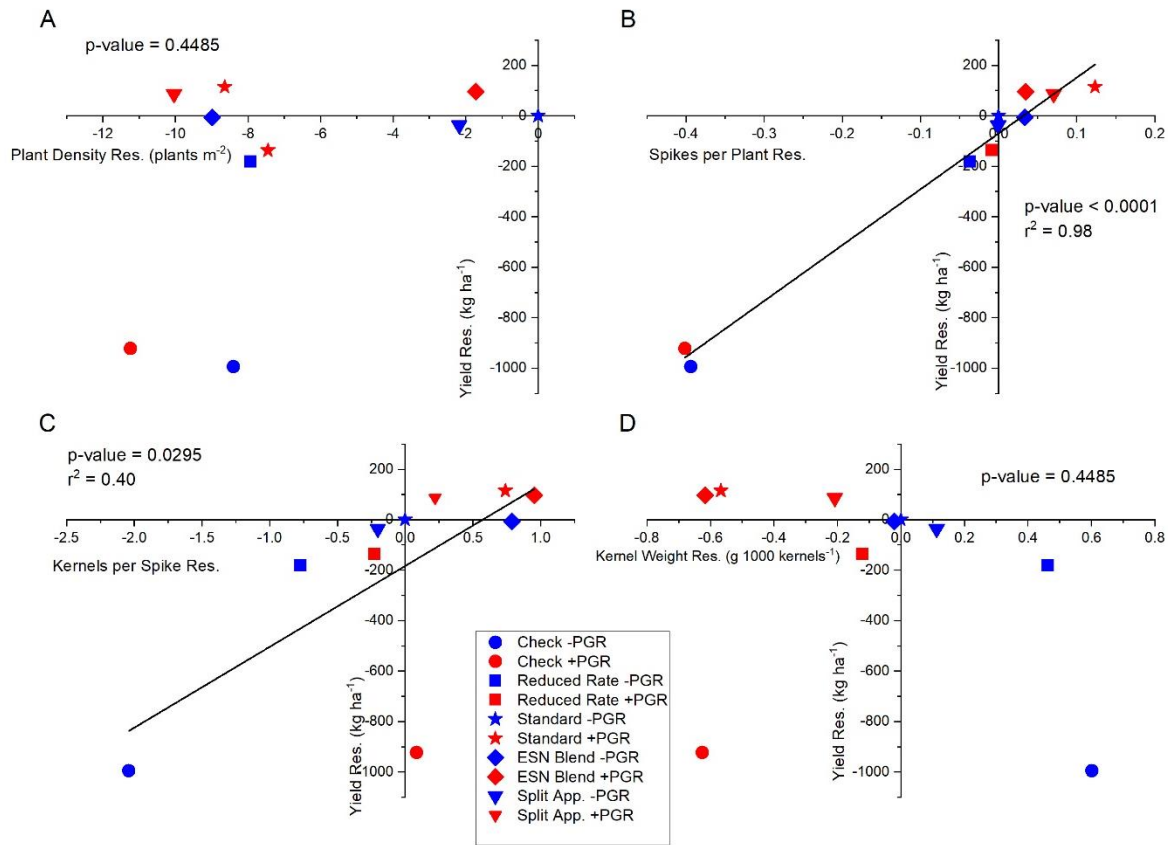


Figure 3.7. Linear regression between yield component (plant density (A), spikes per plant (B), kernels per spike (C), and kernel weight (D)) and grain yield responses (Res.) to changes in nitrogen (N) and PGR relative to the standard N management treatment with no plant growth regulator (PGR) applied (indicated by blue star). Data points on the graph represent the average of each N and PGR treatment combination averaged across site-years and cultivars. Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM

3.4.4 Lodging Risk

3.4.4.1 Site-year

Due to dry conditions and modest yield potential of the site-years in this study, lodging pressure was low. Lodging occurred only at low levels and only at the Manitou19 site-year after

a heavy precipitation event in the last week of July (Figure 3.2). Therefore, in addition to lodging ratings, it is valuable to examine canopy height and stalk strength measurements as indicators of lodging risk in the absence of lodging.

In this experiment the ANOVA indicated a significant influence of site-year on canopy height (Table 3.3). The average canopy height was similar at Carman18 (78 cm), Carman19 (78 cm) and Manitou19 (79 cm), but was slightly shorter at Manitou18 (75 cm). Overall, plant height was shorter than expected during this experiment due to dry growing conditions at all site-years (Table 3.8). Analysis of variance indicated that there was no significant difference in stalk strength between the two 2019 site-years when measured at anthesis (no data at this timing for 2018 site-years). There was a highly significant effect of site-year at maturity when all site-years were included, which accounted for 72% of the variation in stalk strength at maturity (Figure 3.2). At maturity, Carman18 and Manitou18 had significantly higher stalk strength than Carman19 and Manitou19, with no differences between locations in similar years (Table 3.8).

Table 3.8. Least squares means for canopy height, stalk strength (Newtons) measured at anthesis and maturity with a push force meter and visual lodging ratings for the main effects of site-year, cultivar, nitrogen (N) management, and the plant growth regulator (PGR) application of chlormequat chloride (CCC).

Main Effects	Canopy Height	Stalk Strength		Lodging Ratings [†]
		Anthesis [‡]	Maturity	
	cm	Newtons		0-9
<i>Site-year</i>				
Carman18	78 a§		13.6 a	
Carman19	78 a	2.7 a	5.4 b	
Manitou18	75 b		12.7 a	
Manitou19	79 a	2.9 a	6.9 b	
<i>Cultivar</i>				
AAC Brandon	71 c	3.4 a	9.6	1.2 a
AAC Cameron	87 a	2.4 b	9.5	1.1 a
Prosper	75 b	2.5 b	9.8	0.9 a
<i>Nitrogen[¶]</i>				
Check	74 b	2.5 b	8.5 b	0.0 c
Reduced Rate	78 a	3.4 a	10.2 a	0.1 c
Standard	79 a	2.7 b	9.7 a	1.9 ab
ESN Blend	79 a	2.6 b	9.8 a	2.2 a
Split App.	79 a	2.7 b	10.0 a	1.2 b
<i>PGR</i>				
- CCC	80 a	2.5 b	9.7	1.5 a
+ CCC	75 b	3.0 a	9.6	0.6 b

[†] Lodging ratings were calculated by multiplying the lodging severity (1-9 scale; 1 erect, 9 flat) by the percent of the plot lodged (0-100%); Site-year is not a factor for lodging ratings as lodging occurred at only one environment (Manitou19)

[‡] Stalk strength at anthesis was only recorded for 2019 site-years.

[§] Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level. [¶] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESN[™]) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU[™].

3.4.4.2 Cultivar

Analysis of variance for Manitou19, where small levels of lodging occurred, indicated no influence of the main effect of cultivar on lodging ratings. Cultivar significantly influenced canopy height, with differences between cultivars being similar to what would be expected from these cultivars based on cultivar descriptions (Table 3.2). AAC Cameron had the tallest canopy, followed by Prosper and AAC Brandon being the shortest (Table 3.8). Cultivars ranked similarly across all site-years and the significant interactions between cultivar and site-year was due to differences of magnitude. At anthesis, stalk strength for AAC Brandon was significantly greater than for the other cultivars; however, there was no significant difference between cultivars at maturity (Table 3.8). The stalk strength measurements at anthesis align with the lodging ratings published in the cultivar descriptions (Table 3.2).

3.4.4.3 Nitrogen Management

It is well documented that N fertilization has a large influence on the lodging risk of wheat (Berry et al. 2004). In this study, the ANOVA indicated a significant influence of the main effect of nitrogen management on lodging ratings, canopy height and stalk strength at anthesis and maturity (Table 3.3). Additionally, there was a significant effect of the interaction of N management with cultivar for lodging ratings.

At Manitou19 there was no lodging in the zero N check plots (Tables 3.8 and 3.9). When N was applied in a modest amount with the reduced rate treatment, lodging levels were very low and statistically similar to the check treatment for all cultivars tested (Table 3.9). When averaged across cultivars, lodging was significantly increased when N was applied at the high rate regardless of the N source or timing of application (Table 3.8). However, split N application reduced lodging compared to the ESN blend, with neither being significantly different from the standard N management treatment of urea applied entirely at planting (Table 3.8). However, the two-way interaction of N management with cultivar reveals that the three high-rate N treatments did not consistently influence lodging ratings across cultivars (Table 3.9). For the cultivar AAC Brandon, the ESN blend had significantly higher lodging ratings compared to the standard treatment of urea (Table 3.9). There were no significant differences between lodging ratings among any of the high-rate treatments for the cultivar AAC Cameron, while Prosper had a significant reduction in lodging when the high N rate was applied as a split application compared

to entirely at planting in the standard treatment (Table 3.9). Across all cultivars, splitting N applications between seeding and flag leaf showed the most potential to reduce lodging when high N rates were applied. Split applications may reduce lodging by limiting vegetative growth early in the season compared to when large amounts of pre-plant N are applied, and as a result, reduce the shading responses (Mizuta et al. 2020; Sparkes and King 2007). Typically, N applications before stem elongation increase lodging the greatest (Mulder 1954; Miller and Anderson 1963; Baker et al. 1998), while applications after anthesis have no effect on lodging (Webster and Jackson 1993). Ayoub et al. (1993) reported reduced lodging occurrence when N was applied as a split application (60% plants and 40% heading) compared to when applied entirely at planting at one out of four environments tested. The reason for cultivar-dependent N response for lodging ratings is unclear from this study. More work in higher-lodging environmental conditions would be valuable to understand this interaction further.

Table 3.9. Least squares means of the two-way interaction of nitrogen (N) management with cultivar for visual lodging ratings at Manitou19.

<i>N Management</i> [‡]	<i>Cultivar</i>		
	<i>AAC Brandon</i>	<i>AAC Cameron</i>	<i>Prosper</i>
	<i>Visual Lodging Rating</i> [†]		
Check	0.00 b§	0.00 c	0.00 b
Reduced Rate	0.23 b	0.14 bc	0.06 b
Standard	1.18 b	2.21 a	2.22 a
ESN Blend	3.25 a	2.00 ab	1.29 ab
Split App.	1.46 ab	1.1 abc	1.11 b

[†] Lodging ratings were calculated by multiplying the lodging severity (1-9 scale; 1 erect, 9 flat) by the percent of the plot lodged (0-100%)

[‡] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

[§] Within columns and main effects, means followed by the same letter are not significantly different.

The rate, source and timing of treatments with N fertilizer applied did not have a significant influence on canopy height in this study (Table 3.8). It is likely that all treatments with N applied had sufficient N for canopy height during the stem elongation growth stage. Canopy height was significantly lower when zero N fertilizer was applied in the check treatment compared to all other N management treatments (Table 3.8).

Nitrogen management significantly influenced stalk strength when measured at both anthesis and maturity (Table 3.3). When no nitrogen fertilizer was applied, stalk strength was numerically lowest at anthesis and maturity, but it was only significantly lower when measured at maturity (Table 3.8). Plants that are deficient in N will have thinner stems, reducing stem strength, but typically are a low lodging risk because of light spike weight (Mulder 1954). When the low rate of N was applied in the reduced rate treatment, stalk strength at anthesis was significantly increased compared to all high N treatments, this trend continued until maturity although the differences was not significant (Table 3.8). When modest N fertilizer rates were applied, correcting an N deficiency, large increases in stem strength occur paired with large increases in yield; therefore, the spike weight and resulting leverage on the plant is also increased and lodging risk might still increase (Crook and Ennos 1993; Berry et al. 2000). As N fertilizer rates increase further, grain yield gains slow and stem strength begins to weaken, potentially from indirect shading effects of denser crop canopies (Sparkes and King 2007). Mulder et al. (1954) determined that the shading effect of high N canopies resulted in elongation of lower internodes causing reduced stem diameter, stem wall width, and lignified tissue. When high rates of N fertilizer must be applied, limiting the amount of N available to the plant early in the growing season may help limit these shading effects (Mizuta et al. 2020). This was attempted in the split application treatment by withholding half of the N fertilizer until the flag leaf growth stage. However, there was no difference in stalk strength between the standard N management practice and the split application or the ESN blend in this experiment. This study demonstrates the inconsistent reductions in lodging risk through N management strategies when high rates of N are applied, demonstrating the need for additional tools for managing lodging risk.

3.4.4.4 Plant Growth Regulator

The application of a PGR significantly decreased lodging ratings at Manitou19; however, the ANOVA also indicated a significant interaction between PGR and N management (Table 3.3). For all N treatments where a high N rate was applied (standard, ESN blend, and split app),

the application of a PGR reduced lodging ratings (Figure 3.8). There was very little lodging in the check plot and reduced rate N treatments, regardless of PGR application (Figure 3.8).

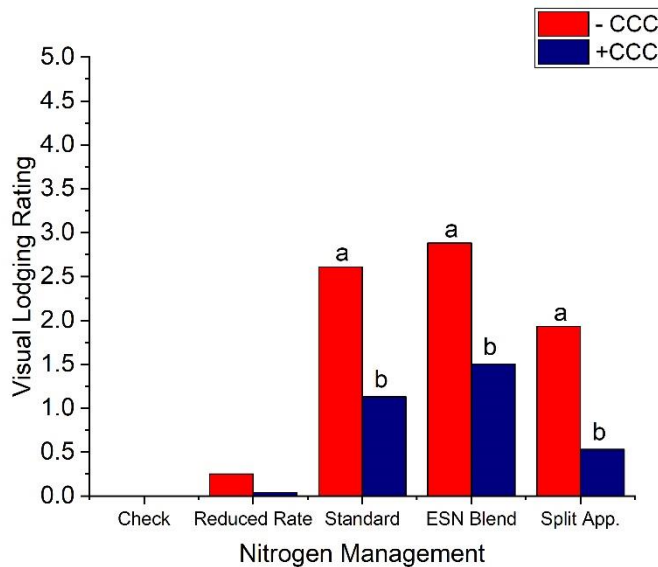


Figure 3.8. The interactive effect of nitrogen fertilizer management (Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM) and application of the plant growth regulator chlormequat chloride (CCC) applied at the beginning of stem elongation on lodging at Manitou19. Lodging ratings were calculated by multiplying the lodging severity (1-9 scale; 1 erect, 9 flat) by the percent of the plot lodged (0-100%). Bars with different lowercase letters indicate significant differences (*P*-value<0.05) between PGR treatments within a N management treatment. The absence of letters indicates no differences

Plant growth regulator application significantly reduced canopy height by 5 cm across all site-years, cultivars, and N treatments (Table 3.8). There was a significant interaction between PGR and site-year that was due to a larger height reduction at Carman18 (9.0 cm) compared to all other site-years (average 4.2 cm). Carman18 was the highest yielding site-year, with early season conditions favorable for plant growth with high temperatures and precipitation when the

crop was in the stem elongation growth stage (Figure 3.2), which may have allowed for a greater response to the PGR applications (Rademacher 2000). There was also a significant interaction of PGR with cultivar that accounted for a very small proportion of the total variance (0.4%) and was due to a slightly larger height reduction in the tall cultivar AAC Cameron (6.5 cm) compared to the two semi-dwarf cultivars, AAC Brandon (5.6 cm) and Prosper (3.9 cm). Gibberellin inhibiting PGRs, such as CCC, reduce height by acting on a similar pathway as common Rht genes in semi-dwarf cultivars (gibberellin biosynthesis); this may result in a weaker response to PGRs in semi-dwarf cultivars compared to tall cultivars (Beharav et al. 1994; Berry et al. 2004). However, cultivar-dependent height reductions are commonly reported with the application of a gibberellin inhibiting PGRs, even among semi-dwarf cultivars (Rademacher 2000). Zhang et al. (2017) reported height reductions ranging from 6 – 33% when CCC was applied across six Canadian semi-dwarf spring wheat cultivars in greenhouse conditions.

In addition to reducing canopy height, PGR application significantly increased stalk strength at anthesis from 2.54 N to 3.02 N (Table 3.8). This agrees with responses measured by Wiersma et al. (2011) who used a similar stalk strength meter and reported a significant linear response of stalk strength (anthesis and soft dough growth stages) to increasing rates of a similar gibberellin inhibiting PGR, TXP. Applications of CCC and TXP have been reported to increase strength of lower internodes in wheat by increasing stem diameter, degree of stem filling, and stem wall width at the soft dough stage in greenhouse conditions (Zhang et al. 2017). There was no effect of CCC application on stalk strength when measured at maturity (Table 3.8).

It was difficult to evaluate the ability of agronomic management strategies to reduce lodging risk in this study due to the low lodging pressure. Additional observations in environments with more growing season moisture and higher yield potential are needed to evaluate the potential of these agronomic management practices to lower lodging risk across when higher yields are achieved.

3.5. Conclusions

Overall, this experiment demonstrates that the environmental conditions during a growing season are the largest determinant of grain yield. This highlighted the need to

understand how we can achieve consistent yield increases through management of current cultivars regardless of unpredictable environmental conditions in the Canadian Prairies.

Ample resources, such as N fertilizer, need to be available for yield component development to maximize yields of current cultivars; however, this must be balanced with management of increased lodging risk. By lowering the rate of N fertilizer applied in this study, lodging risk was reduced and yields were similar to the high rate, but protein concentrations were reduced. This effect would be inflated if higher yields were achieved, limiting the adoption of this practice as a strategy to manage lodging. The most promising N management strategy to reduce lodging risk was splitting the N application timing of a high rate of N fertilizer between seeding and flag leaf growth stages. This practice resulted in similar yields, increased protein content, and reduced lodging risk compared to when N was applied entirely at seeding. To ensure that N is not limited for kernel weight with split application, creating a negative relationship between kernel number and kernel weight, a larger portion of N may need to be applied at seeding. Though split N applications were successful in this experiment, there are risks associated with applying N during the growing season in dryland spring wheat production, such as surface stranding in the absence of timely precipitation. Additionally, time constraints and equipment availability for this additional application during the growing season may limit adoption of split N applications in the eastern Canadian Prairies.

This study highlighted the value of PGRs as a tool to manage lodging risk when high levels of N are required early in the growing season, while increasing yields through increased kernels per spike. The yield components, spikes per plant and kernels per spike, had the greatest relationship with grain yield in this study. Yield response to changes in management (N and PGR) from the high rate of N applied at planting as urea without a PGR application, showed a highly significant linear relationship with changes to spikes per plant. This indicates that any increases in spikes per plant through management will have a positive yield response regardless of cultivar or environmental conditions. When targeting yield responses through spikes per plant or kernels per spike, early season N supply, before anthesis will be critical. This may increase lodging risk further and will likely need to be paired with a PGR application when high yields are achieved.

We must acknowledge that during this study there were modest yield and lodging responses to management practices tested due to environmental conditions that were drier than normal. This made it difficult to determine the potential of the treatments to push yields without increasing lodging. Additionally, the influence of lodging on grain yield, and yield components could not be determined, and would be valuable to investigate further. Additional research to evaluate relationships observed in this study, between grain yield and yield components in response to management, with a greater responsiveness level would be valuable for determining the range of these relationships when targeting high yields in the eastern Canadian Prairies.

CHAPTER 4. MAXIMIZING SPRING WHEAT PRODUCTIVITY IN THE EASTERN CANADIAN PRAIRIES II. GRAIN NITROGEN, GRAIN PROTEIN AND NITROGEN USE

4.1 Abstract

The marketability of spring wheat across the Canadian prairies is largely dependent on grain protein content. New high-yielding cultivars require a large investment in fertilizer nitrogen (N) to achieve milling quality standards. When high rates of N fertilizer are applied, N use efficiencies tend to decrease, lowering returns on investment. The objectives of this study were to identify patterns of N use for spring wheat cultivars and how they are influenced by agronomic management practices. Field trials were conducted in 2018 and 2019 in Manitoba, CA to evaluate N uptake timing, N remobilization from vegetative tissue and the resulting grain N yield and protein content. Three spring wheat cultivars were evaluated using five N fertilizer treatments with and without an application of a plant growth regulator (PGR). When high N rates were applied, average nitrogen use efficiency, for grain N production, was 60%. On average 21-36% of N uptake occurred after anthesis and this portion was highly dependent on late season precipitation. Targeting increases in early season N accumulation and grain fill remobilization, to produce optimal grain N concentrations, may be used to manage risk associated with unpredictable precipitation during the growing season. Cultivars tested produced similar grain N concentrations through fundamentally different N use patterns, indicating that there may be opportunity for breeding programs to target N use patterns that best fit environmental conditions of the Canadian prairies to maximize grain N production.

4.2. Introduction

Spring wheat in the Canadian Prairies is known for its high protein concentrations and exceptional milling quality (Canadian Grain Commission 2019). Genetic improvements have increased grain yield potential across the Prairies and as a result, producers have intensified agronomic management practices to capitalize on that high yield potential (Tomas and Graf 2014). When high yields are achieved, they are commonly associated with low grain protein content (Simmonds 1995), due to N fertilization strategies that do not fully meet crop demand. The eastern Canadian Prairies typically have higher growing season moisture with increased yield potential compared to other regions in the Canadian Prairies. Recent studies in Manitoba have indicated N requirements in excess of 190 kg N ha⁻¹ to reach economic optimum levels of grain yield and protein content of spring wheat (Mangin and Flaten 2018). When high rates of N fertilizer are required, the agronomic, economic, and environmental risks associated with the current practices (N applied before, or at planting, as conventional urea) used across the province are increased. Typically, 98% of spring wheat fields in Manitoba receive N fertilizer applications either before, or at planting, due to time and resource limitations placed on growers by the short growing season (Manitoba Agriculture 2007). Additionally, conventional urea is the most common form of N fertilizer used across the province, which may become vulnerable to losses shortly after application. Consequentially, these practices may reduce the growers return on fertilizer investment and increase the risk of environmental pollution when fertilizing for the yield potential of the current cultivars.

Nitrogen management strategies can be adjusted to maximize uptake of N from the soil and reduce losses to the environment. Enhanced efficiency fertilizers slow the release of N to match N soil supply with crop uptake, reducing the amount of N vulnerable to early season losses. For example, Environmentally Smart Nitrogen (ESNTM) is a polymer-coated urea that is designed to release N slowly after application in response to soil texture, temperature, and to a lesser extent soil moisture (Golden et al. 2011). However, these types of enhanced efficiency fertilizers are more expensive and previous research has not shown a consistent benefit for spring wheat production in Manitoba (Grant et al. 2012), limiting their adoption. Alternatively, delaying a portion of the crops N fertilizer until after the crop is established, allows adjustment of N rates based on growing season conditions and current yield potential. However, limited research in

Manitoba conditions, uncertainty of late season precipitation required for infiltration of added N into the soil, and time constraints have limited adoption of this practice.

When high rates of N are applied early in the growing season, tall dense wheat canopies with reduced stem strength can result, drastically increasing lodging risk (Berry et al. 2004). Lodging compromises the stem and/or root structure, inhibiting resource capture and translocation, and the ability of the crop to produce grain and grain N (Berry et al. 2004). When high yields are expected, a plant growth regulator (PGR) application is commonly applied to decrease stem elongation and reduce lodging risk. However, the influence that PGR applications have on the crop's ability to capture and utilize N for grain N is unclear. When stem elongation is reduced, resources that would have been allocated to the stem may be available for reallocation within the crop, affecting the crop's ability to take up and store N during the growing season.

The quantity and timing of N availability for crop uptake can greatly influence a crop's final grain protein content (Bogard et al. 2010). There are two main pools of N available to the crop for uptake through the root system, soil N and fertilizer N. Soil N can be divided into inorganic N and organic N. Inorganic N can be quantified through a simple soil test; this N source is readily available for crop uptake early in the season and is easily accounted for when making N fertilizer rate decisions. Alternatively, organic N is less available to the crop and will usually not be taken up until it is mineralized into an inorganic form. The rate and total amount of mineralization is very difficult to predict and account for, as it will vary with the growing season conditions, soil characteristics, and past management history of any particular field. Soil N alone is not usually sufficient to meet the crop N demand; therefore, fertilizer N is applied to fill the difference and provide adequate N for crop production. The rate, source, and timing of these fertilizer applications will influence the crop's ability to use this N to produce grain N.

The timing of N uptake from the soil is not constant over the growing season. When spring wheat is being established (seeding to tillering) there is very little N uptake. McGuire et al. (1998) reported only 17% of total above ground N was taken up from emergence to tillering. From tillering to heading the majority of the N for a spring wheat crop grown in Saskatchewan is taken up with maximum rate of uptake being at stem elongation (22-32 days after emergence (DAE)) and the maximum total above ground N being reached just before anthesis (61-68 DAE) (Malhi et al. 2006). During this phase of rapid uptake, the crop's root system absorbs most N as

nitrate and ammonium and assimilates it into organic forms in vegetative tissues. Leaf N is primarily used for photosynthesis as the protein RuBisCO, while stem N is used for structural storage, vascular connections, and reserve/storage (Barraclough et al. 2010; Pask et al. 2012). A large proportion of the vegetative N accumulated early in the growing season will later be remobilized to the spike during the grain fill period to produce grain N (Hawkesford 2014). Averaged across five Canadian Western Hard Red (CWRS) spring wheat cultivars, Wang et al. (2003) estimated 68% of grain N originated from vegetative tissue. In winter wheat, the total amount of N remobilized from vegetative tissue has been reported to range from 50 – 90% of that accumulated until anthesis (Kichley 2007; Foulkes et al. 20011; Kong et al. 2016). It is thought that leaf and stem tissues are the most important source of vegetative N being remobilized to the grain, as roots and chaff only account for 10 - 15% of total N remobilized during the grain fill period (Critchley 2001).

Nitrogen can continue to be taken up by the crop during the grain fill period, but this amount will typically result in a much smaller proportion of the crop's total N uptake compared to N taken up earlier in the season. Malhi et al. (2006) reported that less than 5% of total N was taken up during the post-anthesis period in the black soil zones in Saskatchewan. Alternatively, Przednowek (2003) reported an average of 23% of spring wheat N uptake occurred after anthesis in Manitoba growing conditions. Although post-anthesis N uptake accounts for a smaller proportion of total N uptake, it is thought to contribute heavily to final grain N content. Pask et al. (2012) examined N uptake and remobilization patterns in winter wheat and determined that on average only 10% of the total N uptake occurred during the post-anthesis period, but this N accounted for 30% of the grain N content. Additionally, post-anthesis uptake is reported to allow for increased grain protein content without resulting in lower grain yields that are typical of the grain yield-protein relationship. This is likely due to preferential movement of N taken up during grain fill directly to the developing grain (Bogard et al. 2010). Crop physical characteristics such as depth of rooting system and root longevity will facilitate late season N uptake; however, N uptake cannot occur when soil moisture conditions are dry (Foulkes 2009; Hawkesford 2014), which is often the case in dryland wheat production systems during the grain fill period in the Northern Great Plains.

Large amounts of N fertilizer are often required to reach milling market protein standards of high-yielding spring wheat. To maximize N uptake and utilization of these fertilizer applications for grain N it is important to understand the patterns of crop N uptake and N use in these new high-yielding cultivars under intensive management practices in the eastern Canadian Prairie province of Manitoba. The objectives of this study were to (1) determine N uptake, accumulation, and remobilization patterns of high-yielding spring wheat cultivars and how these patterns are influenced by agronomic practices such as N management and PGR application and (2) measure the N use efficiencies for grain N production by spring wheat and potential for improvement through agronomic management in the eastern Canadian Prairies.

4.3. Materials and Methods

4.3.1 Site Descriptions and Agronomic Management

Trials were conducted at two locations during the 2018 and 2019 growing seasons for a total of four site-years. Field trials were located at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB, and in a commercial field near Manitou, MB. Soil was sampled at 0-15, 15-60 and 60-120 cm depths for characterization of residual soil nutrients in the spring before planting at each location (Table 4.1). To estimate soil N mineralization that occurred during the growing season, post harvest soil NO₃-N samples were taken from the 0-120 cm depth in treatments where zero additional N fertilizer was applied. Nitrogen mineralized was estimated for each site by subtracting soil nitrate depletion from total N uptake by the crop in the check plots where no fertilizer N was applied. Depletion of soil nitrate reserves in the check plots was calculated by subtracting the amount of soil NO₃-N at the 0-120 cm depth for post-harvest soil samples from pre-plant soil samples. Growing season precipitation and temperature data were collected at each field site from April to Sept using a WatchDog 2700 series weather station (Spectrum Technologies, Aurora, IL, USA).

Table 4.1. Characteristics of each experimental site-year; location, year, previous crop, spring soil residual nutrients (nitrate-N (NO₃-N), Olsen phosphorus (P), potassium (K), sulfur(S) and soil organic matter (SOM)), soil texture and dates of key field operations (seeding, plant growth regulator (PGR) application, in-season split N application and harvest

				Site-year			
				Carman18	Carman19	Manitou18	Manitou19
Location				Carman, MB	Carman, MB	Manitou, MB	Manitou, MB
Year				2018	2019	2018	2019
Latitude, Longitude				49.496611°N, 98.040352°W	49.500878°N, 98.030846°W	49.087722°N, 98.501826°W	49.080626°N, 98.515924°W
Previous Crop				Soybean	Canola	Canola	Canola
<i>Spring Soil Samples</i>							
		<i>Depth</i>					
NO ₃ -N	(kg ha ⁻¹)	0 - 120 cm		71	108	103	90
Olsen P	(mg ha ⁻¹)	0 -15 cm		8	7	10	22
K	(mg ha ⁻¹)	0 - 15 cm		136	384	369	386
S	(kg ha ⁻¹)	0 - 60 cm		78	155	179	119
SOM	(%)	0 - 15 cm		3	5.9	7.3	6.7
Texture				Sandy Loam	Sandy Clay Loam	Clay Loam	Clay Loam
<i>Fall Soil Samples</i>							
NO ₃ -N	(kg ha ⁻¹)	0 - 120 cm		16	31	26	47
Estimated Soil N Mineralization [†]				114	37	64	61
<i>Field Operations</i>							
Seeding [‡]				May 7, 2018	April 26, 2019	April 29, 2018	May 7, 2019
PGR Application				June 9, 2018	June 5, 2019	June 7, 2018	June 14, 2019
Split N Application				June 21, 2018	June 20, 2019	June 18, 2018	June 26, 2019
Harvest				August 14, 2018	August 8, 2019	August 15, 2018	August 23, 2019

[†]Estimated mineralization calculated by spring residual N, N Uptake in check plot with no N fertilizer applied and postharvest N soil sample in check plot. N uptake in Check + (Fall soil NO₃-N - Spring soil NO₃-N)

[‡] N fertilizer applied at the time of planting, other than the portion of N applied in-season in the split N application that was applied at the flag leaf stage (GS39)

Spring wheat seeding rate was calculated to target the Manitoba recommended plant density of 250 plants per m⁻² (Manitoba Agriculture 2018) using 1000-seed weight, germination percentage and a 15 percent mortality factor. Seed was treated with tebuconazole (3.0 g L⁻¹), prothioconazole (15.4 g L⁻¹), and metalaxyl (6.2 g L⁻¹) formulated as Raxil Pro fungicide (Bayer Crop Science Canada) at a rate of 325 mL product per 100 kg seed weight. Seeding was completed using an 8-row small plot forced air seeder with 20.3 cm row spacing and knife openers, and midrow banding capabilities. Seed-placed phosphorus was applied as mono-ammonium phosphate (11-52-0) at a rate of 19.6 kg P ha⁻¹ for all plots.

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. The fungicide Twinline (BASF Canada) which contains pyraclostrobin (130 g L⁻¹) and metconazole (80 g L⁻¹) was applied at a rate of 494 mL ha⁻¹ at all sites when plots reached the flag leaf stage (GS39) (Zadoks et al. 1974) to control leaf diseases. The fungicide Prosaro-XTR with the active ingredients prothioconazole (125 g L⁻¹) and tebuconazole (125 g L⁻¹), was applied at anthesis (GS60) at all locations to control fusarium head blight. Dates of field operations for individual trial locations are presented in Table 4.1.

4.3.2. Treatments and Experimental Design

A four-replicate split-split plot randomized as a Randomized Complete Block Design was used for each experiment. Spring wheat cultivar was the main plot factor; N treatment was the first split plot factor and PGR application was the split-split plot factor. Three cultivars were chosen based on contrasting grain protein concentrations and lodging risk. The three cultivars tested included AAC Brandon (Canadian Western Hard Red, CWRS), AAC Cameron (CWRS), and Prosper (Canadian Northern Hard Red, CNHR). AAC Brandon has been widely adopted across Manitoba due to high yield potential paired with consistently high protein content and a very good lodging rating. AAC Cameron is a newly introduced tall cultivar with similar yield and protein as AAC Brandon, but a slightly lower lodging rating (good, rather than very good). Prosper has been adopted by producers for its very high yield, but protein content tends to be lower as is indicated by its inclusion in the CNHR wheat class, and it has a lodging rating similar to AAC Cameron (Manitoba Seed Growers' Association Inc. et al. 2020).

The sub-plot treatment factor was N fertilizer management, including a check plot with no fertilizer N applied, a standard N fertilizer treatment and three management strategies (rate, source and application timing) targeted to evaluate practices to maximize N efficiency. The standard practice consisted of 156 kg N ha⁻¹ applied as conventional urea, midrow banded at planting. The N rate chosen for the standard practice was based on previous research evaluating N requirements for high-yielding spring wheat in Manitoba (Mangin and Flaten 2018). A reduced rate treatment of 78 kg N ha⁻¹ applied as conventional urea, midrow banded at planting, was included as it is reflective of a traditional N rate used to produce spring wheat in Manitoba in the past. Nitrogen source was evaluated using a blend of ESNTM, a polymer-coated urea and conventional urea (112 kg N ha⁻¹ as ESN: 44 kg N ha⁻¹ as urea) at the same total rate of N as for the standard N fertilizer treatment and applied through midrow banders at planting. ESN is typically blended with conventional urea to ensure early season N availability if conditions aren't favorable for N release from ESN granules, and to buffer the high cost of ESN. A split N application was tested by applying a rate of N that was similar, in total, to the standard practice, but applying portions of that rate at two different application timings during the growing season. At planting 78 kg N ha⁻¹ of N fertilizer was applied as conventional urea through midrow banders; the remaining 78 kg N ha⁻¹ was applied broadcast on the soil surface as SuperUTM (Koch Fertilizer) at flag leaf timing (GS 39). SuperU contains urease and nitrification inhibitors and was used to reduce volatilization risk of the midseason-applied N.

When large amounts of N fertilizer are being applied, lodging is often a concern for growers; therefore, a PGR application was also included in this experiment. The sub-sub plot treatment was the addition or absence of the PGR, chlormequat chloride (CCC), applied to all combinations of cultivars and N treatments. This PGR, trade name ManipulatorTM620 (Belchim Canada), was applied at the onset of stem elongation (GS 31) at 1.8 L ha⁻¹; CCC was applied as a foliar application to the canopy using a CO₂ backpack sprayer with 100 L ha⁻¹ water volume and flat fan nozzles on a four nozzle two-meter-wide boom.

4.3.3 Data Collection

Plots were 8 m long by 1.63 m wide with designated areas for destructive in-season sampling and non-destructive measurements. The front 1.5 m and back 1.5 m of plot length were used for destructive sampling to quantify above ground N uptake at anthesis and maturity. In

these areas, a 0.5 m of row length from rows 4 or 5 was sampled at ground level when plots were at anthesis and at maturity. Plots were considered to have reached the anthesis stage when 50% of the spikes in the entire plot area had reached anthesis and maturity was considered when 50% of the peduncles in the plot had lost their green coloration. Samples were divided into leaf lamina, stem (stem + leaf sheath), and spikes, before being oven dried at 80 degrees for 24 hrs. Oven dried samples of each plant part were weighed, then finely ground (1 mm) using a Cyclone Mill Twister (Retsch USA Verder Scientific, Inc, Newton, PA), and a subsample was sent to AGVISE laboratories for total N analysis by Dumas combustion. The N accumulation for each plant part at anthesis and maturity was then determined by multiplying the dry matter mass by the total N concentration.

Total above ground N content was calculated by summing the N content of all three plant parts together for each plot and sampling timing. Post-anthesis N uptake was calculated by subtracting anthesis N uptake from N uptake at maturity for each plot. Nitrogen uptake efficiency (NUpE) was calculated for each plot using the formula in equation (1).

$$\text{NUpE} = \text{Above Ground N at Maturity} / (\text{Soil Residual Nitrate (0-120 cm)} + \text{Fertilizer N}) \quad (1)$$

Nitrogen remobilization (NRm) from each type of vegetative tissue during the grain fill period was calculated by subtracting N content in that particular vegetative tissue at anthesis from the N content remaining at maturity. Nitrogen remobilization efficiency (NRmE) was calculated to determine the portion of total N remobilized from each vegetative tissue. Equations 2 and 3 represent how calculations for NRm and NRmE were conducted.

$$\text{Leaf NRm} = \text{Leaf N Content at Anthesis} - \text{Leaf N Content at Maturity} \quad (2)$$

$$\text{Leaf NRmE} = (\text{Leaf N Remobilization} / \text{Leaf N Content at Anthesis}) * 100 \quad (3)$$

The middle 5 m row length of rows 2-7 of each plot was used for non-destructive in-season measurements and was taken to harvest for grain yield and N determination. Rows 1 and 8 were removed before harvest operations to minimize edge effects. Grain yield was collected using a small plot combine. Grain samples 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 before being sent to AGVISE Laboratories for total N analysis by combustion. Grain N yield was calculated for each plot by multiplying grain yield mass by grain N concentration. Protein content for each plot was calculated by multiplying total N concentration by the factor of 5.7.

Grain nitrogen utilization efficiency (GNUtE) was calculated using equation 4. Additionally, the overall grain N use efficiency (GNUE) was calculated using equation 5.

$$\text{GNUtE} = \text{Grain N} / \text{Total N Uptake at Maturity} \quad (4)$$

$$\text{GNUE} = \text{NUtE} \times \text{GNUtE} \quad (5)$$

4.3.4 Statistical Analysis

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute, 2001) with site-year, cultivar, nitrogen, and PGR and their interactions as fixed factors. Random factors in the model included block nested within site-year and the interaction of block with cultivar and block with cultivar and nitrogen to account for the split-split plot arrangement for each site-year. Significant main plot effects and interactions between model effects ($P < 0.05$) were determined using an analysis of variance (ANOVA). Assumptions for ANOVA were examined visually using PROC UNIVARIATE to test normality of residuals and the homogeneity of variances. For each response variable the total type 3 sums of squares was partitioned to determine the relative contribution of each model factor to the overall variability of response (Brown 2008). Due to the large number of possible interactions in this analysis, this allowed for the result interpretation to focus on significant main effects and interactions that have potential to produce a biologically relevant response ($> 5\%$ of total variation in response). Means groupings were determined for significant effects using Tukey's Honest Significant Difference (HSD) with a probability of 5% ($P < 0.05$).

4.4. Results and Discussion

4.4.1 Grain Protein and Grain N Yield

4.4.1.1 Site-year

Grain protein content was not significantly different among the four site-years (Table 4.2), with protein contents ranging from 12.8 – 13.3% (Table 4.3). In comparison, there were highly significant differences in grain yield among site-years, with Carman18 having the highest yield of 5590 kg ha⁻¹ and Carman19 the lowest with 4110 kg ha⁻¹ (Table 4.3). Grain yields achieved in this study were modest due to dry conditions across all site-years, with total growing season (April – September) precipitation being 68 – 78% of the 30-year long term average (338 and 348 mm for Carman and Manitou, respectively) (Figure 4.1). Typically, there is a negative grain yield and protein relationship, with high yields resulting in low protein contents and vice versa; however, there are exceptions to this relationship when protein concentrations increase without reduced grain yield, such as when large amounts of late season N uptake occur (Bogard et al. 2010).

Growers are commonly paid a premium based on grain protein concentrations making it an important economical value; however, to understand fundamental processes that are driving these differences it is important to look at grain N yield of the crop (kg ha⁻¹). Grain N yield differed significantly across site-years (Table 4.2), which accounted for 26% of the total variance for grain N yield (Figure 4.2). Grain N yield was highest at the two Carman site-years and lowest at the two Manitou site-years with no significant differences between the two growing seasons at each location (Table 4.3). Grain protein concentration differences between site-years was small and non-significant; therefore, grain yield differences appear to be driving grain N yield differences between site-years (Table 4.3).

Table 4.2. Analysis of variance for main effects of site-year, cultivar, nitrogen, plant growth regulator and their interactions on grain protein, grain N yield, above ground N uptake, N remobilization (NRm), and the N use efficiencies N uptake efficiency (NUpE), N remobilization efficiency (NRmE), grain N utilization efficiency (GNUtE) and grain nitrogen use efficiency (GNUE)

Sources of Variation	df	Response Variable													
		Grain Protein	Grain N Yield	Above ground N Uptake			NUpE	Stem Tissue			Leaf Tissue			GNUtE	GNUE
				Pre-anthesis	Post-anthesis	Total		Anthesis N Content	NRm	NRmE	Anthesis N Content	NRm	NRmE		
Site-year (SY)	3	ns	***	***	***	***	***	***	**	ns	***	***	*	***	***
Cultivar (C)	2	***	**	**	***	ns	ns	***	***	ns	**	**	ns	ns	***
SY x C	6	ns	*	**	ns	ns	ns	**	*	ns	**	*	ns	ns	*
Nitrogen (N)	4	***	***	***	***	***	***	***	***	*	***	***	ns	ns	***
SY x N	12	*	***	***	*	ns	***	*	**	**	***	**	ns	ns	***
C x N	8	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
SY x C x N	24	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Plant Growth Regulator (PGR)	1	***	ns	ns	ns	ns	*	**	*	ns	ns	ns	ns	*	ns
SY x PGR	3	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
C x PGR	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY x C x PGR	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N x PGR	4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY x N x PGR	12	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
C x N x PGR	8	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY x C x N x PGR	24	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)		10	22	26	61	26	46	28	33	13	33	37	7	30	40

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

ns, not significant at the 95% confidence level

Table 4.3. Means groupings for grain yield, grain protein concentration, grain nitrogen (N) yield, N Uptake Efficiency (NUpE), grain N utilization efficiency (GNUtE) and grain N use efficiency (GNUE) for the main effects of site-year, cultivar, nitrogen (N) management and plant growth regulator (PGR) application

Main Effects	Grain Yield	Grain Protein	Grain N Yield	NUpE	GNUtE	GNUE
	kg ha ⁻¹	%	kg ha ⁻¹	%	%	%
<i>Site-year</i>						
Carman18	5590 a†	12.8	126 a	142 a	72 bc	102 a
Carman19	4110 d	13.0	116 a	100 b	61 c	57 c
Manitou18	4969 b	13.3	94 b	78 c	102 a	74 b
Manitou19	4499 c	12.8	102 b	85 c	81b	68 bc
<i>Cultivar</i>						
AAC						
Brandon	4899 a	13.3a	113 a	102	82	79 a
AAC						
Cameron	4513 b	13.2a	107 b	97	79	72 c
Prosper	4964 a	12.4b	109 ab	105	77	75 b
<i>N Management‡</i>						
Check	4032 b	11.1 d	84 c	159 a	79	113 a
Reduced Rate	4830 a	12.4 c	107 b	107 b	78	78 b
Standard	5047 a	13.6 b	120 a	80 c	79	61 c
ESN Blend	5034 a	13.6 b	117 a	80 c	78	61 c
Split App	5015 a	14.1 a	120 a	81 c	81	63 c
<i>PGR</i>						
Untreated	4746 b	13.1 a	109 a	103 a	78 b	75
Treated	4837 a	12.9 b	110 a	100 b	80 a	75

† Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level. The absence of letters indicated no significant differences.

‡ Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESN™) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU™.

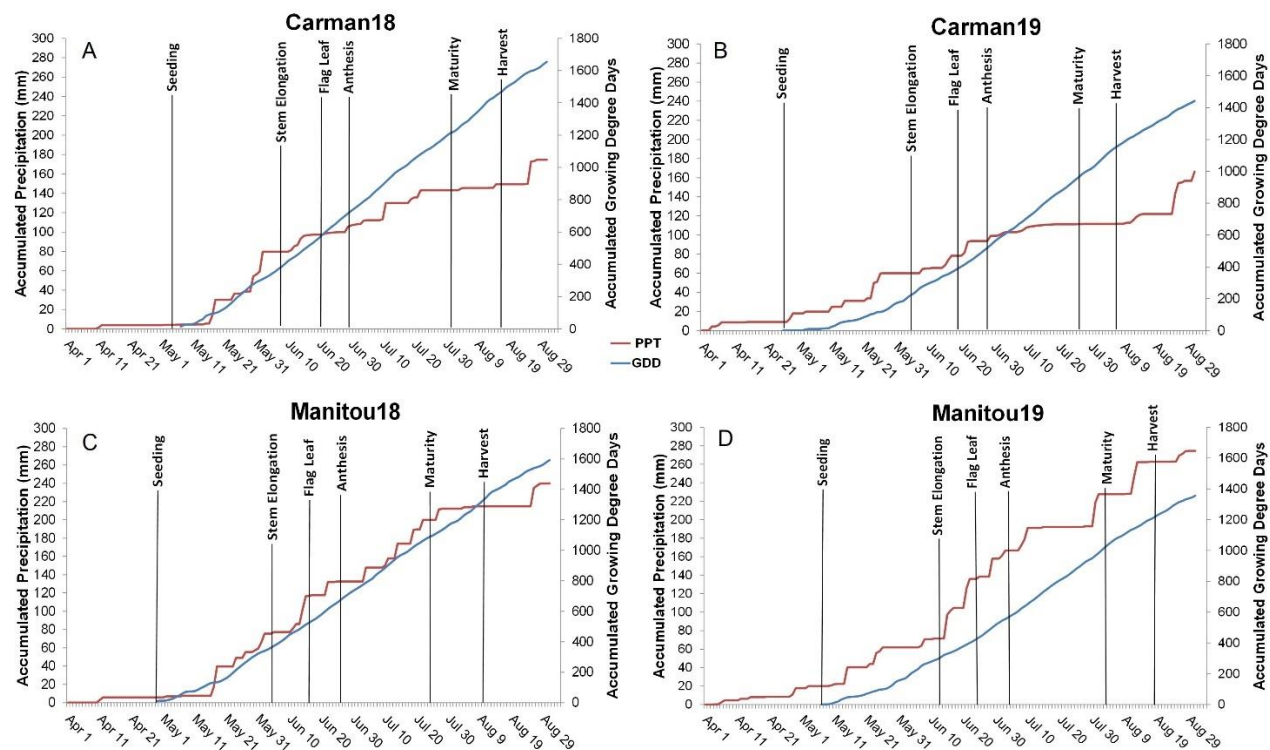


Figure 4.1. Growing season accumulated precipitation (red line starting April 1) and growing degree days (blue line starting at seeding) for Carman18, Carman 19, Manitou18 and Manitou19. Seeding, harvest and the average growth stages for each site-year is indicated by vertical lines

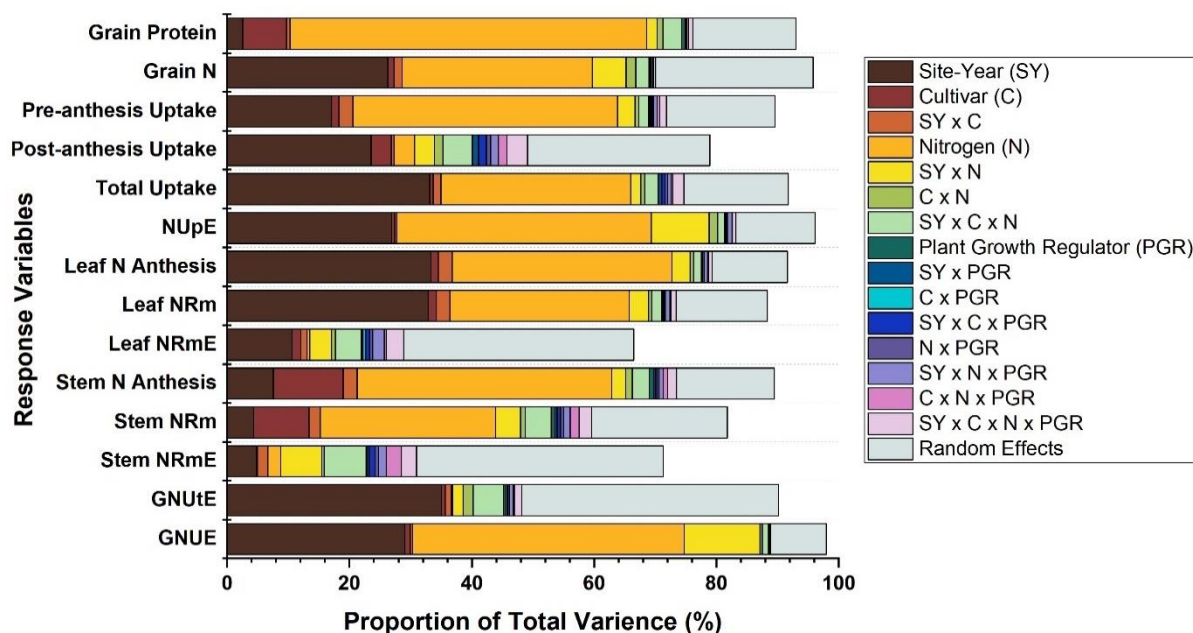


Figure 4.2. Proportion of total variance allocated to main effects and their interactions for each response variable calculated by partitioning the total type 3 sums of squares for each response variable.

4.4.1.2 Cultivar

Cultivar accounted for 7% of the variation in response to grain protein content, but only 1% of the variation in grain N yield, although the cultivar effect was significant for both factors in the ANOVA (Table 4.2 and Figure 4.2). AAC Brandon and AAC Cameron produced similar grain protein concentrations (13.3% and 13.2%, respectively) that were higher than the cultivar Prosper (12.4%), which was expected based on the class differences between the cultivars (Table 4.3). Grain yields were similar for AAC Brandon and Prosper (4899 and 4963 kg ha⁻¹, respectively), while AAC Cameron yielded significantly lower (4513 kg ha⁻¹) (Table 4.3). Cultivar differences in grain N yield were small with AAC Brandon having the highest N yield of 113 kg ha⁻¹, followed by Prosper with 109 kg ha⁻¹ and lastly, AAC Cameron at 107 kg ha⁻¹.

4.4.1.3 Nitrogen and PGR Management

Nitrogen management had a significant effect on both grain protein content and grain N yield (Table 4.2), accounting for the largest portion of variation for both response variables (58% and 31%, respectively, Figure 4.2). Grain protein and grain N yield were 2.5% and 36 kg N ha⁻¹ lower, respectively, when no additional N fertilizer was applied, compared to the standard N management practice of 156 kg N ha⁻¹ applied at planting (Table 4.3). Grain protein and grain N yield were also significantly lower for the reduced N rate treatment compared to when the high rate of N was applied regardless of N source or timing (Table 4.3).

The standard N treatment that consisted of a high rate of N, applied as urea at planting, produced similar grain protein content and grain N yields as the ESN blend (Table 4.3), also applied at planting. When N fertilizer application was split between seeding and flag leaf timing (GS39) there was a significant (0.5 %) increase in grain protein content compared to when similar rates of N were applied entirely at planting. However, there was no difference in grain N yield between the split application and the standard N treatment, indicating that the small, statistically insignificant yield advantage for the standard N treatment compared to the split application may have compensated for the lower grain protein content in the standard N treatment. There was a significant interaction between site-year and N management for grain N that accounted for 6% of the variability (Table 4.2, Figure 4.2). This interaction was due to differences in magnitude of the response between different N rates at each site-year; the ranking of treatments was similar at all site-years (data not shown).

The application of a PGR significantly decreased grain protein content from 13.1% in the untreated to 12.9% with a PGR application (Tables 2, 3). However, this did not result in a decrease in grain N yield because the reduced grain protein content was compensated for by an increase in grain yield with a PGR application (Table 4.3).

4.4.2 N Uptake Timing and NUpE

4.4.2.1 Site-year

Analysis of variance indicated a significant influence of site-year for pre-anthesis, post-anthesis, and total above ground N uptake (Table 4.2). The main effect of site-year accounted for 17% of the variation in pre-anthesis N uptake (Figure 4.2). Carman18, Manitou18, and Manitou19 had similar pre-anthesis N uptake of 140, 131, and 160 kg N ha⁻¹, respectively, all of which were greater than the uptake of 103 kg ha⁻¹ at Carman19 (Table 4.4). The small uptake of

N at Carman19 was probably due to low precipitation from seeding to anthesis (Figure 4.1), resulting in lower pre-anthesis N uptake compared to the three other site-years.

Table 4.4. Least squares means groupings for pre-anthesis, post-anthesis, and total above ground N uptake for the main effects of site-year and cultivar.

	Above Ground N Uptake		
	Pre-anthesis	Post-anthesis	Total
	kg N ha ⁻¹		
<i>Site-year</i>			
Carman18	140 a†	80 a	220 a
Carman19	103 b	49 a	152 c
Manitou18	131 a	71 a	202 b
Manitou19	126 a	34 b	159 c
<i>Cultivar</i>			
AAC Brandon	107 b	60 a	167
AAC Cameron	114 a	46 b	159
Prosper	114 a	50 b	164

†Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level

Site-year accounted for the largest percentage of variation in post-anthesis N uptake (24%), indicating that in this experiment late season uptake was dependent on growing season conditions more than genetics or management practices (Figure 4.2). Post-anthesis N uptake was highest at Carman18 (80 kg N ha⁻¹) and Manitou18 (71 kg N ha⁻¹) and lowest at Carman19 (49 kg N ha⁻¹) and Manitou19 (34 kg N ha⁻¹) (Table 4.4). These differences in post-anthesis N uptake are likely due to more early season precipitation at the 2018 site-years, resulting in increased soil moisture available to facilitate root N uptake during the post-anthesis period (Kong et al. 2016). However, this will result in increased uptake of N only if there are also abundant quantities of plant available N in the soil during this time. Conditions that favor N uptake also favor the mineralization of N from soil organic matter, increasing the available soil N during the later stages of the growing season (St. Luce et al. 2011). There was a large range of estimated mineralization for the four site-years, with Carman18 having 114 kg N ha⁻¹ and Carman19 having 37 kg N ha⁻¹ (Table 4.1).

Total N uptake during the growing season was highest at Carman18, followed by Manitou18, Manitou19, and Carman19 and ranged from 152 – 220 kg N ha⁻¹ (Table 4.4). Across

all site-years 68% of the total N was taken up before anthesis with 32% taken up during the grain fill period. This contrasts with previous research on dryland wheat production in Saskatchewan by Malhi et al. (2006) and Wang et al. (2003), which measured almost no additional N uptake after anthesis. In comparison, in a study conducted under more similar environments in Manitoba, Przednowek (2003) reported an average of 23% of the total growing season N uptake by spring wheat was taken up after anthesis. Differences in late-season soil moisture availability probably explain differences in N uptake timing between Manitoba and the drier environments in Saskatchewan and Southern Alberta.

To understand differences in NUpE between site-years, estimated N mineralized during the growing season must be considered, as this supply of N is not accounted for in the NUpE calculation. As a result, the site-years with large amounts of estimated growing season mineralization such as Carman18 led to NUpE values greater than 100% (Table 4.3). For example, Carman18 had the highest average NUpE of 142%, but also had a large amount of estimated mineralization (114 kg N ha^{-1}) compared to the other site-years (Table 4.1). Manitou18 and Manitou19 had similar NUpE values of 78% and 85%, and these site-years also had similar estimated amounts of N mineralization, at 64 and 61 kg N ha^{-1} , respectively. However, the amount of estimated mineralization doesn't explain the high NUpE at Carman19 (100%) as this site had relatively low growing season mineralization of 37 kg N ha^{-1} . One of the reasons for the high NUpE at Carman19 could be the significant increase of 1.5 – 4.1 days to anthesis (DTA) at this site-year compared to the other site-years (Appendix Table B1), a result of low early season temperatures at this site-year. Brasier et al. (2019) reported a significant positive correlation ($r=0.63$) between DTA and NUpE in winter wheat. This may have been the case at the Carman19; however, in our study, when combined across all site-years and treatments there was a significant negative correlation between NUpE and DTA ($r= - 0.36$) (Table 4.5). This indicates that this relationship between DTA and NUpE may not be consistent across management and cultivars.

Table 4.5. Pearson correlations for individual plot data ($n = 120$) from grain protein, grain N yield, pre-anthesis N uptake, post-anthesis N uptake, total N Uptake, N uptake efficiency (NUpE), Leaf N content at anthesis, Leaf N remobilization (NRm), leaf N remobilization efficiency (NRmE), stem N content at anthesis, Stem NRm, stem NRmE, grain N utilization efficiency (GNUtE), grain N use efficiency (GNUE), days to anthesis (DTA) and grain fill duration (GFD) and days to maturity (DTM).

	Grain Protein	Grain N Yield	Pre-Anthesis Uptake	Post-Anthesis Uptake	Total Uptake	NUpE	Leaf Anthesis N	Leaf N Rm	Leaf NRmE	Stem Anthesis N	Stem N Rm	Stem NRmE	GNUtE	GNUE	DTA	GFD	DTM
Grain Protein	1																
Grain N	0.51***	1															
Pre-Anthesis Uptake	0.65***	0.54***	1														
Post-Anthesis Uptake	0.26***	0.35***	0.23**	1													
Total Uptake	0.58***	0.57***	0.80**	0.76***	1												
NUpE	-0.64***	-0.09	-0.42**	0.11	-0.20*	1											
Leaf Anthesis N	0.56***	0.50***	0.95***	0.41***	0.88***	-0.30**	1										
Leaf N Rm	0.51***	0.49***	0.94***	0.37***	0.85***	-0.26**	0.99***	1									
Leaf NRmE	-0.15	0.05	0.35***	-0.13	0.15	0.21*	0.43***	0.52***	1								
Stem Anthesis N	0.67***	0.48***	0.92***	0.13	0.68***	-0.45***	0.80***	0.78***	0.23*	1							
Stem N Rm	0.60***	0.45***	0.88**	-0.5	0.55***	-0.40***	0.73***	0.73***	0.31**	0.97***	1						
Stem NRmE	-0.15	-0.06	0.02	-0.70***	-0.41***	0.10	-0.10	-0.05	0.36***	0.07	0.31**	1					
GNUtE	0.18*	-0.46***	0.21*	0.17	0.24**	-0.38***	0.30***	0.28**	0.12	0.13	0.07	-0.16	1				
GNUE	-0.55***	-0.29**	-0.29**	0.18*	-0.07	0.87***	-0.13	-0.09	0.34***	-0.38***	-0.34***	0.06	0.08	1			
DTA	0.20*	-0.06	-0.22*	-0.09	-0.20*	-0.36***	-0.29**	-0.33***	-0.49***	-0.05	-0.08	-0.13	-0.03	-0.49***	1		
GFD	0.50***	0.31***	0.59***	0.47***	0.69***	-0.42***	0.69***	0.66***	0.04	0.41***	0.32**	-0.29**	0.48***	-0.20*	-0.03	1	
DTM	0.51***	0.19**	0.30**	0.30***	0.38***	-0.56***	0.32**	0.26**	-0.29***	0.27**	0.18*	-0.31***	0.34***	-0.48***	0.66***	0.73***	1

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

4.4.2.2 Cultivar

The ANOVA indicated that the three cultivars did not differ in the total amount of N taken up during the growing season, but there were significant differences in the timing of uptake among cultivars (Table 4.2). Prosper and AAC Cameron took up similar amounts of N during the both the pre- and post anthesis timings, with 29-30% of their total N taken up after anthesis (Table 4.4). Alternatively, AAC Brandon took up significantly more of its N total during the post-anthesis period (36%) compared to the other cultivars. This may explain the high grain yield, protein concentrations, and grain N yield for AAC Brandon compared to the other two cultivars. Bogard et al. (2010), reported higher grain protein concentrations in cultivars with high post-anthesis N uptake, regardless of grain yield. Cultivar differences in the ability to take up late season N from the soil could be due to differences in root density and length at depths and/or the ability to maintain root activity during the grain fill period (Bogard et al. 2010; Foulkes et al. 2011). Overall, cultivar accounted for a small proportion (<4%) of the total variation for N uptake at all timings during the growing season (Figure 4.2) and there was no significant difference in overall NUpE between cultivars (Tables 4.2 and 4.3).

4.4.2.3 Nitrogen and PGR Management

Nitrogen management had a highly significant effect on pre-anthesis, post-anthesis, and total N uptake during the growing season (Table 4.2). There was a significant interaction of N by site-year for pre-anthesis and post-anthesis uptake, but not for total N uptake. Due to these interactions and the large influence site-year had on N uptake and availability; the effects of N management strategies are discussed for individual site-years as well as combined across site-years.

Nitrogen treatment accounted for 43% of the variability in pre-anthesis N uptake, the greatest proportion of all model factors (Figure 4.2). When no N fertilizer was applied, pre-anthesis N uptake was 57 kg N ha⁻¹ less than for the standard N treatment averaged across site-years (Figure 4.3A). At Carman18 and Carman19 pre-anthesis N uptake was similar for all of the treatments where N was applied. At Manitou18, ESN blended with urea at planting had significantly more pre-anthesis N uptake than the reduced rate application, but it was statistically similar to the standard treatment and the split application. Alternatively, at Manitou19 the

standard N application resulted in significantly higher pre-anthesis N uptake than both the reduced rate and the ESN blend but was similar to the split N application treatment.

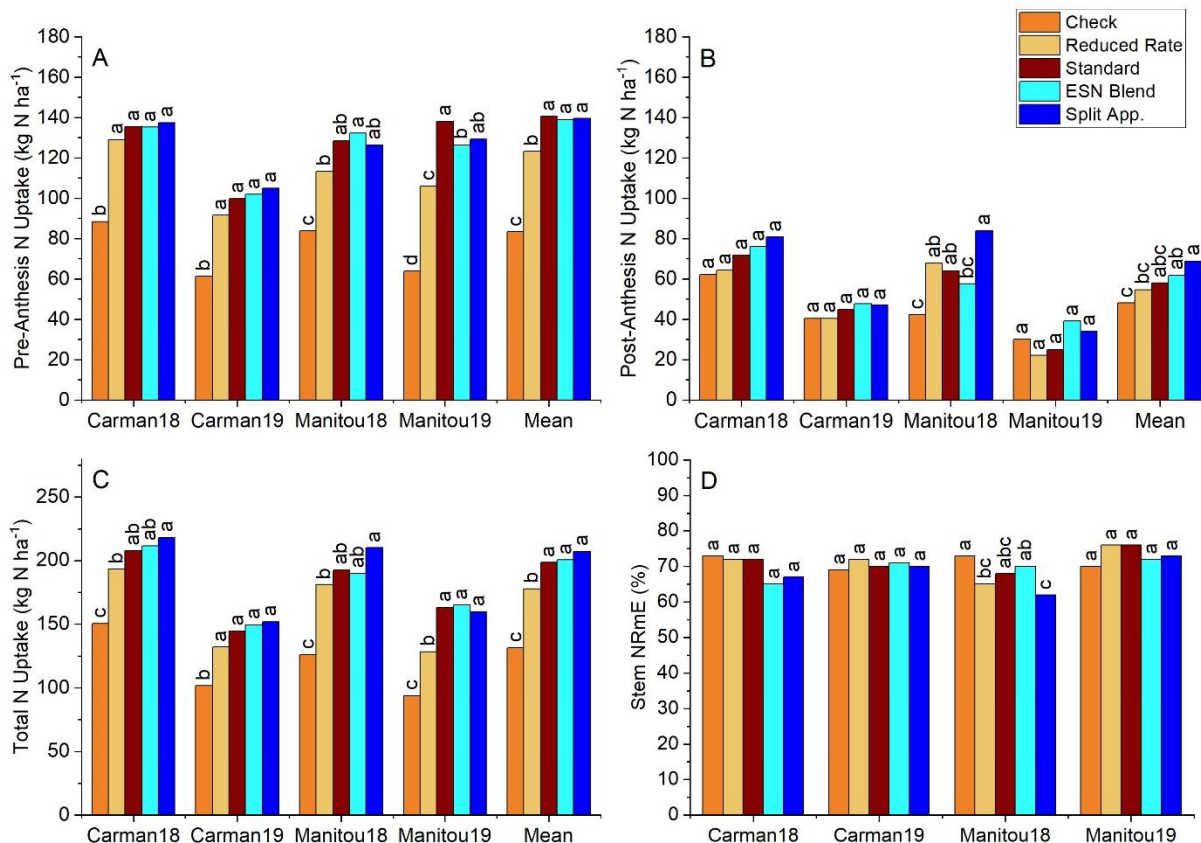


Figure 4.3. Pre-anthesis (a), post-anthesis (b) and total (c) above ground nitrogen (N) uptake as well as (d) leaf tissue N remobilization efficiency (NRmE) at each site-year and overall, as influenced by nitrogen management. Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

Differences in response between N management practices at Manitou18 and Manitou19 are likely linked to early season precipitation and temperature differences between sites before the stem elongation period in May. Accumulated May precipitation at Manitou18 was 81% of the LTA with average daily temperature and accumulated GDDs very close to normal, compared to

Manitou19 that only had 37% of LTA May precipitation and a lower average daily temperature and GDDs (Figure 4.1). In favorable conditions such as in Manitou18, N will become available for uptake from ESN granules, while in cool dry conditions, like those at Manitou19, release of N from ESN granules may be delayed (Grant et al. 2012). When results for the full N rate treatments were combined across all site-years there was no difference in pre-anthesis N uptake between the standard practice and the ESN blend or split N applications.

Nitrogen treatments had a significant effect on post-anthesis N uptake; however, this effect accounted for a much smaller proportion of the variability (3%) compared to pre-anthesis uptake (43%) (Table 4.2, Figure 4.2). When examining post-anthesis uptake at individual site-years, there were no significant differences in post-anthesis N uptake between N treatments (including the check) at Carman18, Carman19, or Manitou19 (Figure 4.3B). At Manitou18, split applications of N increased late season uptake compared to all other N treatments, but the differences were only significant compared to the check and ESN blend treatments (Figure 4.3B). Manitou18 had consistent precipitation events during the grain fill period (Figure 4.1) and the longest grain fill duration (32 days) compared to Carman18, Carman19 and manitou19 (30, 29 and 30 days, respectively), likely allowing for greater levels of post-anthesis uptake when N was available. There was a significant positive correlation between GFD and post-anthesis N uptake ($r = 0.47$) across all treatment factors in this study, indicating the importance of the late season maturity period for late season N uptake.

When the effect of N treatments is considered on mean post-anthesis N uptake across all site-years, split N applications had the numerically greatest uptake (69 kg N ha^{-1}), followed by ESN blend (62 kg N ha^{-1}), and the standard treatment (58 kg N ha^{-1}), with no statistically significant differences between these full N rate treatments (Figure 4.3B). Split N application resulted in a significantly greater post-anthesis N uptake compared to the reduced rate, but there was no difference between the reduced rate and the standard treatment or the ESN blend (Figure 4.3B). As long as precipitation occurs after application to enable fertilizer N to infiltrate into the soil, split N applications will increase N availability during the post-anthesis period. When all N fertilizer is applied at planting, it is all susceptible to early season losses, but when a portion is withheld until later in the season, the risk of early season losses is eliminated for that portion resulting in increased season long N supply with similar total N rates (Shi et al. 2012). In theory, ESN blends should also protect N fertilizer from early season losses and improve late season

availability, which may explain the small, but insignificant increase in late season N uptake with ESN across site-years. If conditions in this experiment had been more favorable for early season N losses through denitrification and leaching, a larger benefit from the ESN blend and split N applications may have occurred compared to the standard practice.

The response of total growing season N uptake to N management strategies had similar trends at all site-years with no significant differences between the standard treatment and the ESN blend or the split N application (Figure 4.3C). The lack of differences is likely due to dry growing conditions during this experiment, resulting in small amounts of N losses. When N losses are large the benefit from enhanced N management strategies such as ESN blends and split applications will increase, and greater total N uptake would be expected. As expected, across all site-years the reduced rate treatment resulted in significantly less N uptake during the growing season than all three full rate N management practices.

At the reduced N rate, NUpE was 107% compared to 80-81% for the three full rate N treatments, indicating that when fertilizer N rates are low, the plant is more efficient in utilizing fertilizer N and soil N reserves (Table 4.3). This is commonly reported in the literature (Brasier et al. 2019). Similar to total N uptake, there were no differences in NUpE between the standard N treatment and the ESN blend or the split N application treatments. There was a significant interaction of N management with site-year that accounted for 9.5% of the variability in NUpE across response variables (Table 4.2, Figure 4.2). This interaction was due to differences in magnitude of the response of N rate at each site-year related to growing season mineralization at each site (data not shown). For example, there was an increase in NUpE with the reduced rate (147%) treatment compared to the full rate of N applied at planting as urea (103%) at Carman18, which had very large amounts of mineralization (Table 4.1). However, at Manitou19, a site with much less growing season mineralization (Table 4.1), there was a much smaller increase in NUpE for similar treatments (85% reduced rate and 74% full rate) (data not shown).

The application of the PGR chlormequat chloride at stem elongation did not have a significant influence on pre-anthesis, post-anthesis, or total N uptake during the growing season (Table 4.2). PGR applications significantly increased days to anthesis by 0.2 days and days to maturity by 0.6 days (Appendix Table B1), but this was not enough to significantly influence N uptake. NUpE was 100% when PGR was applied compared to 103% when no PGR was applied (Table 4.3); this small, but statistically significant difference accounted for only 0.1% of the total

variation. However, because there were no significant differences in N uptake with PGR application it is unlikely this small reduction in NUpE would have an agronomically significant influence on crop productivity.

4.4.3. Vegetative N Remobilization and NRmE

4.4.3.1 Site-year

The amount of N accumulated in the vegetative tissue before anthesis determines how much N is available in the plant to be remobilized to the grain during the grain fill period. There was a significant influence of site-year on N accumulation in both the pre-anthesis leaf and stem tissue (Table 4.2). However, site-year accounted for a much larger proportion of the variation of response for leaf N content (33%) compared to stem N content (7%) at anthesis (Figure 4.2). The range of N accumulated at anthesis was 35 – 60 kg N ha⁻¹ in leaf tissue and 40 – 49 kg N ha⁻¹ in stem tissue (Table 4.6). This range of accumulation of N at anthesis was similar to reports for other CWRS spring wheat cultivars (Wang et al. 2003) and was slightly smaller than the ranges listed for high-yielding winter wheat production (Gaju et al. 2014). The difference between N content in tissue at anthesis and maturity represents the amount of N that was remobilized to the developing grain during grain fill. The amount of NRm from vegetative tissue was very strongly correlated to the amount of N accumulated at anthesis $r = 0.99$ for leaf tissue and $r = 0.97$ for stem tissue (Table 4.5). This strong relationship is well-documented, with N accumulation at anthesis being primarily responsible for total NRm from vegetative tissue to grain during grain fill for both winter and spring wheat production (Wang et al. 2003; Barbottin et al. 2005; Kichey et al. 2007). As a result, there was a similar response to site-year for NRm as N accumulation at anthesis for both leaf and stem tissue (Table 4.6). The range of NRm across site-years was 27 – 50 kg N ha⁻¹ for leaf tissue and 28 – 35 kg N ha⁻¹ for stem tissue (Table 4.6). The NRmE of leaf tissue was higher than that of stem tissue, with leaf NRmE at 78-84% and stem NRmE at 68-73% (Table 4.6). Due to the increased structural role of stem N, it is expected that less of the total N content in the stem will be available for remobilization compared to leaf tissue (Pask et al. 2012).

Table 4.6. Least squares means groupings for leaf and stem tissue nitrogen (N) content at anthesis, N content at maturity, N remobilization (NRm), and nitrogen remobilization efficiency (NRmE) for the main effects of site-year, cultivar, nitrogen (N) management, and plant growth regulator (PGR) application

Main Effects	Leaf Tissue				Stem Tissue			
	Anthesis	Maturity	NRm	NRmE	Anthesis	Maturity	NRm	NRmE
	kg N ha ⁻¹	kg N ha ⁻¹	kg N ha ⁻¹	%	kg N ha ⁻¹	kg N ha ⁻¹	kg N ha ⁻¹	%
<i>Site-year</i>								
Carman18	60a†	10a	50a	84a	49a	15a	35a	70
Carman19	35d	7c	27d	78b	40c	11b	28b	71
Manitou18	55b	10a	44b	81ab	47a	15a	32a	68
Manitou19	46c	8b	38c	82ab	44b	11b	32a	73
<i>Cultivar</i>								
AAC Brandon	48b	9	39b	80	40c	12c	28c	70
AAC Cameron	47b	9	39b	81	50a	14a	36a	71
Prosper	51a	9	43a	82	45b	13b	32b	70
<i>Nitrogen</i>								
Check	30c	5c	25c	81	29c	8d	21c	71
Reduced Rate	48b	9b	40b	81	43b	12c	31b	72
Standard	56a	10a	46a	81	51a	14b	37a	72
ESN™ Blend	56a	10a	45a	81	50a	15ab	35a	69
Split App	55a	10a	45a	80	51a	16a	35a	68
<i>PGR</i>								
Untreated	50	9	41	81	46a	13a	33a	71
Treated	48	9	40	81	44b	13b	31b	70

† Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level. The absence of letters indicates no significant differences

Kichey et al. (2007) reported very similar NRmE of 72% for stems (stems +leaf sheath) and 80% for leaves, while other studies have reported similar leaf NRmE paired with much lower stem NRmE ranging from 48 – 55% (Barraclough et al. 2010; Pask et al. 2012; Kong et al. 2016). Relative consistency in NRmE across site-years in this study indicates that the amount of N remobilized from the vegetative tissue was more dependent on the ability of the crop to take up N early in the season, rather than the efficiency of remobilization during grain fill. There have been reports of NRmE being influenced by environmental conditions during the grain fill period. For example, when the ability of N to be taken up from the soil is inhibited by a soil moisture

deficit, NRm from vegetative tissue increased, resulting in a 13% increase in NRmE compared to a crop with no water moisture stress (Kong et al. 2016). Even with low growing season precipitation across site-years in this study, 30 - 80 kg N ha⁻¹ were taken up during the grain fill period, indicating N availability during this time probably was not limited enough to see increases in NRmE.

4.4.3.2 Cultivar

There was a significant effect of cultivar on N accumulation at anthesis and NRm for both leaf and stem tissue, but cultivar accounted for a very small proportion of the variability in leaf N (1%) compared to stem N (11%) (Table 4.2, Figure 4.2). Leaf N accumulation at anthesis was significantly greater in the cultivar Prosper compared to both AAC Brandon and AAC Cameron, but the differences were only 3 and 4 kg N ha⁻¹, respectively (Table 4.6). The greater early season leaf N accumulation in Prosper compared to AAC Brandon and AAC Cameron resulted in 3 - 4 kg N ha⁻¹ higher NRm from Prosper's leaf tissue (Table 4.6). This agrees with work by Wang et al. (2003) which reported new high-yielding spring wheat cultivars produced adequate grain protein by increasing N accumulation in the leaf tissue early in the season and then remobilizing more during the grain fill period.

Stem N accumulation at anthesis was highest for the cultivar AAC Cameron (50 kg N ha⁻¹), followed by Prosper (45 kg N ha⁻¹) and lastly AAC Brandon (40 kg N ha⁻¹). This trend followed the heights of the three cultivars indicating that cultivars with longer stems were able to accumulate more N in stem tissue by anthesis and as a result remobilize more stem N during the grain fill period (Table 4.6). All cultivars tested were equally as efficient in remobilizing N from leaf (80 – 82%) and stem (70 – 71%) tissue. Cultivar variation in NRmE has been previously reported, but differences were commonly associated with factors such as disease and lodging resistance, neither of which were substantial issues in our experiment (Barbottin et al. 2005; Kichey et al. 2007; Foulkes et al. 2011).

4.4.3.3 Nitrogen and PGR Management

The standard N treatment resulted in 26 and 22 kg N ha⁻¹ more N accumulated in the leaf and stem tissue, respectively, compared to the check treatment. As a result, there was 21 and 16 kg N ha⁻¹ less remobilized from the stem and leaf tissue, respectively, for the check (Table 4.6). Similarly, the reduced rate treatment significantly lowered N accumulation and remobilization in

both the leaf and the stem tissue compared to the standard treatment. There were no significant differences in N accumulation or overall NRm between treatments with the full rate of N applied (Standard, ESN Blend, Split N) (Table 4.6). Across these full rate N treatments, plant N accumulated at anthesis ranged from 55 - 56 kg N ha⁻¹ for leaf tissue and 50 – 51 kg N ha⁻¹ for stem tissue, while remobilized N ranged from 45 – 46 kg N ha⁻¹ (leaf) and 34 – 37 kg N ha⁻¹ (stem).

NRmE from leaf tissue was not influenced by N management, with all treatments remobilizing approximately 80% of their accumulated N (Table 4.6). The main effect of stem NRmE was also not significant in the ANOVA; however, there was a significant interaction between site-year and N management that accounted for 7% of the variability in response (Table 4.2 and Figure 4.2). Examination of the influence of N management on stem NRmE at individual site-years revealed no significant differences in NRmE at Carman18, Carman19, or Manitou19 (Figure 4.3D). However, treatment differences occurred at Manitou18, corresponding to the differences in late season N uptake at this site (Figure 4.3B). NRmE in the stem tissue was smallest for the N management strategies that increased late season N uptake, such as the split N application, and largest for treatments that took up the least N late in the season, such as the check and ESN treatments. Across all site-years there was a highly significant negative correlation coefficient ($r = -0.70$) between post-anthesis N uptake and stem NRmE. Previous research has reported reduced whole plant NRmE with increased late season N uptake as well as increased NRmE with reduced access to soil N late in the season (Barbottin et al. 2005; Bogard et al. 2010; Pask et al. 2012; Gaju et al. 2014; Kong et al. 2016). Kong et al. (2016) suggested that this relationship may be a result of the developing grain being the primary sink at this time, allowing for new N taken up to be preferentially transported to the spike. Results from this study suggest that the relationship between late season N uptake and NRmE is primarily driven by the stem rather than the leaf tissue, supporting work done by Pask et al. (2012), that suggested the stem N has more flexibility in NRm as it has a portion of N serving a reserve or storage function.

When the PGR CCC was applied there were no changes in the crop's ability to accumulate or remobilize N in the leaf tissue (Table 4.2). However, there was a statistically significant, but small influence of PGR application on stem N accumulation and remobilization (Table 4.2). There was a 2 kg N ha⁻¹ reduction in accumulated stem N at anthesis, which translated into 2 kg N ha⁻¹ less being remobilized from stem tissue of plants that had been treated

with CCC (Table 4.6). This response was small, accounting for <1% of the variability of response and at this level it is unlikely that it would result in an agronomically important role in N use of the crop.

4.4.4 GNUtE and GNUE

4.4.4.1 Site-year

Grain N utilization efficiency is a measure of how the crop uses N that is taken to produce grain N, regardless of when the N is taken up during the growing season. Site-year significantly influenced GNUtE and accounted for 35% of the variability in response (Table 4.2 and Figure 4.2). Manitou18 had the highest GNUtE (102%), followed by Manitou19 (81%), Carman18 (72%), and lastly Carman19 (61%) (Table 4.3). There was a significant positive relationship between GNUtE and GFD ($r=0.48$) (Table 4.5). When conditions are favorable for longer grain fill periods, by late season precipitation or lower temperatures for example, the crop appears to be more efficient at producing grain N with the N taken up during the entire growing season. Pask et al. (2012) reported 30% of the N supplied to the grain during grain fill originated from post-anthesis uptake, even though only 10% of total N uptake was during the post-anthesis period. This may be occurring because as GFD increases, and N uptake continues, a greater proportion of the total N uptake is occurring in the post-anthesis period. In the current study GFD was also positively and strongly correlated with post-anthesis uptake ($r=0.47$) and leaf NRm ($r=0.66$), but less strongly correlated with stem NRm ($r=0.32$, Table 4.5). This indicates that there is likely more N being remobilized from leaf tissue rather than stem tissue when environmental conditions lengthen the GFD. GNUtE differences across site-years were likely a result of both the proportion of N uptake in the post-anthesis period as well as remobilization from the leaf tissue.

GNUE is the product of NUpE and GNUtE, allowing it to account for the ability of the crop to capture N and use that N to produce grain N at maturity. Carman18 had the highest GNUE of all site-years tested, which was likely due to very large amount of soil N mineralized at that site, allowing for a NUpE of 142% (Table 4.3). In contrast, Manitou18 had the second highest GNUE (74%), but had the lowest NUpE of only 78%. In this case, high GNUE was a result of high GNUtE allowing the plant to produce grain N from the total amount of N taken up

during the season, highlighting the different mechanisms utilized by crops to produce grain N under different growing conditions.

4.4.4.2 Cultivar

There were no significant differences for GNUtE between the three cultivars tested with values ranging from 77 – 82%. There were, however, differences among cultivars for GNUE with AAC Brandon having the highest (79%), followed by Prosper (75%), and lastly AAC Cameron (72%) (Table 4.3). These differences may be accounted for by the timing of N uptake rather than the total N uptake, as there were no differences in NUpE between cultivars. AAC Brandon took up a larger portion of N in the post-anthesis period compared to the other varieties, leading to a numerically, though not significantly, higher GNUtE and a significantly higher GNUE (Table 4.3).

4.4.4.3 Nitrogen Management and PGR

Nitrogen management strategies tested in this experiment did not influence GNUtE of the spring wheat crop, even when no additional N fertilizer was applied (Tables 2 and 3). This means that there was very little opportunity to use N fertilization to manipulate GNUtE for increases in final grain N yields. Additionally, the only difference in GNUE between N treatments was across different N rates. GNUE increased from 61% to 78% when the N rate was reduced from 156 to 78 kg N ha⁻¹ due to increased NUpE with lower N rates (Table 4.3). There was a significant interaction of N management with site-year for GNUE that accounted for 12% of the variation in GNUE (Table 4.2). However, this interaction was due to the magnitude of response to N management across site-years and the ranking of each treatment did not change across site-years. This magnitude interaction was a result of the interaction of N with site-year for NUpE, primarily in response to differences in N availability from in-season mineralization at each site.

Application of PGR significantly increased the GNUtE from 78% to 80%, likely as a result of delayed maturity, compared to the treatments where no PGR was applied (Table 4.3 and B1). It is common for PGR applications to delay maturity in spring wheat (Rademacher 2016), which may allow for more N remobilization, or an increased proportion of N taken up later in the season, even though these processes were not affected significantly in this experiment. There was no difference in the GNUE with and without a PGR application as the PGR reduced NUpE which offset the increased GNUtE in this experiment (Table 4.3).

4.5 Conclusions

When high rates (156 kg N ha^{-1}) of N were applied, the average NUpE was 80% and NUtE was also 80%; as a result, the final GNUE was approximately 60%. These results show that for spring wheat production in the eastern Canadian prairies, only 60% of the N available to the crop (excluding mineralized N) is being used for grain N production during the growing season, with 20% not being taken up from the soil and another 20% remaining in vegetative tissue at maturity. Post-anthesis uptake was generally high, with 21-36% of the total growing season N taken up after anthesis, but this uptake was highly dependent on environmental conditions. Split N application was the only management practice tested that had the ability to significantly increase post-anthesis N uptake, and as a result grain protein, but only when paired with sufficient late season precipitation. The amount of NRm from the leaf and stem tissue was highly dependent on the amount of N accumulated by each tissue type at anthesis, with leaf and stem tissue remobilizing 80% and 70%, respectively. An exception to this relationship was when large amounts of N were taken up post-anthesis and NRmE from the stem tissue was reduced.

Overall, there was very little influence of N management and PGR applications on the efficiency of NRm during the grain fill period. This, paired with the dependence of post-anthesis uptake on adequate late season soil moisture supplies, indicates that producers should focus on management practices that promote early season N uptake. This will allow the crop to buffer against dry conditions in the late growing season that limit post-anthesis uptake, while producing adequate grain N through remobilization of previously accumulated N. As a result, pre-plant or at planting applications of N fertilizer appear to be the most robust method to manage N for dryland wheat production, despite its environmental risks. However, this study shows that in the black soil zone of the eastern Canadian prairies, there appears to be a large portion of N taken up during the post-anthesis period even when total growing season precipitation is well below the LTA, and more so if precipitation occurs during the post-anthesis period. Therefore, in this region of the Canadian prairies, spring wheat will be less reliant on vegetative remobilization for grain N. This is likely not the case for other large dryland spring wheat growing areas in the western Canadian prairies. For example, in the drier western regions near Melfort, SK and Lethbridge, AB the LTA precipitation is 72% and 69% of that in Carman, MB, respectively (Government of Canada 2021).

The cultivars AAC Brandon and Prosper had fundamentally different paths for grain N production. AAC Brandon took up a greater proportion of the total N after anthesis, while Prosper accumulated more early season N to increase NRm during grain fill. This genetic variation in how cultivars take up and utilize N suggests that there is opportunity for breeding programs to target N use patterns that are most suited for specific growing regions in the Canadian prairies.

CHAPTER 5. CANOPY MANAGEMENT: THE BALANCE BETWEEN LODGING RISK AND NITROGEN USE FOR SPRING WHEAT PRODUCTION IN THE CANADIAN PRAIRIES

5.1 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 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 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) resulting in modest yields and low lodging pressure. However, low plant density, split N, and CCC applications all showed potential to reduce lodging risk without reducing grain yield or protein concentration. Split N and 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.

5.2 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 increases 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 semi-dwarfing 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, semi-dwarfing 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, 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 to 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, also measured at anthesis (LAI) ($R^2 = 0.9385$ and 0.7271 , respectively), which could be used to predict lodging risk.

Canopy management 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 to 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 gibberellic 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 canopy management 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 yields 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 (GS10-GS60) (Zadoks et al. 1974), which is remobilized to the developing grain during the grain fill period (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 post-anthesis, during the grain fill period, to increase final grain N.

However, post-anthesis N uptake is heavily reliant on soil moisture availability during the post-anthesis 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 post-anthesis N uptake to meet grain protein quality requirements, increasing marketing risk for the farmer.

The ability of canopy management 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, split N application, and application of CCC on early-season CWRS wheat vegetative growth and lodging risk and (2) determine how canopy biomass alterations, through agronomic management, influence crop N uptake and remobilization for grain N yield in CWRS wheat.

5.3 Materials and Methods

5.3.1. 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 (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 5.1). 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 (Figure 5.1).

Table 5.1. Characteristics of each site-year 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			49.496611°N,	49.500878°N,	49.087722°N,	49.080626°N,
Longitude			98.040352°W	98.030846°W	98.501826°W	98.515924°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			07-May-18	26-Apr-19	29-Apr-18	07-May-19
Plant Growth Regulator Application			09-Jun-18	05-Jun-19	07-Jun-18	14-Jun-19
Split N Application [†]			21-Jun-18	20-Jun-19	18-Jun-18	26-Jun-19
Harvest			14-Aug-18	08-Aug-19	15-Aug-18	23-Aug-19

[†]In crop N fertilizer treatments applied at the flag leaf growth stage with the first application made at seeding

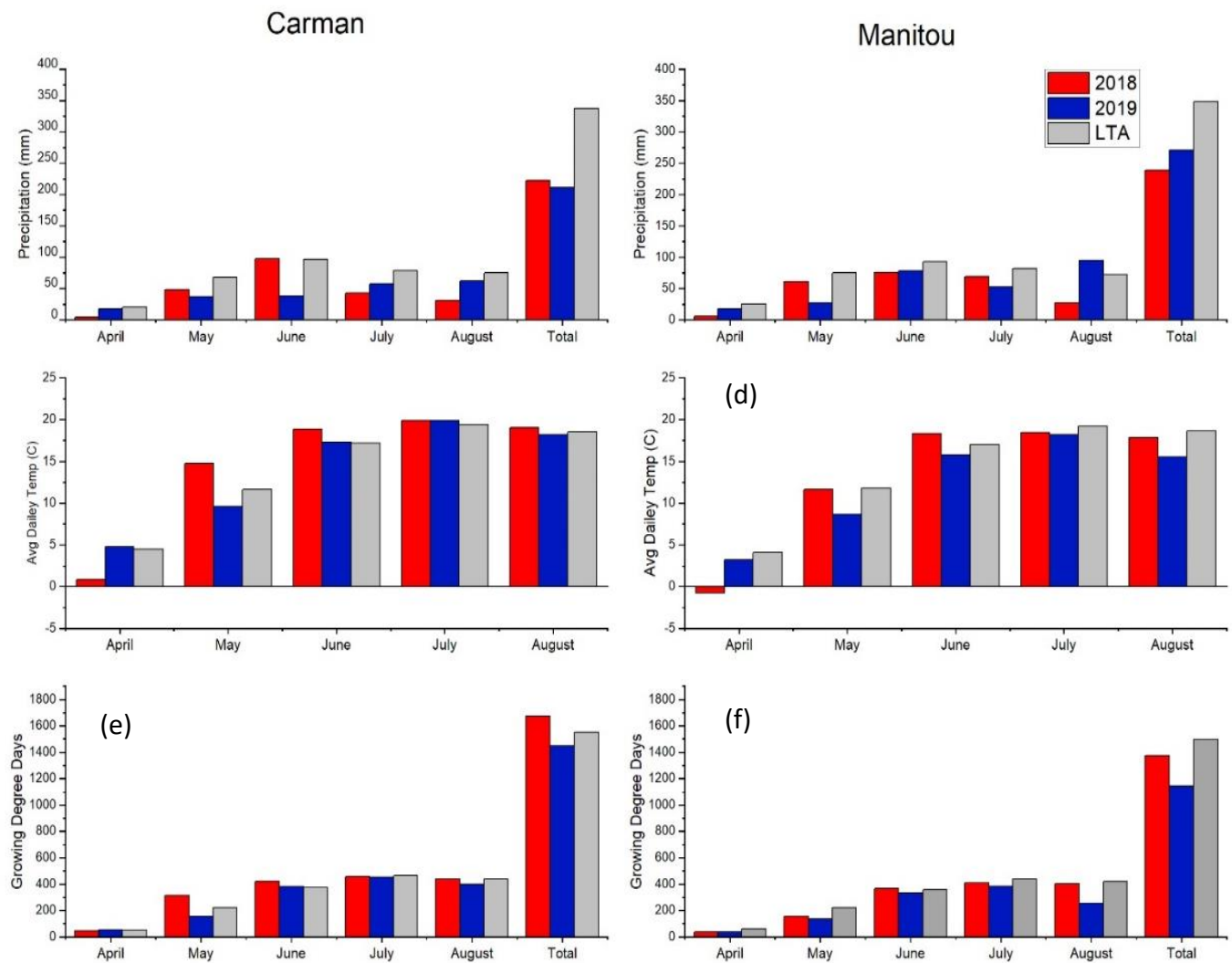


Figure 5.1. Monthly growing season (April – August) precipitation, average daily temperature and growing degree days for 2018 and 2019 at Carman (a,c,e) and Manitou (b,d,f) compared to the 30-year long term average (LTA)(1988 -2018).

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 semi-dwarf 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 plant density treatments using 1000-seed weight, germination percentage, and an assumed 15 percent 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 mono-ammonium phosphate (11-52-0) at a rate of $19.6 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ 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 (GS39). The fungicide Prosaro-XTR (prothioconazole (125 g L^{-1}) and tebuconazole (125 g L^{-1}), was applied to reduce incidence and severity of Fusarium head blight at anthesis (GS60) at all site-years. Dates of major field operations for individual site-years are presented in Table 5.1.

5.3.2 Treatments and Experimental Design

The trial was designed as a split-plot with four blocks at each site-year. Plant density was the main plot factor, and three treatments were to target low ($150 \text{ plants m}^{-2}$), medium ($250 \text{ plants m}^{-2}$), and high ($350 \text{ plants m}^{-2}$) plant densities. The medium plant density is the current provincial recommendation for spring wheat production in Manitoba (Manitoba Agriculture 2020). The low plant density was included as a canopy management strategy to reduce lodging risk (Berry et al. 2000). The high plant density was included to reflect the current trend in Manitoba to use high plant density 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 fertilizer treatments 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 fertilizer 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 (GS 39), 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 (GS 31-32) at 1.8 L ha^{-1} using a CO₂ backpack sprayer with 100 L ha^{-1} water volume and flat fan nozzles.

5.3.3 Data Collection

Plots were 8 m long with designated areas for destructive and non-destructive 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 (GS85), approximately two 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. Leaf Area Index (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 (GS65) and maturity (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 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 hrs. 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 stem to total DM were 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 dry matter 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 (NR_m) 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 percent 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 resisting 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 non-destructive 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 plot was calculated by multiplying total N concentration by the factor of 5.7 (Williams et al. 1998).

5.3.4 Statistical Analysis

Data were analyzed using the PROC MIXED procedure of SAS version 9.4 (SAS Institute, 2001) with site-year, plant density, N timing, PGR, and their interactions as fixed factors. Random factors in the model included block nested within site-year and the interaction of block with planting density to account for the split plot arrangement at each site-year. 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 Honest Significant Difference ($p < 0.05$). 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 correlations among plot means of response variables across all site-years.

5.4 Results and Discussion

5.4.1 Growing Season Conditions

Overall, during the growing season precipitation was 64 to 78% of the long-term average (LTA) of the four site-years where the trials were conducted (Figure 5.1). However, the pattern of precipitation differed between the two 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

were 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 site-year had greater growing degree days (GDD) compared the LTA due to high temperature in the month of May, alternatively in 2019 the Carman site-year experienced lower GDDs in May leading to slightly lower growing season GDD compared to 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 site-years.

5.4.2 Grain Yield

Analysis of variance indicated significant effects of site-year (SY), the interaction of site-year with plant density (SY x PD), and the main effect of plant growth regulator (PGR) for grain yield (Table 5.2). Car18 and Man18 had significantly higher yields than Car19 and Man19 (Table 5.3). At both site-years in 2018, there was generally more early-season precipitation (May/June) and a greater number of growing degree days (GDD) (April – Aug) compared to the 2019 site-years (Figure 5.1), which likely led to higher yields in the 2018 site-years compared to the 2019 site-years

At Car18, the high plant density treatment resulted in 357 and 429 kg ha⁻¹ higher grain yield compared to the low and medium plant densities, respectively. There was no effect of plant density on grain yield at the other three site-years (Appendix Table C1). 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 plant density 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.

Table 5.2. Analysis of variance for main effects of site-year (SY), plant density (PD), nitrogen application timing (NT), plant growth regulator (PGR) and their interactions for grain yield, protein content and grain nitrogen (N) yield, canopy structure measurements (total anthesis dry matter (DM), vegetative anthesis DM(leaf + stem), the ratio of leaf and stem DM to total DM, canopy height, leaf area index (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	Response Variable																		
	df	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			Pre-Anthesis	Post-Anthesis	Anthe-sis					Maturity	
Site-year (SY)	3	***	ns	***	ns	ns	***	***	*	ns	*	***	***	***	***	***	n/a	*	***
Plant Density (PD)	2	ns	ns	ns	ns	ns	ns	**	*	**	***	ns	***	***	***	***	*	*	***
SY x PD	6	*	ns	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	ns
SY x NT	3	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	n/a	ns	ns
PD x NT	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SY x PD x NT	6	ns	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 x PGR	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
PD x PGR	2	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	***	ns	ns
SY x PD x PGR	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns
NT x PGR	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

SY x NT x PGR	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	n/a	ns	ns
PD x NT x PGR	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	***	ns	ns	ns	ns	ns
SY x PD x NT x PGR	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	n/a	ns	ns

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

ns, non-significant

† 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

Table 5.3. Least squares means for the influence of main effects of site-year, plant density, nitrogen application timing, and plant growth regulator (PGR) on grain yield and canopy structure response variables including plant density, total dry matter (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 leaf area index (LAI)

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

[†] Leaf Area Index (LAI) was measured only at Man19 and Car19 environments due to equipment constraints

[‡] 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

[§]CCC, Chlormequat chloride

As a result, plants moved quickly through the tillering growth stage, which didn't allow for the medium and low plant densities at Car18 to produce similar spike densities as the high plant density treatment. This led to a yield advantage through increased spike density in the high plant density treatments (Appendix Table C2).

PGR application significantly increased yield by 158 kg ha⁻¹ (3%) across all other treatment factors in this experiment (Table 5.3). 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 to applying all N at planting (Tables 2 and 3).

5.4.3 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 produce 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).

5.4.3.1 Dry Matter at Anthesis

Total above-ground dry matter (DM), and vegetative DM at anthesis were not significantly influenced by site-year, but the ratio of leaf to total DM and stem to total DM at anthesis varied significantly across site-years (Table 5.2). The two 2018 site-years had a significantly higher ratio of leaf to total DM compared to the two 2019 site-years, which followed the same trend as grain yield at each site-year (Table 5.3). 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 site-years. 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).

Analysis of variance indicated that there was no significant influence of plant density on total DM, vegetative DM, or the ratio of leaf to total DM (Table 5.2). However, there was a significant interaction of plant density with site-year for total DM, and vegetative DM. Man18

was the only site-year where there was a significant effect of plant density on total DM. Man18 and Car19 had significant effects of PD on vegetative DM at anthesis (Table 5.4). At Man18, low plant density resulted in the largest total DM at anthesis (5100 kg ha⁻¹) and the high plant density producing the smallest total DM (4440 kg ha⁻¹). For vegetative DM, there was a similar trend at Man18, where low plant density resulted in higher vegetative DM (3743 kg ha⁻¹) compared to the medium (3463 kg ha⁻¹) and high (3277 kg ha⁻¹) plant densities. In contrast, at Car19 the high plant density resulted in the highest vegetative DM (3645 kg ha⁻¹), and the low plant density treatment produced the lowest vegetative DM (3330 kg ha⁻¹) (Table 5.4). This may be accounted for by the exceptionally low precipitation in May/June at the Car19 site-year (Figure 5.1).

Table 5.4. Least squares means of the interactions of site-year with plant density and site-year with nitrogen (N) application timing for total and vegetative (leaf + stem) dry matter at anthesis.

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

[†]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

There was a significant effect of plant density on the ratio of stem to total DM (Table 5.2). When averaged across all other model factors, the high plant density treatment had a small, but significantly higher ratio of stem to total DM (0.46) compared to both the medium (0.45) and low (0.45) plant density treatments (Table 5.3). It was expected that low plant density treatments would have had a higher stem to total DM ratio, because the low plant density treatment did not reduce total spike density (Appendix Table C2). 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 N application timing (NT) was not significant for any of the anthesis DM measurements, but there was a significant interaction between site-year and NT for both total DM and vegetative DM (Table 5.2). At three out of the four site-years, the split N applications tended to reduce total DM at anthesis (Table 5.4). 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 5.4). Reduced early-season biomass is expected when N is applied as a split application because early-season N availability is lower, which will limit 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 5.2 and 5.3). This was expected due to the influence of PGR applications on stem elongation. Additionally, there was a significant interaction of PGR and plant density for total DM at anthesis (Table 5.2). The application of CCC significantly reduced total DM at anthesis from 4980 to 4630 kg ha⁻¹ the medium plant density (Appendix Table C3). High plant density treatments had a similar trend as the medium density, but this was not significant at p=0.05. At low plant 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 5.2). 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 more tillers emerged and developed after the main stem, which delayed days

to anthesis, compared to higher plant densities (Table 5.5). The increased days of vegetative growth, as indicated by days to anthesis, observed with low plant densities may have contributed to additional DM accumulation, offsetting DM reductions resulting from reduced height when a PGR is applied.

Table 5.5. Least squares means for main effects of site-year, plant density, nitrogen (N) application timing and plant growth regulator (PGR) on grain N yield, pre-anthesis N uptake, percent of total N uptake as pre-anthesis uptake, post-anthesis N uptake, percent of total uptake as post-anthesis uptake, N remobilization (NRm) during the grain fill period, days to anthesis (DTA), and grain fill duration (GFD)

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

[†]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

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 5.2). 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 5.3). There was also a significant effect of the two-way interaction between PD and PGR for total DM at anthesis (Table 5.2). Total DM at anthesis was significantly reduced from 4980 to 4630 kg ha⁻¹ (7%) when CCC was applied on the medium plant density treatment (Appendix Table C3). There were no significant differences in total DM for the low or high plant densities when CCC was applied (Appendix Table C3).

5.4.3.2 Canopy Height

Overall canopy height was shorter than expected due to the dry growing season conditions experienced in this study (Figure 5.1). The average canopy height significantly varied across site-years ranging from 72.2 cm at Car18 to 76.2 cm at Car19 (Table 5.3), 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 5.2). Plant height was slightly higher at the low plant density (74.7 cm) compared to plant height at the high plant density (72.8cm) (Table 5.3). 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 increased seeding rate.

Plant growth regulator applications target reductions in canopy height. In this experiment the application of CCC reduced stem height by 3.5 cm when averaged across all site-years and other treatment factors (Table 5.3). Height decreases with a PGR application were small due to the already short canopy, but they were consistent across all site-years, plant densities, and N application timings. There was no influence of N application timing on canopy height (Tables 5.2 and 5.5).

5.4.3.3 Leaf Area Index

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). Leaf area index was measured only in 2019 due to equipment limitations. There were no significant differences in LAI measured at flag leaf among the 2019 site-years, but the ANOVA indicated a significant effect of both plant density and N timing on LAI (Table 5.2). The LAI increased from 1.85 to 2.17 from low to high plant density when measured at flag leaf (GS39) (Table 5.3), 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 2007). 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 plant density when measurements were collected earlier in the season at stem elongation.

Split N application also significantly lowered LAI by 9% compared to when N was applied entirely at planting (Tables 5.2 and 5.3). 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 5.3). 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 5.2).

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 pre-anthesis growth stages may be reduced, having detrimental effects on the crop's ability to later remobilize N to the grain.

5.4.4 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 5.2). 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 (Appendix Table C1). 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 5.5).

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 site-year and PGR on grain N yield (Table 5.2). 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 5.5). These differences in grain N yield across site-years corresponded to the differences in yield across site-years, as average grain protein concentrations were similar at all site-years (Appendix Table C1).

The application of the PGR CCC had a small, but significant, positive influence on grain N yield (3 kg N ha⁻¹) (Table 5.5). This small increase could be a result of the small, but significant, increase in grain yield when a PGR was applied (Table 5.3). There were no significant effects of plant density or its interactions with nitrogen timing or PGR on grain protein content or grain N content in this experiment (Table 5.2).

5.4.5 N Uptake and Remobilization

5.4.5.1 Pre-Anthesis 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, pre-anthesis N uptake was significantly influenced by site-year, plant density and the 3-way interaction of PD x NT x PGR (Table 5.2). As plant density increased from low to high, there was a reduction in the pre-anthesis N uptake from 142 to 132 kg N ha⁻¹ (Table 5.5). There was a significant ($p > 0.0001$) correlation between vegetative DM at anthesis and N uptake at anthesis ($r = 0.82$) (Appendix Table C4), indicating that any reduction in biomass prior to anthesis will also likely reduce pre-anthesis N uptake.

The 3-way interaction was attributed to higher pre-anthesis N uptake with the low plant density, when a PGR was applied, and N was applied entirely at planting compared to the same N treatment when no PGR was applied (Figure 5.2a). There were no differences in pre-anthesis N uptake at the medium or high plant densities. This corresponded with the increased leaf dry matter when a PGR was applied at the low plant density to spring applied N (Appendix Figure C1), indicating that the relationship between dry matter and N uptake at anthesis was driven by leaf dry matter 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 dry matter accumulation and N uptake than at higher plant densities.

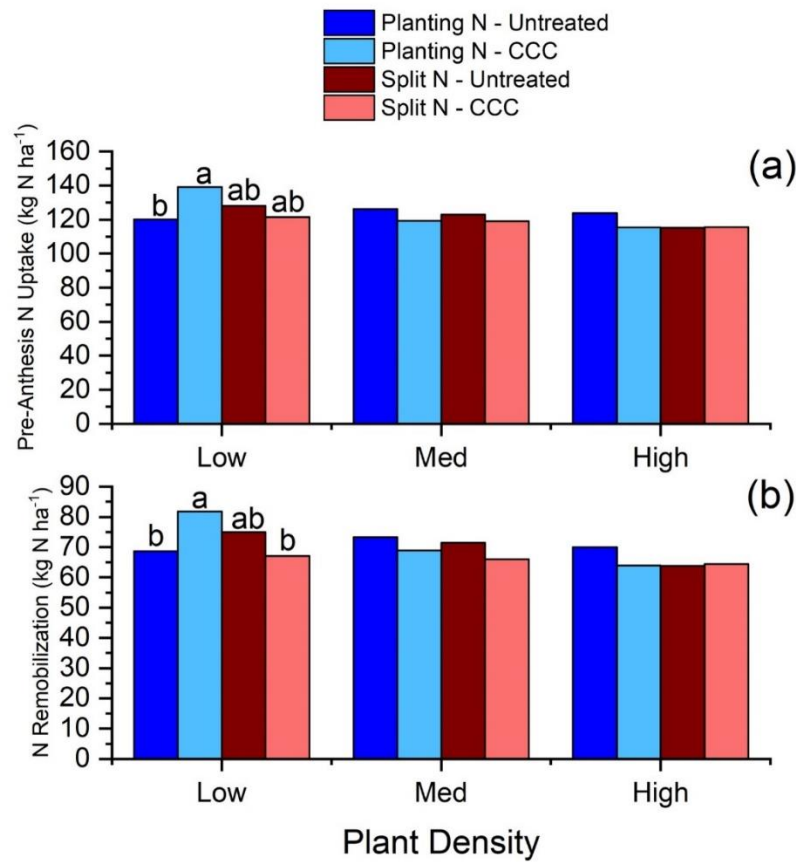


Figure 5.2. Interaction of low (target 150 plants m⁻²), medium (target 250 plants m⁻²) and high (target 350 plants m⁻²) plant densities with plant growth regulator (PGR) application and nitrogen (N) fertilizer application timing for (a) pre-anthesis N uptake and (b) N remobilization during the grain fill period. Bars with similar letters within each plant density treatment indicate no significant difference at the 0.05 probability level.

5.4.5.2 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 pre-anthesis 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 pre-anthesis N uptake and N remobilized from the vegetative tissue (leaf lamina, leaf sheath and stem) during this experiment ($r=0.92$) (Appendix Table C4). As a result, any treatment which had higher pre-anthesis N uptake would also have higher N remobilization, which held true for both the main effect of plant density (Table 5.5) and the three-way PD x N x PGR interaction (Figures 5.2a and 5.2b). Low planting densities had the highest amount of remobilization while high densities had the lowest (Table 5.5). Within, the low planting density, when all N fertilizer was applied at planting, the PGR treatment had greater remobilization due to the increased pre-anthesis N uptake at anthesis (Figure 5.2a). This interaction was consistent across pre-anthesis N uptake and NRm (Table 5.2), indicating that more work is needed to explain what is driving this interaction.

There was also a significant effect of site-year on the total amount of N remobilized during the grain fill period (Table 5.2). 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 5.5). There was a similar trend in pre-anthesis N uptake between the four site-years; however, there were no significant differences between them. This variation in remobilization between site-years can be attributed to the compound effect of pre-anthesis N uptake paired with differences in grain fill duration (GFD) (Table 5.5). The site-years with longer GFD had more NRm. For example, Man18 had the longest grain fill duration (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 ($p<0.0001$) correlation between GFD and NRm ($r=0.39$) (Appendix Table C4). 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).

5.4.5.3 Post-Anthesis N Uptake

Nitrogen uptake from the soil is influenced substantially by soil moisture availability and N availability, which can be unpredictable during the post-anthesis period in dryland wheat production across western Canada. This could explain the significant effect of site-year on post-anthesis N uptake in this experiment (Table 5.2). Averaged across all treatments 103 kg N ha⁻¹ was taken up at Car18 during the post-anthesis period; this was statistically similar to the 83 kg N ha⁻¹ taken up at Man18 (Table 5.5). These site-years both had larger post-anthesis N uptake compared to Car19 (56 kg N ha⁻¹) and Man19 (51 kg N ha⁻¹). The differences in post-anthesis uptake between site-years 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 (Figure 5.1).

There was a three-way interaction between SY x NT x PGR for post-anthesis N uptake (Table 5.2). In Car19 and Man18, post-anthesis uptake was significantly increased when N fertilizer application was split and CCC was applied (Table 5.6). There was no significant difference between N treatments when CCC was not applied, nor between any treatments at Car18 and Man19.

Table 5.6. Least squares means for the interaction of site-year, nitrogen (N) application timing, and plant growth regulator (PGR) application on post-anthesis N uptake.

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

[†]Within columns, and interactions, 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

The application of a PGR may have facilitated late-season N uptake at the Car19 and Man18 site-years. 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 days to anthesis by 0.2 days, which could have allowed for a greater development of the root system influencing N capture efficiency (Table 5.5). In this experiment, PGR application did not increase grain fill duration (anthesis to maturity), indicating that the length of the post-anthesis 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 system 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 post-anthesis N uptake at Car18 and Man19 (Table 5.6). This indicates that late-season soil N supply was sufficient when N was applied entirely at planting for these sites-years. In-season losses of N from seeding to flag leaf at these site-years 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 post-anthesis had a positive correlation with final grain N yield ($p < 0.0001$, $r = 0.39$) (Appendix Table C4). This indicates the importance of both vegetative N remobilization and post-anthesis N uptake for grain N yield production, with 57 – 72% of N taken up pre-anthesis and 28-43% taken up post-anthesis in this study (Table 5.5). However, post-anthesis uptake of N can be extremely variable depending on growing season conditions, as observed by the large variation in post-anthesis uptake across site-years in this study (51- 103 kg N ha⁻¹) (Table 5.5). 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 – 87 kg N ha⁻¹ (Table 5.5). 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.

5.4.6 Lodging Risk

5.4.6.1 Lodging Ratings

Canopy management 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 site-years of this experiment, conditions were drier than normal (Figure 5.1a and 1b, resulting in short crop canopies with very little lodging pressure (Table 5.7).

Table 5.7. Least squares means for the main effects of site-year, plant density, nitrogen (N) application timing, and plant growth regulator (PGR) on lodging ratings and stalk strength measured at anthesis and maturity

		Lodging Rating [†]		Stalk Strength [‡]	
		Anthesis		Maturity	
		0-9 scale [§]		Newtons	
Site-year					
	Car18	n/a	n/a	12.36	a
	Car19	n/a	3.24 a [¶]	5.07	b
	Man18	n/a	n/a	13.23	a
	Man19	0.73	2.53 b	6.09	b
Plant Density					
	Low	0.05 b	3.10 ab	10.11	a
	Med	0.83 ab	3.18 a	9.19	b
	High	1.29 a	2.37 b	8.27	c
N Timing					
	Planting	0.75	2.66	9.11	
	Split	0.70	3.11	9.27	
PGR					
	Untreated	1.17 a	2.68	8.86	
	CCC	0.28 b	3.09	9.52	

[†] Lodging ratings were taken only at Man19 environment due to very low natural occurrence of lodging at all other environments

[‡] Stalk strength at anthesis was measured only at the two 2019 environments due to equipment limitations

[§] Lodging ratings were calculated by multiplying the lodging severity (0-9 scale) by the percent of the plot lodged (0-100%)

[¶] 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

However, there was one small lodging event at Man19 after a heavy rainfall on July 31, 2019. At Man19, PD, PGR and PD*PGR had a significant effect on lodging ratings (Table 5.2). Low plant densities had negligible amounts of lodging but lodging increased as the plant density increased to medium and high (Table 5.7). Averaged across all other treatments, the application of CCC significantly reduced lodging ratings from 1.17 to 0.28 (Table 5.7). The ANOVA also indicated a significant interaction of plant density with PGR, which revealed that when lodging did occur, at high and medium plant densities, PGR applications significantly reduced lodging (Figure 5.3). However, when there were very low levels of lodging in the low plant densities, there was no difference in lodging occurrence (Figure 5.3). 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.

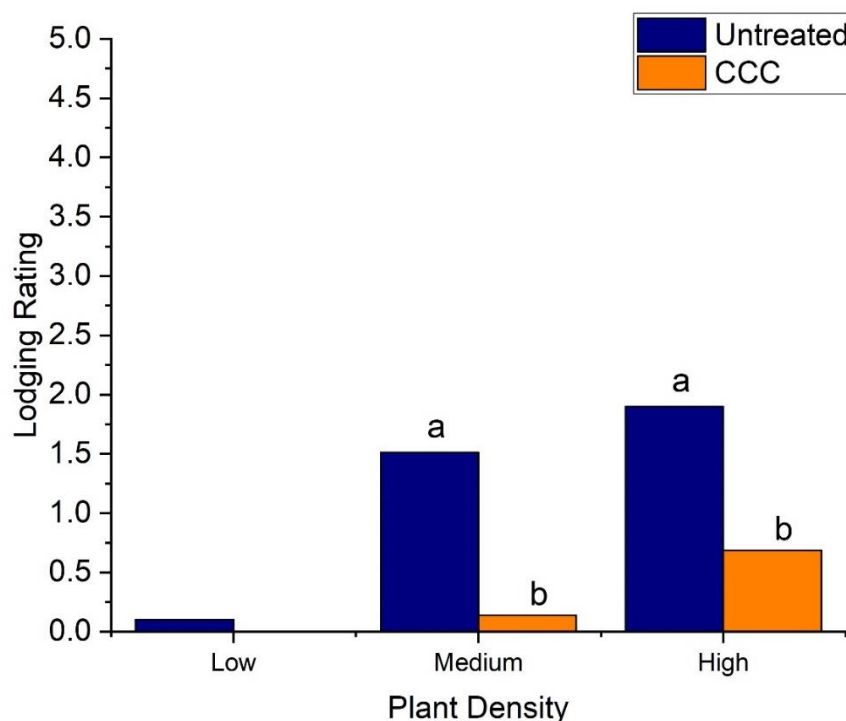


Figure 5.3. Interaction of the plant densities (low (target 150 plant m⁻²), med (target 250 plants m⁻²) and high (target 350 plants m⁻²)) and a plant growth regulator (PGR) application for visual lodging ratings at the Man19 site-year. Lodging ratings were calculated by multiplying the lodging severity (1-9 scale) by the percent of the plot lodged. Bars with different letters within each plant density treatment indicate significant differences at the 0.05 probability level; absence of letters indicates no significant differences between columns.

5.4.6.2 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 (Appendix Table C4). As expected, stalk strength was higher at maturity than anthesis (Table 5.7). 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 site-year and plant

density (Table 5.2). At anthesis, plants at Car19 had significantly higher stalk strength than Man19 (Table 5.7). At maturity, Car18 and Man18 had significantly stronger stalks than Car19 and Man19 (Table 5.7).

At both growth stages, stalk strength was lower for high plant densities and increased as plant density was reduced (Table 5.7). 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 5.2). However, there was a trend for both split N and PGR applications to increase stalk strength (Table 5.7). 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). Plant growth regulators 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 dry matter at anthesis with lodging. With the conditions experienced in this experiment, the only relationship between early-season dry matter and stalk strength at anthesis was a weak negative relationship ($p=0.0436$, $r=-0.20$) (Appendix Table C4). 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.

5.5 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 dry matter at anthesis and canopy height, showed inconsistent treatment responses, depending on the response variable. It is possible that dry matter 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). Dry matter samples taken at stem elongation (GS31-32) may have provided a better relationship with lodging risk compared to dry matter sampled at anthesis (GS65). Leaf area index 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 canopy management strategies of low plant densities, split N and PGR application may reduce lodging occurrence in environments more favorable to lodging.

Vegetative dry matter at anthesis was highly correlated to pre-anthesis N uptake, which then influenced NRm during the grain fill period. This relationship is visualized in Figure 5.4. The amount of N provided to the grain from NRm during the grain fill period ($72 - 87 \text{ kg N ha}^{-1}$) was similar to the amount of N from post-anthesis uptake ($51 - 103 \text{ kg N ha}^{-1}$), indicating the importance of both N sources for grain N. However, the variability in post-anthesis 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 pre-anthesis 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 ($4592 - 5821 \text{ kg ha}^{-1}$) were achieved,

grain N yield and protein content were not reduced with these canopy management strategies, as post-anthesis N uptake was substantial at all site-years ranging from 28 – 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 canopy management treatments (low plant density, 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 to 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.

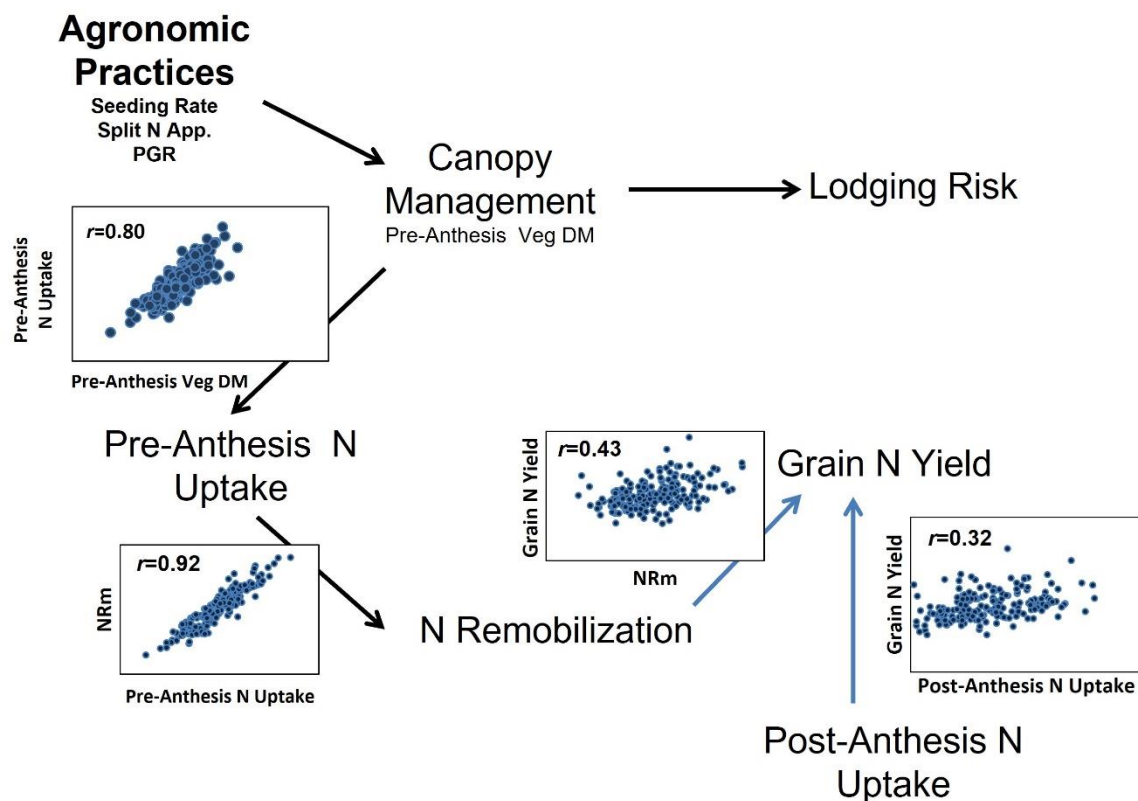


Figure 5.4. Conceptual diagram for relationships between dry matter, nitrogen (N) uptake at anthesis, N remobilization, lodging, and grain N yield, including Pearson correlation coefficients (r) between variables. Due to the lack of lodging pressure during the experiment, the measured relationship between canopy management and lodging risk is unknown.

This study indicated that canopy management strategies such as reduced plant density, 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 weren't 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 non-uniform 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 only cultivar used in this experiment. AAC Brandon is a semi-dwarf cultivar and may respond differently to PGRs, N management and plant densities compared to other CWRS 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 to many other CWRS 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 amounts of growing season precipitation, reducing crop canopy size through canopy management 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.

CHAPTER 6. EVALUATION OF CHLORMEQUAT CHLORIDE, CULTIVAR, PLANT DENSITY, NITROGEN MANAGEMENT AND THEIR INTERACTIONS ON LODGING RESISTANCE OF SPRING WHEAT IN WESTERN CANADA

6.1 Abstract

Concerns about lodging in wheat are increasing across western Canada due to intensified management practices and rising yields. Plant morphology and composition determine the crop's ability to resist root and shoot lodging, both of which are heavily dependent on agronomic management practices and cultivar selection. Plant growth regulators (PGRs) reduce stem height to reduce lodging; however, a detailed description of their influence on the plant's ability to resist both root and shoot lodging has not been evaluated in western Canadian growing conditions using current management practices. The objective of this study was to determine the ability of spring wheat management options (PGR, cultivar selection, N management and planting density) to decrease lodging risk. The efficacy of PGR applications as influenced by changes to management practices was also evaluated. Detailed sampling was done from two large experiments to create three sub-experiments focused on cultivar, N management, and plant density, with each sub-experiment also examining the interaction of the main factor with the application of the PGR chlormequat chloride (CCC). Stem and root morphology, stem structural fiber analysis, and stem strength and flexibility indicator measurements were taken from each sub-experiment to evaluate susceptibility to lodging. Low plant density and split N applications showed the most promise to reduce lodging risk in spring wheat. Application of PGR consistently reduced stem length and there was evidence that PGR can increase stem strength and root plate size. However, these responses were dependent on site-year and interactions with agronomic practices such as N management and planting density. Therefore, more research is required to better understand the factors driving these responses.

6.2 Introduction

Severe lodging can cause yield losses of up to 80%; however, the occurrence of lodging is unpredictable and dependent on multiple factors, including growing season weather conditions (Berry and Spink 2012). Lodging is a general term referring to the displacement of the crop from the vertical position, which can occur through two different mechanisms in wheat. The stem can bend or break at the lower internodes causing stem lodging, or the entire plant can rotate from the root cone and root lodging will result (Berry 2019). Wind and rain place leverage on individual stems and plants, and if this leverage exceeds the strength of the stems, or the plant's anchorage system, lodging will occur. The intensity of leverage placed on the plant is influenced by the plant's morphological characteristics. A tall canopy with high biomass will intercept large amounts of wind and rain, increasing leverage. A plant with more stems will experience more leverage on the entire plant and therefore anchorage system (Berry et al. 2004). Across western Canada, the proportion of lodging occurrence that is contributed to either root or shoot lodging is currently unknown, but both forms are known to occur in spring wheat. Environmental conditions impact the type of lodging that is likely to occur in any given growing season (Berry 2019).

The ability of the crop to resist lodging is dependent on the plant morphology that influences stem and anchorage strength (Berry et al. 2007). Stem strength, or the ability of the stem to resist bending and breaking, has positive relationships with stem diameter, stem wall width, stem stiffness, and stem lignin and cellulose content (Crook and Ennos 1993; Crook et al. 1994; Berry et al. 2000; Wiersma et al. 2011; Wang et al. 2012; Berry 2019; Wu et al. 2019). Anchorage strength of a plant is highly dependent on soil moisture content and texture. As moisture content increases and texture becomes coarser, soil shear strength decreases, reducing anchorage strength of a plant (Crook and Ennos 1993). However, the size of the plant's structural root plate has been shown to have a highly positive relationship with anchorage strength, as the root plate spread and depth increase, anchorage strength increases (Crook and Ennos 1993; Berry et al. 2000). Agronomic management practices alter plant morphological characteristics influencing lodging risk. The response of stem and anchorage strength to agronomic management practices may interact with each other, as well as environmental conditions, making it difficult to predict efficacy of any specific management practice to reduce lodging.

Plant growth regulators (PGR) are gaining popularity in dryland spring wheat production across the Canadian prairies as lodging is resurfacing as a production concern. The high yield potential of current cultivars has intensified management practices with very high rates of nitrogen (N) fertilizer application to meet yield and grain protein content targets. High yields combined with increased N fertilizer application rates will result in increased lodging risk. The most common PGRs currently used in western Canada are gibberellin (GA) inhibitors such as chlormequat chloride (CCC) and trinexipac-ethyl (TXP). Gibberellin inhibitors reduce plant height by inhibiting the GA biosynthesis pathway during the stem elongation phase (Rademacher 2016). Reducing leverage placed on the stem through height reduction is thought to be the main mechanism in which PGR's lower lodging severity. However, hormonal system alterations and reallocation of resources within the plant when stem elongation is inhibited may also influence lodging risk (Green 1986). Crook and Ennos (1995) and Zhang et al. (2017b) reported that the application of CCC at the beginning of stem elongation increased the stem diameter of lower internodes, while Berry et al. (2000) saw no effect of CCC on stem diameter. Stem wall width and stem degree of filling has also been reported to increase with CCC application in greenhouse experiments on Canadian spring wheat cultivars (Zhang et al. 2017b). The strength (ability of a stem to resist being bent or broken) of stems may also be increased with the application of GA inhibiting PGRs (Crook and Ennos 1995; Wiersma et al. 2011; Zhang et al. 2017b) but may reduce stem flexibility calculated using Young's modulus of elasticity (Crook and Ennos 1995; Berry et al. 2000).

Fiber cells in the stem tissue provide support to the stem, and their abundance and arrangement may be altered with the application of stem shortening PGRs. Zhang et al. (2017) reported a clear increase in cellulose content when CCC and TXP were applied to six different spring wheat cultivars in greenhouse conditions. Additionally, Wiersma et al. (2011) reported a significant linear relationship between stem acid detergent lignin (ADL) content and rate of application of TXP in spring wheat. Chlormequat chloride applications have been reported to increase root to shoot ratio and the number of crown roots, but there is no evidence that the structural root plate depth or spread at maturity is altered. However, studies investigating root effects on mature plant root plates are limited (Crook and Ennos 1995; Berry et al. 2000). PGR applications are the only agronomic management practices targeted solely for reduction of

lodging risk in western Canada, but many other common management practices have the ability to alter plant morphology in a way that affects lodging.

Increased plant density is widely known to increase lodging occurrence in wheat through decreased stem and anchorage strength. When plants m^{-2} were increased from 200 to 400 Berry et al. (2000) reported a 50% decrease in anchorage strength and a 15% decrease in stem strength. Decreases in anchorage strength with high plant densities were accounted for by reduced roots per plant, lower crown root thickness and reduced depth and spread of the structural root plate (Berry et al. 2000). Additionally, increased stem diameter, wall thickness, cell wall lignification, and number of vascular bundles have been reported to contribute to increased stem strength with reduced plant densities (Berry et al. 2000; Zheng et al. 2017). These differences in stem strength characteristics with reduced plant densities are largely attributed to reduced canopy shading early in the growing season, similar to the effects of large amounts of early season N fertilizer application on stem strength (Whaley et al. 2000; Sparkes and King 2008).

Applications of large amounts of N fertilizer early in the growing season increase lodging risk in wheat by decreasing stem strength and, to a lesser extent, anchorage strength (Farquhar and Meyer-Phillips 2001; Berry 2019;). Early N supply promotes abundant vegetative growth which increases shading within the canopy. Shading influences the quality and quantity of light penetrating the canopy, resulting in the development of weaker stems (Sparkes and King 2008). Reduced dry weight per unit internode length, reduced lignification of stem sclerenchyma cells, and reduced stem diameter and wall width have also been observed when high N rates were applied before stem elongation, potentially increasing lodging risk. (Berry et al. 2000; Wu et al. 2019; Mizuta et al. 2020). Crooke and Ennos (1995) reported a 17% decrease in anchorage strength with high N rates due to decreases in crown root number and root bending strength but reported no influence of high N rates on the spread or depth of the structural root plate, similar to results reported by Berry et al. (2000). Other agronomic management practices that have been shown to reduce lodging risk in wheat include soil rolling and delayed seeding; however, these practices are not specific to spring wheat cultivation in western Canada.

Much of the work completed on the influence of agronomic management on plant morphology have been completed in either winter wheat, irrigated spring wheat, or in high moisture production areas of the world. Spring wheat production in western Canada is influenced

by a short growing season with highly unpredictable growing season moisture, which may influence how agronomic management practices alter plant characteristics that affect lodging. Additionally, the ability of a PGR to alter stem and plant leverage, stalk strength and anchorage strength, needs to be evaluated across cultivars, planting densities and N management practices specific to western Canadian wheat production. This will provide producers with additional management strategies to reduce lodging risk of current spring wheat cultivars. The objectives of this study were to (1) determine the ability of spring wheat management (PGR, cultivar selection, N management, and planting density) to decrease leverage and increase stem and anchorage strength and (2) determine the effect of PGR application on lodging risk when used in combination with cultivars, N management and planting densities commonly used in western Canadian wheat production.

6.3 Materials and Methods

6.3.1 Treatments and Experimental Design

During each of the 2018 and 2019 growing seasons, two large field trials were established at two locations in southern Manitoba to evaluate agronomic management practices in spring wheat as described in (Chapter 3 and 5). Experiment 1 was a split-split plot design with cultivar as the main factor, N treatment as the sub-plot factor and PGR treatment as the sub-sub plot factor (Chapter 3.3.2, Table 3.2). Experiment 2 was a split-plot design with plant density as the main plot factor and combinations of N application timing and PGR application as sub-plot factors (Chapter 5.3.2). Three sub-experiments were created and sampled from within the two large main experiments to investigate the influence of a PGR application and its interactions with cultivar, N management and plant density on lodging risk. Each sub-experiment was a split-plot design, with sub-experiment 1A and 1B sampled from experiment 1 and sub-experiment 2A sampled from experiment 2.

Sub-experiment 1A consisted of the three cultivars, AAC Brandon (CWRS), AAC Cameron (CWRS) and Prosper (CNHR) with and without the application of the PGR chlormequat chloride (CCC) (Table 6.1). Cultivars were chosen based on their acreage across the province, lodging rating, and yield potential. AAC Brandon is a semi-dwarf cultivar that has had very high adoption across Manitoba due to high yield and protein content, and very good lodging

and disease resistance ratings. AAC Cameron is very similar to AAC Brandon; however, it is a tall cultivar with midge resistance and has a slightly poorer lodging rating than AAC Brandon. Prosper is known for its very high yield potential, but slightly lower protein content. It is a semi-dwarf cultivar but has a similar lodging rating as AAC Cameron (Manitoba Seed Growers' Association Inc 2020).

Sub-experiment 1B focused on five N fertilizer treatments and their interactions with the PGR CCC (Table 6.1). A check plot with no additional N fertilizer was included to determine overall response to N. The standard treatment was chosen to mirror a typical N fertilizer practice for spring wheat in Manitoba, in which 156 kg N ha⁻¹ was applied at planting as midrow banded urea. The standard N fertilizer rate was based on a previous study by Mangin and Flaten (2018) that determined the economic optimum N rate for spring wheat in MB. A reduced rate of 78 kg N ha⁻¹ applied at planting as urea was included to demonstrate the trade-off between applying high N rates targeting yield and protein potential, and the associated lodging risk. A blend of Environmentally Smart Nitrogen™ (ESN) (112 kg N ha⁻¹), a polymer-coated urea, with conventional urea (44 Kg N ha⁻¹) was applied at planting with midrow banding. This treatment was designed to reduce early season losses of N to the environment compared to conventional urea alone. A split N application with half of the total N fertilizer (78 kg N ha⁻¹) applied at planting and the remainder (78 kg N ha⁻¹) applied at flag leaf stage (GS 39) (Zadoks et al. 1974). This treatment was included to limit early season N availability to what is required for yield formation, and to avoid unnecessary early season vegetative growth while providing additional late season N required for protein production. The spring applied portion of N fertilizer was applied as midrow banded urea and the in-season portion applied at flag leaf was SuperU™ (Koch Fertilizer) broadcast on the soil surface. SuperU is an enhanced efficiency fertilizer that was used to reduce volatilization losses from applying N to the soil surface with uncertainty of precipitation for incorporation.

Table 6.1. Treatment list for sub-experiments included in this study, sampled from larger experiments at four site-years described in Chapters 3 and 5. The main effects of cultivar, nitrogen (N) management, and plant density were investigated as well as their interactions with the plant growth regulator (PGR) chlormequat chloride (CCC). Sub-experiments 1B and 2A were measured entirely on the cultivar AAC Brandon.

MAIN PLOT				SPLIT PLOT		
Sub-experiment 1A						
Cultivar				PGR		
	<i>Class</i> [†]	<i>Lodging Rating</i> [‡]			<i>Product</i>	<i>App. Timing</i>
AAC Brandon	CWRS	VG		- CCC	Untreated	
AAC Cameron	CWRS	G		+ CCC	Chlormequat chloride	Stem Elongation (GS31 [§])
Prosper	CNHR	G				
Sub-experiment 1B						
N Management				PGR		
	<i>Total N Rate</i>	<i>App. Timing</i>	<i>N Source</i>		<i>Product</i>	<i>App. Timing</i>
Check	0			- CCC	Untreated	
Reduced Rate	78 kg N ha ⁻¹	Seeding	Urea	+ CCC	Chlormequat chloride	Stem Elongation (GS31 [§])
Standard	156 kg N ha ⁻¹	Seeding	Urea			
ESN Blend	112 + 44 kg N ha ⁻¹	Seeding	ESN + Urea			
Split N App.	78 + 78 kg N ha ⁻¹	Seeding + Flag Leaf	Urea + SuperU			
Sub-experiment 2A						
Plant Density				PGR		
	<i>Target Density</i>				<i>Product</i>	<i>App. Timing</i>
Low	150 plants m ⁻²			- CCC	Untreated	
Med	250 plants m ⁻²			+ CCC	Chlormequat chloride	Stem Elongation (GS31 [§])
High	350 plants m ⁻²					

[†] Canadian wheat classification, CWRS; Canadian western red spring, CNHR; Canadian northern hard red

[‡] Lodging rating from Seed Manitoba 2020, VG; Very good, G; Good.

[§] Zadoks growth stage 31, first node detectable and 1 cm above tillering node

Sub experiment 2A evaluated the effects of three plant densities and their interaction with PGR on lodging risk (Table 6.1). Low, medium and high plant densities were included, with the medium plant density targeting 250 plants m⁻², the current provincial recommendation for spring wheat (Manitoba Agriculture 2020). The low plant density targeted 150 plants m⁻² and the high density targeted 350 plants m⁻². Seeding rates were adjusted to target plant densities based on the thousand kernel weight, germination, and a 15% mortality factor for each seed lot. All treatments in sub-experiments in 1B and 2A were completed using the cultivar AAC Brandon.

In all experiments CCC, formulated as ManipulatorTM620 (Belchim Canada), was applied at the onset of stem elongation (GS 31) at 1.8 L ha⁻¹ of product. Chlormequat chloride was applied as a foliar application to the canopy using a CO₂ backpack sprayer with 100 L ha⁻¹ water volume and flat fan nozzles (AIXR TeeJet AIXR110015). Detailed information regarding field operations for the main experiments, from which all sub-experiments were sampled from, can be found in (Table 3.1) for experiment 1 and (Table 5.1) for experiment 2.

6.3.2 Data Collection

Detailed lodging related measurements were taken from the destructive sampling areas of each plot (front or back 1.5 m of plot length) two weeks after anthesis at approximately the start of the soft dough stage (GS 85). All plants in a 0.5 m length of row were removed to a depth of 30 cm using a spade. Plants were placed in a water bath to gently remove soil from the roots and separate samples into individual plants. The number of plants and shoots per plant were counted for each 0.5 m row length sampling area per plot. The main stem was identified on each plant and plants were then clipped at ground level. Lengths of the main stem and tiller stems (2A only) were recorded from ground level to tip of the spike (excluding awns). Main stem and tiller lengths were averaged across all plants and tillers collected from each plot. The length of the second basal internode on the main stem was measured from the middle of the bordering nodes. The diameter of the second basal internode was taken using a digital caliper at the center of the internode and recorded for each main stem. Internode lengths and stem diameters were averaged for all main stems from the same plot. All root cones were washed, and the structural root plate spread (width) and depth were recorded. The structural root plate was defined as the portion of the lignified crown roots with a rhizosheath and is described in detail in Berry (2000). All above ground plant tissue was divided into leaves, stems (stem + leaf sheath) and spikes, and oven

dried at 80 degrees for 24 hrs. Oven dried samples of each plant part were weighed to determine dry weights. Stem samples were taken from select plots (main effects only) within the sub-experiments for structural fiber analysis. The main effects of cultivar, N management and plant density were sampled from sub-experiments 1A, 1B, and 2A, respectively, from the treatments with no PGR application. The main effect of PGR was sampled from sub-experiment 2A, in the medium plant density treatments. Samples were fine (1 mm) ground using a Cyclone Mill Twister (Retsch USA Verder Scientific, Inc, Newton, PA) and then taken to Central Testing laboratory (Winnipeg, MB) for neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) analysis using methods developed by Van Soest (1990) to estimate lignin, cellulose and hemicellulose content. ADL was used to estimate lignin, cellulose content was estimated by subtracting ADL from ADF content, and lastly hemicellulose was estimated by subtracting ADF from NDF. Specific laboratory procedures used can be found at Ankom Technologies (2021).

As an indication of lodging risk of each plot, stalk strength (resisting force) and elasticity (spike displacement) indicator measurements were taken two weeks after anthesis, immediately after destructive plant sampling, with a push-force meter (Stalker) manufactured at Marchetto Lab at the University of Minnesota (Heuschele et al. 2019). Measurements were taken by pushing on 1.2 m of row length at half the plant height and recording the resisting force of the plant when it was rotated 45 degrees from the vertical position. Additionally, the resisting force measurements taken during the bending and unbending process, along with crop height measurements, were used to calculate the spike displacement for each plot. Two measurements were taken per plot, one from row 3 and one from row 6, and averaged before analysis. Spike displacement is an indicator of flexibility of the stem, which is important to consider in addition to stem strength, when assessing the crop's ability to resist stem lodging. A detailed description of how these data are collected and analyzed to calculate resisting force and spike displacement can be found in Heuschele et al. (2020).

6.3.3 Statistical Analysis

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute, 2001) with site-year, the main effects (cultivar, N management or planting density), and sub-plot effect (PGR) and their interactions as fixed factors. Random factors in the model included block nested

within site-year and the interaction of block with the main effect to account for the split plot arrangement at each site-year and sub-experiment. 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 evaluated using PROC UNIVARIATE to test normality of residuals and the homogeneity of variance was examined visually. Site-year was included as a fixed effect as interactions of treatments with environmental conditions are of interest, but the main effect of site-year alone will not be discussed in detail. Means groupings were determined for significant effects using Tukey's Honest Significant Difference ($P < 0.05$). When there was a significant interaction between model factors, the SLICE statement in PROC MIXED was used to determine means groupings within individual factors. PROC CORR was used to determine the relationships between plant characteristics using data from individual plots.

6.4 Results and Discussion

6.4.1 Stem and Plant Leverage

Wind and rain place leverage on the upper portions of the stems resulting in bending at the stem's base, increasing lodging risk (Berry 2019). The amount of stem and plant leverage that results from any particular amount of wind or rain is a result of the crop's height, biomass, and the number of stems per plant. Analysis of variance for main stem height indicated the main effect of PGR was significant in all sub-experiments and the interaction with site-year was significant in sub-experiments 1A and 1B (Table 6.2). Across all site-years and other treatments, the application of CCC reduced height of the main stem by 4.1 cm (1A), 6.8 cm (1B) and 5.2 cm (2A) (Table 6.3). The interactions of PGR with site-year for sub-experiments 1A and 1B was due to differences in the magnitude of the height reduction with CCC application (Table 6.4). Height reductions were largest at Car18 (7.6 and 9.6 cm, sub-experiment 1A and 1B, respectively) and smallest at Car19 (0.7 and 4.6 cm, sub-experiment 1A and 1B, respectively). As reported in Chapter 5, precipitation for Car18 was higher than the long-term average (LTA) in the month of June, compared to Car19, which had well below the LTA monthly precipitation (Figure 5.1). In western Canada, stem elongation typically begins in the first half of June in spring wheat. The higher moisture availability at Car18 during this time would have promoted plant growth and stem elongation, allowing for a greater reduction in stem length with PGR application compared to drier site-years during this critical growth stage, such as Car19.

Table 6.2. Analysis of variance for the three sub-experiments. Sub-experiment 1A examined the effect of site-year (SY), cultivar (C), the plant growth regulator (PGR) chlormequat chloride and their interactions. Sub-experiment 1B examined the effects of SY, nitrogen fertilization (N), PGR and their interactions using the cultivar AAC Brandon. Sub-experiment 2A examined SY, plant density (PD), PGR and their interactions using the cultivar AAC Brandon. Variables tested include main stem and tiller (2A only) height, biomass, shoots per plant, internode length, stem diameter force displacement, root plate spread and depth, all measured at the soft dough stage.

Analysis of Variance											
Variable	df	Main Stem Height	Tiller Height	Dry Matter	Spike per plant	Internode Length	Stem Diameter	Resisting Force	Spike Displacement	Root Spread	Root Depth
<i>Sub-experiment 1A: Cultivar x PGR</i>											
Site-Year (SY)	3	ns		*	***	***	***	***	*	**	ns
Cultivar (C)	2	***		*	**	**	***	ns	***	ns	ns
SY x C	6	ns		ns	ns	**	ns	ns	ns	ns	ns
PGR	1	***		ns	ns	**	ns	*	***	ns	**
SY x PGR	3	*		ns	ns	ns	ns	ns	ns	***	ns
C x PGR	2	ns		*	ns	ns	ns	ns	ns	ns	ns
SY x C x PGR	6	ns		ns	ns	ns	ns	ns	ns	**	ns
<i>Sub-experiment 1B: Nitrogen x PGR</i>											
Site-Year (SY)	3	ns		*	***	***	***	***	ns	***	***
Nitrogen (N)	4	***		***	***	**	**	*	ns	ns	**
SY x N	12	*		*	ns	ns	***	ns	ns	**	***
PGR	1	***		ns	ns	***	ns	ns	ns	ns	ns
SY x PGR	2	*		ns	ns	ns	ns	ns	ns	ns	ns
N x PGR	4	ns		ns	ns	*	ns	ns	ns	ns	*
SY x N x PGR	12	ns		ns	ns	ns	ns	ns	ns	ns	ns
<i>Sub-experiment 2A: Plant Density x PGR</i>											
Site-Year (SY)	3	**	*	ns	**	***	***	***	*	*	*
Plant Density (PD)	2	ns	ns	ns	***	ns	***	***	ns	***	*
SY x PD	6	ns	ns	ns	ns	ns	ns	ns	*	**	*
PGR	1	***	**	ns	ns	***	ns	ns	***	ns	ns
SY x PGR	3	ns	*	ns	ns	ns	ns	ns	ns	ns	*
PD x PGR	2	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
SY x PD x PGR	6	ns	ns	*	ns	ns	ns	ns	ns	ns	ns

ns, Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

Table 6.3. Least squares means of the main effects for the three sub-experiments 1A (cultivar and plant growth regulator (PGR)), 1B (nitrogen (N) management and PGR) and 2A (plant density and PGR) influencing plant leverage such as main stem height, average tiller height, dry matter, and spikes per plant at two weeks after anthesis.

		Main Stem Height cm	Tiller Height cm	Dry Matter g m ⁻²	Spikes per plant
Sub-experiment 1A					
Cultivar					
	AAC Brandon	70.9	b [†]	888	b
	AAC Cameron	83.5	a	1014	a
	Prosper	74.1	b	957	ab
PGR					
	- CCC [‡]	78.2	a	978	2.3
	+ CCC	74.1	b	928	2.3
Sub-experiment 1B					
N Management[§]					
	Check	63.7	b	728	b
	Reduced Rate	69.7	a	862	a
	Standard Rate	70.9	a	889	a
	ESN Blend	69.7	a	850	a
	Split N	69.6	a	867	a
PGR					
	- CCC	72.1	a	849	2.0
	+ CCC	65.4	b	830	2.0
Sub-experiment 2A					
Plant Density					
	Low	71.4	68.9	944	3.3
	Medium	70.5	66.9	921	2.2
	High	71.3	65.9	906	1.7
PGR					
	- CCC	73.7	a	908	2.3
	+ CCC	68.5	b	939	2.5

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[‡] CCC, Chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

[§] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU.

Table 6.4. Least squares means of stem height for interactions of the plant growth regulator (PGR) chlormequat chloride (CCC) and nitrogen (N) management with site-year for main stem height in sub-experiment 1A and sub-experiment 2A, and average tiller length for the interaction of PGR with environment in sub-experiment 2A.

		Site-Year			
		Car18	Car19	Man18	Man19
Main Stem Height					
cm					
Sub-experiment 1A					
PGR					
- CCC [†]		78.7 a [‡]	75.8	77.6 a	80.6 a
+ CCC		71.2 b	75.1	72.9 b	77.3 b
Sub-experiment 1B					
N management[§]					
Check		64.6	64.0 b	64.7	61.4 b
Reduced Rate		68.2	71.9 a	69.9	68.8 ab
Standard Rate		70.1	71.7 a	69.7	72.0 a
ESN Blend		68.8	69.0 a	64.9	76.2 a
Split N		69.4	70.5 a	66.7	71.8 a
PGR					
- CCC		73.01 a	71.73 a	70.09 a	73.51 a
+ CCC		63.43 b	67.09 b	64.32 b	66.56 b
Tiller Height					
cm					
Sub-experiment 2A					
PGR					
- CCC		68.6 a	71.4	69.1	65.5
+ CCC		61.4 b	68.9	67.6	65.3

[†] CCC, Chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

[‡] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[§] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU.

Main stem height of AAC Cameron was 12.6 and 9.4 cm taller than AAC Brandon and Prosper, respectively (Table 6.3). The relative height differences observed correspond with the cultivar descriptions for plant height (Manitoba Seed Growers Association Inc. 2020). There was no significant interaction of PGR with cultivar, indicating that height reductions from the application of CCC were similar across all three cultivars tested. AAC Brandon and Prosper both have semi-dwarfing alleles which are GA insensitive and the cultivar AAC Cameron does not have a semi-dwarfing allele (Mergoum et al. 2013; Cuthbert et al. 2016; Fox et al. 2017). Because of this, the response of AAC Brandon and Prosper was expected to be less than AAC Cameron; however, preliminary work out of the University of Alberta showed that there was no relationship between cultivar response to GA inhibitors and the presence or absence of dwarfing alleles (personal communications, Linda Hall, 2019).

Overall, when no additional N fertilizer was applied, main stem height was shorter compared to all other N fertilization treatments in sub-experiment 1B (Table 6.3). However, there was a significant interaction with site-year. Differences in main stem height were not significant at Car18 or Man18, but there were significant differences at Car19 and Man19 (Table 6.4). At Car19 the check plot was significantly shorter than all other N treatments, which were all similar in main stem length. At Man19, the check plot was significantly shorter than all full rate N treatments, but not significantly different than the reduced rate treatment (Table 6.4). Car19 and Man19 both had precipitation well below the long-term average early in the growing season (May and June). This moisture deficit, paired with low N availability in the reduced rate and check N treatments at Car19 and Man19, likely were the driving factors influencing this site-year by N interaction for plant height. There were no interactions observed between the application of a PGR and N management for plant height (Table 6.2).

Analysis of variance results of sub-experiment 2A indicated that there was no significant effect of plant density or the interaction of plant density and PGR on main stem height (Table 6.2). Reports of the effect of plant density on canopy height of spring wheat are inconsistent (Mehring 2016); therefore, the lack of response in this experiment was not unexpected.

Average tiller height was measured for sub-experiment 2A only, to further explore the influence of tillering on PGR efficacy. The ANOVA indicated a significant effect of PGR and the interactions of PGR with site-year for tiller height (Table 6.2). Overall, the reduction in tiller

height (2.8 cm) with the PGR application was smaller than the reduction in main stem height (5.2 cm) (Table 6.3). This was anticipated as the application timing of the PGR was staged based on the timing of the main stem rather than tillers. The interaction of PGR with site-year was due to the magnitude of height reduction (Table 6.4). Numerically, PGR application reduced tiller height at all site-years, but the height reduction was only significant at Car18 where tiller height was reduced by 7.2 cm (Table 6.4).

Total plant dry matter two weeks after anthesis was not significantly affected by the main effect of PGR in any of the sub-experiments; however, in sub-experiment 1A there was a significant interaction of cultivar with PGR (Table 6.2). Overall, AAC Cameron had significantly more dry matter than AAC Brandon, while Prosper was not significantly different from either AAC Cameron or AAC Brandon (Table 6.3). The application of a PGR significantly reduced dry weight of AAC Cameron by 158 g m^{-2} , but had no effect on the dry weight of the other two cultivars (Figure 6.1). This interaction was not due to greater reduction in height of AAC Cameron with a PGR application as there was no interaction of cultivar with PGR for main stem height (Table 6.2). Therefore, the reduction in dry matter with CCC application in AAC Cameron may have been due to Cameron having an increased stem dry weight per unit length compared to the other cultivars, resulting in similar height reductions with larger overall dry matter reduction; however, these data were not collected in this experiment. Alternatively, AAC Brandon and Prosper are both GA insensitive due to semi-dwarfing alleles that are not present in AAC Cameron, and as a result AAC Cameron may have been more responsive to GA inhibiting PGRs for dry matter production, even if there were no differences between the three cultivars for height reductions with a PGR application.

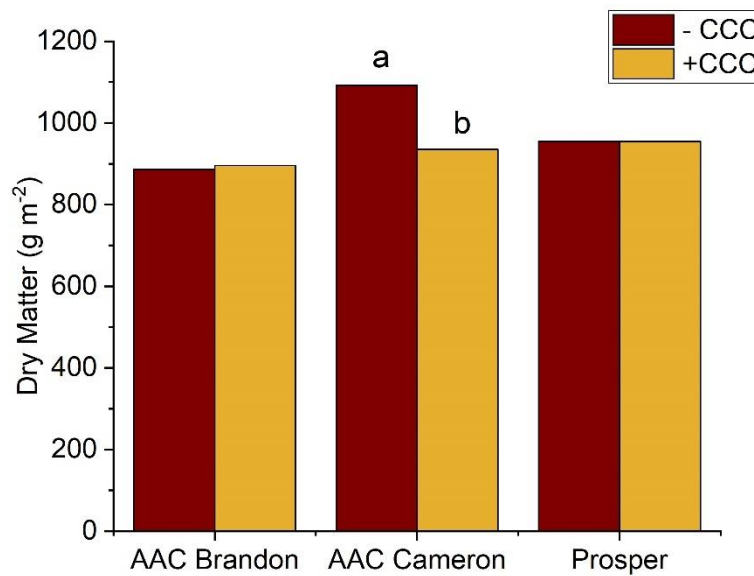


Figure 6.1. The interaction of cultivar with plant growth regulation chlormequat chloride (CCC) (- absence or + presence) applied at Zadoks growth stage 31 for dry matter at soft dough stage in sub-experiment 1A. Within cultivars, bars with different letters are significantly different at the 0.05 probability level, absence of letters indicates no significant differences within cultivars.

Analysis of variance of experiment 1B determined that there was a significant effect of N as well as the interaction of N and site-year for dry matter at two weeks after anthesis (Table 6.2). When averaged across all site-years the check treatment had reduced dry matter compared to all other treatments, which all had similar masses of dry matter (Table 6.3), similar to the pattern for main stem height. The interaction of N by site-year determined that there were no significant differences in N treatments at Car18 and Man18, but there were significant differences at the two 2019 locations (Table 6.5), also similar to the pattern for main stem height. At Car19, the reduced N rate treatment had a significantly larger dry matter than the check plot, while all other full rate N treatments did not differ significantly from both the check and reduced rate treatment. At Man19, the ESN blend produced significantly higher dry matter at the soft dough stage than the check treatment, but all other treatments were similar to both the check and the ESN blend (Table 6.5). There was no significant interaction of PGR and N treatment for dry matter two weeks after anthesis, which was approximately the soft dough stage (Table 6.2).

Table 6.5. Least squares means of the interactions of nitrogen (N) management with site-year in sub-experiment 1B and the 3-way interaction of plant density with PGR and environment in sub-experiment 2A for above ground dry matter two weeks after anthesis

		Site-Year				
		Car18	Car19		Man18	Man19
		Dry Matter g m ⁻²				
Sub-experiment 1B						
N Management [†]						
	Check	861	617	b [‡]	760	674 b
	Reduced Rate	881	879	a	887	801 ab
	Standard Rate	953	852	ab	823	928 ab
	ESN Blend	927	758	ab	731	987 a
	Split N	988	770	ab	765	915 ab
Sub-experiment 2A						
Plant Density	PGR					
Low	- CCC [§]	945	894	ab	954	935
	+ CCC	862	920	ab	910	1131
Med	- CCC	963	833	b	840	986
	+ CCC	927	995	a	932	898
High	- CCC	885	907	ab	803	960
	+ CCC	937	904	ab	938	909

[†]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU.

[‡]Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[§]CCC, Chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

The sub experiment 2A resulted in a significant 3-way interaction between site-year, plant density and PGR for dry matter (Table 6.2). When this interaction was examined at individual site-years it was determined that at Car19 the application of CCC significantly increased dry matter by 162 g m⁻² at the medium plant density only (Table 6.5). There was no effect of PGR application in the low or high plant densities at Car19 (Table 6.5). Additionally,

there was no significant effect of PGR or planting density at any of the other three site-years (Table 6.5).

Plant leverage is determined by the leverage placed on all stems of an entire plant, and as a result is highly dependent on the number of stems per plant. Analysis of variance results indicated that there was no significant effect of PGR on the final number of spike-bearing stems per plant 2 weeks after anthesis in any of the sub-experiments (Table 6.2). This agrees with previously reported research (Cox and Otis 1989; Berry et al. 2000; Rajala et al. 2002). In contrast, there are reports that CCC increased stems per plant by altering apical dominance and reduced tiller mortality (Craufurd and Cartwright 1989; Peltonen and Peltonen-Sainio 1997).

There were significant differences among cultivars in the number of spikes per plant with Prosper producing 0.4 and 0.5 more spikes per plant than AAC Brandon and AAC Cameron, respectively (Table 6.3). This phenomenon may be due to lower plant stands resulting from poorer stand establishment and increased tillering for Prosper compared to the other two cultivars (Table 3.4).

The number of spikes per plant for the N check plots was significantly lower than all of the treatments with applied N (Table 6.3). There were no differences in spikes per plant among any of the applied N treatments. Therefore, when N was deficient, tiller production and survival may be reduced, but this effect was easily corrected when N fertilizer was applied at even a modest rate. Otteson et al. (2007) reported similar findings with no differences in spikes per plant between modest and high rates of N.

Plant density had a significant effect on spikes per plant, which is expected as cereals compensate for low plant densities by producing additional stems to capture available resources. Low plant density averaged 3.3 spikes plant⁻¹, medium 2.2 spikes plant⁻¹ and 1.68 spikes plant⁻¹ for the high density (Table 6.3).

6.4.2 Stem Morphology, Composition, and Strength

The ability of the crop's stem to avoid breakage and bending is often referred to as stem strength. Indicators of stem strength include a number of different plant characteristics such as plant morphology, chemical compounds, and internal structure. This study focused on external morphology of the second basal internode and structural fiber compounds in the stem tissue.

When stem lodging occurs in wheat, the stem typically breaks at the lower internodes. The length and diameter of these lower internodes are important characteristics influencing the stems' ability to resist breakage (Berry et al. 2007).

The main effect of PGR significantly affected the length of the second basal internode in all three sub-experiments (Table 6.2). Reduction of second basal internode length with a PGR application ranged from 0.5 cm in sub-experiment 1A to 0.9 cm in sub-experiment 1B (Table 6.6). The PGR was applied at the beginning of stem elongation (GS 32) when the second node was formed, and the second basal internode was beginning to elongate. By applying a growth regulator at this timing, it is expected that the second basal internode would be reduced (Rademacher 2015).

In sub-experiment 1A the ANOVA determined there were significant effects of cultivar and interaction of cultivar with site-year for second basal internode length (Table 6.2). Overall AAC Cameron had the longest internode length compared to AAC Brandon and Prosper, which corresponds with the main stem height of this cultivar (Tables 6.3 and 6.6). The interaction of cultivar by site-year for second basal internode length showed that there were significant differences between cultivars at the Car18 and Man19 site-years (Table 6.7). Similar to the main stem length, there was no interaction of cultivar with PGR application for the second basal internode length, indicating all cultivars responded in a similar manner to CCC application.

The significant main effect of the N treatment for internode length was due to a reduced internode length in the check treatment that had no additional N fertilizer applied (Tables 6.2 and 6.6). All applied N treatments, other than the ESN blend, had internode lengths that were significantly greater than the check when averaged across all site-years. The significant interaction of the N with PGR treatments was due to differences in the magnitude of internode shortening among N treatments with PGR application. Internode length was reduced by the smallest amount (0.54 cm) with the standard N treatment and the largest reduction in internode length occurred when no N was applied in the check plots (1.33 cm) (Appendix Table D1). This indicates that when an N deficiency is corrected, there is a large increase in internode length, which was not completely counteracted by the PGR application.

Table 6.6. Least squares means for the main effects of cultivar, plant growth regulator (PGR) chlormequat chloride (CCC), nitrogen (N) management, and plant density on plant characteristics influencing second basal internode length, stem diameter at the mid point of the second basal internode, resisting force, spike displacement, and root plate spread and depth for sub-experiments 1A, 1B and 2A.

	Internode Length		Stem Diameter		Resisting Force		Spike Displacement		Root Plate Spread		Root Plate Depth	
	(cm)		(mm)		(Newtons)		(m)		(cm)		(cm)	
Sub-experiment 1A												
Cultivar												
AAC Brandon	9.2	b [†]	2.69	b	2.72		0.568	c	3.88		6.15	
AAC Cameron	10.0	a	2.92	a	3.15		0.683	a	3.63		5.91	
Prosper	9.4	b	2.87	a	3.27		0.617	b	3.82		6.09	
PGR												
- CCC [‡]	9.8	a	2.83		2.52	b	0.633	a	3.73		5.76	b
+ CCC	9.3	b	2.82		3.56	a	0.613	b	3.83		6.34	a
Sub-experiment 1B												
N Management [§]												
Check	8.6	b	2.58	b	3.52	ab	0.553		4.05		6.58	ab
Reduced Rate	9.3	a	2.67	a	3.64	ab	0.582		3.99		6.84	a
Standard Rate	9.2	a	2.69	a	2.51	b	0.556		3.88		6.15	b
ESN Blend	9.2	ab	2.63	ab	3.38	ab	0.574		3.93		6.64	ab
Split N	9.3	a	2.70	a	4.20	a	0.566		3.84		6.95	a
PGR												
- CCC	9.6	a	2.67		3.44		0.568		3.93		6.64	
+ CCC	8.7	b	2.63		3.46		0.564		3.94		6.63	
Sub-experiment 2A												
Plant Density												
Low	9.4		2.80	a	4.91	a	0.592		4.18	a	6.15	a
Medium	9.4		2.66	b	3.03	b	0.586		3.77	b	5.78	b
High	9.2		2.57	c	3.22	b	0.584		3.24	c	5.91	ab
PGR												
- CCC	9.7	a	2.65		3.63		0.600	a	3.75		5.94	
+ CCC	8.9	b	2.70		3.81		0.574	b	3.72		5.95	

[†]Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[‡]CCC, Chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

[§] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU.

Table 6.7. Least squares means for the interaction of cultivar with site-year for internode length in sub-experiment 1A and nitrogen (N) management with site-year for stem diameter in sub-experiment 1B.

Site-Year									
Car18				Car19		Man18		Man19	
Internode Length									
cm									
Sub-experiment 1A									
Cultivar									
AAC Brandon		8.11	b [†]	10.49		8.68		9.55 b	
AAC Cameron		10.02	a	10.69		8.56		10.56 a	
Prosper		8.59	b	11.07		8.69		9.28 b	
Stem Diameter									
mm									
Sub-experiment 1B									
N Management [‡]									
Check		2.36	b	2.68		2.70 ab		2.56 b	
Reduced Rate		2.26	bc	2.86		2.78 a		2.78 ab	
Standard Rate		2.50	a	2.79		2.52 b		2.97 a	
ESN Blend		2.24	c	2.74		2.63 ab		2.89 a	
Split N		2.27	bc	2.88		2.75 ab		2.88 a	

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[‡] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

Plant density did not significantly influence internode length; however, there was a significant interaction of PGR with plant density (Table 6.2). When plant density was low, the PGR treatment did not have a significant effect on the second internode length, but at the medium and high plant densities, CCC application significantly reduced internode length (Figure 6.2). The timing of PGR application was determined using the average main stem growth stage for all plant density treatments, which was much more variable in low plant density treatments. This variability may explain why there was no reduction in internode length with the low plant density treatments. However, the differences in PGR efficacy with plant densities is likely a result of more factors than just crop stage variability. Figure 6.2 demonstrates that for internode

length of the main stem, the largest reduction with CCC application was at high plant densities and the smallest reductions at low plant densities.

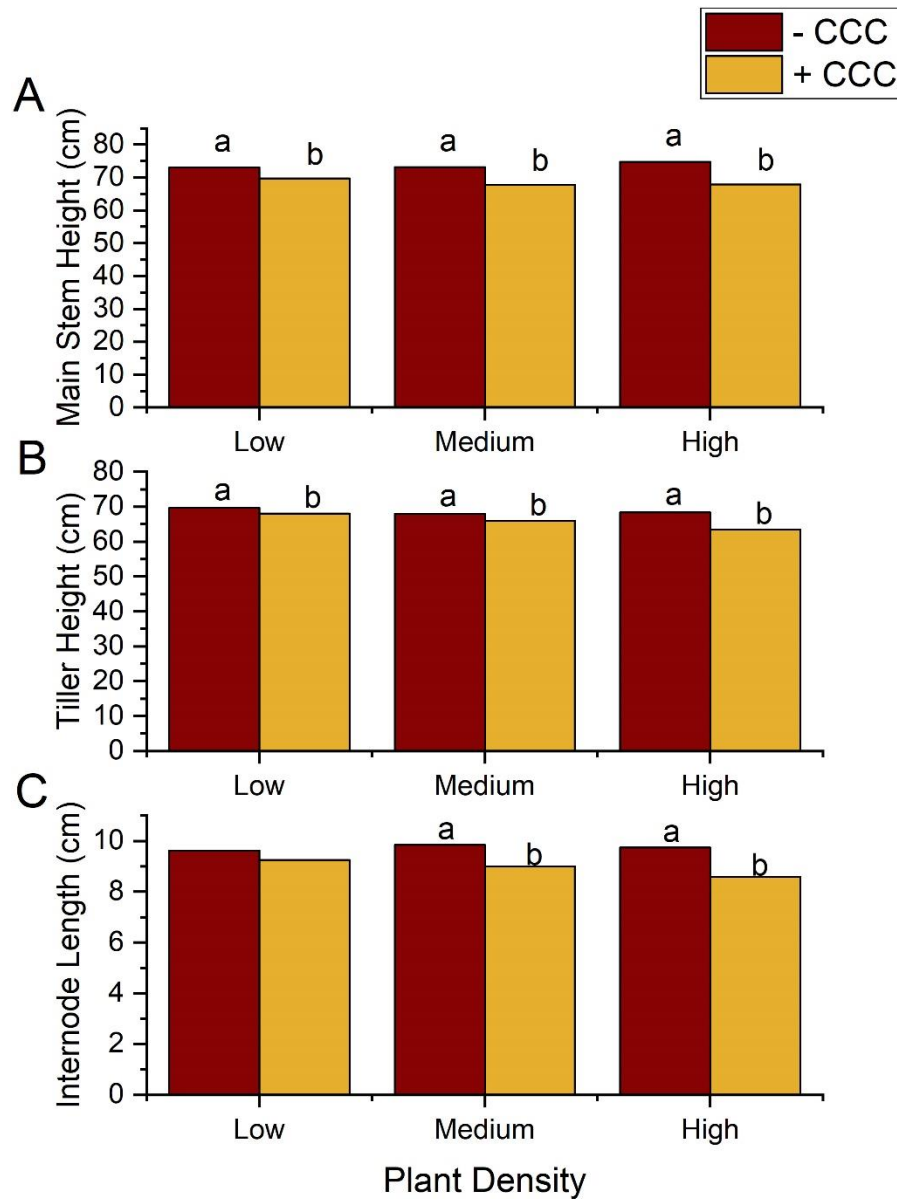


Figure 6.2. Columns indicate least squares means for the interaction of plant density with plant growth regulator (PGR) (- absence or + presence) for main stem height (A), tiller height (B), and internode length (c) for sub-experiment 2A. Columns with different lowercase letters within a plant density indicate a significant difference at the 95% confidence level.

The stem diameter of the second basal internode was measured at the midpoint between nodes on the main stem. Correlation analysis determined that across all three sub-experiments there was a highly significant positive relationship between stem diameter and internode and main stem length (Appendix Table D2-D4). There was no significant effect of PGR, or interactions of PGR with other management factors on stem diameter in any of the sub-experiments (Table 6.2). A greenhouse experiment testing six spring wheat cultivars in Ontario reported a consistent increase in stem diameter following the application of GA inhibitors CCC and TXP (Zhang et al. 2017b). However, in experiments conducted in the field, the response of stem diameter to CCC application appears to be less consistent. Berry et al. (2000) reported no differences in stem diameter when CCC was applied to winter wheat at stem elongation (GS 32).

There was a significant effect of cultivar on stem diameter with AAC Brandon having a significantly smaller stem diameter than both AAC Cameron and Prosper (Tables 6.2 and 6.6). This was unexpected as AAC Brandon has the greatest lodging resistance (Table 3.2) ranking and stem diameter is a main component of stem strength (Berry et al. 2016). Based on lodging resistance, AAC Brandon would be expected to have a larger stem diameter than both other cultivars. These differences in stem diameter indicate that plant characteristics other than stem diameter contribute to AAC Brandon's very good lodging resistance.

The ANOVA for sub-experiment 1B indicated a significant effect of both site-year and N treatment, as well as the interaction between N and site-year for stem diameter (Table 6.2). Overall, check plots had a reduced stem diameter compared to all other treatments other than the ESN Blend, which did not differ significantly from the check and other N treatments (Table 6.6). This response agrees with work by Berry et al. (2000) showing increases in stem diameter when moderate rates of N were applied. However, the interaction of N with site-year demonstrated the response of stem diameter to N treatment was very environmentally specific and there were no consistent trends across site-years (Table 6.7). The underlying causes of these interactions are unclear, and more research is needed to better understand the interaction of N fertilization and environmental conditions for stem diameter.

Stem diameter was the highest at the low plant density and decreased with increasing plant densities. Stem diameter for the low plant density treatments was 0.23 mm larger than the high plant density treatment (Table 6.6). These results agree with previous studies that reported higher

stem diameter with low planting densities (Zheng et al. 2017). The larger stem diameter with low plant densities is likely due to reduced shading and resource competition early in the growing season compared to higher plant densities (Sparkes and King 2008).

Structural fiber content of plant stems contributes to stem strength (Jung et al. 1993). Stem lignin, cellulose and hemicellulose content were measured to determine the influence of the main effects of PGR, cultivar, N management and plant density on stem fiber content. Lignin improves the mechanical strength of the plant stem cell wall; therefore, any changes in lignin content are predicted to affect stem strength. Analysis of variance results indicated that cultivar was the only management practice that had a significant influence on lignin content (Table 6.8). Overall, the cultivar Prosper had less lignin than AAC Cameron and AAC Brandon (Table 6.9), but there was an interaction with site-year that indicated there were no significant differences at the Man18 and Man19 sites (Table 6.10). At Car18, AAC Cameron had higher concentrations of stem lignin than Prosper, but AAC Cameron and Prosper were not significantly different from AAC Brandon. At Car19 AAC Cameron had a significantly higher stem lignin concentration than the other cultivars (Table 6.10).

The lack of response of stem lignin concentration to agronomic management practices was unexpected as previous reports have indicated sensitivity of lignin to management practices. Wiersma et al. (2007) reported a linear increase in lignin concentration in spring wheat stems when treated with increasing rates of the GA inhibitor TXP. However, means separation did not show significant differences in lignin content with and without TXP applications. N management influences lignin content with N fertilizer application increasing lignin content when correcting a N deficiency, but any further increases of N rate to excess levels reduces stem lignin content (Mulder 1954; Chen et al. 2018). Zhang et al. (2017a) reported that, when N was applied as a split application, lignin content of the second basal internode was higher compared to when a similar amount of N was applied entirely at planting. Additionally, no significant differences in lignin content with low plant densities were observed, but there was a trend for higher lignin at low plant densities compared to high plant densities (Table 6.9).

Table 6.8. Analysis of variance for stem lignin, cellulose and hemicellulose content in stem tissue for the main effects of cultivar, nitrogen (N) management, plant density and plant growth regulator (PGR). Data from cultivars were collected from sub-experiment 1A, data for N management were sampled from sub-experiment 1B, and data for plant density and PGR were collected from sub-experiment 2A.

	Lignin	Cellulose	Hemicellulose
<i>Cultivar</i>			
Site-Year (SY)	***	***	*
Cultivar (C)	***	***	*
SY x C	*	ns	ns
<i>N Management</i>			
SY	***	***	**
Nitrogen (N)	ns	*	ns
SY x N	ns	***	ns
<i>Plant Density</i>			
SY	**	***	*
Plant Density (PD)	ns	ns	ns
SY x PD	ns	ns	ns
<i>PGR</i>			
SY	***	***	ns
PGR	ns	**	ns
SY x PGR	ns	ns	ns

ns, Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

Table 6.9. Least squares means for the main effects of cultivar, nitrogen (N) management, plant density and the plant growth regulator (PGR) chlormequat chloride (CCC) for lignin, cellulose, and hemicellulose content in stem tissue. Data from cultivars were sampled from sub-experiment 1A, data for N management were sampled from sub-experiment 1B, and data for plant density and PGR were collected from sub-experiment 2A.

	Lignin Content		Cellulose Content		Hemicellulose Content	
	%		%		%	
<i>Cultivar</i>						
AAC Brandon	6.17	a [†]	33.33	b	16.91	ab
AAC Cameron	6.56	a	34.98	a	17.07	a
Prosper	5.58	b	31.28	c	15.65	b
<i>N Management</i> [‡]						
Check	5.93		33.60	ab	17.43	
Reduced Rate	5.78		33.57	ab	17.06	
Standard Rate	6.15		33.26	b	17.28	
ESN Blend	5.70		34.25	a	17.59	
Split N	5.84		33.79	ab	17.75	
<i>Plant Density</i> [§]						
Low	6.02		34.00		17.63	
Medium	5.79		33.94		17.38	
High	5.84		33.80		18.01	
<i>PGR</i> [¶]						
- CCC	5.84		33.80	a	18.01	
+ CCC	5.68		32.68	b	17.27	

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[‡] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

[§] Plant density low target 150 plant m⁻², medium target 250 plants m⁻², high target 350 plants m⁻²

[¶] CCC, chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

Table 6.10. Least squares means for the interactions of cultivar with site-year for stem lignin content and nitrogen (N) management by environment for stem cellulose content at the soft dough growth stage. Data from cultivars were sampled from sub-experiment 1A and data for N management were collected from sub-experiment 1B.

		Site-Year							
		Car18		Car19		Man18		Man19	
		Lignin Content							
		%							
Cultivar									
	AAC Brandon	7.7	ab [†]	6.1	b	5.3		5.5	
	AAC Cameron	8.1	a	7.4	a	4.8		5.9	
	Prosper	6.8	b	5.9	b	4.6		5.0	
		Cellulose Content							
		%							
N Management [‡]									
	Check	34.5	ab	34.5	a	33.6		31.7	
	Reduced Rate	34.0	b	33.7	ab	35.4		31.3	
	Standard Rate	34.2	b	32.9	ab	34.9		31.1	
	ESN Blend	36.3	a	33.2	ab	34.5		32.9	
	Split N	35.5	ab	32.2	b	35.1		32.3	

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

[‡] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

Others have reported that low plant densities produce stems with high lignin content due to low early season shading (Sparkes and King 2008). Zheng et al. (2017) reported a very consistent increase in lignin content of the second basal internode with reduced plant densities that was positively correlated with the breaking strength of that internodes. In the current study there were no significant effects of N treatment or plant density on lignin content. Lack of significant differences may be due to small sample size for the sub-experiments, or because lignin content was measured from all plant stem material (main stems plus tillers) rather than in only the lower internodes of the main stems, which may have reduced the magnitude of differences between treatments.

Cellulose forms the structure of individual cell walls and although it is linked with lignin content, it is possible that agronomic management practices will influence cellulose content differently than lignin content. Wang et al. (2012) concluded that differences in lodging amongst cultivars was much more dependent on cellulose content than lignin content. Application of a PGR significantly reduced the cellulose content of stems from 33.8% to 32.7% (Table 6.9). Gibberellins are known to promote the differentiation of fiber cells; therefore, it is not surprising that by inhibiting GA biosynthesis with the application of the GA inhibitor CCC, cellulose content was reduced (Aloni 1987). Nitrogen management also had a significant effect on cellulose content, but this effect was dependent on site-year (Table 6.8). At Car18 the ESN blend had significantly higher cellulose content than both the reduced rate and standard N practices, with the check and split N being similar to all other treatments (Table 6.10). At Car19 the check plot had statistically increased cellulose content compared to the split N treatment, but was similar to all other treatments (Table 6.10). There were no differences in the N fertilizer treatments for stem cellulose content at the Man18 or Man19. There was no effect of plant density on stem cellulose content in this experiment (Table 6.8).

Similar to lignin, hemicellulose was significantly influenced only by spring wheat cultivar (Table 6.8). The differences among cultivars followed trends similar to lignin and cellulose with AAC Cameron having the highest hemicellulose content and Prosper having the lowest (Table 6.9).

Concentrations of structural components play a role in stem strength; however, the arrangement and interactions of these components may be just as important as their concentrations for determining lodging resistance in cereals (Knapp et al. 1987). This is demonstrated by examining the relationships between the total content of structural fiber components compared to stem strength and flexibility when influenced by various management practices. To determine susceptibility of a crop to lodge, the stem strength (ability to resist being pushed away from vertical) and stem flexibility (movement of the spike when stem is being pushed from vertical) must be taken into consideration (Heuschele et al. 2020). If stems are very strong, they may be able to resist breakage, but if increased strength is not paired with some level of increased flexibility, the leverage placed on the stems by wind and rain will be transferred down the stem to the anchorage system, potentially increasing root lodging risk. Stem strength

(measured by resisting force) and flexibility (measured by spike displacement) indicators measured two weeks after anthesis determined that agronomic practices may be influencing stem strength (resisting force) and flexibility (spike displacement) differently.

The application of a PGR had a significant effect only on stem strength, measured as resisting force required to push the stems over to a 45-degree angle, in sub-experiment 1A with no influence for both 1B and 2A (Table 6.2). In sub-experiment 1A CCC increased the stem strength, measured as resisting force, by 1.04 Newtons compared to when no PGR was applied (Table 6.6). In the literature, increases in stem strength by PGR applications were linked to increased structural fiber components, stem diameter, stem wall width (degree of filling) as well as alterations to the cell wall arrangement, with decreased stem wall cell length, but increased width and total number (Zhang et al. 2017a; Zheng et al. 2017). PGR application did not have an influence on stem diameter in this study and reduced the cellulose content of stems. Therefore, the increase in stem strength in sub-experiment 1A when a PGR was applied is likely due to internal cell structure and arrangement changes rather than external morphology or absolute fiber contents.

When stem strength is increased by a PGR application, it is likely that stem flexibility is also influenced. The ANOVA indicates that flexibility, as indicated by spike displacement, was influenced by the PGR application in both sub-experiment 1A and 2A (Table 6.2). PGR application reduced spike displacement by 0.02 m in 1A and 0.026m in 2A (Table 6.6). There was no interaction of PGR with any of the other management practices for stem strength or flexibility indicators.

Cultivars tested in this experiment did not vary in resisting force, but there was a significant influence of cultivar on spike displacement (Table 6.2). Correlation analysis indicated that there was a significant negative relationship between stem strength (resisting force) and internode length in sub-experiment 1A (Appendix Table D2). This indicated that cultivars with longer lower internodes had reduced stem strength compared to cultivars with shorter lower internode length. Alternatively, there was a significant positive relationship between stem flexibility (spike displacement) and internode length in sub-experiment 1A (Appendix Table D2). AAC Cameron had the highest displacement, followed by Prosper and lastly AAC Brandon

(Table 6.6), which agrees with the plant height differences between the three cultivars (Table 6.3).

The ANOVA indicated that N management had a significant influence on resisting force, but not the spike displacement (Table 6.2). Split N applications increased resisting force compared to the standard N practice where N was applied entirely at planting (Table 6.6). This agrees with a number of other experiments that showed splitting N between planting and in-season increased stem strength, quantified by stem breakage strength (Chen et al. 2018; Wu et al. 2019; Mizuta et al. 2020). Changes in plant density also influenced the stem strength indicator resisting force. Wheat grown under low plant densities had increased resisting force compared to both medium and high plant density (Table 6.6). Correlation analysis determined that there was a significant positive relationship between spikes per plant and resisting force in both sub-experiment 1A and 2A, reflecting the response to plant density (Appendix Table D4). However, this relationship was not significant in sub-experiment 1B when N was a main experimental factor, indicating that when N levels are also influencing the number of stems per plant, the benefit of increased stems per plant for stem strength are masked.

There was a significant interaction of plant density with site-year for spike displacement (Table 6.2). At Manitou19 high plant density treatments had reduced spike displacement (0.56 m) compared to low and medium densities (0.59 and 0.60, respectively) (Appendix Table D5). There was a highly significant positive relationship between stem diameter and spike displacement in sub-experiment 2A (Appendix Table D3). As plant density increased, there was a corresponding decrease in stem diameter and as a result spike displacement. Both nodes and internodes act as a single mechanical system, with internode walls providing rigidity and strength, while nodes contribute to flexibility by acting as spring joints (Niklas 1997, 1998). Only internode characteristics were measured in this experiment; however, as stem diameter increased, node diameter is also expected to increase, which would cause the diaphragm inside the node to become thinner and more flexible (Heuschele et al. unpublished). This shows that when crops are grown in high densities, they may have both reduced strength and flexibility, and as a result they will likely be more prone to both stem and root lodging.

The relationships between structural fiber components and stem strength and flexibility indicators were very inconclusive across this experiment and raise a number of questions. There

was a negative correlation between lignin, cellulose or hemicellulose, and resisting force in sub-experiments 1A and 2A, and in sub-experiment 1B the relationship was only significant for hemicellulose (Appendix Tables D2-D4). Spike displacement had a positive relationship with lignin, cellulose, and hemicellulose content in sub-experiment 1A where cultivar was the main influencing factor (Appendix Table D2). In contrast, there was no relationship between lignin or cellulose, and spike displacement for sub-experiments 1B and 2A that were focused on management influences of N fertilization and planting density rather than cultivar differences (Appendix Tables D3-D4). These inconclusive findings reinforce the conclusions drawn by Niklas (1997, 1998) that stalk strength and flexibility of wheat is dependent not only on the quantity of structural components but also the ratios of those components and how they interact within the cellular arrangement of the stems (Niklas 1997, 1998).

6.4.3 Anchorage Strength

The effect of management practices on anchorage strength is usually overlooked in agronomic studies because it is highly dependent on the environmental conditions, as well as the soil type. The main plant characteristic influencing anchorage strength is the size of the structural root plate. The spread of the root plate was significantly influenced only by PGR application in sub-experiment 1A, where there was an interaction of PGR with site-years as well as the 3-way interaction of cultivar with PGR and site-year (Table 6.2). This interaction revealed that Car18 was the only site-year that had significant differences between PGR treatments, and those differences were only for the cultivars AAC Brandon and AAC Cameron (Figure 6.3). Root plate spread increased 0.97 cm and 0.82 cm when CCC was applied to AAC Brandon and AAC Cameron, respectively. This indicates that the response of root plate spread to PGR application was very dependent on environmental conditions and cultivars.

The structural root plate depth had a more consistent response to PGR application than root plate spread. In the ANOVA for sub-experiment 1A, the main effect of PGR was significant with no interaction with cultivar or site-year (Table 6.2). PGR application increased root plate depth by 0.58 cm across all other treatments in sub-experiment 1A (Table 6.6). In sub-experiment 1B the main effect of PGR was not significant for root plate depth, but the interaction of PGR with N management was, and revealed that PGR only increased root plate depth when the standard N management practice of 156 kg N ha⁻¹ was applied at planting (Figure 6.4). This

indicated that early season N availability may influence the root plate response of wheat to CCC applications. In contrast, the response of root plate depth to CCC application in sub-experiment 2A was very inconsistent across site-years, with Car18 being the only site-year with a significant difference (Appendix Table D6).

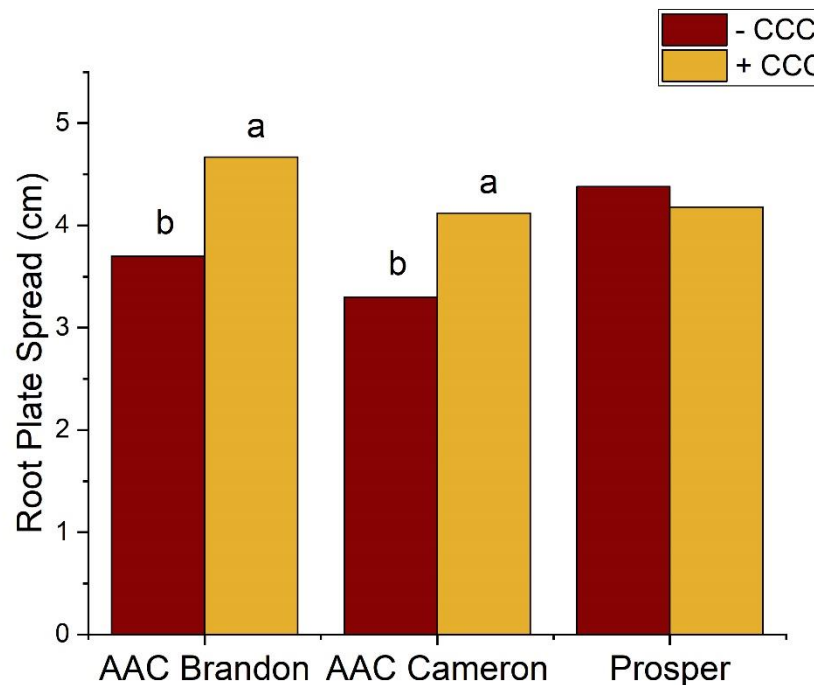


Figure 6.3. Columns indicate the least squares means of the of interaction of the three cultivars AAC Brandon, AAC Cameron and Proser with plant growth regulator application of chlormequat chloride (- absence or + presence) at the Man18 environment for root plate spread two weeks after anthesis. Columns with different lower case lettered for a single cultivar indicate a significant effect of PGR on root plate spread. The absence of letters indicates no significant difference between PGR treatments within a cultivar.

At Car18, CCC application increased the root plate depth by 0.75 cm (Appendix Table D6). There is very little research on the influence of PGR applications on root spread and depth with Berry et al. (2000) and Crook and Ennos (1995) both reporting no effect of CCC on wheat root plate size. The application of GA inhibitors have been shown to promote root growth by

redirection of resources during the stem elongation growth phase, increasing the root to shoot ratio (De et al. 1982). How this effect is influenced by environmental conditions and cultivars is unknown, but warrants additional research as there appears to be potential for CCC to increase root plate size of spring wheat under certain circumstances.

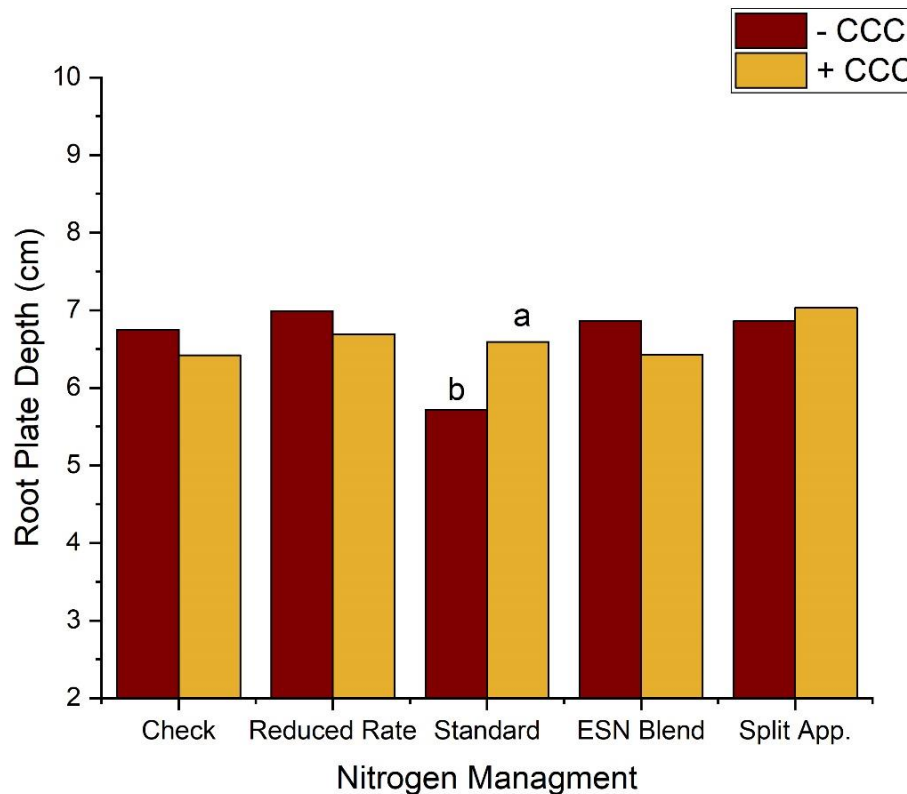


Figure 6.4. Columns indicated the least squares means for the interaction of nitrogen (N) management with the plant growth regulator chlormequat chloride (CCC) (- absence or + presence) on root plate depth in sub-experiment 1B, averaged across all environments. Columns with different lower case lettered for N management treatments indicate a significant effect of PGR on root plate spread. The absence of letters indicates no significant difference between PGR treatments within a N management treatment.

The influence of N on both root plate spread, and depth was dependent on environmental conditions as indicated by significant interactions in the ANOVA with site-year (Table 6.2).

Root plate spread was reduced with the standard N practice compared to when no additional N fertilizer was applied in the check treatment in Car18, with no significant differences between all other N management practices (Table 6.11). There were no differences in root spread with N treatment at the three other site-years. Root plate depth was significantly influenced by N at both Car18 and Man18, but there were no differences between treatments at Car19 or Man19. At Car18 the standard N management practice had reduced root plate spread compared to the check, reduced rate and split plot treatments. At Man18 the standard treatment only resulted in a significantly smaller root plate depth than the split N treatment (Table 6.11).

Table 6.11. Least squares means for the interaction of nitrogen (N) management with site-year for root plate depth and spread in sub-experiment 1B.

Site-Year									
		Car18		Car19		Man18		Man19	
Sub-experiment 1B									
Root Plate Spread									
cm									
N Management†									
Check		5.20	a†	3.38		3.75		3.85	
Reduced Rate		4.75	ab	3.60		3.84		3.76	
Standard Rate		4.19	b	3.29		3.85		4.17	
ESN Blend		4.71	ab	3.26		3.53		4.20	
Split N		4.82	ab	3.59		3.48		3.45	
Root Plate Depth									
cm									
N Management									
Check		8.33	a	5.29		6.90	ab	5.80	
Reduced Rate		8.38	a	6.05		7.03	ab	5.90	
Standard Rate		6.66	b	5.79		5.51	b	6.66	
ESN Blend		8.07	ab	5.92		6.58	ab	6.00	
Split N		8.33	a	6.54		7.44	a	5.48	

[†]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

[‡]Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

These results suggest that there is potential to increase wheat anchorage system through N fertilization management. When N is applied in high amounts, it is beneficial to apply N as a split application by applying a modest amount at planting and the remainder at the flag lead stage to maximize resources allocated to the root plate development. This is similar to the results observed by Wu et al. (2019) in an eastern Canada study on the response of anchorage strength to split N applications.

Plant density also had a significant influence on the plant's root plate spread and depth (Table 6.2). Overall, reduced plant density increased both the root plate spread and depth compared to the other two plant densities (Table 6.6). This was expected, as plants grown under low plant densities will produce more stems per plant, each of which produce a crown root that would increase root plate potential (Whaley et al. 2000; Berry 2019). Berry et al. (2000) similarly reported that when plant density was reduced from 400 to 200 plant m⁻² the result was a wider, deeper root plate in wheat. Both root plate spread and depth response to plant density had a significant interaction with site-year (Table 6.2). When the response of plant density on root plate spread was examined at each site-year, the results indicated that reduced root spread with high plant densities was not significant at the Car19 location (Table 6.12). For root plate depth, high plant densities produced shallower root plates at Man18 and Man19, with no differences observed at the other two site-years (Table 6.12). The site-year specific response of root plate size to plant density may be due to soil type and moisture conditions at the different site-years. Additionally, in some site-years, the separation in achieved plant densities was less than what was targeted, reducing the differences between treatments.

Table 6.12. Least squares means for the interaction of plant density with site-year for root plate spread and root plate depth in sub-experiment 2A.

		Site-Year							
		Car18		Car19		Man18		Man19	
Sub-experiment 2A									
Root Plate Spread									
cm									
Plant Density [†]									
Low		3.83	a [‡]	3.58		4.64	a	4.66	a
Medium		3.56	ab	3.63		3.88	b	4.01	a
High		3.17	b	3.29		3.30	b	3.23	b
Root Plate Depth									
cm									
Plant Density									
Low		6.27		5.56		6.68	a	6.10	a
Medium		6.38		5.52		5.87	b	5.34	b
High		6.58		5.72		5.83	b	5.52	b

[†] Plant density low target 150 plant m⁻², medium target 250 plants m⁻², high target 350 plants m⁻²

[‡] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

6.5 Conclusions

Low plant densities resulted in an increased stem diameter of the second basal internode and increased structural root plate spread and depth compared to high planting densities in this study. As a result, stem strength, as well as stem flexibility, increased with low plant densities, making it a very promising option as a lodging management tool. Producers may be hesitant to adopt low plant densities because it takes longer for the canopy to close in the spring, which may decrease the crop's ability to compete with early emerging weeds. Additionally, when there is increased tillering, maturity is more variable throughout the canopy, which has potential to create difficulty in staging and efficacy of other crop production practices. For example, the length of the second basal internode wasn't significantly reduced by the application of a PGR at low plant densities, but it was reduced at the medium and high plant densities.

Splitting the application of N from entirely at planting to half at planting and half at flag leaf was the most promising N management strategy tested for reducing lodging risk. There was no influence on stem diameter and internode length, but stem strength, as indicated by resisting force, was increased compared to the standard practice. Additionally, root plate depth increased

when N was applied as a split application compared to entirely at planting. By limiting N availability early in the season, it is likely that early season vegetation is reduced, limiting shading in the canopy and allowing for a stronger stem and anchorage system to form. Split N applications had the additional benefit of increasing grain protein content through increased late season uptake of N from the soil (Table 4.3). However, applying N as a split timing requires an additional pass during the growing season and adequate moisture to facilitate N incorporation into the soil and uptake by the crop. This may limit adoption of this practice in the short growing season of dryland wheat production in western Canada.

Plant growth regulator application consistently reduced plant height across all cultivars and site-years tested in this study but did have reduced efficacy in low plant densities. Stem strength, as indicated by resisting force, was increased with PGR application, but it was commonly paired with reduced flexibility, as indicated by spike displacement, potentially diverting leverage to the anchorage system. There was evidence that PGR applications have potential to increase structural root plate depth and spread in this study, but it was highly dependent on N fertility and environmental conditions. These results indicate that the application of a PGR, in particular CCC, at the beginning of stem elongation, may reduce lodging risk in more ways than just reduced leverage through decreased stem height. However, the consistency of plant responses to PGR across environmental conditions and management practices requires additional research.

Berry et al. (2007) and Pin (2016) described the ideal major plant morphological characteristics required to reduce lodging occurrence to once in a 25-year period for spring wheat in Mexico and winter wheat in the UK. Both studies had an ideal plant height of 70 cm, which is similar to semi-dwarf spring wheat cultivars in Canada, with cultivars in this study ranging from 70 – 83 cm. The stem diameter of the second basal internode ranged from 2.69 – 2.92 mm in this study, which was very low compared to ideal estimates of 4.11 – 4.67 mm in a 6t ha⁻¹ spring wheat crop in Mexico. Root plate spread is thought to be the main characteristic influencing root lodging and it is heavily dependent on plant density, but in a 200 plants m⁻² winter wheat crop the ideal root spread was 5.7 cm (Berry 2007). In this study with spring wheat the root plate spread ranged from 3.63 – 3.88 cm with similar plant densities. When our results in Canadian spring wheat cultivars are compared with ideotype models in other wheat growing regions of the

world, further reduction in plant height is not likely to be an avenue for future increases in lodging resistance. There is room for improvement in both stem diameter and root plate spread to increase lodging resistance, which should be targeted by future breeding efforts and agronomic management decisions.

CHAPTER 7. RAPID *IN SITU* NON-DESTRUCTIVE EVALUATION OF LODGING RISK IN DRYLAND AGRONOMIC WHEAT RESEARCH

7.1 Abstract

Natural occurrence of lodging in small-plot research to record visual ratings is unpredictable, highly dependent on environmental conditions, and does not differentiate between root and shoot lodging. Detailed plant characteristics can be used to indicate lodging risk; however, such measurements are destructive and extremely time-consuming for research projects that are not focused solely on lodging evaluation. The Stalker, a push force meter, is a tool that can be used non-destructively to rapidly indicate stem strength and elasticity, which may be useful to measure lodging risk in small plot research by predicting both root and shoot lodging potential. The objective of this study was to evaluate the ability of the Stalker to detect agronomic management practices that are known to reduce lodging risk (reduced plant density, split nitrogen (N) applications and plant growth regulator (PGR) applications). Stalk strength (resisting force) and elasticity (spike displacement, energy, and power) measurements were taken at anthesis and physiological maturity from a small plot agronomic research trial. The Stalker was able to identify high and low lodging risk practices. Lower plant density led to increased stem strength (measured by resisting force) and stem flexibility (measured by spike displacement) compared to high plant densities, indicating a decreased risk of both stem and root lodging when low plant densities were used. Overall, the Stalker is a new tool for rapid and non-destructive measurements of lodging risk in small plot agronomic research trials and can indicate both stem and root lodging risk by measuring indicators of both stem strength and elasticity.

7.2 Introduction

A large portion of spring wheat (*Triticum aestivum* L.) research is focused on evaluating agronomic management practices to maximize yield and protein. Many of these agronomic management strategies will have an effect on lodging risk of the crop. Lodging, the shift of the crop from the vertical to horizontal position, occurs through two different mechanisms, both of which are known to occur in wheat. Stem lodging is a result of stem bending, or breakage, when the wind- and/or rain-induced leverage placed on an individual stem exceeds the stem strength, or ability to resist bending and breakage (Berry et al. 2004). Stem lodging of wheat most commonly occurs at the lower internodes. Root lodging occurs when the leverage placed on all stems of a plant exceed the anchorage strength, causing the plant to rotate at the base from the root cone (Berry et al. 2004). Anchorage strength is highly dependent on soil moisture and texture, as well as structural rooting area, all of which make its estimation very difficult in the absence of lodging.

Reducing plant density of a crop, delaying or splitting nitrogen (N) fertilization, and applying plant growth regulators (PGR) have been reported to significantly reduce lodging risk in spring wheat (Berry et al. 2000; Zhang et al. 2017a; Zheng et al. 2017; Wu et al. 2019; Mizuta et al. 2020). However, the influence of management practices on lodging in agronomic field trials cannot typically be assessed unless natural lodging occurs, and visual lodging ratings are possible. Due to the unpredictable nature of natural lodging and small plot sizes, the probability of differential lodging occurring across a research trial to allow for evaluation of treatment effects on lodging is low.

A number of studies have demonstrated that, in the absence of natural lodging, detailed plant morphological measurements can give a good estimate of the potential lodging risk of a crop. For example, stem diameter, stem wall width, height at center of gravity, and root plate spread are all major characteristics of stem and anchorage strength of a plant (Berry et al. 2003b, 2007, 2016). However, all of these are destructive measurements and are extremely time-consuming. As a result, they are unlikely to be adopted in agronomic research that is not focused solely on reducing lodging risk. A non-destructive method to rapidly measure lodging risk in cereals that can be completed across many plots and trial locations would be an extremely beneficial tool for the agronomic research community. An *in situ* push force meter, used non-

destructively, has been proposed for this purpose and has successfully determined lodging susceptibility in small plot cereal production trials (Berry et al. 2003; Heuschele et al. 2020; Wiersma et al. 2007). Berry et al. (2003a) was able to account for 60% and 50% of the stem and root lodging occurrence, respectively, in different cultivars of wheat using a push force meter. Berry et al. (2003a) used different experimental conditions to evaluate stem lodging risk versus root lodging risk. The force required to push stems away from the vertical position was measured when the soil was dry, and the root cone was held strongly in the soil, to estimate stem strength. Anchorage strength was estimated by pushing plant stems away from vertical after irrigation when soil strength had been reduced. The requirement of irrigation to estimate root lodging risk is a major downfall of this strategy as many agronomic field research programs do not have access to irrigation systems and irrigation may not be desirable to meet other project objectives in dryland production.

Wiersma et al. (2011) used a push force meter similar to the meter used by Berry et al. (2003a) to indicate stem strength of spring wheat that had been treated with various rates of the plant growth regulator trinexipac-ethyl (TXP). This work demonstrated the value of this device in evaluating agronomic management practices for lodging susceptibility. The measurement of a stem strength indicator alone evaluates only the susceptibility of the crop to stem lodging. Heuschele et al. (2020) demonstrated the ability of a similar push force meter, the Stalker, to capture both stem elasticity (spike displacement, energy and power) and stem strength (resisting force) in cereals by incorporating resisting force data readings from returning the crop to the vertical position after pushing it away from vertical, expanding the versatility of the push force meter. If increases in stem strength are not paired with increases in stem elasticity, or flexibility, root lodging risk may be increased. Stems may divert the leverage placed on the stems by wind and rain down the stem to the anchorage system, increasing whole plant leverage and ultimately root lodging risk. Therefore, by capturing both stem strength and elasticity indicators with a non-destructive rapid push force measurement, the influence of agronomic management practices on both stem and root lodging can be estimated.

The ability of the three elasticity measurements, spike displacement, energy, and power, to differentiate between lodging-susceptible and lodging-resistant wheat cultivars was investigated by Heuschele et al. (2020). Power exhibited by the stems when the crop was pushed

away from vertical to a 45-degree angle and returned upright was the most responsive elasticity measurement in wheat when determining differences between cultivars. In addition to work done by Heuschele et al. (2020) on responses across cultivars, there is value in understanding how elasticity indicators derived from this push force device are influenced by agronomic management practices known to influence lodging risk. Therefore, the objectives of this study were to (1) demonstrate the potential of the Stalker (Heuschele et al. 2019) to evaluate the influence of agronomic management practices such as plant density, N application timing, and PGR applications on both stem and root lodging, and (2) to identify which elasticity measurements derived from the Stalker (spike displacement, change in energy, change in power) have potential to differentiate between agronomic practices when measured at anthesis and maturity in wheat.

7.3 Materials and Methods

Field trials were established at four site-years in south central Manitoba, CA to evaluate the effect of agronomic management practices on lodging risk of spring wheat. Site descriptions and agronomic management of these trials can be found in detail in Chapter 5.3. In brief, the trial was designed as a split-plot experiment with four blocks at each testing environment. Plant density was the main plot factor, and three treatments were included to target low (150 plants m⁻²), medium (250 plants m⁻²) and high (350 plants m⁻²) plant densities. The sub plot factor was a compound treatment of a combination of N fertilizer application timing and PGR application. Two N fertilizer application treatments were included, one with all of the N fertilizer applied at planting (urea midrow banded) and the second with a split application of half of the total amount applied at planting (urea, midrow banded) and half applied at the flag leaf stage as SuperU™ (Koch Fertilizer) surface broadcast. The total amount of fertilizer N applied for both timing treatments was 156 kg N ha⁻¹, based on previous research evaluating N requirements for high-yielding spring wheat in Manitoba (Mangin and Flaten 2018). Both N treatments were tested in combination with and without the PGR chlormequat chloride (CCC), (Manipulator™620 (Belchim Canada)). The PGR was applied to the canopy at the onset of stem elongation (Zadok's GS 31) (Zadoks et al. 1974) at 1.8 L ha⁻¹ using a CO₂ backpack sprayer with 100 L ha⁻¹ water volume and AIXR TeeJet flat fan nozzles (AIXR110015). All treatments were measured using

the spring wheat cultivar AAC Brandon, a semi-dwarf, high-yielding, cultivar that is widely grown across western Canada (Cuthbert et al. 2016).

The Stalker, an *in situ* push force meter (Heuschele et al. 2019), was used to take measurements at anthesis and physiological maturity from two sampling areas within each plot (Figure 7.1). Measurements captured by the Stalker included the resisting force applied to the instrument by all stems in a crop row (1.2 m row length) as the crop was rotated away from vertical to 45-degrees (bending) and back to vertical (unbending) at half height of the crop (where force was applied). Additionally, the meter recorded the angle of the stems as force was applied, and the time point of each force measurement (one per millisecond). The push bar height on the Stalker was adjusted before each measurement to ensure that the crop was being rotated at half crop height and crop height was recorded (excluding awns). The resisting force, in Newtons (N), at 45-degrees was captured as an indicator of stem strength. Therefore, stem strength is defined as being proportional to the amount of force needed to push the stems to 45-degrees. Resisting force measurements during the entire bending and unbending process were used to calculate three indicators of stem elasticity. Indicators of elasticity that were calculated included spike displacement (m), energy applied and returned, or change in energy (J), and the power exhibited at bending (mW) of the stems. These three traits allow for the calculation of a stress strain curve of an unideal material (i.e., plant stems) which is equivalent to Youngs' Modulus, a common measurement of material elasticity (Niklas 1992). A detailed description of the calculations and physics behind these measurements and their ability to estimate elasticity in cereal crops can be found in Heuschele et al. (2020).

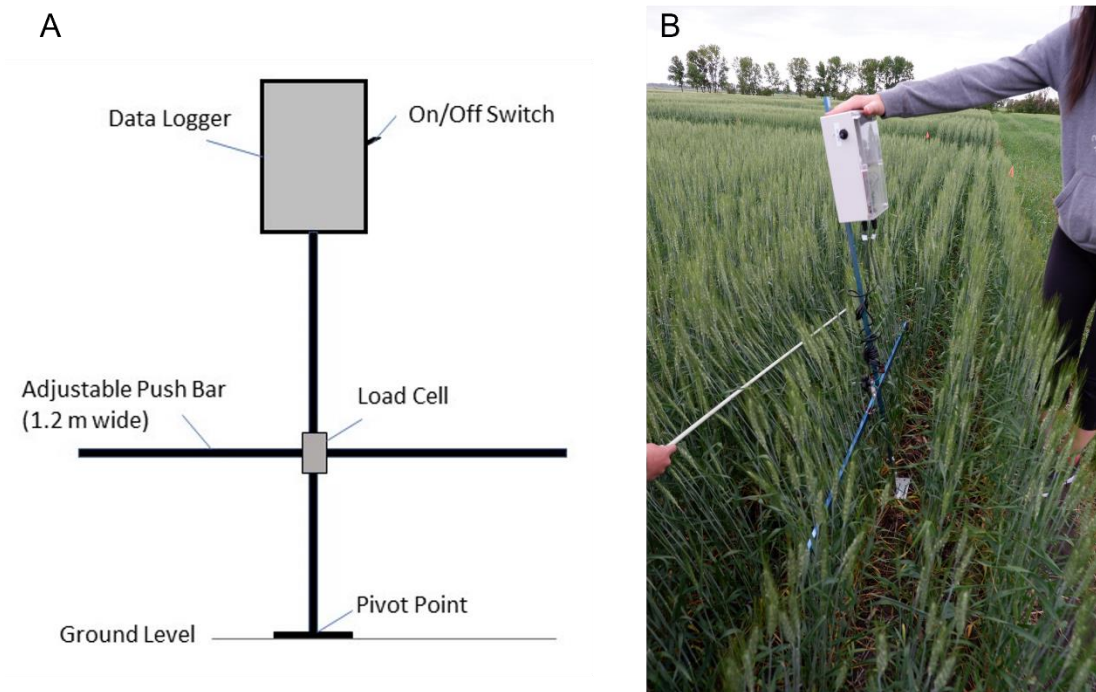


Figure 7.1. An illustration of the Stalker push force meter (A), with labeled data logger, load cell, adjustable push bar and pivot point and (B) the Stalker being used to capture resisting force measurements from a 1.2 m of row length in a wheat plot, while the adjacent row held out of the way to avoid interference.

Crop rows adjacent to the row being measured were held away from the meter with a rod to ensure there was no interference with the measurements as the crop row was rotated away from vertical (Figure 7.1). Two measurements were taken per plot in rows 2 and 7 of the eight-row plot, and the measurements for resisting force (N), spike displacement (m), energy (J) and power (mW) were averaged within each measurement timing and plot. Due to equipment constraints, measurements at anthesis were taken from only the two 2019 site-years, while measurements at maturity were taken from all four site-years.

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute, 2001) with plant density, N treatment, PGR, and their interactions as fixed factors. Random factors in the model included site-year, block nested within site-year, and the interaction of block with planting density to account for the split plot arrangement at each site-year. Significant main plot effects and interactions between model fixed effects (P -value<0.05) were determined using an analysis

of variance (ANOVA). Assumptions for ANOVA analysis were evaluated using PROC UNIVARIATE to test normality of the residuals, and the residuals were visually examined for homogeneity of variance. Significant differences between means were determined using Tukey's Honest Significant Difference with P -value=0.05.

7.4 Results and Discussion

Growing season precipitation was lower than normal during the 2018 and 2019 growing seasons (April 1 to September 1) with approximately 60 – 75 % of the 30-year long term average (Chapter 5, Figure 5.1). As a result, there was no natural lodging when measurements were taken. The absence of natural lodging was beneficial because it avoided the confounding influence of differential lodging among plots when the Stalker was used (Berry et al. 2003a; Heuschele et al. 2019).

The influence of plant density on lodging risk in spring wheat was revealed by resisting force measurements at anthesis and maturity, as well as spike displacement at maturity (Tables 7.1 and 7.2). The resisting force when the crop was pushed away from vertical was reduced in the high plant density treatments compared to the medium and low densities by 0.73 and 0.81 N, respectively, at anthesis and 1.82 and 0.88 N, respectively, at maturity (Tables 7.1 and 7.2). There was no significant difference in resisting force between the medium and low plant densities at anthesis, but at maturity the medium plant density resulted in significantly less resisting force than the low plant density treatments. This response was expected because as plant densities increase, lodging risk also increases due to reduced stem strength caused by increased competition and shading within the canopy (Sparkes and King 2008). In addition to reducing stalk strength, there was a reduction in stem elasticity, measured by spike displacement, for the high plant density treatment at maturity, compared to the low plant density treatment (Table 7.2). This result indicates that when low plant densities are established, stem strength (measured by resisting force) and elasticity (measured by spike displacement) are greater than at high plant densities. There was no significant influence of plant density on the elasticity measurements, energy, or power, in this experiment at anthesis or maturity (Table 7.1 and 7.2).

Table 7.1. Analysis of variance, least squares means and standard errors (SE) of stem strength (resisting force (N)) and elasticity (spike displacement (m), energy (J), and power (mW)) indicators calculated by push force meter at anthesis and crop height (m) for the main effects of plant density, nitrogen (N) application timing and the application of a plant growth regulator (PGR) chlormequat chloride (CCC). Measurements were taken from and averaged across 2 site-years on the spring wheat cultivar AAC Brandon.

Response Variable		Resisting Force		Spike Displacement		Anthesis				Power		Height					
						Energy											
		N		SE	m		SE	J		SE	mW		SE	m		SE	
Plant Density																	
	Low	3.10	a [†]	0.39	0.582		0.01	-55.0	a	5.7	2.49	b	0.17	0.79	a	0.01	
	Medium	3.18	a	0.39	0.581		0.01	-65.8	a	5.7	2.97	a	0.17	0.79	a	0.01	
	High	2.37	b	0.39	0.579		0.01	-55.9	a	5.8	2.24	b	0.17	0.78	a	0.01	
N Timing																	
	Spring N	2.66		0.37	0.583		0.01	-50.6	a	4.4	2.28	b	0.15	0.79	a	0.01	
	Spring + Flag Leaf N	3.11		0.37	0.578		0.01	-67.3	b	4.5	2.84	a	0.15	0.79	a	0.01	
PGR Application																	
	- CCC	2.68		0.37	0.594	a	0.01	-49.9	a	4.5	2.24	b	0.15	0.81	a	0.01	
	+ CCC	3.09		0.37	0.568	b	0.01	-67.9	b	4.4	2.89	a	0.15	0.76	b	0.01	
Analysis of Variance																	
Sources of Variation		df															
Plant Density (PD)		2		**		ns		ns		ns		ns		ns		ns	
Nitrogen Timing (NT)		1		ns		ns		**		*		ns		ns		ns	
PD*NT		2		ns		ns		ns		ns		ns		ns		ns	
Plant Growth Regulator (PGR)		1		ns		***		**		*		ns		***		***	
PD*PGR		2		ns		ns		ns		ns		ns		ns		ns	
NT*PGR		1		ns		ns		ns		ns		ns		ns		ns	
PD*NT*PGR		2		ns		ns		ns		ns		ns		ns		ns	

ns, Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

[†]Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level. The absence of letters indicates no significant differences.

Table 7.2. Analysis of variance, least squares means and standard error (SE) of stem strength (resisting force (N)) and elasticity (spike displacement (m), energy (J), and power (mW)) indicators calculated by push force meter and crop height (m) at physiological maturity for the main effects of plant density, nitrogen (N) application timing and the application of a plant growth regulator (PGR) chlormequat chloride (CCC). Measurements were taken and averaged across 4 site-years on the spring wheat cultivar AAC Brandon.

Response Variable		Resisting Force		Spike Displacement		Maturity		Power		Height				
						Energy								
<i>Plant Density</i>		N	SE	m	SE	J	SE	mW	SE	m	SE			
	Low	10.09	a [†]	2.09	0.561	a	0.02	-87.2	56.9	7.13	0.51	0.76	0.02	
	Medium	9.15	b	2.09	0.552	ab	0.02	-101.1	56.9	7.15	0.51	0.75	0.02	
	High	8.27	c	2.09	0.545	b	0.02	-73.0	56.9	6.32	0.51	0.74	0.02	
<i>N Timing</i>														
	Spring N	9.09		2.09	0.554		0.02	-84.0	56.7	7.05	0.48	0.75	0.01	
	Spring + Flag Leaf N	9.25		2.09	0.552		0.02	-90.2	56.7	6.69	0.48	0.74	0.01	
<i>PGR Application</i>														
	- CCC	8.84		2.09	0.565	a	0.02	-90.6	56.7	6.84	0.48	0.76	a	0.01
	+ CCC	9.50		2.09	0.541	b	0.02	-83.6	56.7	6.89	0.48	0.73	b	0.01
Analysis of Variance														
Sources of Variation		df												
Plant Density (PD)		2	***		*		ns		ns		ns			
Nitrogen Timing (NT)		1	ns		ns		ns		ns		ns			
PD*NT		2	ns		ns		ns		ns		ns			
Plant Growth Regulator (PGR)		1	ns		***		ns		ns		***			
PD*PGR		2	ns		ns		ns		ns		ns			
NT*PGR		1	ns		ns		ns		ns		ns			
PD*NT*PGR		2	ns		ns		ns		ns		ns			

Ns, Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

[†]Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level. The absence of letters indicates no significant differences.

Nitrogen application timing significantly influenced stem elasticity indicators measured at anthesis through changes to energy and power (Table 7.1). Change in energy of the stem when being bent and unbent decreased from -50.6 to -67.3 J when N was applied as a split application compared to entirely at planting (Table 7.1). This change indicates that less of the kinetic energy put into the stem when it was bending was returned to the stem during unbending. The mechanism driving this difference is unknown; however, the stem was either able to absorb greater amounts of energy, or the energy was transferred down the stem to the anchorage system with the split N application timing treatments. The effect of split N application on change in power at anthesis was opposite to the change in energy, with the split N application having a 0.56 mW increase in power compared to when N fertilizer was applied entirely at planting (Table 7.1). Heuschele et al. (2020) reported similar findings when lodging resistant cultivars had significantly greater change in power measured at maturity compared to lodging susceptible wheat cultivars. There were no significant effects of N application timing on resisting force or spike displacement, regardless of the measurement timing; however, there was a trend for increased resisting force with split N applications. These results indicate that split N applications may produce a stronger stem than when the N was applied entirely at planting, likely reducing stem lodging risk. However, the reduction of whole stem elasticity could potentially negatively impact root lodging risk.

Plant growth regulators are applied to reduce lodging risk by reducing stem height through decreased number and size of structural cells in the stem (Zhang et al. 2017). Therefore, it is not surprising that in this study PGR application influenced stem elasticity measurements. Analysis of variance results indicated that at anthesis PGR application had a significant influence on all three elasticity measurements (spike displacement, energy, and power), while the only significant effect at maturity was spike displacement (Tables 7.1 and 7.2). Spike displacement was decreased with the application of a PGR at both anthesis and maturity (Tables 7.1 and 7.2). Change in energy at anthesis was also reduced with the PGR application from -49.9 to -67.9 J, while change in power increased from 2.24 to 2.89 mW (Table 7.1). Stalk strength, as indicated by resisting force, wasn't significantly increased with a PGR application at a *P*-value of 0.05; however, at both anthesis and maturity, there was a trend for increased resisting force with PGR application (*P*-values 0.09 and 0.06, respectively). This suggests that stem strength is likely being increased with the applications of a PGR, but unlike when it is increased from reduced

plant densities, it is paired with a reduction in whole stem elasticity. The balance of how stem strength and elasticity influence the natural occurrence of lodging will be highly dependent on which lodging mechanisms are stressed in a given growing season by environmental conditions (Berry et al. 2004).

Indicators of stalk strength (resisting force), as well as the elasticity measurement (power), increased when measured at physiological maturity compared to anthesis. Heuschele et al. (2020) documented the same phenomenon, which occurs because as the plant matures, structural fiber components are deposited in the stem cell walls, increasing mechanical support as the spike fills (Jung et al. 1993; Niklas 1992). Displacement and change in energy were in a similar range for both anthesis and maturity measurement timings. The differences in lodging resistance of the same cultivar under different management treatments in this experiment were most easily identified when measured at anthesis, after the stem has just completed stem elongation. In contrast, when cultivars with different lodging susceptibilities were compared, push force measurements at maturity were most informative compared to at heading (Heuschele et al. 2020).

7.5 Conclusions

This study showed that measurements indicating stalk strength and elasticity derived from the Stalker have potential to measure lodging risk among agronomic management practices for spring wheat. These risks can be assessed without the occurrence of naturally or artificially induced lodging. Low plant density, split N fertilizer application and PGR applications are agronomic management practices that are commonly known to reduce risk of lodging in cereals. Indicators of stalk strength and whole stem elasticity measurements from the Stalker were able to differentiate between these agronomic practices and practices with a known high risk of lodging. Additionally, when these measurements were paired together, it was possible to differentiate between practices that mostly increased stem strength (PGR and split N fertilization) and those that increased both strength and whole stem elasticity (reduced plant densities). This differentiation between the effect of management on stem strength and stem elasticity will contribute to understanding of how agronomic practices influence both stem and root lodging.

Measurements taken at anthesis had an increased ability to differentiate between management practices with high and low lodging risk compared to measurements taken at maturity. Adding a measurement at the soft dough stage may be beneficial to explore, as that is when lodging is likely to result in the greatest yield and quality losses in the crop (Berry et al. 2004), and may strengthen the relationship between measurements and potential losses from lodging. This study had a small number of site-years, especially for the anthesis timing; therefore, more work would be warranted to determine the best relationship between measurement timing and lodging risk. Additionally, responses were examined using only one cultivar, AAC Brandon, which is a semi-dwarf cultivar with a very good rating for lodging resistance. It would be important to determine whether the differences in stem strength and flexibility in response to agronomic management observed in this study would translate to other spring wheat cultivars.

CHAPTER 8. GENERAL DISCUSSION AND CONCLUSIONS

8.1 Effective tools for managing lodging risk while maximizing yield and protein in spring wheat on the eastern Canadian Prairies

This research has provided a better understanding of how producers on the eastern Canadian Prairies can use agronomic management to reduce lodging risk of spring wheat while producing high-yielding crops with acceptable protein concentrations. To fully understand the effect of key management strategies on crop production, the response of individual yield components, nitrogen uptake and utilization, as well as detailed plant characteristics that influence that crop's ability to resist lodging were examined throughout this thesis. Environmental conditions during this research were not conducive for lodging; however, these conditions did allow for an equivalent evaluation of treatments to assess how individual, and combinations of, management strategies would perform in the absence of lodging. This is an important consideration, as lodging is highly unpredictable and management decisions are made proactively. Therefore, in order for producers to adopt management practices to reduce lodging risk, there cannot be a yield or protein penalty when lodging does not occur. The research in this thesis highlighted reduced plant densities, split N fertilizer applications, and plant growth regulator applications as management practices that have promise as lodging mitigation strategies that can either maintain or improve grain yield and protein.

Low (150 plants m^{-2}) or medium (250 plants m^{-2}) plant densities produced a crop with characteristics that would allow it to resist lodging compared to a crop with a high plant density (350 plant m^{-2}) (Chapters 5 and 6). Stem and anchorage strength consistently increase with increased stem diameter and structural root plate. As a result, lower plant densities were the only management strategy tested that reduced both stem and root lodging risk. Yield and protein levels were maintained across planting densities; however, there were circumstances where yield was lower with high plant densities due to extremely dry conditions during the tillering growth stage. There are a number of factors that may need to be considered before moving towards reduced plant densities for lodging management. Poor competitive ability with early emerging weeds in the early growing season may challenge weed management programs. This is especially a concern as the abundance of herbicide resistance weeds in Canada is increasing and there is a shift in focus towards cultural control methods for weed management. When low plant densities

are established, there are more tillers per plant, which increases the variability in growth stages among stems within a crop. This increased variability may make staging for crop input application challenging for producers and in some instances may reduce the efficacy of some inputs, such as PGRs (Chapter 6) and fungicides.

By splitting the application of N fertilizer and applying a portion at seeding, to satisfy early crop demand, and the remainder at flag leaf timing, we were able to produce a high-yielding crop, with higher grain protein and stem strength compared to when N was applied entirely at planting. Increases in stem strength were not as dramatic as with reduced plant density, but split N was the most promising N management strategy tested in this project (Chapter 3 and 6). The amount of N applied at planting, when paired with soil residual N, was sufficient to meet early season crop N demand for development of yield components, while limiting excess N that would either be lost to the environment or taken up by the plant to produce excessive vegetative growth. Previous research has shown that excessive vegetative growth can increase intraspecific competition for resources and result in weak stems that are more prone to lodge. The in-season application of N at the flag leaf growth stage increased the availability of N to the crop during the post-anthesis growth stages, which allowed the crop to take up additional N later in the season and increased grain protein content. Additionally, this strategy has the added benefit of allowing for adjustments to the total amount of N applied to a field based on the early season establishment and environmental conditions, making it easier to match crop demand and supply compared to applying all N fertilizer at, or before, planting. In-season precipitation events are unreliable in dryland production, particularly across western Canada; therefore there has been, and will continue to be, hesitation around in-season N fertilizer applications in spring wheat. This study verified the importance of precipitation events to allow the crop to utilize in-season applied N fertilizer for yield and protein (Chapter 3 and 4). Additionally, this strategy may not be readily adopted as it will require an additional pass across a field, increasing production costs, in a busy time of the growing season when farm equipment and labour is often occupied by disease management programs.

Due to the limitations of reduced plant densities and split N applications described above, it is increasingly important for farmers across western Canada to have a tool to reduce lodging risk, even if large amounts of N fertilizer are applied early in the season with high plant

densities. The application of the PGR, CCC, increased the crop's ability to resist lodging, while increasing grain yield. Stem strength was increased through reductions in the lower internode length and overall canopy height. When the canopy was shortened, grain yield increased through a higher number of kernels per spike, likely due to resource reallocation from stem elongation to the developing spike (Chapter 3). In some instances, the increase in grain yield with a PGR application led to a reduction in final grain protein content; however, the total grain N yield was similar with and without a PGR application, and total N uptake was constant (Chapter 4). The major benefit to using a PGR as a lodging management strategy is that crop establishment and early season environmental conditions are known before the decision to apply needs to be made. This gives the opportunity to evaluate the lodging risk of individual fields prior to committing to a PGR application. The timing of PGR application typically falls in between herbicide and fungicide applications timings. Therefore, there is limited ability to combine the application of a PGR in a tank mix with other products, resulting in an additional pass across a field. An additional limitation of this strategy is that level of response appears to be cultivar specific, and it is unlikely that as new cultivars are registered they will be screened for their response to PGRs. Therefore, caution should be taken with new cultivars until a pattern of response is established.

The two lodging management strategies evaluated in the study that did not successfully improve lodging resistance, or result in reductions in yield and protein, were reduced N fertilizer rates and a high rate of N fertilizer as a blend of conventional urea and ESN. Applying a reduced rate of N was a very effective strategy to reduce lodging; however, this strategy was consistently accompanied with reduced grain protein content and grain N yield, making it an unacceptable strategy that would not be adopted on farm. It was anticipated that when high rates of N were applied as an ESN blend, the controlled release fertilizer would allow for a single early season N fertilizer application and provide benefits similar to a split application, without the additional in-season application. However, in the dry environmental conditions experienced in this experiment, the ESN blend did not provide any advantage over applying N fertilizer entirely as conventional urea at planting, for lodging resistance, grain yield or protein content (Chapter 3, 4 and 6). With this lack of benefit and the increased cost associated with purchasing ESN compared to conventional urea, these studies would not support the adoption of ESN blends for spring wheat production in western Canada as a lodging management tool.

Grain yield will continue to be the producers first priority for spring wheat production, followed by maintaining acceptable grain protein content. This thesis looked extensively at how management influences individual yield components and how these relationships influenced final grain yield. It was clear that early season supply of nitrogen, before anthesis, was important for yield development. There was a highly predictable increase in grain yield when the management treatments evaluated in this study resulted in increased number of spikes per plant compared to all other yield components. Additionally, there was typically a negative relationship between kernel weight and grain yield. However, when high rates of N were applied to the crop early in the season, this negative relationship was overcome (Chapter 3).

Once grain yield potential is established, producers will begin to evaluate if they have sufficient N available to the crop to maintain high grain protein concentrations. Nitrogen is typically rapidly taken up from the tillering to heading growth stages, stored in vegetative tissue, and then remobilized to the grain during the grain fill period. This thesis demonstrated that the amount of N remobilized to the grain is directly proportional to the amount of N the crop takes up in the pre-anthesis growth stages, once again emphasizing the importance of early season resource availability. Additionally, this thesis identified that wheat can take up N during the post-anthesis growth stage and will prioritize this late season N to the grain for protein development. In the eastern Canadian Prairies, a large percentage of total N uptake can occur in the post-anthesis growth stages (21-36%), even in seasons with below normal precipitation (Chapter 4). As a result, wheat grown in this region may be less reliant on early season N accumulation and remobilization for grain protein production compared to drier growing regions with minimal late season N uptake in the western Canadian Prairies.

This thesis evaluated overall N use efficiency for grain N production in the eastern Canadian Prairies. When high rates of N fertilizer were applied, only 60% of the fertilizer and soil residual N available to the crop (excluding mineralized N) were used for grain N production. Nitrogen uptake efficiency was 80%, with 20% not being taken up from the soil, and N utilization efficiency of that portion being 80% for grain N production, leaving 20% in vegetative tissue at maturity (Chapter 4). This thesis determined that there was very little opportunity to increase grain protein by manipulating N remobilization from the vegetative tissue with changes in management. In fact, the crop seemed to adjust the amount of N remobilization

from stem tissue to compensate for late season N uptake. As a risk management strategy, our work recommends that management practices that promote early season N uptake be used to buffer dry conditions that may limit late season N uptake. This would allow the crop to provide adequate N to the grain for protein production through remobilization in conditions where late season N uptake is limited. This would be especially true in areas of the western Canadian Prairies that have much lower long-term average growing season precipitation compared to the areas tested in this study where late season N uptake was maintained, even with below normal precipitation.

Despite the agronomic, economic and environmental risks associated with large amounts of N applied early in the growing season, it remains a strong option for producers that want to continue producing high yields and protein contents. However, early N applications will promote dense canopies that are prone to lodging and will need to be balanced by managing lodging risk. As yields continue to rise the application of PGRs will become a more critical tool for managing lodging of spring wheat in the eastern Canadian Prairies. The ability to evaluate lodging risk during the growing season before management action needs to be taken is extremely valuable, as lodging occurrence in the eastern Canadian Prairies is highly variable across fields and growing seasons. Additionally, the ability of PGR applications to increase grain yield through kernels per spike that was uncovered in the work of this thesis, may cover the added input cost of this input.

8.2 Future Research

There remains a number of unknowns after this work that if investigated would increase our ability to provide producers across the eastern Canadian Prairies with management recommendations for spring wheat. A large portion of the research in this thesis is focused on management strategies to mitigate stem and root lodging of spring wheat across the Canadian Prairies. However, there is currently very little research quantifying the amount, or type, of lodging and how that relates to total yield loss. Due to the unpredictable nature of lodging risk and its dependence on environmental conditions, this information would be most valuable if quantified over long-term studies and could be related to specific conditions. This would allow for targeted approaches to lodging management on the prairies.

Overall lodging was very low during this study due to dry environmental conditions, making it difficult to measure the ability of agronomic management practices to reduce lodging under conditions that are more conducive to lodging. It would be valuable to evaluate strategies that have shown promise in this project under conditions of high lodging pressure in the field. This would allow for a better understanding of the level of control these strategies could provide and potential economic benefit. Low levels of lodging did not allow for proper evaluation of the relationships between lodging occurrence and the lodging risk measures used in this study, including, stem strength and elasticity indicators, plant morphological characteristics and stem structural composition (Chapter 6 and 7). Little is known about these relationships in Canadian spring wheat and evaluation could help direct future research focused on reducing lodging risk.

The completion of this thesis has raised a number of questions related to the efficacy of PGRs, in particular CCC. The ability of the crop to take up N from the soil was increased with the application of a PGR, at a limited number of site-years. This may be due to the influence of a PGR on the rooting structure of the plant when stem elongation is inhibited. There is very little research on the influence of PGR applications on rooting structure of mature plants. This is likely due to the challenges associated with measuring rooting structure in a field setting. However, a better understanding of the potential of a PGR application to influence N capture from the soil could aid in further exploitation of this beneficial effect, potentially leading to increases in grain yield and protein content. A second question is around their interactions with plant density for N and dry matter accumulation and N remobilization identified in Chapter 6. When low plant densities were established and there was a large number of tillers per plant, the application of a PGR increased leaf dry matter, leaf N accumulation and leaf N remobilization. This effect was consistent across two environments, but the driving factor for this effect is currently unknown, and if determined, would help better understand when PGR's can be used to maximize grain yield and protein.

Patterns of N accumulation and remobilization to grain N appeared to be cultivar specific (Chapter 4). This indicates that there is genetic variation that may be able to be exploited in breeding efforts to produce cultivars that are better able to produce grain N for particular growing conditions or regions.

Lastly, the canopy management strategies presented in Chapter 5 as methods to reduce lodging risk should be evaluated in higher yielding environments. In this study we did not see any yield or protein disadvantage from these strategies, but yield was also likely limited due to dry conditions. It would be valuable to determine the influence of reductions in early season vegetative growth to yield and protein in high-yielding environmental conditions to better understand the longevity of these strategies if spring wheat yields continue to increase in the coming decades.

CHAPTER 9. REFERENCE MATERIAL

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9.2 Appendices

9.2.1. Appendix A. Chapter 3

Table A1. Pearson correlation analyses (r values) of individual plot data for grain yield, plant density, spike density, spikes per plant, kernels per spike, kernel weight, days to anthesis (DTA), grain fill duration (GFD), days to maturity (DTM), accumulated precipitation (PPT) (Apr 1 to Sept 1) and accumulated growing degree days (GDD) from seeding to maturity for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

		Grain Yield	Plant Density	Spikes per Plant	Kernels per Spike	Kernel Weight	DTA	GFD	DTM	PPT	GDD
	<i>n</i>										
Grain Yield	120	1.00									
Plant Density	90	0.10	1.00								
Spikes per Plant	120	0.38**	-0.78***	1.00							
Kernels per Spike	90	0.69***	0.30**	-0.08	1.00						
Kernel Weight	120	-0.22**	-0.51***	0.30**	-0.60***	1.00					
DTA	120	-0.37***	-0.13	0.04	-0.26**	0.07	1.00				
GFD	120	0.70***	0.02	0.49***	0.47***	-0.14	-0.03	1.00			
DTM	120	-0.08	0.01	-0.06	0.10	-0.03	0.56***	0.21*	1.00		
PPT	120	0.12	-0.29**	0.34**	0.19*	0.01	-0.31***	0.40***	0.09	1.00	
GDD	120	0.69***	0.12	0.06	0.81***	-0.31***	-0.57***	0.45***	-0.05	0.48***	1.00

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

Table A2. Combined analysis of variance for the main effects of environment (E), cultivar (C), nitrogen (N) management, plant growth regulator (PGR), and their interactions for spike density, kernel number, days to anthesis, grain fill duration, and days to maturity for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

Sources of Variation	df	Response Variable				
		Spike Density	Kernel Number	Days to Anthesis	Grain Fill Duration	Days to Maturity
Site-year (SY)	3	0.0146	<.0001	<.0001	<.0001	<.0001
Cultivar (C)	2	<.0001	<.0001	<.0001	<.0001	<.0001
SY x C	6	0.0069	0.0052	<.0001	0.0256	0.0002
Nitrogen (N)	4	<.0001	<.0001	<.0001	<.0001	<.0001
SY x N	12	0.0035	0.0649	0.0327	0.0007	0.0017
C x N	8	0.8279	0.3394	0.9353	0.074	0.4019
SY x C x N	24	0.1282	0.2989	0.8068	0.142	0.4738
Plant Growth Regulator (PGR)	1	0.0767	<.0001	<.0001	<.0001	<.0001
SY x PGR	3	0.3428	0.0309	0.0007	<.0001	<.0001
C x PGR	2	0.198	0.939	0.2085	0.8307	0.817
SY x C x PGR	6	0.5548	0.8198	0.4469	0.2211	0.0457
N x PGR	4	0.6253	0.6771	0.7837	0.2608	0.3854
SY x N x PGR	12	0.5534	0.4495	0.5433	0.0749	0.1896
C x N x PGR	8	0.3773	0.5824	0.3579	0.8838	0.9511
SY x C x N x PGR	24	0.675	0.7808	0.52	0.8557	0.8206

Table A3. Least squares means for spike density and kernel number for the main effects of site-year, cultivar, nitrogen (N) management and plant growth regulator application for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

Main Effects	Spike Density	Kernel Number	Days to Anthesis	Grain Fill Duration	Days to Maturity
	m ⁻²	m ⁻²	days	days	days
<i>Site-year</i>					
Carman18	452 a [†]	16166 a	44.0 d	30.6 b	74.6 c
Carman19	416 ab	11485 c	48.7 a	29.8 c	77.6 b
Manitou18	407 b	14361 b	47.3 b	32.3 a	79.6 a
Manitou19	445 ab	12451 c	44.8 c	30.3 b	75.1 c
<i>Cultivar</i>					
AAC Brandon	436 a	14362 a	45.9 b	31.6 a	77.2 a
AAC Cameron	410 b	12767 c	46.1 b	29.3 b	75.5 b
Prosper	445 ab	13717 b	46.5 a	31.1 a	77.6 a
<i>N Management[‡]</i>					
Check	369 b	11370 c	45.7 b	28.4 c	74.2 a
Reduced Rate	437 a	13645 b	46.2 a	29.7 b	75.9 b
Standard	452 a	14416 a	46.4 a	31.4 a	77.9 a
ESN Blend	444 a	14410 a	46.5 a	31.2 a	77.7 a
Split App.	448 a	14237 ab	46.2 a	31.8 a	78.1 a
<i>PGR</i>					
Untreated	427.4	13335 b	46.1 b	30.4 a	76.4 b
Treated	433.0	13896 a	46.3 a	30.7 a	77.0 a

[†]Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

[‡]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

Table A4. Least squares means for the interactions of cultivar, nitrogen (N) management and plant growth regulator (PGR) with site-year for the response variables days to anthesis (DTA), grain fill durations (GFD) and days to maturity (DTM) for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

Main Effects	Site-year											
	Carman 18	Carman 19	Manitou 18	Manitou 19	Carman 18	Carman 19	Manitou 18	Manitou 19	Carman 18	Carman 19	Manitou 18	Manitou 19
	Days to Anthesis				Grain Fill Duration				Days to Maturity			
	days				days				days			
<i>Cultivar</i>												
AAC Brandon	43.9 b [‡]	48.2 b	47.5	44.0 c	32.1 a	29.5 a	32.4 ab	31.1 a	75.9 a	77.8 a	79.9	75.1 b
AAC Cameron	43.8 b	48.7 ab	47.5	44.7 b	29.3 c	28.0 b	31.1 b	28.6 b	73.1 c	76.8 b	78.7	73.3 c
Prosper	44.3 a	49.0 a	46.9	45.6 a	30.5 b	29.3 a	33.2 a	31.2 a	74.8 b	78.3 a	80.2	76.8 a
<i>N Management</i> [§]												
Check	43.5 b	48.2	47.3	43.7 b	28.8 b	27.6 b	29.7 d	27.4 b	72.3 b	75.8 b	77.1 b	71.1 b
Reduced Rate	44.1 ab	48.6	47.5	44.7 ab	29.4 b	28.7 ab	32.1 c	28.8 c	73.5 a	77.3 ab	79.6 a	73.4 b
Standard	44.2 a	48.9	47.1	45.0 a	31.6 a	29.1 ab	33.6 ab	31.7 ab	75.8 a	78.1 a	80.8 a	76.8 a
ESN Blend	44.1 a	48.8	47.3	45.5 a	31.8 a	29.3 a	31.9 bc	31.7 bc	75.9 a	78.2 a	79.2 ab	77.2 a
Split App.	43.9 ab	48.7	47.2	45.0 a	31.5 a	29.8 a	34.0 a	31.9 a	75.5 a	78.7 a	81.3 a	76.9 a
<i>PGR</i>												
Untreated	43.8 b	48.6	47.1 b	44.7	30.1 b	28.9	31.9 b	30.4	74.0 b	77.7	79.0 b	75.1
Treated	44.1 a	48.6	47.6 a	44.8	31.1 a	28.9	32.6 a	30.2	75.2 a	77.6	80.2 a	75.1

[‡] Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

[§] Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

Table A5. Pearson correlation analyses (r values) of individual plot data for grain yield, plant density, spike density, spikes per plant, kernel number per hectare, kernel weight, days to anthesis (DTA), grain fill duration (GFD), days to maturity (DTM), accumulated precipitation (PPT) (Apr 1 to Sept 1) and accumulated growing degree days (GDD) from seeding to maturity for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

		Grain Yield	Plant Density	Spikes per Plant	Kernels per Spike	Kernel Weight	DTA	GFD	DTM	PPT	GDD
	<i>n</i>										
Grain Yield	120	1.00									
Plant Density	90	0.10	1.00								
Spikes per Plant	120	0.38**	-0.78***	1.00							
Kernels per Spike	90	0.69***	0.30**	-0.08	1.00						
Kernel Weight	120	-0.22**	-0.51***	0.30**	-0.60***	1.00					
DTA	120	-0.37***	-0.13	0.04	-0.26**	0.07	1.00				
GFD	120	0.70***	0.02	0.49***	0.47***	-0.14	-0.03	1.00			
DTM	120	-0.08	0.01	-0.06	0.10	-0.03	0.56***	0.21*	1.00		
PPT	120	0.12	-0.29**	0.34**	0.19*	0.01	-0.31***	0.40***	0.09	1.00	
GDD	120	0.69***	0.12	0.06	0.81***	-0.31***	-0.57***	0.45***	-0.05	0.48***	1.00

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

9.2.2. Appendix B. Chapter 4

Table B1. Least squares means for days to anthesis (DTA), grain fill duration (GFD), and days to maturity (DTM) for the main effects of site-year, cultivar, nitrogen (N) management, and plant growth regulator (PGR) application. Anthesis being when 50% of spikes reached anthesis, and maturity when 50% of the peduncles had lost green coloration for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

Main Effects	DTA <i>days</i>	GFD [†] <i>days</i>	DTM <i>days</i>
<i>Site-year</i>			
Carman18	44.0 d [‡]	30.6 b	74.6 c
Carman19	48.7 a	29.0 c	77.6 b
Manitou18	47.3 b	32.3 a	79.6 a
Manitou19	44.8 c	30.3 b	75.1 c
<i>Cultivar</i>			
AAC Brandon	45.9 b	31.3 a	77.2 a
AAC Cameron	46.2 b	29.3 b	75.5 b
Prosper	46.5 a	31.1 a	77.6 a
<i>Nitrogen Management[§]</i>			
Check	45.7 b	28.4 c	74.1 c
Reduced Rate	46.2 a	29.8 b	76.0 b
Standard	46.4 a	31.5 a	77.9 a
ESN Blend	46.5 a	31.2 a	77.7 a
Split App.	46.3 a	31.8 a	78.1 a
<i>PGR</i>			
Untreated	46.1 b	30.4 b	76.4 b
Treated	46.3 a	30.7 a	77.0 a

[†] Grain fill duration was calculated by subtracting days to anthesis from days to maturity

[‡] Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

[§]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESN[™]) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU[™].

Table B2. Main effects of environment, cultivar, N fertilization, and plant growth regulator (PGR) on wheat leaf, stem, and spike dry matter yields and N concentrations at anthesis and maturity for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

Main Effects	Leaf				Stem				Spike			
	Anthesis		Maturity		Anthesis		Maturity		Anthesis		Maturity	
	Dry Matter	N Conc.	Dry Matter	N Conc.	Dry Matter	N Conc.	Dry Matter	N Conc.	Dry Matter	N Conc.	Dry Matter	N Conc.
	g m ⁻²	%	g m ⁻²	%	g m ⁻²	%	g m ⁻²	%	g m ⁻²	%	g m ⁻²	%
<i>Environment</i>												
Carman18	129.0 a [†]	4.61 a	88.4 ab	1.08 a	228.1 b	2.15 a	296.6 a	0.49 ab	120.1 a	2.60 a	784.6 a	2.50 a
Carman19	98.7 b	3.46 d	72.8 c	0.98 b	237.0 b	1.67 c	232.4 b	0.49 ab	119.8 a	2.37 b	595.3 c	2.24 b
Manitou18	128.7 a	4.23 b	96.3 a	1.07 a	230.8 b	2.05 b	281.5 a	0.54 a	119.1 a	2.41 b	709.2 b	2.48 a
Manitou19	123.5 a	3.66 c	82.8 b	0.98 b	257.0 a	1.66 c	270.6 a	0.42 b	163.5 a	2.24 c	650.7 bc	2.15 b
<i>Cultivar</i>												
AAC Brandon	119.3 a	3.95 b	86.7 a	1.04 a	202.4 c	1.94 a	232.7 c	0.50 a	127.7 a	2.53 a	682.8 b	2.41 a
AAC Cameron	119.9 a	3.83 c	85.6 a	0.98 b	275.7 a	1.81 b	314.5 a	0.46 b	127.7 a	2.35 b	645.5 c	2.38 a
Prosper	120.7 a	4.19 a	82.9 a	1.07 a	236.6 b	1.89 a	263.7 b	0.49 a	136.5 a	2.34 b	726.5 a	2.23 b
<i>Nitrogen[‡]</i>												
Check	88.9 b	3.27 c	65.1 b	0.79 d	207.1 b	1.42 c	229.9 b	0.36 d	110.2 b	2.19 c	590.7 b	1.98 d
Reduced Rate	123.0 a	3.88 b	87.5 a	0.97 c	247.4 a	1.77 b	277.1 a	0.44 c	134.1 a	2.38 b	697.5 a	2.25 c
Standard	129.7 a	4.28 a	90.8 a	1.12 ab	245.5 a	2.11 a	278.1 a	0.52 b	135.5 a	2.49 a	709.1 a	2.46 b
ESN [™] Blend	130.1 a	4.23 a	91.5 a	1.10 b	247.1 a	2.04 a	281.8 a	0.53 ab	137.0 a	2.47 a	716.2 a	2.46 b
Spilt App.	128.1 a	4.29 a	90.4 a	1.16 a	244.1 a	2.08 a	284.7 a	0.56 a	136.3 a	2.50 a	711.3 a	2.57 a
<i>PGR</i>												
Untreated	121.2 a	3.99 a	85.5 a	1.03 a	245.5 a	1.86 b	281.6 a	0.47 b	131.5 a	2.39 b	683.7 a	2.35 a
Treated	118.7 a	3.99 a	84.6 a	1.03 a	230.9 b	1.90 a	259.0 b	0.49 a	129.8 a	2.42 a	686.2 a	2.33 a

[†]Within columns and main effects, means followed by the same letter are not significantly different at the 0.05 probability level.

[‡]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of Environmentally Smart Nitrogen (ESNTM) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

Table B3. Nitrogen budget to estimate soil N mineralization at each environment using 0 -120 cm soil residual NO₃-N levels. Soil mineralization was calculated by: N uptake in 0 N Check + (Fall soil NO₃-N - Spring soil NO₃-N).

	Carman		Manitou	
	2018	2019	2018	2019
	kg ha ⁻¹			
Planting Soil residual NO ₃ -N				
0-60 cm	43	78	67	63
60-120 cm	28	30	36	28
Total	71	108	103	91
Fall Residual NO ₃ -N				
0 - 60 cm	8	27	11	44
60 - 120 cm	8	4	15	3
Total	16	37	64	61
Soil N Depletion (Fall - Spring)	-55	-77	-77	-44
Crop N Uptake (0 N Check)	169	114	141	105
Estimated Soil N Mineralization	114	37	64	61

9.2.3. Appendix C. Chapter 5

Table C1. Least squares means for grain yield, protein, and grain N yield for the main effects of plant density, nitrogen (N) application timing, and plant growth regulator (PGR) application of chlormequat chloride (CCC) as well as their interactions with site-year.

		Grain Yield				Grain Protein Concentration					Grain N Yield				Mea n	
		Car18	Car19	Man18	Man19	Mean	Car18	Car19	Man18	Man19	Mean	Car18	Car19	Man18		Man19
		kg ha ⁻¹					%					kg N ha ⁻¹				
<i>Plant Density</i>																
Low	5726 b [†]	4739	5318	4649	5108	14.1	14.3	14.2	14.4	14.3	141	119	133	117	128	
Med	5654 b	4467	5392	4760	5068	14.4	14.5	13.9	14.1	14.2	143	114	131	118	126	
High	6083 a	4572	5372	4504	5133	14.0	14.4	14.0	14.0	14.1	150	116	131	110	127	
<i>Nitrogen Timing[‡]</i>																
Planting	5767	4598	5432	4686	5121	14.0	14.2	13.7	13.9	13.9 b	141	114	130	114	125 b	
Split	5875	4587	5289	4590	5085	14.4	14.7	14.4	14.4	14.5 a	148	118	133	116	139 a	
<i>PGR</i>																
Untreated	5796	4431	5298	4569	5024 b	14.3	14.5	14.1	14.1	14.2	145	112	131	113	125 b	
CCC	5846	4754	5423	4707	5182 a	14.1	14.4	13.9	14.1	14.2	144	120	132	117	128 a	

[†] Within columns, and main effects, means followed by the same letter are not significantly different at the 0.05 probability level; absence of letters indicates no significant differences within columns

[‡] Planting = 156 kg N ha⁻¹ applied at seeding as urea; Split = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperUTM.

Table C2. Least squares means for the site-year by low (target 150 plants m⁻²), medium (target 250 plants m⁻²), and high (target 350 plants m⁻²) plant density interaction for spike density for trials conducted in 2018 and 2019 in Carman and Manitou, MB.

Spike Density	Site-year			
	Car18	Car19	Man18	Man19
	spikes m ⁻²			
Low	466 b [†]	459	409	457
Medium	485 ab	444	409	443
High	522 a	439	406	423
ANOVA <i>p</i> -value (SY*PD)			0.0133	

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level; absence of letters indicates no significant differences within columns

Table C3. Least squares means for the interaction of low (target 150 plants m⁻²), medium (target 250 plants m⁻²), and high (target 350 plants m⁻²) plant density and the plant growth regulator (PGR) application of chlormequat chloride (CCC) on total above-ground dry matter (DM) at anthesis for trials conducted in 2018 and 2019 in Carman and Manitou, MB.

PGR Application	Total DM at Anthesis			
	Plant Density			
	Low	Med	High	
	kg ha ⁻¹			
Untreated	4780	4980 a [†]	4880	
CCC	4930	4630 b	4620	

[†]Within columns, and main effects, means followed by the same letter are not significantly different at the 0.05 probability level; absence of letters indicates no significant differences within columns

Table C4. Pearson correlation matrix (*r* values) for individual plot data for yield, protein, grain nitrogen (N) yield, vegetative dry matter (stem + leaf tissue) at anthesis (Veg DM AN), leaf area index (LAI), canopy height, N uptake at anthesis, N remobilization (NRm), post-anthesis (PA) N uptake, visual lodging ratings, stem strength measured at anthesis (AN) and maturity (MT), as well as days to anthesis (DTA) and grain fill duration (GFD) for trials conducted in 2018 and 2019 in Carman and Manitou, MB.

	<i>n</i>	Yield	Protein	Grain N	Veg	LAI	Heights	N	NRm	PA	Lodging	Strength	Strength	DTA	GFD
			n	Yield	DM			Uptake		Uptake	Rating	AN	MT		
					AN			AN							
Yield	191	1													
Protein	191	-0.03***	1												
Grain N	191	0.94***	0.06	1											
Veg DM															
AN	191	0.05	0.05	0.06	1										
LAI	96	0.06	-0.23*	-0.06	0.01	1									
Heights	192	-0.00	-0.07	-0.02	0.31***	-0.06	1								
N Uptake															
AN	191	0.43***	-0.03	0.43***	0.82***	-0.01	0.14*	1							
NRm	192	0.42***	-0.01	0.43***	0.75***	-0.14	0.12	0.92***	1						
PA					-				-						
Uptake	189	0.38***	-0.03	0.39***	0.41***	0.14	-0.21*	-0.19*	0.27***	1					
				-											
Lodging	192	-0.22**	-0.15*	0.27***	0.08	0.17	0.04	-0.06	-0.15*	-0.19**	1				
Strength															
AN	96	0.25**	-0.03	0.23*	-0.20	-0.00	0.16	-0.07	-0.06	0.21*	-0.19	1			
Strength															
MT	191	0.65***	-0.09	0.64**	-0.04	0.05	-0.21**	0.31***	0.34***	0.41***	-0.23**	0.14	1		
				-											
DTA	192	-0.27***	0.08	0.26***	0.16*	-0.25*	0.33***	0.10	0.10	-0.23**	-0.29***	0.32**	-0.14	1	
GFD	192	0.54***	-0.12	0.52***	0.15*	0.05	0.11	0.45***	0.39***	0.32***	-0.19*	0.01	0.52***	0.05	1

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.0001 probability level

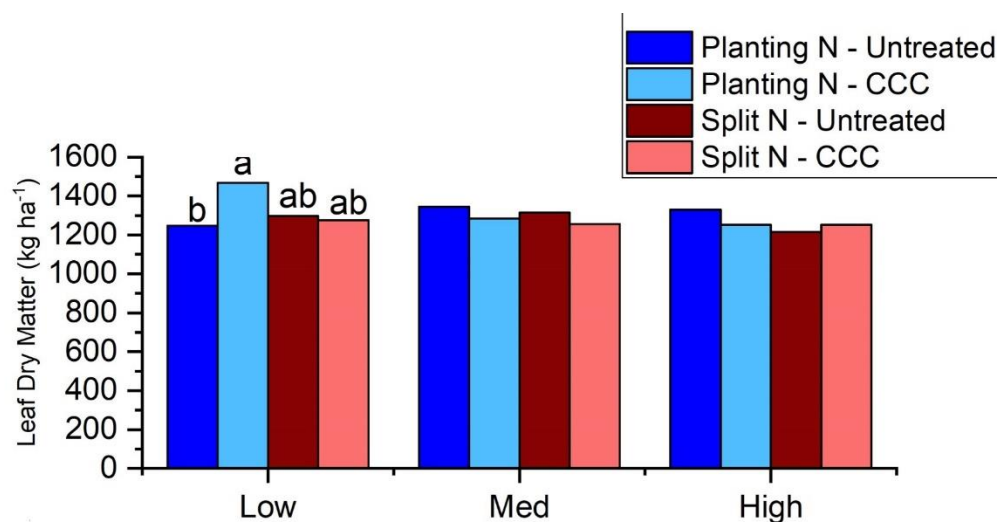


Figure C1. Interaction of low (target 150 plants m⁻²), medium (target 250 plants m⁻²) and high (target 350 plants m⁻²) plant densities with the plant growth regulator (PGR) application of chlormequat chloride (CCC) and nitrogen (N) fertilizer application timing for leaf tissue dry matter (DM) at anthesis for trials conducted in 2018 and 2019 in Carman and Manitou, MB. Bars with similar letters within each plant density treatment indicate no significant difference at the 0.05 probability level.

9.2.4. Appendix D. Chapter 6

Table D1. The interaction of nitrogen (N) management with the plant growth regulator (PGR) application for chlormequat chloride (CCC) (- absence, + presences) for internode length in sub-experiment 1B for trials conducted in 2018 and 2019 in Carman and Manitou, MB.

<i>PGR</i>				
	- CCC [†]		+ CCC	
	Internode Length			
	cm			
<i>N Management</i> [‡]				
Check	9.29	a [§]	7.96	b
Reduced Rate	9.86	a	8.84	b
Standard Rate	9.43	a	8.98	b
ESN Blend	9.53	a	8.86	b
Split N	9.92	a	8.71	b

[†] CCC, Chlormequat chloride applied at the beginning of stem elongation (Zadoks Growth stage 31)

[‡]Check = 0 additional N fertilizer applied; reduced rate = 78 kg N ha⁻¹ applied at seeding as urea; Standard = 156 kg N ha⁻¹ applied at seeding as urea; ESN Blend = 112 kg N ha⁻¹ of environmentally Smart Nitrogen (ESN) blended with 44 kg N ha⁻¹ urea applied at seeding; Split App = 78 kg N ha⁻¹ applied at seeding as urea and 78 kg N ha⁻¹ applied at flag leaf as SuperU

[§]Within rows means followed by the same letter are not significantly different at the 0.05 probability level.

Table D2. Correlation Matrix (*r* values) of plant stem strength variables for sub-experiment 1A that investigates the influence of spring wheat cultivar and its interactions with plant growth regulator application for trials conducted in 2018 and 2019 at Carman and Manitou, MB. Correlation analysis was done using all individual plot data

	<i>n</i>	Main Stem Height	Dry Matter	Spikes plant ⁻¹	Internode length	Stem Diameter	Stem Strength	Stem Flexibility	Lignin	Cellulose	Hemicellulose
Main Stem Height	96	1	0.17	-0.03	0.73	0.51	-0.28	0.63	0.41	0.25	-0.09
Dry Matter	96		1	0.28	-0.04	0.30	0.19	0.01	-0.01	0.06	-0.22
Spikes plant ⁻¹	96			1	-0.11	0.31	0.48	0.02	0.03	0.30	0.17
Internode length	96				1	0.57	-0.55	0.64	0.40	-0.02	0.10
Stem Diameter	96					1	0.19	0.10	0.24	-0.30	-0.11
Stem Strength	48						1	-0.17	-0.52	-0.30	-0.37
Stem Flexibility	48							1	0.56	0.60	0.051
Lignin	47								1	0.12	0.11
Cellulose	47									1	-0.03
Hemicellulose	47										1

ns Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

Table D3. Correlation Matrix (*r* values) of plant stem strength variables for sub-experiment 1B that investigates the influence of nitrogen (N) management and its interactions with plant growth regulator application for trials conducted in 2018 and 2019 at Carman and Manitou, MB. Correlation analysis was done using all individual plot data

	<i>n</i>	Main Stem Height	Dry Matter	Spikes plant ⁻¹	Internode length	Stem Diameter	Stem Strength	Stem Flexibility	Lignin	Cellulose	Hemicellulose
Main Stem Height	160	1	0.49	0.36	0.58	0.36	0.05	0.35	0.23	0.13	-0.25
			****	****	****	****	ns	**	*	ns	*
Dry Matter	159		1	0.54	0.04	0.04	0.15	0.29	0.19	0.17	-0.07
				****	ns	ns	ns	**	ns	ns	ns
Spikes plant ⁻¹	160			1	-0.21	-0.15	0.21	0.02	0.07	0.27	-0.041
					**	ns	ns	ns	ns	**	ns
Internode length	160				1	0.67	-0.32	0.23	-0.20	-0.25	-0.17
						****	**	*	ns	*	ns
Stem Diameter	160					1	0.02	0.28	-0.34	-0.44	-0.40
							ns	*	**	****	****
Stem Strength	80						1	0.12	0.06	-0.20	-0.52
								ns	ns	ns	****
Stem Flexibility	80							1	0.16	0.03	-0.20
									ns	ns	ns
Lignin	80								1	0.16	0.12
										ns	ns
Cellulose	80									1	0.20
											ns
Hemicellulose	80										1

ns Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

Table D4. Correlation Matrix (*r* values) of plant stem strength variables for sub-experiment 2A that investigates the influence of plant density and its interactions with plant growth regulator application for trials conducted in 2018 and 2019 at Carman and Manitou, MB.

	<i>n</i>	Main Stem Height	Dry Matter	Spikes plant ⁻¹	Internode length	Stem Diameter	Stem Strength	Stem Flexibility	Lignin	Cellulose	Hemicellulose
Main Stem Height	96	1	0.42	0.07	0.46	0.54	0.09	0.86	0.20	0.38	-0.13
			***	ns	***	***	ns	***	ns	**	ns
Dry Matter	95		1	0.25	0.12	0.25	0.21	0.49	0.19	0.27	-0.09
				*	ns	*	ns	***	ns	ns	ns
Spikes plant ⁻¹	96			1	-0.16	0.16	0.33	0.31	-0.13	-0.25	-0.32
					ns	ns	*	*	ns	ns	*
Internode length	96				1	0.55	-0.26	0.30	0.21	-0.06	0.12
						***	ns	*	ns	ns	ns
Stem Diameter	96					1	0.32	0.62	-0.04	-0.32	-0.13
							*	***	ns	*	ns
Stem Strength	48						1	0.24	-0.51	-0.35	-0.63
								ns	*	ns	**
Stem Flexibility	48							1	0.11	0.29	-0.50
									ns	ns	*
Lignin	64								1	0.40	0.51
										**	***
Cellulose	64									1	0.13
											ns
Hemicellulose	64										1

Correlation analysis was done using all individual plot data.

ns Not significant at the 0.05 probability level

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

Table D5. Least squares means for the interaction of plant density with site-year for spike displacement (m) from the vertical position when the crop row was rotated to 45 degrees at half canopy height with a push force meter in sub-experiment 2A measured two weeks after anthesis for trials conducted in 2019 at Carman and Manitou, MB.

	Car19	Man19	
	<i>Spike Displacement</i>		
	<i>m</i>		
<i>Plant Density</i>			
Low	0.5956	0.5876	a [†]
Med	0.5865	0.5847	a
High	0.6075	0.5606	b

[†] Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

Table D6. Least squares means for the three-way interaction of cultivar, PGR and site-year for root plate spread in sub-experiment 1A and the 2-way interaction of plant growth regulator (PGR) with environment on root plate depth for sub-experiment 2A

				Site-Year			
				Car18	Car19	Man18	Man19
Sub-experiment 1A							
				Root Plate Spread			
				cm			
Cultivar x PGR							
AAC Brandon	-	CCC	3.70	bc [†]	3.39	3.90	4.01
	+	CCC	4.67	a	3.19	3.80	4.33
AAC Cameron	-	CCC	3.30	c	3.24	3.62	4.12
	+	CCC	4.12	ab	3.23	3.57	3.85
Prosper	-	CCC	4.38	ab	3.51	3.45	4.11
	+	CCC	4.18	abc	3.34	3.57	4.07
Sub-experiment 2A							
				Root Plate Depth			
				cm			
PGR							
	-	CCC	6.78	a	5.61	5.91	5.46
	+	CCC	6.03	b	5.59	6.34	5.85

[†]Within columns means followed by the same letter are not significantly different at the 0.05 probability level, absence of letters indicates no significant differences within columns

9.3 List of Abbreviation

ADL, acid detergent lignin

ADF, acid detergent fiber

ANOVA, analysis of variance

CCC, chlormequat chloride

CM, Canopy Management

CNHR, Canadian Northern Hard Red

CWRS, Canadian Western Red Spring

DTA, days to anthesis

DTM, days to maturity

ESN, Environmentally Smart Nitrogen™

GA, gibberellic acid

GFD, grain fill duration

GNUE, grain nitrogen use efficiency

GNUE, grain nitrogen utilization efficiency

LTA, long-term average

N, nitrogen

NDF, neutral detergent fiber

NRm, nitrogen remobilization

NRmE, nitrogen remobilization efficiency

NUpE, nitrogen uptake efficiency

PGR, plant growth regulator

TKW, thousand kernel weight

TXP, trinexipac-ethyl