Plant Spatial Arrangement to Maximize Spring Wheat (*Triticum aestivum* L.) Yield in Manitoba in Dry Conditions

BY

SAMANTHA CLEMIS

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Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

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ABSTRACT

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Spring wheat (*Triticum aestivum* L.) currently accounts for the second-largest area of seeded acres in Manitoba. However, information is limited on the optimal plant spatial arrangement to maximize seed yield for modern spring wheat cultivars grown in Manitoba, particularly following a soybean crop. The objectives of this research project were to determine row spacing and seeding density combinations in two modern spring wheat cultivars that maximize seed yield and if the preceding crop (canola or soybean) affects this relationship. Field experiments were conducted at Carman, Howden, and Portage la Prairie, Manitoba, in 2019 and 2020. AAC Brandon and Cardale spring wheat cultivars were subjected to three row spacings (9.5, 19, and 38 cm), four seeding densities (200, 300, 400, and 500 target plants m^{-2}), and two stubble types (canola and soybean). Below-average precipitation was received throughout the growing season at all site-years. AAC Brandon and Cardale seed yield was significantly greater when seeded at the more narrow (9.5 cm or 19 cm) row spacings compared with the wider (38 cm) row spacing. Narrow row spacing treatments resulted in increased and more rapid ground cover, suggesting improved water, sunlight, and nutrient utilization by spring wheat plants. Increasing AAC Brandon and Cardale plant density generally did not influence seed yield. Cardale spring wheat was more responsive to changes in row spacing and seeding density treatments compared with AAC Brandon spring wheat. Collectively, this research indicates that in dry growing conditions, spring wheat growers in Manitoba have the opportunity to increase seed yields by seeding spring wheat at narrower row spacings following a canola or soybean crop. However, more research on producer constraints may lead to increased narrow row adoption by growers. Further research is also necessary to investigate the yield-density relationship during growing seasons that receive more average or above-average precipitation.

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LIST OF ABBREVIATIONS

- C19 = Carman 2019 site-year
- H19 = Howden 2019 site-year
- P19 = Portage la Prairie 2019 site-year
- C20 = Carman 2020 site-year
- H20 = Howden 2020 site-year
- S = Stubble type
- C = Cultivar
- SD = Seeding density
- RS = Row spacing
- SS = Sum of squares
- n.s. = Not significant

1.0 INTRODUCTION

Spring wheat (*Triticum aestivum* L.) is one of Manitoba's most important crop species, accounting for almost one-third of the annual crop acreage annually (MASC, 2019). Wheat produces grain kernels, which are ground into flour and used to make staple food products such as bread and noodles (Liu et al., 2020). When spring wheat is grown, growers and agronomists must make important management decisions that affect plant spatial arrangement, including crop row spacing and plant density. However, research is limited on the optimal plant spatial arrangements to maximize seed yield for modern spring wheat cultivars grown in Manitoba. New agronomic approaches that maximize spring wheat yield substantially affect Manitoba wheat production. By manipulating standard row spacing and plant density configurations, new configurations that allow spring wheat to capture and utilize above- and below-ground resources such as water, sunlight, and nutrients more effectively may be found (Chen et al., 2008; Hussain et al., 2013).

In Manitoba, the growing season is relatively short, and rainfall is variable, so the early-season and effective acquisition of these environmental resources are essential for crop biomass accumulation and yield (Chen et al., 2008). Plants arranged equidistantly from each other in more spatially uniform stands have been proven to enhance crop performance and yield due to improved resource utilization by delayed intraspecific competition (Kemp et al., 1983; Olsen et al., 2004; Weiner et al., 2001). Increased uniformity is typically accomplished by seeding at narrower row widths to achieve more equidistant spacing both within and between crop rows (Kemp et al., 1983; Weiner et al., 2001). Spatially uniform stands provide earlier canopy closure, increased crop light interception, and suppressed weed growth (Fahad et al., 2015; Satorre & Maddonni, 2019). Plants at narrower rows also occupy a larger portion of the soil surface, providing access to nutrients typically not accessible by crop plants at wider rows (Hussain et al., 2013). Furthermore, because there is more exposed soil at wider row spacings, soil moisture is more easily lost through evaporation (Eberbach & Pala, 2005). If plant stands become too dense, however, plants may develop weak roots and stems, which contributes to the lodging of the plants (Berry, 2019). A dense plant stand may also have reduced aeration and increased humidity within the crop canopy, creating ideal conditions for disease development (Manitoba Agriculture and Resource Development, n.d.-b; Jones et al., 2018).

With the shift in Manitoba crop rotations to include soybeans, the aforementioned lack of research on spatial arrangement extends to wheat grown in rotation with soybeans and canola. Differences in stubble height, water retention, seedling emergence, soil microbial communities, and nutrient use between soybean and canola may require different optimum management practices in following wheat crops.

Revisiting plant spatial arrangements that maximize seed yield for modern spring wheat cultivars represents a critical component of crop management in modern wheat cultivars and is necessary to maintain and improve wheat productivity as a whole. The objectives of this study were:

1) To determine row spacing and seeding density combinations in two modern spring wheat cultivars that maximize seed yield
2) To determine if crop stubble type affects the spatial arrangement and yield relationship

It can be hypothesized that AAC Brandon and Cardale spring wheat will yield better when seeded at narrower row spacings than when seeded at wider row spacings, and yield will respond positively to increasing plant density due to more effective use of available growth resources and faster canopy closure. In addition, spring wheat grown in soybean stubble at increased plant densities will yield better at narrow row spacings as soybeans are a low-residue crop. Furthermore, as canola produces more residue than soybeans, spring wheat grown in canola stubble at increased plant densities will yield better at slightly wider row spacings.

2.0 LITERATURE REVIEW

2.1 Wheat History

Wheat (*Triticum aestivum* L.*)* is a member of the grass family, and it was domesticated about 12,000 years ago in the Fertile Crescent in the Middle East (Kilian et al., 2010). The domestication of wheat occurred by natural cross-pollination of wild species and selection by humans (Campbell, 2015). Larger grain size and reductions in seed-shatter were pivotal traits in wheat domestication (Eckardt, 2010). After domestication, wheat cultivation expanded from the Fertile Crescent to other areas of Asia and into Africa and Europe and led to the transition from hunter-gatherer societies to sedentary agricultural-based societies (Eckardt, 2010; Kilian et al., 2010). Wheat was first cultivated in Canada in 1605 at Port-Royal, Nova Scotia and was introduced in Manitoba around 1815 as European settlers made their way to the eastern parts of the Canadian Prairies (Campbell, 2015). Wheat cultivars successfully grown in Europe did not fare well in the Canadian climate due to a shorter growing season, resulting in the delayed maturation of spring wheat (Campbell, 2015). In 1904, Sir Charles E. Saunders developed the wheat cultivar Marquis which was better suited to grow in Canadian prairie conditions as it matured earlier without sacrificing yield potential and milling or baking properties (Rasmussen, 2010). The release of this cultivar to Canadian farmers in 1909 resulted in a rapid increase in wheat production (Rasmussen, 2010).

2.2 Wheat Production

Worldwide wheat grain production exceeded 732 million tonnes in 2018, making it the second most produced grain crop after maize (FAO, 2020). In 2018, Canada ranked 6th top wheat-producing country. Canada produced over 32 million tonnes of wheat grain in 2018, with Manitoba producing 4.7 million tonnes of wheat grain (FAO, 2020; Statistics Canada, 2018). Canada is also one of the top three wheat exporters in the world, exporting 22.9 million tonnes in 2018, with the majority of the wheat going to markets in the United States, Peru, Indonesia, Japan, and China (Alberta Wheat Commission, 2020; FAO, 2020). The demand for wheat production continues to rise as the world population increases because wheat is one of the most consumed grains in the world (Liu et al., 2020). There also has been a recent focus on improving crop productivity on existing farmland (Edgerton, 2009). The green revolution, beginning in the 1950s, caused a period of increased wheat production due to the development of new, high-yielding varieties and the expansion of land area used for crop production (Grassini et al., 2013). However, the amount of arable land available for crop production worldwide is limited (May et al., 2020). Consequently, to satisfy the growing demand for grain, wheat production growth must come from yield gains. If increasing wheat yields by seeding spring wheat via optimized plant spatial arrangements can increase production without requiring additional land, it could help address the world's growing demand.

2.3 Wheat Classification

Nine main wheat market classes are recognized in Western Canada, grouped by their functional characteristics (Canadian Grain Commission, 2019). Canada Western Red Spring (CWRS) is the predominant wheat market class, accounting for 60% of annual production (Canadian Wheat, 2019). Canada Western Red Spring is hard red spring wheat seeded in the spring and harvested in the fall. In 2018, hard red spring wheat was seeded to almost one-third of Manitoba's annual crop acreage (MASC, 2019). Canada Western Red Spring wheat is known for (1) its superior milling quality because minimal protein is lost during this process, and (2) its superior baking quality due to its strong gluten strength that provides elasticity needed for dough to rise (Canadian Grain Commission, 2019). The end uses for CWRS wheat are high volume pan breads or as a blend with other wheat to produce noodles, flatbread, and common wheat pasta (Canadian Grain Commission, 2019). In recent years, AAC Brandon and Cardale have been two of the most commonly grown CWRS cultivars in Manitoba (MASC, 2019, 2020a). In 2018, over 600 thousand hectares of AAC Brandon and 68 thousand hectares of Cardale were seeded (MASC, 2019). AAC Brandon wheat was released in 2014 and developed at the Swift Current Agriculture and Agri-food Canada Research and Development Centre located in Swift Current, Saskatchewan (Cuthbert et al., 2017). AAC Brandon spring wheat was derived from the cross Superb/CDC Osler//ND44 (Cuthbert et al., 2017). Cardale wheat was released in 2011 and developed at the Agriculture and Agri-Food Canada Cereal Research Centre located in Winnipeg, Manitoba (Fox et al., 2013). Cardale spring wheat was derived from the cross McKenzie/Alsen (Fox et al., 2013). These cultivars were introduced to provide growers with high yielding, high protein, semi-dwarf wheat with moderate resistance to fusarium head blight (Cuthbert et al., 2017; Fox et al., 2013).

2.4 Current Spring Wheat Seeding Recommendations in Manitoba

The current Canada Western Red Spring (CWRS) wheat seeding recommendations promoted by the government of Manitoba (Manitoba Agriculture and Resource Development, n.d.-f) are standard, broad guidelines. Based on a 37 g per thousand seed weight (TSW), it is recommended to seed within the range of 84 lb/ac to 120 lb/ac (1.4 bu/ac to 2 bu/ac) to achieve a plant population of about 250 plants m^{-2} to 300 plants m^{-2} (23 plants ft^{-2} to 28 plants ft^{-2}) (Manitoba Agriculture and Resource Development, n.d.-f). Information on seeding recommendations for specific row spacings is absent. Common row spacings for spring wheat in Manitoba range from 19 cm to 38 cm (7.5 inches to 15 inches) (personal observation). Row spacing is dependent on available seeding equipment and field management practices. In areas of Manitoba where moisture conservation is not a concern, growers commonly use conventional tillage systems to incorporate crop residue, so seeding at a narrower, 19 cm row spacing is possible. In areas where growers practice conservation tillage to conserve moisture, a wider row spacing (26 cm to 38 cm) is more common due to excess crop residue in the field. A wider row spacing allows for greater residue clearance, preventing crop residue from interfering with seeding equipment and crop establishment (Green, 1999).

2.5 Wheat Growth, Development, and Yield Components

In Canada, the BBCH (**B**iologische **B**undesanstalt, Bundessortenamt and **CH**emical Industry) developmental scale has become the universal scale for staging all plant species (Lancashire et al., 1991). The decimal code is based on the well-known cereal crop code developed by Zadoks et al. (1974). Cereal crop development is categorized into ten principal stages: germination, leaf development, tillering, stem elongation, booting, inflorescence emergence/heading, flowering/anthesis, development of fruit, ripening, and senescence (Lancashire et al., 1991).

Factors affecting wheat growth and development can be categorized as either abiotic or biotic. Abiotic factors include temperature, water availability, and nutrient availability. The minimum soil temperature needed for wheat germination is about 3.5°C to 5.5°C (De Jong & Best, 1979). In Manitoba, growers typically seed spring wheat between late April and mid-May. Generally, earlier seeding is attributed to a greater yield potential, as a result of better soil moisture utilization by plants throughout the growing season, less weed competition, reduced insect and disease pressure, and the potential to avoid heat damage at flowering (Manitoba Agriculture and Resource Development, n.d.-e; MASC, 2020b). Spring wheat requires about 96 to 102 days to reach maturity depending on the cultivar, thus is typically harvested in August or September (Seed Manitoba, 2019). The ideal growth temperature for wheat is between 12°C and 25°C (Acevedo et al., 2009). Low temperatures early in the growing season can cause poor germination, uneven seedling emergence, and poor crop establishment (Tobeh & Jamaati-e-Somarin, 2012). The critical upper threshold temperature is 29°C, above which wheat yield is affected negatively (Acevedo et al., 2009; Carew et al., 2018). For germination to occur, the seed must achieve 35% to 45% water content by weight (Evans et al., 1975). A wheat crop in Manitoba ideally needs an average of 275 mm to 325 mm of water from seeding to maturity (Manitoba Agriculture and Resource Development, n.d.-a). Temperature and water stress can negatively affect germination, vegetative growth, tiller production, dry matter partitioning, reproductive organ development, reproductive processes, and grain filling, thereby reducing grain yield and quality (Sehgal et al., 2018). Yield losses due to temperature or water stress are greatest during flowering and grain filling due to its direct effect on grain number and composition compared with the vegetative growth and development phases (Sehgal et al., 2018). Soil fertility is also an important factor that affects crop seed yield, and soil tests should be conducted to manage nutrients.

Biotic factors that influence wheat growth and development include insects, pathogens, and weeds. Most recently, in Manitoba, grasshoppers and cutworms have been the main insect pests in wheat (Gavloski, 2018, 2019). Warm, dry weather causes grasshopper populations to rise rapidly, causing chewing damage to leaves and stems, and yield is most affected when stems are partially or completely severed at the distal end just below the heads of the crop (Jones, 1995). Cutworms cut off plant stems near the ground by feeding on the base of the plant (Manitoba Agriculture and Resource Development, n.d.-c). One of the most common fungal diseases in the Canadian Prairie provinces (Manitoba, Saskatchewan, and Alberta) is fusarium head blight (*Fusarium graminearum*) (Aboukhaddour et al., 2019). Fusarium head blight causes premature bleaching of one or many spikelets in a head; infected spikelets are often sterile (Aboukhaddour et al., 2019). The most troublesome and abundant weed species in spring wheat in the Canadian Prairies are green foxtail, wild buckwheat, barnyard grass, and wild oats (Beckie et al., 2016). In Manitoba fields, populations of group 1- and group 2-resistant green foxtail and wild oats and group 2-resistant wild buckwheat and barnyard grass are present (Barker, 2020; Beckie et al., 2016). Weeds reduce yield potential because they compete with the crop for light, water, nutrients, and space (Khaliq et al., 2013).

Wheat growth and development has a direct effect on seed yield. The four key yield components of wheat are the number of plants per unit area, the number of heads plant^{-1}, the number of seeds head^{-1}, and individual seed weight (Slafer, 2007). Wheat crop yields primarily depend on the rate of plant biomass accumulation, influenced by the availability of above- and below-ground resources (sunlight, water, nutrients), their capture, and their conversion to harvestable grain (Satorre & Maddonni, 2019). Each yield component is sensitive to many environmental and management conditions (Kondić et al., 2017; Sehgal et al., 2018).

2.6 Plant Spatial Arrangement

Plant spatial arrangement refers to how crop plants are distributed in a field (Satorre & Maddonni, 2019). The distribution of plants significantly affects a crop's ability to capture and use above- and below-ground resources (sunlight, water, nutrients), essential for biomass accumulation and yield (Chen et al., 2008). The efficient use of environmental resources by spring wheat is important in Manitoba because the province has a short growing season, and rainfall is variable. Row spacing and plant density are regarded as the most significant modifiers of early and effective crop resource capture (Chen et al., 2008; Satorre & Maddonni, 2019). Plants arranged equidistantly from each other in more spatially uniform stands have enhanced crop performance and yield due to improved resource utilization and delayed intraspecific competition (Kemp et al., 1983; Olsen et al., 2004; Weiner et al., 2001). Plants in uniform stands capture more sunlight in early developmental stages, reduce water-soil losses through direct evaporation, and grow for longer periods before encountering space occupied by neighbours

(Kemp et al., 1983; Satorre & Maddonni, 2019). Plant spatial uniformity is typically accomplished by seeding at narrower row widths and greater plant densities to achieve equidistant spacing both within and between crop rows (Kemp et al., 1983; Weiner et al., 2001). Weiner et al. (2001) evaluated spring wheat spatial uniformity in Denmark. They noted that spring wheat seeded in a uniform spatial arrangement resulted in 9% greater yields compared with the plants arranged in distinct rows. Traditional row spacing for spring wheat production in Manitoba can be as wide as 38 cm, creating an uneven distribution of plants throughout the field. Wide gaps between rows, paired with plants aggregated together within the rows, results in intraspecific light, water, and nutrient competition much earlier during crop development than if plants were more uniformly dispersed throughout the field (Griepentrog et al., 2009). Although, there can be obstacles to achieving the ideal arrangement of crop plants. Growers may be limited by their seeding equipment, as their machinery may not have the versatility required to achieve ideal row spacing and seed placement within rows (Griepentrog et al., 2009).

2.6.1 Row Spacing Effects on Seed Yield and Yield Components

Research is lacking on row spacing effects on seed yield for modern spring wheat cultivars grown in Manitoba. Although, research in the Northern Great Plains indicates the potential yield benefit of growing spring wheat at narrower row spacings (Table 2.1). In Montana, Chen et al. (2008) reported an average 32% yield increase when spring wheat was seeded at 15 cm row spacings compared with 30 cm row spacings. As row spacing was narrowed, plant density remained unaffected, but yield increases resulted from increased tiller density (tillers m^{-2}) and, as a result, increased head density (heads m^{-2}). Tillers are secondary shoots that develop from axillary buds of basal leaves. Chen et al. (2008) reported a terminal drought during the 2005 experimental year. Terminal drought is defined as a drought that occurs during the flowering and fruit development stages from which the plants do not recover (Hussain et al., 2018). In 2005, Chen et al. (2008) observed that spring wheat produced two more seeds $head^{-1}$ when seeded at narrower (15 cm) row spacings compared with the wider (30 cm) row spacings. In the 2004 experimental year, row spacing was not observed to have influenced the number of seeds $head^{-1}$. Individual seed weight was non-responsive to row spacing in both experimental years.

In Saskatchewan, McConkey & Miller (1999) reported seed yield advantage when reducing row spacing from 30 cm to 20 cm in no-tillage and conventional tillage systems, of 10% and 12%, respectively. Growing season precipitation was about 5% and 6% below the long-term (30-year) average for the two site-years. Thus, the yield increase observed at the narrow row spacings was attributed to faster soil exploration by the roots and quicker canopy closure, reducing soil water evaporation.

Briggs (1975) studied the effects of spring wheat row spacing in Alberta and found that reducing row spacing from 23 cm to 15 cm increased yields by an average of 20%. Above-average growing season precipitation was reported during both experimental years (1972 & 1973). Information on yield components was absent from this study.

Table 2.1 Summary of the literature examining row spacing and/or plant density effects on seed yield in spring wheat in the Northern Great Plains.

Source	Location	Cultivar(s)	Row Spacing (cm)	Density (plants m^{-2})	Seed Yield Response
May et al. (2020)	Indian Head, Saskatchewan	AC Goodeve	25, 30, 35, 40	250	• 19% increase at 25 cm from 40 cm at 1 of 4 site-years
Chen et al. (2008)	Moccasin, Montana	McNeal	15, 30	89 – 388	• 14 to 32% increase at 15 cm • asymptotic (yield-density relationship)
Carr et al. (2003)	Dickinson, North Dakota	AC Minto; Amidon; Bergen; Grandin; Norm	20	123 – 371 (seeds m^{-2})	• parabolic (yield-density relationship)
Johnston & Stevenson (2001)	Melfort, Saskatchewan	CDC Teal	23, 30	115 – 260	• no response to row spacing • linear (yield-density relationship)
McConkey & Miller (1999)	Swift Current, Saskatchewan	Katepwa	20, 30	116	• 10 to 12% increase at 20 cm
Lafond & Derksen (1996)	Indian Head, Saskatchewan	Biggar	10, 20, 30	83 – 490[a]	• no response to row spacing • asymptotic (yield-density relationship)
Lafond (1994)	Indian Head, Saskatchewan	Laura	10, 20, 30	83 – 490[a]	• no response to row spacing • asymptotic (yield-density relationship)
Baker (1981)	Saskatoon, Floral, & Hagen, Saskatchewan	Neepawa; Manitou; Napayo; Sinton; Glenlea; Pitic 62; Chester; Canuck	30	110 – 430 (seeds m^{-2})	• linear (yield-density relationship)
Faris & DePauw (1981)	Beaverlodge & Fort Vermilion, Alberta; Dawson Creek, British Columbia	Neepawa; Norquay; Line X	23	50 – 1100	• parabolic (yield-density relationship)
Briggs (1975)	Edmonton, Alberta	Glenlea; Pitic 62; Neepawa	15, 23, 30	81 – 245[a]	• 20% increase at 15 cm from 23 cm • linear (yield-density relationship)
Guitard et al. (1961)	Beaverlodge, Fort Vermilion, & McLennan, Alberta	Saunders; Thatcher	15	81 – 490[a]	• asymptotic (yield-density relationship)

[a] Information on actual plant density was absent from the study; only seeding rate in kg/ha was provided. Target plant densities were calculated by using seeding rate (kg/ha), estimated TSW (37 g), and estimated expected seedling survival rate (90%).

In contrast, several studies have shown no yield response to growing spring wheat at narrower row spacings, indicating that decreasing row spacing does not always increase spring wheat yield. A recent study performed in Saskatchewan by May et al. (2020) reported that spring wheat seed yield was unresponsive to row spacing as it decreased from 40 cm to 25 cm at three of the four experimental years in a no-tillage system (2014, 2015, & 2016). The effects of row spacing on plant (plants m^{-2}), head (heads m^{-2}), and seed (seeds m^{-2}) densities, along with individual seed weight, were generally inconsistent among the experimental years. In 2014, as row spacing was narrowed, plant density was unresponsive, head density increased, seed density was unresponsive, and individual seed weight decreased. Above-average growing season precipitation was noted in 2014. In the 2015 growing season, precipitation was about 20% below the long-term (1981-2010) average. As row spacing was narrowed, there was a curvilinear increase in plant density and head density, and both seed density and individual seed weight were unresponsive. In 2016, as row spacing was narrowed, a curvilinear decrease in plant density was observed. Head density and individual seed weight increased, while seed density was unresponsive. Growing season precipitation was similar to the long-term average in 2016. There was an exception during one experimental year (2013) where seed yield increased by 19% as row spacing decreased from 40 cm to 25 cm. In 2013, the growing season precipitation was about 30% below the long-term average, and at the wider row spacings, plant density decreased and could not be compensated for by the other yield components as in the other experimental years.

Two separate studies in Saskatchewan, conducted by Lafond (1994) and Johnston & Stevenson (2001), reported that spring wheat seed yield was unresponsive to row spacing as it decreased from 30 cm to 10 cm and 23 cm, respectively, in a no-tillage system. Lafond (1994) and Johnston & Stevenson (2001) observed that as row spacing was widened, plant (plants m^{-2}) and head (heads m^{-2}) density decreased, but this was compensated for by an increase in seed density (seeds $head^{-1}$). Individual seed weight was unresponsive to row spacing in both studies. According to Lafond's (1994) study, two experimental years received growing-season precipitation that was 8% and 23% below the long-term (30-year) average, while two experimental years received growing-season precipitation that was 15% and 40% above the long-term average. Johnston & Stevenson (2001) did not report the precipitation conditions during this study.

Another study in Saskatchewan by Lafond & Derksen (1996) also observed a lack of seed yield response when decreasing row spacing from 30 cm to 10 cm. Lafond & Derksen (1996) reported that as row spacing was narrowed, plant density (plants m^{-2}) increased, but head (heads m^{-2}) and seed (seeds $head^{-1}$) density, along with individual seed weight, remained unaffected. Precipitation conditions during this study were not reported.

Studies involving the effect of narrower row widths (< 19 cm) on spring wheat yield for currently available cultivars in Manitoba are lacking; in addition, little research has been completed in general on the effect of row widths narrower than 10 cm on spring wheat yield (Table 2.1). Plant spatial arrangements that maximize seed yield for spring wheat grown in Manitoba may be better understood if a wider range of row widths were examined.

2.6.2 Plant Density Effects on Seed Yield and Yield Components

Plant density effects on seed yield are less consistent than row spacing. Mehring (2017) assessed the effect of plant density on seed yield for twelve different spring wheat cultivars. The yield response at high densities differed among the cultivars. Seed yield increased as plant density increased and remained constant, decreased, or increased at high densities depending on the spring wheat cultivar. Select spring wheat cultivars did not have a seed yield response to increasing plant densities. Yield-density models help to describe relationships between plant density and crop yield (Panik, 2014). Well studied yield-density relationships can be classified as (1) asymptotic: yield increases with increasing plant density to a maximum and then becomes relatively constant at high densities, (2) parabolic: yield reaches a maximum and then declines with increasing plant density, or (3) linear: yield increases or decreases linearly as plant density increases (Panik, 2014; Yahuza, 2011).

An asymptotic yield-density relationship has been demonstrated in several spring wheat studies in the Northern Great Plains (Chen et al., 2008; Lafond & Derksen, 1996; Lafond, 1994; Guitard et al., 1961) (Table 2.1). In Montana, Chen et al. (2008) assessed a spring wheat density range from 89 to 388 plants m^{-2} and found that yield increased from 89 to 200 plants m^{-2} and became constant as plant density increased further. As plant density increased, head density (heads m^{-2}) increased, but seed density (seed $head^{-1}$) decreased. Thus, at lower plant densities (<

200 plants m^{-2}), the increase in head density was greater than the decrease in seed density, resulting in a yield increase with increased plant density. When plant densities increased above 200 plants m^{-2}, an increase in head density was accompanied for by a direct decrease in seed density resulting in the yield plateau at higher plant densities. Fewer tillers survived to produce wheat heads in 2005 than in 2004 due to drought conditions. In 2004, plant density did not influence individual seed weight. In 2005, plant density had an inconsistent effect on individual seed weight. Individual seed weight was lower in 2005 than in 2004 due to the drought conditions in July and August.

Two experiments conducted in Saskatchewan by Lafond & Derksen (1996) and Lafond (1994) also reported an asymptotic yield-density relationship as they tested a density range from 83 to 490 plants m^{-2}. Lafond & Derksen (1996) noted a 13% yield increase from the lowest to the highest plant densities, with 11% of the yield increase occurring as plant density increased from 83 to 170 plants m^{-2}, thus further increases in plant density accounted for very little additional yield increase. Lafond (1994) observed the same yield-density response with a different spring wheat cultivar and attributed the yield increase to an increase in head density (heads m^{-2}). As plant density increased, seed density (seeds $head^{-1}$) and individual seed weight decreased. In Alberta, Guitard et al. (1961) tested a range of spring wheat plant densities from 81 to 490 plants m^{-2} and found that maximum yield was achieved at 250 plants m^{-2} with a yield plateau at densities beyond 250 plants m^{-2}. As plant density increased linearly, a curvilinear decrease in head density (heads $plant^{-1}$) was observed. Seed density (seeds $head^{-1}$) and individual seed weight were influenced to a lesser extent by plant density. There was a smaller, curvilinear decrease in the seed density and a small linear decrease in individual seed weight as plant density increased. Guitard et al. (1961) did not report the precipitation conditions during this study.

A study performed in England by Gooding et al. (2002) found that spring wheat yield increased asymptotically within a plant density range of 75 to 350 plants m^{-2}, with the greatest yields occurring at plant densities of 250 plants m^{-2}. Yield increases at low plant densities resulted from increased head density (heads $plant^{-1}$) and a small seed density increase (seed $head^{-1}$). The individual seed weight response to plant densities varied depending on the spring wheat cultivar. The individual seed weight of Axona spring wheat declined slightly with increasing plant densities, whereas the individual seed weight of Chablis spring wheat increased as plant densities increased to 300 plants m^{-2}. Precipitation conditions during this study were not reported.

A parabolic yield-density relationship was reported by Carr et al. (2003) and Faris & DePauw (1981) (Table 2.1). In North Dakota, Carr et al. (2003) observed a parabolic yield-density relationship as seeding density increased from 123 to 371 seeds m^{-2} (information on actual plant stand densities was absent from this study). The optimum seeding density for maximizing yield occurred at 250 seeds m^{-2}. The seeding density did not influence individual seed weight. The growing season precipitation was 22% to 58% above the long-term (30-year) average at three of the four site-years. Data for the other spring wheat yield components was not collected. Faris & DePauw (1981) assessed a wide range of spring wheat densities (50 to 1100 plants m^{-2}) in Alberta and British Columbia. The plant density that resulted in the greatest yields varied per spring wheat cultivar, with the highest yields reported in the cultivars Norquay, Line X, and Neepawa at plant densities of 550 plants m^{-2}, 300 plants m^{-2}, and 250 plants m^{-2}, respectively. As plant density increased, head density increased (heads m^{-2}), seed density (seed head^{-1}), and individual seed weight decreased. Initially, the increase in plant and head density caused yields to rise, but the correlated decrease in seeds head^{-1} eventually maintained the number of seeds m^{-2}. Yields were then reduced at the highest seeding rates due to low individual seed weights. At the first site-year, the growing season precipitation was 60% above the long-term (30-year) average, while at the second site-year, the growing season precipitation was 25% below the long-term average. In the previous spring wheat studies reporting asymptotic yield-density relationships, the highest plant density was 490 plants m^{-2} (Lafond, 1994; Lafond & Derksen, 1996; Guitard et al., 1961). It is possible, as plant densities increase beyond this number, the yield-density relationship may change from asymptotic to parabolic.

A linear increase in seed yield with increasing plant densities has been reported in multiple studies (Johnston & Stevenson, 2001; Baker, 1981; Briggs, 1975) (Table 2.1). In Saskatchewan, Johnston & Stevenson (2001) assessed a small range of spring wheat densities (115 to 260 plants m^{-2}) and found that yield increased by 6% as plant density increased from 174 to 260 plants m^{-2} in one experimental year (1997). This seed yield increase was attributed to increased seed density (seeds head^{-1}) as plant density increased. Head density (head m^{-2}) was not influenced by plant density, and individual seed weight decreased as plant density increased. In the other two experimental years (1998 & 1999), yield decreased by 9% as plant density increased from 144 to 195 plants m^{-2} and 188 to 255 plants m^{-2}, respectively. This seed yield decrease was attributed to lodging, as lodging reduced seed density and individual seed weight. In Saskatchewan, Baker (1981) evaluated spring wheat response to a seeding rate range of 110 to 430 seeds m^{-2} (information on actual plant stand densities was absent from this study) and found a linear yield increase as seeding rates increased. Data for the other spring wheat yield components was not collected. The growing season precipitation was 5% to 50% below the long-term (30-year) average among site-years. In Alberta, Briggs (1975) also reported a general pattern of high yields obtained at the highest plant density (245 plants m^{-2}) in all cultivars tested. Plant density did not influence individual seed weight in two of the three cultivars. Glenlea spring wheat was the only cultivar that showed a relationship between plant density and individual seed weight. As plant density increased, Glenlea individual seed weight increased. Data for the other spring wheat yield components was not collected. The plant density range in the studies performed by Johnston & Stevenson (2001) and Briggs (1975) was narrow, as the maximum plant density was 260 plants m^{-2}. It is possible, as plant densities increase beyond this number, the yield-density relationship may change from linear to asymptotic or parabolic.

The existing literature on spring wheat yield-density relationships is outdated; thus, the yield-density relationship of current spring wheat cultivars is unknown (Table 2.1). Research is needed on currently available spring wheat cultivars to better understand the yield-density relationship in the Manitoba environment.

2.6.2.1 Statistical Analysis Approaches for Yield-Density Relationships

Regression analysis is a statistical method commonly used to determine the relationship between plant density and yield. Regression models may be linear or non-linear, and researchers find the statistical model that best fits their data. A regression model fits the data well if the differences between the observed data values and the predicted values are small, and these differences are known as residuals. In general, a linear regression model describes a situation where the yield of a crop increases linearly or curvilinearly (i.e., quadratic) as plant density increases (Yahuza, 2011). Non-linear regression models can fit a large variety of relationships, and statistical criteria are used to compare the goodness of fit among models (Archontoulis &

Miguez, 2015). To discover the complete yield-density relationship of a genotype, a wide range of plant densities must be included in the experiment.

2.6.3 Resource Capture, Dry Matter Production, and Ground Cover

By manipulating row spacing and plant density configurations, configurations that allow spring wheat to capture and utilize above- and below-ground resources most effectively may be found (Chen et al., 2008; Hussain et al., 2013). Improved resource utilization can maximize biomass accumulation and plant productivity (Chen et al., 2008; Hussain et al., 2013). Studies have shown a positive correlation between biomass accumulation and seed yield. Spring wheat seeded in 15 cm rows accumulated more biomass than in 30 cm rows (Chen et al., 2008). Plant spatial arrangement was better optimized at 15 cm row spacings compared with the 30 cm row spacings, resulting in an environment that facilitated better resource utilization, faster biomass accumulation, tiller survival, and head production, resulting in increased yields. In addition, plant biomass increased with increasing plant density (89 to the 388 plants m^{-2}). May et al. (2020) reported a linear increase in biomass and seed yield as row spacing decreased from 40 cm to 25 cm. Gooding et al. (2002) noted that biomass followed an asymptotic relationship as plant density increased from 75 to 350 plants m^{-2}. The response of plant yield to increasing plant density as an asymptotic relationship is known as the 'law of constant final yield' (LCFY). The LCFY states that initially, biomass increases in proportion to density and then reaches a plateau where biomass remains constant to any further increases in density (Weiner & Freckleton, 2010). This effect is related to plant interference. As shown in Figure 2.1, plant competition is absent at low densities, causing a linear increase in total biomass with density. At high densities, plant competition is present, so plant growth is limited by resource competition, decreasing the size of individual plants, causing biomass and yield to become independent of density (Weiner & Freckleton, 2010). The plant density at which the plateau begins can vary depending on the spring wheat cultivar and environmental conditions (Weiner & Freckleton, 2010). Increased plant densities may also contribute to increased leaf area index (LAI) of the crop (the green leaf surface area per unit area of ground) (Puckridge & Donald, 1967; Satorre & Maddonni, 2019). The greater the LAI, the more light that is intercepted, positively affecting crop growth and biomass accumulation, assuming no other limitations to growth. Puckridge & Donald (1967) noted that as LAI increased, light interception increased asymptotically. When LAI values are low at early plant growth and development, wheat grown in spatially uniform stands has been shown to intercept more light (Satorre & Maddonni, 2019).

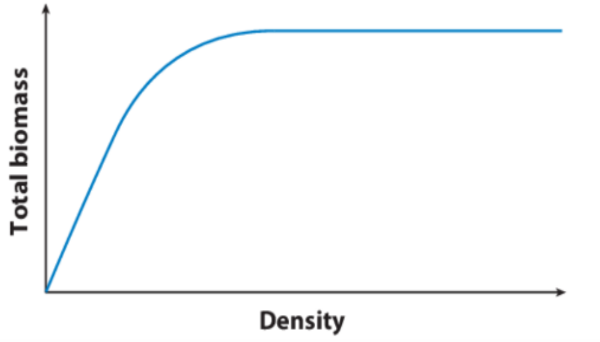

Figure 2.1 The 'law of constant final yield' adapted from Weiner & Freckleton (2010).

Rapid biomass accumulation in a more spatially uniform stand contributes to earlier canopy closure. Early canopy closure can suppress weed growth, as there is less space and fewer resources available for invasive plants (Blackshaw et al., 2005; Fahad et al., 2015). Fahad et al. (2015) assessed crop row spacing and weed seedling emergence. Less weed growth occurred at a row spacing of 11 cm compared with row spacings of 15 cm and 23 cm. At narrower rows, crops exploit the available space more effectively, resulting in more efficient use of available resources and greater crop biomass accumulation, reducing the space available for the growth of weeds (Weiner et al., 2001). Wider crop rows provide excellent recruitment and growth conditions for weeds due to the absence of an overlapping crop canopy, allowing weeds greater access to sunlight and more space to access water and nutrients (Weiner et al., 2001). When weeds are present at the early growth stages of a wheat crop, the damage to yields can be detrimental (Fahad et al., 2015). When spring wheat is seeded at wider row spacings, concerns arise regarding inefficient utilization of resources. In general, plants at narrow row spacings cover the soil surface more rapidly, and narrow row spacing also provides access to nutrients typically not utilized by plants growing at wider rows (Hussain et al., 2013). Furthermore, soil moisture can easily be lost through evaporation at wider row spacings, as there is an increased area of exposed soil compared with the narrower rows; this occurs when increased incident radiation can penetrate the soil surface rather than the crop canopy (Eberbach & Pala, 2005). McConkey &

Miller (1999) reported that water use efficiency (WUE) for wheat plants at 20 cm row spacings was on average 10% greater than at 30 cm row spacings. Water use efficiency refers to how efficiently a plant captures water and converts it into plant biomass or grain (Hatfield & Dold, 2019). This improved WUE resulted from reduced soil water evaporation due to faster canopy closure and quicker soil exploration by plants at the 20 cm rows.

2.6.4 Harvest Index

Harvest index (HI) can be used to examine the relationship between above-ground biomass accumulation and grain yield. Harvest index measures the efficiency of plants to produce seed and is the ratio of grain yield to total above-ground biomass (Porker et al., 2020). Increases in HI have been attributed to increases in grain yield (Duan et al., 2018; Porker et al., 2020; Siddique et al., 1989). Harvest index values for spring wheat are generally between 0.45 to 0.50, with maximum values of 0.60 (Sierra-Gonzalez et al., 2021), and can be influenced by cultivar, growing environment, and management conditions. Low harvest indices can be attributed to increased plant stress (Unkovich et al., 2010). Chen et al. (2008) reported that in both experimental years (2004 & 2005), HI, along with seed yield, was greater at the narrower, 15 cm row spacings (2004 HI = 0.41; 2005 HI = 0.34) compared with the wider, 30 cm row spacings (2004 HI = 0.34; 2005 HI = 0.32). Harvest index was reduced in 2005 due to a drought in July and August. In contrast, May et al. (2020) observed that HI and seed yield were not influenced by row spacing, as row spacing decreased from 40 cm to 25 cm in three of the four experimental years. In one experimental year, there was a curvilinear increase in HI from 0.30 to 0.38 as row spacing increased, with the highest HI values of 0.43 and 0.45 occurring with the row spacings of 30 cm and 35 cm, respectively. The responses of HI to plant density found in previous studies were inconsistent. In 2004, Chen et al. (2008) reported that as plant density increased (89 to the 388 plants m^{-2}), HI decreased, whereas, in 2005, plant density did not influence HI. In contrast, Gooding et al. (2002) observed a linear relationship between plant density (75 to 350 plants m^{-2}) and HI in two spring wheat cultivars, although HI values differed between cultivars. Baker (1981) also reported that the average HI values for eight spring wheat cultivars ranged from 0.41 to 0.49, indicating differences among cultivars from resource allocation to seed production.

2.6.5 Intraspecific Competition and Shade-Avoidance Response

Intraspecific competition refers to competition among members of the same species for limited resources (Satorre & Maddonni, 2019). It is not uncommon for crop monocultures to experience intraspecific competition, as plants are typically grown at high densities (Page et al., 2010). Intraspecific competition negatively affects plant survival, biomass accumulation, and crop yield potential, resulting in the 'law of constant final yield' (Satorre & Maddonni, 2019; Weiner & Freckleton, 2010). In China, Liu et al. (2008) studied four spring wheat competition levels: (1) no competition (100 plants m^{-2}); (2) slight competition (300 plants m^{-2}); (3) intermediate competition (1,000 plants m^{-2}); (4) intensive competition (3,000 and 10,000 plants m^{-2}). Above-ground biomass decreased with increased spring wheat density due to increased intraspecific competition suppressing plant growth. Wheat populations of 3,000 and 10,000 plants m^{-2} also experienced self-thinning during the vegetative period. Intraspecific competition associated with increased plant density may cause additional tiller abortion and plant mortality (Johnston & Stevenson, 2001). Das & Yaduraju (2011) noted that wheat plants seeded at the same densities experienced more intraspecific competition when grown at the narrower, 18.5 cm rows compared with the wider, 22.5 cm rows indicated by reduced biomass and leaf area. Plants growing in dense populations are exposed to increased far-red radiation (FR) reflected by neighbouring plants. Increased FR elicits a shade-avoidance response (Ballaré, 1999). Shade avoidance response causes morphological changes such as accelerated stem elongation, reduced tillering, decreased leaf area, and leaf heliotropy (Ballaré, 1999; Weiner et al., 2017). This adjustment in morphology and architecture allows the plant leaves to reach the top of the canopy, capturing more sunlight (Pierik & De Wit, 2014). These responses boost an individual plant's fitness in a crowded population but decrease overall population yield due to weakened stems and reduced resource allocation to root growth, tillering, and leaf area (Weiner et al., 2017; Wille et al., 2017). In addition to the reduced allocation of resources to reproductive yield, shade-avoidance response reduces weed suppression and increases the risk of lodging (Wille et al., 2017).

2.6.6 Lodging

Lodging refers to the permanent displacement of a plant stem from its vertical orientation (Berry, 2019). Lodging can occur due to stem breakage (stem lodging) or root anchorage failure (root lodging) (Shah et al., 2019). Lodging results in less light interception in ripening crops and makes harvest difficult as it limits the amount of crop collected, negatively affecting yield (Berry, 2019). Dense plant populations are more susceptible to lodging, as there is greater competition between plants for light and nutrients, potentially weakening plant stems and roots (Berry, 2019; Shah et al., 2019). The mechanism by which weak stems and roots develop is attributed to shade-avoidance response (Berry, 2019; Wille et al., 2017). Several studies have shown that increasing plant populations increases lodging in wheat (Faris & DePauw 1981; Johnston & Stevenson, 2001). Berry et al. (2000) reported that reducing winter wheat plant populations from 400 plants m^{-2} to 200 plants m^{-2} decreased root lodging. Establishing fewer plants allowed roots to grow wider and deeper, increasing the anchorage system's strength. Wheat cultivars differ in their ability to resist lodging which is negatively associated with plant height (Navabi et al. 2006). Seed Manitoba assigns a lodging rating to each wheat cultivar that ranges from very poor to very good (Seed Manitoba, 2021). AAC Brandon and Cardale spring wheat have a lodging rating of very good (Seed Manitoba, 2021).

2.6.7 Disease Development

Plant spatial arrangements can influence crop canopy microclimates and thus disease development (Turkington et al., 2004). A dense plant stand may have reduced aeration and increased humidity within the crop canopy which can lead to increased disease development (Manitoba Agriculture and Resource Development, n.d.-b). Fusarium head blight (FHB) is one of the most damaging fungal diseases to spring wheat production on the Canadian Prairies (Aboukhaddour et al., 2019). Infection can occur from several *Fusarium* species*,* but the predominant pathogen in Manitoba is *F. graminearum*, causing floret sterility and poor seed filling (Gilbert & Tekauz, 2000). A common symptom of FHB is the premature bleaching of one or many of the seeds in a head, resulting in shrivelled, lightweight, and chalky white grain from the blighted heads (Manitoba Agriculture and Resource Development, n.d.-d). Infected seeds may have high levels of the mycotoxin deoxynivalenol (DON), making the grain unfit for human consumption or animal feed (Gilbert & Tekauz, 2000). Fusarium head blight has caused annual losses of $50 million in Manitoba, creating a need to mitigate outbreaks and severity in spring wheat production systems (The Canadian Phytopathological Society, 2003). Spring wheat seeded in less dense stands allows greater air movement within the crop canopy, increasing moisture loss and creating an environment non-conducive to FHB development (Turkington et al., 2004). Plant spatial arrangements that encourage airflow are particularly important during periods of frequent rain, heavy dews, or high relative humidity (Turkington et al., 2004). In addition to plant spatial arrangement, cultivar selection is important for FHB management, as spring wheat cultivars differ in their resistance to FHB. Seed Manitoba provides a resistance rating for each wheat cultivar that ranges from susceptible to resistant (Seed Manitoba, 2021). AAC Brandon and Cardale spring wheat both have a resistance rating of moderately resistant (Seed Manitoba, 2021). There currently are no Canada Western Red Spring (CWRS) wheat cultivars available in western Canada with complete resistance to FHB.

2.6.8 Grain Protein

Canada Western Red Spring (CWRS) wheat is known for its high grain protein content (Canadian International Grains Institute, 2013). Over the last three years, the average protein range for CWRS wheat in Manitoba ranged from 13.9% to 15.5% (Seed Manitoba, 2019, 2020, 2021). The protein content of a wheat crop can be of economic importance for a grower, as grain companies may pay a premium for higher protein wheat. Protein premiums are dependent on supply and demand. When there is an abundant supply of high protein wheat, premiums decline or become non-existent, whereas premiums rise when high protein wheat is scarce (McKenzie, 2016). The grain protein concentration of a wheat crop can be influenced by genotype, available nitrogen, and environmental conditions (Fowler et al., 1990). In Manitoba in recent years, the average protein content in AAC Brandon and Cardale spring wheat has been 14.2% to 14.3% and 14.5%, respectively (Seed Manitoba, 2019, 2020, 2021). While genetic differences between cultivars can influence protein content, adequate nitrogen availability is the most critical management factor in producing high protein grains (Carew et al., 2018). In dry growing seasons, seed yield response to available nitrogen is low, so the uptake of plant nitrogen by the crop will increase grain protein concentration (Fowler et al., 1990).

In some studies, spring wheat spatial arrangement has also influenced protein content. Gooding et al. (2002) and Kolb et al. (2012) reported that protein content decreased as plant density increased, from 75 to 350 plants m^{-2} and 400 to 600 plants m^{-2}, respectively. Chen et al. (2008) also reported that protein content decreased as plant density increased from 89 to 388 plants m^{-2} at one experimental year, but at the second experimental year, protein content was not responsive to changes in seeding density. Although, Ozturk et al. (2006) and Carr et al. (2003) reported that grain protein was unresponsive to plant density as plant density increased from 325 to 625 plants m^{-2} and 123 to 371 plants m^{-2}, respectively. Chen et al. (2008) and May et al. (2020) observed that widening row spacing from 15 cm to 30 cm and 25 cm to 40 cm, respectively, did not influence seed protein content. Although, some studies involving winter wheat have reported greater protein concentrations at wider row spacings (25 cm and 38 cm) compared with narrower row spacings (13 cm and 19 cm) (Capouchová et al., 2008; Hiltbrunner et al., 2005). There is limited information on whether stubble type influences the protein concentration of spring wheat. Miller et al. (2002) reported that spring wheat produced 8% and 5% higher protein concentrations when spring wheat was grown on pulse and oilseed stubble, respectively, compared with wheat stubble. Although, the broadleaf and oilseed crop stubbles used in these experiments did not include soybean or canola stubble.

2.6.9 Influence of Stubble Type

In Manitoba, wheat is most likely seeded in soybean or canola stubble, as wheat, soybeans, and canola made up 80% of the seeded hectarage in 2018 (MASC, 2019). Soybean hectares in Manitoba were low before 2011 but increased rapidly from 2011 to 2017, and as a result, soybeans have become part of a typical crop rotation (Soy Canada, 2020). The increase in hectarage was due to the release of earlier maturing, glyphosate-resistant varieties. These new varieties made it possible to grow high-yielding soybeans across all parts of Manitoba (Manitoba Pulse and Soybean Growers, n.d.). Due to the recent rise in soybean hectarage, information is limited on the effect of spatial arrangement for wheat cultivars following soybean. Typically, soybeans are harvested as close to the ground as possible as the lowest pods on the plant are typically not far above the soil surface, resulting in short stubble (typically between 9 cm to 20 cm depending on the lowest pod heights) (Tkachuk, 2019). In contrast, canola residue height is taller, typically ranging between 25 cm to 30 cm after swathing (Kandel & Hanson, 2019). Tall stubble can positively affect soil moisture reserves by increasing snow capture and reducing soil water evaporation (Caprio et al., 1985). Thus, with possibly reduced soil water reserves in previous soybean fields, seeding spring wheat in more spatially uniform stands may be important for more effective water uptake. Cutforth (2012) assessed the effect of standing versus cultivated canola stubble on spring wheat yield in Saskatchewan. Wheat grown in tall stubble in 23 cm row widths showed significantly greater water use efficiency than when grown in cultivated stubble, translating to improved wheat yields. However, tall stubble may cause poor seedling emergence, as excess residue can affect seed placement within the seedbed (Lockwood, 2000). Jessop & Stewart (1983) assessed crop residue effects on wheat seedling emergence and found that wheat seedling emergence was reduced by 40% when seeded in canola residue compared with a non-residue control treatment.

Canola plants are unique because they do not form associations with arbuscular mycorrhizal (AM) fungi in the soil (Lambers & Teste, 2013). The roots of about 90% of plant species, including soybeans and wheat, can be colonized by AM fungi (Diagne et al., 2020). Arbuscular mycorrhizal fungi are soil fungi that form mutualistic symbiotic relationships with plants. Arbuscular mycorrhizal fungi develop hyphae that penetrate the plant roots' epidermal cells or root hairs (Monreal et al., 2011). The fungi benefit from this association by gaining access to plant photosynthetic products. The host plant benefits as the hyphae serve as extensions of the root, exploring areas of the soil not reachable by plant roots, increasing soil water availability and nutrients (Monreal et al., 2011). These associations benefit crop yield potential by increasing the ability of plants to acquire relatively immobile nutrients in the soil, such as phosphorus (Lambers & Teste, 2013). In a canola crop year, AM fungi numbers decline, and following a canola crop, there is a lag in time before AM fungi re-establish the hyphal networks connecting to roots. Therefore, AM fungi are less present in the soil during the early stages of the following growing season, affecting crops such as spring wheat (Karasawa & Takebe, 2012). The lack of AM fungi may affect early phosphorus uptake in the following crop, and phosphorus is important for optimal plant growth, development, and yield (Diagne et al., 2020). Following a non-mycorrhizal crop like canola, a spatially uniform stand may be extra beneficial as resource utilization in each plant is maximized. This facilitates improved resource capture, including nutrients and water (Chen et al., 2008).

Soybean plants are unique when compared with most crop species grown in Manitoba because nitrogen-fixing bacteria can colonize their root system. These bacteria can transform atmospheric nitrogen into mineral nitrogen, and mineral nitrogen is readily assimilated by the plant. Nitrogen is an essential nutrient as it positively affects plant growth and development, resulting in higher yields (Sulieman & Tran, 2016). However, a soybean crop does not leave much nitrogen in the soil after harvest (Heard, 2012). In Manitoba, Heard (2012) assessed residual soil nitrate-N following previous crops and discovered that residual soil nitrate-N levels following a soybean crop were consistently lower than most other Manitoba crops (corn, wheat, canola, and flax). The low nitrate levels can be attributed to a large amount of nitrogen removed with the soybeans. Although, proper fertilizer management can ensure sufficient nitrogen levels for the following crop.

Manitoba Agriculture Services Corporation (2021b) produced crop rotation tables showing the effect of the previous year's stubble type on present year crop yields. It showed that spring wheat has a 7% greater average seed yield response when seeded in soybean stubble compared with canola stubble. Miller et al. (2002) reported a 21% average seed yield increase when spring wheat was grown in pulse stubble compared with wheat stubble, whereas seed yield did not differ when grown in oilseed stubble. Differences in stubble height, water retention, seedling emergence, soil microbial communities, and nutrient use between soybean and canola may demand different management practices for wheat crops to optimize seed yield when seeded in soybean versus canola stubble.

3.0 MATERIALS AND METHODS

3.1 Site Description

Field experiments were initiated in 2019 at three locations in southern Manitoba: the Ian N. Morrison Research Station in Carman, Kelburn Farm in Howden, and the Crop Diversification Centre in Portage la Prairie. In 2020, experiments were established at the Ian N. Morrison Research Station in Carman and Kelburn Farm in Howden. COVID-19 restrictions precluded the establishment of the experiment at the Crop Diversification Centre in Portage la Prairie. The location and soil characteristics of each experimental site are listed in Table 3.1.

Table 3.1 Location and soil characteristics of experimental sites in 2019 and 2020 (Manitoba Agriculture, 2020).

Site-year	**Latitude (N)**	**Longitude (W)**	**Soil Series** ***(texture)***	**Drainage**
Carman 2019 & 2020	49°30’ 4.9674”	98°1’ 43.341”	Rignold *(sandy clay loam)*	Imperfect
Howden 2019 & 2020	49°41’ 46.86”	97°6’ 51.354”	Scanterbury *(clay)*	Imperfect
Portage la Prairie 2019	49°57’ 30.132”	98°16’ 31.9476”	Neuhorst *(clay loam)*	Imperfect

3.2 Experimental Design and Treatments

The experimental design was a four-way factorial randomized complete block design using a split-plot arrangement with four replicates. Stubble type, cultivar, seeding density, and row spacing were the four factors. The main plot was stubble type with two levels, canola or soybean stubble. Within each main plot, there were 24 sub-plots comprised of the fully balanced suite of cultivar, row spacing, and seeding density combinations. Two commonly grown Canada Western Red Spring (CWRS) wheat cultivars (AAC Brandon and Cardale) were seeded at four different seeding rates (220, 330, 440, or 550 seeds m^{-2}) and three different row spacings (9.5, 19, or 38 cm). Wheat was seeded at 10% additional seed (220, 330, 440, or 550 seeds m^{-2}) to achieve target plant densities of 200, 300, 400, or 500 plants m^{-2}. Border plots were established at both ends of each replicate to minimize edge effects.

3.3 Site Management

3.3.1 Field Preparation

Canola and soybean crops that provided the stubble types were harvested at maturity in September the season before establishing the wheat treatments. Soil samples, separated according to stubble type, were collected from two depths (0-15 cm and 15-60 cm), using a Dutch auger, at each location in the spring. The samples were sent to Agvise Laboratories (Northwood, North Dakota, USA) for analysis to determine soil fertility (N-P-K-S) levels (Table 3.2) and requirements (Table 3.3). Prior to seeding, granular fertilizer was broadcast and incorporated based on Agvise recommendations to target a 4035 kg/ha (60 bu/ac) wheat seed yield goal. Pre-emergent weed control was not required in the 2019 and 2020 growing seasons due to the absence of weeds at the time of seeding. Seedbeds were not tilled prior to seeding.

Table 3.2 Spring soil nutrient status at each experimental site in 2019 and 2020.

Site-Year	Previous Crop	N (0-15 cm) [a] N (15-60 cm) [a]	P [b]	K [c]	S (0-15 cm) [d] S (15-60 cm) [d]	Soil pH	O.M. (%) [e]
		kg ha^{-1}	ppm	ppm	kg ha^{-1}		
Carman 2019	Canola	19.1 26.9	21.0	270.0	40.4 134.5	7.2	4.1
	Soybean	13.5 14.6	20.0	246.0	67.3 94.2	7.0	4.0
Howden 2019	Canola	23.5 23.5	24.0	373.0	71.7 107.6	7.5	7.3
	Soybean	49.3 30.3	32.0	461.0	35.9 31.4	7.8	6.9
Portage la Prairie 2019	Canola	22.4 33.6	14.0	307.0	134.5 403.5	8.1	5.4
	Soybean	19.1 16.8	14.0	261.0	24.7 329.5	8.5	5.0
Carman 2020	Canola	12.3 6.7	32.0	184.0	9.0 6.7	6.7	2.0
	Soybean	11.2 7.8	30.0	182.0	6.7 6.7	7.4	1.8
Howden 2020	Canola	37.0 35.9	41.0	679.0	40.4 29.1	7.2	7.2
	Soybean	39.2 17.9	71.0	611.0	13.5 13.5	6.7	8.1

[a] N = residual nitrates

[b] P = residual phosphorus as determined by the Olsen test

[c] K = residual potassium

[d] S = residual sulfur

[e] O.M. = organic matter

Table 3.3 Agvise fertilizer recommendations at each experimental site in 2019 and 2020.

Site-Year	Previous Crop	N [a]	P [b]	K [c]	S [d]
		kg ha^{-1}			
Carman 2019	Canola	123.3	16.8	11.2	0.0
	Soybean	78.5	16.8	11.2	0.0
Howden 2019	Canola	132.4	16.8	11.2	0.0
	Soybean	44.8	16.8	11.2	0.0
Portage la Prairie 2019	Canola	117.7	16.8	11.2	0.0
	Soybean	78.5	16.8	11.2	0.0
Carman 2020	Canola	152.4	16.8	11.2	10.1
	Soybean	135.6	16.8	11.2	13.5
Howden 2020	Canola	71.7	16.8	11.2	0.0
	Soybean	79.6	16.8	11.2	0.0

[a] N = actual nitrogen
[b] P = actual phosphorus
[c] K = actual potassium
[d] S = actual sulfur

3.3.2 Seeding

Seeding operations were performed with a low-disturbance, double-disc opener drill (JT-13DVS, R-Tech Industries Ltd, Homewood, Manitoba, Canada), capable of seeding 19 cm and 38 cm rows. The 9.5 cm rows were seeded using two successive offset passes at the 19 cm row spacing, each seeded at half the required density. Sub-plots were 6 m by 2.5 m, resulting in six rows in the 38 cm row width, twelve rows in the 19 cm row width, and twenty-four rows in the 9.5 cm row width. Wheat was seeded into moist soil (approximately 3-5 cm) in all experiments. Seeding dates are listed in Table 3.4.

Table 3.4 Seeding dates during the 2019 and 2020 growing seasons.

Site-Year	Seeding Date
Carman 2019	9-May
Howden 2019	28-May
Portage la Prairie 2019	23-May
Carman 2020	22-May
Howden 2020	28-May

3.3.3 In-Season Pesticide Applications

Post-emergent weed control was conducted at all five site-years at the tillering stage (BBCH 21-24: one to four tillers detectable). For descriptions of the developmental stages, refer to the BBCH cereal stages guide (Appendix 8.1). At Carman 2019 and 2020, and Howden 2020, a tank mix of pyroxsulam (Simplicity GoDRI, Corteva Agriscience) and MCPA (MCPA Ester 600, Nufarm Agriculture) was applied mid-June at 15 g a.i. ha^{-1} and 371 g a.i. ha^{-1}, respectively. The herbicides were applied using a tractor-mounted sprayer (R-Tech Industries Ltd, Homewood, Manitoba, Canada) calibrated to deliver 128 L ha^{-1} at 275.8 kPa using flat-fan nozzles. At Howden 2019, a tank mix of flucarbazone (Everest 3.0, UPL AgroSolutions Canada) and florasulam + halauxifen (Paradigm, Corteva Agriscience) was applied at the end of June at a dose of 19 g a.i. ha^{-1} and 25 g a.i. ha^{-1}, respectively. The herbicides were applied using a tractor-mounted sprayer (New Holland SP.310, CNH Industrial, Amsterdam, Netherlands) calibrated to deliver 94 L ha^{-1} at 275.8 kPa using flat-fan nozzles. At Portage la Prairie 2019, a tank mix of florasulam + MCPA Ester (Frontline XL, Corteva Agriscience) and pinoxaden + fluroxypyr (Axial Xtreme, Syngenta Canada) was applied at the end of June at 351 g a.i. ha^{-1} and 170 g a.i. ha^{-1}, respectively. The herbicides were applied using a tractor-mounted sprayer (Summers, Summers Manufacturing Inc., Devils Lake, North Dakota, USA) calibrated to deliver 166 L ha^{-1} at 275.8 kPa using flat-fan nozzles. In July of 2019 and 2020, two-striped grasshoppers were controlled with insecticide at experimental sites where the economic threshold was exceeded (>12 grasshoppers m^{-2}) (Manitoba Agriculture and Resource Development, 2021). The insecticides were applied using a tractor-mounted sprayer (R-Tech Industries Ltd, Homewood, Manitoba, Canada) calibrated to apply 128 L ha^{-1} at 275.8 kPa using flat-fan nozzles.

3.4 Data Collection

3.4.1 Seedling Emergence Counts

Early season seedling emergence counts were taken to determine plant stand densities. In 2019, seedling emergence counts took place at the leaf development stage (BBCH 11: first leaf unfolded). Emerging seedlings were counted in two adjacent one-meter rows in two randomly chosen locations in each sub-plot. To avoid potential edge effects, no counts were taken from the outside rows or the front or back half meter of each sub-plot. Outside rows were avoided for all measurements. In 2020, the area counted remained the same, but due to COVID-19 restrictions limiting manual labour at the Carman location, counts were done remotely using digital images. Using a meter stick placed on the ground within each sub-plot, overhead photos targeting a one-meter row length of two adjacent rows were taken. This was done twice in each sub-plot, resulting in two images per sub-plot. The images were uploaded onto a computer, and using *ImageJ*, an image processing and analysis software (National Institutes of Health, Bethesda, MD), the contrast of the images were adjusted to facilitate visual separation of individual wheat plants. The seedlings were then counted from the images. At the Kelburn location, where COVID-19 related field occupancy was not an issue, the 2020 seedling emergence counts were collected using the same method as in 2019. Plant density (plants m^{-2}) was then calculated by multiplying plants per meter row by rows per meter.

3.4.2 Ground Cover Digital Image Analysis

Digital image analysis was used to determine ground cover. Overhead photos targeting the middle section of each sub-plot were taken at five different developmental stages: leaf development (BBCH 11), tillering (BBCH 21, BBCH 21-23, BBCH 21-24: one to four tillers detectable) and stem elongation (BBCH 31: first node at least one cm above tillering node). At Howden 2020, only three developmental stages were photographed (BBCH 21, BBCH 21-24, BBCH 31) due to wet field conditions that limited plot access during two developmental stages (BBCH 11, BBCH 21-23). The images were then processed using the Canopeo app (Version 1.1.7, Oklahoma State University, Stillwater, OK) and MATLAB software (MathWorks, Natick, MA) to determine percent ground cover in each experimental unit. The accuracy of Canopeo can be influenced by shadows (Patrignani & Ochsner, 2015). As ground cover approaches 100%, Canopeo may underestimate ground cover due to the shading of lower leaves in the canopy. Area under the ground cover curve (AUGCC) evaluated ground cover speed. The AUGCC was calculated for each sub-plot using the following formula:

$$AUGCC\ (\%\ days) = \left[\left(\frac{\%\mathrm{GC} @ \mathrm{t}_0 + \%\mathrm{GC} @ \mathrm{t}_1}{2}\right) * (t_1 - t_0)\right] + \left[\left(\frac{\%\mathrm{GC} @ \mathrm{t}_1 + \%\mathrm{GC} @ \mathrm{t}_2}{2}\right) * (t_2 - t_1)\right] + \ldots \quad \text{[eq. 1]}$$

Where %GC is percent ground cover and t_i is measurement day. The unit of measurement for t_i is Julian days, where t_0 is the day of seeding. There were five measurement days (t_1, t_2, t_3, t_4, t_5), with %GC at t_0 equal to zero.

3.4.3 Plant Height, Plant Biomass, and Headcounts

Plant height, plant biomass, and headcount measurements took place when the crop reached the ripening stage (BBCH 83-89: early dough to fully ripe). Three height measurements were taken per sub-plot (front, middle, and back), measuring from the soil to the distal end of the head of erect plants and averaged. Above-ground plant biomass was collected by cutting three different half-meter rows per sub-plot (front, middle, and back). Heads in two of the three samples collected for biomass were counted to estimate head density (heads m^{-2}). Head number per plant was then calculated by dividing head density (heads m^{-2}) by plant density (plants m^{-2}). The plant biomass samples were oven-dried at 60°C for 48 hours. Dried biomass samples from each sub-plot were weighed to determine dry matter weight.

3.4.4 Seed Yield

Harvest operations were performed with a plot combine at Carman (Massey Ferguson 8XP, Kincaid Equipment Manufacturing, Haven, Kansas, USA) and at Howden and Portage la Prairie (Wintersteiger classic; Ried im Innkreis, Austria). Harvest took place when the crop reached the senescence stage (BBCH 97: plant dead). Harvest dates are listed in Table 3.5. A 12 m^2 area was harvested in each sub-plot at Carman (header width 2 m, sub-plot length 6 m), and a 9.3 m^2 area was harvested in each sub-plot at Howden and Portage la Prairie (header width 1.55 m, sub-plot length 6 m). The samples were dried on a forced ambient air-drying bed, and the dry weight of the harvested sample was determined. The grain was cleaned using a grain cleaner (Clipper M2BC, Bluffton, IN), and the clean seed samples were weighed. Grain moisture was tested by first recording the weight of the seed samples, drying the samples in an oven at 60°C for 48 hours, and then reweighing the dried samples. Moisture content was calculated using the following formula:

$$\%\ seed\ moisture\ content = \left(\frac{\text{wet seed weight (g)} - \text{dry seed weight (g)}}{\text{wet seed weight (g)}}\right) * 100 \qquad \text{[eq. 2]}$$

Seed yield (kg ha^{-1}) was then determined, correcting for moisture content by subtracting the adjusted seed weight (clean weight * seed moisture content) from the clean seed weight.

Table 3.5 Harvest dates during the 2019 and 2020 growing seasons.

Site-Year	Harvest Date
Carman 2019	4-Sep
Howden 2019	18-Sep
Portage la Prairie 2019	19-Sep
Carman 2020	4-Sep
Howden 2020	10-Sep

3.4.5 Thousand-Seed Weight and Grain Protein

Seed counting and protein analysis were done at The Point Field Research Laboratory in Winnipeg, Manitoba. Three 250 seed sub-samples from every sub-plot were counted using a seed counter (ESC-1, Agriculex Inc., Guelph, ON) and weighed. The average weight from these three samples was multiplied by four to calculate thousand-seed weight (TSW). Seed density (seeds m^{-2}) was calculated by dividing grain yield (kg ha^{-1}) by TSW (g 1000 S^{-1}). The number of seeds head^{-1} was calculated by taking the seed density (seeds m^{-2}) and dividing it by head density (heads m^{-2}). A 500 g to 700 g seed sub-sample from each sub-plot was used to determine grain protein content. The samples were analyzed using a near-infrared grain analyzer (Infratec$^{\mathrm{TM}}$, FOSS, Hillerød, Denmark).

3.4.6 Harvest Index

Grain Harvest Index (HI) was determined for each sub-plot using the formula below:

$$HI = \frac{\text{Seed yield (grain weight/unit area)}}{\text{Biological yield (biomass weight/unit area)}} \qquad \text{[eq. 3]}$$

Where biological yield is above-ground plant biomass. Harvest index evaluated how efficiently the plants in each sub-plot converted dry matter into grain yield.

3.5 Statistical Analysis

Statistical analysis was performed using SAS® OnDemand for Academics (SAS Institute Inc., Cary, NC, USA). Each site-year was analyzed as a four-way factorial using a split-plot arrangement. Prior to analysis, residuals for the following response variables: seed yield, plant density, heads plant^{-1}, seeds head^{-1}, thousand-seed weight, harvest index, biomass, plant height, grain protein, and area under the ground cover curve (AUGCC) were tested for normality within each site-year using the Shapiro Wilks test in the univariate procedure (PROC UNIVARIATE). Homogeneity of variance was tested and corrected using the repeated statement as necessary to minimize the Akaike information criterion (AIC). Analysis of variance (ANOVA) was used to test treatment effects and their interactions within each site-year using the mixed model procedure (PROC MIXED) for the following response variables: seed yield, plant density, heads plant^{-1}, seeds head^{-1}, thousand-seed weight, harvest index, biomass, plant height, grain protein, and AUGCC. The fixed effects included stubble, cultivar, seeding density, row spacing and their interactions. Fixed effects were considered significant at $p < 0.05$. Replicates by stubble were considered random effects. Denominator degrees of freedom were computed using the Satterthwaite method. Treatment means were separated using the lsmeans statement and the pdmix 800 macro (Saxton, 1998) based on Tukey's Honest Significant Difference (HSD) test ($\alpha = 0.05$). The Type 3 option was used to estimate the sum of squares which were used to examine which effects explained most of the variation in seed yield, and in addition to *p*-values, were used to determine how to proceed with the statistical analysis. The glimmix procedure (PROC GLIMMIX) was used to test treatment effects and their interactions for ground cover response using the beta distribution. The fixed effects included stubble, cultivar, seeding density, row spacing and their interactions. Replicates by stubble were considered random effects. The default link function with the beta distribution was used (Logit).

In this experiment, low plant densities were absent. Thus, to model the effects of plant densities, additional ANOVA analysis was conducted within each site-year using the mixed model procedure (PROC MIXED). Using estimate statements, this analysis modeled and compared the slopes of the response variable seed yield for all cultivar, row spacing, and stubble type combinations in relation to actual plant density, a continuous variable, rather than seeding density, a categorical variable. The fixed effects included stubble, cultivar, and row spacing, actual plant density, and their interactions. Intercepts were compared using the lsmeans statement and the pdmix 800 macro (Saxton, 1998) based on Tukey's Honest Significant Difference (HSD) test ($\alpha = 0.05$). The fixed effects included stubble, cultivar, and row spacing. For both the slope and intercept analysis, fixed effects were considered significant at $p < 0.05$, and replicates by stubble were considered random effects. Denominator degrees of freedom were computed using the Satterthwaite method. The SGPLOT procedure (PROC SGPLOT) was used to create scatter plot graphs to visually determine if the effects were linear or curvilinear (i.e., quadratic) at each site-year.

The correlation procedure (PROC CORR) was used to determine Pearson's correlation coefficient (r) for seed yield and all four yield components (plant density, head number per plant, seed number per head, and thousand-seed weight) as a measure of the linear correlation between the variables at each site-year.

4.0 RESULTS

4.1 Seed Yield

The primary factor affecting variation in seed yield was site-year, which accounted for 50.7% of the total sum of squares (Table 4.1). Seed yields ranged from 2351 kg ha^{-1} to 3744 kg ha^{-1} (35 bu ac^{-1} to 56 bu ac^{-1}) on average across all site-years. The greatest seed yields were observed at Howden 2020, and the lowest seed yields were observed at Carman 2019.

Table 4.1 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) in the dependent variable seed yield in the combined analysis (Carman 2019 and 2020, Howden 2019 and 2020, Portage la Prairie 2019). The model factors included: site-year, stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

Effect	*p*-value	% SS
Site-year (SY)	**<.0001**	**50.74**
Stubble Type (S)	**0.0019**	2.94
SY*S	0.0872	2.09
Cultivar (C)	0.3218	0.02
SY*C	**<.0001**	1.14
S*C	0.0702	0.07
SY*S*C	0.1169	0.15
Seeding Density (SD)	**<.0001**	0.59
SY*SD	0.4684	0.24
S*SD	0.1918	0.10
SY*S*SD	0.2937	0.29
C*SD	0.7635	0.02
SY*C*SD	0.7402	0.18
S*C*SD	0.9751	0.00
SY*S*C*SD	0.7612	0.17
Row Spacing (RS)	**<.0001**	**14.56**
SY*RS	**<.0001**	1.21
S*RS	**0.0349**	0.14
SY*S*RS	**<.0001**	1.09
C*RS	0.0752	0.11
SY*C*RS	0.5064	0.15
S*C*RS	0.1596	0.08
SY*S*C*RS	0.1731	0.24
SD*RS	0.2047	0.18
SY*SD*RS	0.0648	0.74
S*SD*RS	0.9627	0.03
SY*S*SD*RS	0.9938	0.21
C*SD*RS	0.9620	0.03
SY*C*SD*RS	0.9731	0.26
S*C*SD*RS	0.5905	0.10
SY*S*C*SD*RS	0.9854	0.24
Rep(S)	.	1.83
Residual	.	**20.07**

Differences in seed yield were likely due to differences in environmental conditions and pests among the site-years. Monthly air temperature and precipitation data in 2019 and 2020 and long-term (1981 to 2010) averages are presented for each site-year in Table 4.2. Weather data was obtained from nearby weather stations at Carman, St. Adolphe, and Portage la Prairie. Mean air temperature during the growing season (May to August) among the site-years ranged from 16.2°C to 17.5°C (MAFRD, 2019, 2020), which closely matched long-term average air temperatures (Government of Canada, 2019). Air temperature during the 2020 growing season was on average 0.9°C warmer than in 2019. Total precipitation during the growing season ranged from 174.2 mm to 242.4 mm among the site-years (MAFRD, 2019, 2020), which was only 55% to 75% of the long-term average precipitation during the growing season (Government of Canada, 2019). This resulted in dry growing conditions. Foliar plant diseases were not present in these experiments due to the dry growing conditions. Due to significant precipitation in the fall of 2019, total precipitation throughout the non-growing season (September to April) was greatest prior to the 2020 growing season, specifically at Howden. This led to increased soil moisture recharge, which likely was a main factor in contributing to the improved seed yields at Howden 2020.

Two-striped grasshoppers were present in early July at all site-years. At Howden 2019 and Portage la Prairie 2019, the numbers were below the economic threshold (0 to 6 grasshoppers m^{-2}), but at Carman 2019, the numbers were above the economic threshold (>12 grasshoppers m^{-2}) (Manitoba Agriculture and Resource Development, 2021). Two-striped grasshoppers were controlled with insecticide only when the economic threshold was exceeded (>12 grasshoppers m^{-2}). Chlorpyrifos (Lorsban 4E, Corteva Agriscience) was applied at Carman on July 8th at 395 g a.i. ha^{-1}. The wheat surrounding the trial, which also contained grasshoppers, was not treated with insecticide, and thus by July 22nd, the number of grasshoppers was above the economic threshold again and required additional treatment. On July 30th, a third application of insecticide was required. After the third application, the grasshopper population remained below the economic threshold. The infestations of the two-striped grasshoppers may have contributed to the reduced yields at Carman 2019. In 2020, by mid-July, the grasshoppers surpassed the economic threshold at both Carman and Howden, so on July 22nd and July 28th, respectively, chlorantraniliprole (Coragen, FMC Corporation) was applied at a dose of 50 g a.i.

ha^{-1}. One spray in both locations was sufficient to keep the grasshopper population below the economic threshold for the remainder of the growing season.

The combined analysis on spring wheat seed yield also revealed several high-level interactions with site-year (e.g., site-year*stubble type*row spacing) (Table 4.1). Consequently, spring wheat seed yield and all other explanatory response variables were analyzed within each site-year to facilitate interpretation and simplify visualization of the results.

Table 4.2 Mean air temperature (°C) and total precipitation (mm) (MAFRD, 2018, 2019, 2020) for September 2018 to August 2020, and long-term averages (Government of Canada, 2019) at each site-year.

Site-Year	Sept. – April [a]	May	June	July	August	Growing Season [b]	Growing Season LTA [c]
	Mean Air Temperature (°C)						**%**
Carman 2019	-5.6	9.6	17.3	19.6	18.1	16.2	97
Carman 2020	-3.7	10.7	18.3	20.2	18.7	17.0	102
Carman LTA [c]	-3.1	11.6	17.2	19.4	18.5	16.7	
Howden 2019	-6.0	10.3	17.8	19.2	17.9	16.3	96
Howden 2020	-4.0	10.5	19.2	21.0	19.2	17.5	104
Howden LTA [c]	-4.3	12.2	17.0	19.4	18.8	16.9	
Portage la Prairie 2019	-5.2	9.8	17.4	20.4	18.5	16.5	101
Portage la Prairie LTA [c]	-4.3	10.9	16.8	19.3	18.1	16.3	

Site-Year	Sept. – April [a]	May	June	July	August	Growing Season [b]	Growing Season LTA [c]
	Total Precipitation (mm)						**%**
Carman 2019	185.5	37.0	37.9	57.4	61.7	194.0	61
Carman 2020	258.8	26.5	70.5	54.0	24.4	175.4	55
Carman LTA [c]	225.7	69.6	96.4	78.6	74.8	319.4	
Howden 2019	164.0	33.1	31.2	123.2	54.9	242.4	75
Howden 2020	267.2	11.6	49.4	43.9	88.7	193.6	60
Howden LTA [c]	217.3	61.5	99.7	91.7	72.4	325.3	
Portage la Prairie 2019	259.1	33.1	34.6	68.1	38.4	174.2	59
Portage la Prairie LTA [c]	237.4	58.4	90.0	78.4	68.3	295.1	

[a] Beginning of September of the previous year until the end of April of the seeding year
[b] Beginning of May until the end of August
[c] Long-term average (LTA; 1981-2010)

4.1.1 Seed Yield Response to Row Spacing

Once separated by site-year, it was evident that row spacing was the most important factor leading to differences among spring wheat seed yields in these experiments (15.9% to 61.2% of the total variation) (Table 4.3). Spring wheat seeded at the narrower, 9.5 cm or 19 cm row spacings consistently resulted in greater seed yields when compared with the wider, 38 cm row spacing (Figure 4.1).

Table 4.3 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable seed yield at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS
Stubble Type (S)	0.5082	1.27	0.1393	7.86	0.0964	6.17	0.1083	7.50	0.0640	**17.57**
Cultivar (C)	0.1476	0.74	0.2279	0.11	0.0650	0.97	**<.0001**	9.03	**0.0066**	1.85
S*C	0.7833	0.03	0.8460	0.00	0.9354	0.00	**0.0001**	2.64	0.5624	0.08
Seeding Density (SD)	0.2758	1.36	0.1210	0.43	0.0819	1.91	**0.0040**	2.37	**0.0371**	2.11
S*SD	0.4635	0.90	0.7621	0.08	0.2638	1.12	0.5908	0.33	0.1689	1.24
C*SD	0.6390	0.59	0.6923	0.11	0.2139	1.27	0.7822	0.18	0.8021	0.24
S*C*SD	0.9092	0.19	0.2960	0.27	0.2797	1.08	0.4769	0.43	0.9241	0.11
Row Spacing (RS)	**<.0001**	**36.47**	**<.0001**	**61.15**	**<.0001**	**27.54**	**<.0001**	**31.67**	**<.0001**	**15.89**
S*RS	0.1584	0.71	**0.0142**	0.63	**<.0001**	6.96	**<.0001**	4.73	0.0886	1.19
C*RS	0.4041	0.86	**0.0313**	0.51	0.6342	0.25	**0.0208**	1.36	0.6974	0.17
S*C*RS	0.6589	0.24	0.8939	0.02	0.2502	0.78	0.1667	0.62	0.1083	1.09
SD*RS	0.9251	0.70	0.0774	0.84	0.6761	1.12	0.3793	1.10	**0.0305**	3.50
S*SD*RS	0.7502	0.90	0.5143	0.38	0.9790	0.32	0.8201	0.49	0.9197	0.48
C*SD*RS	0.8390	0.54	0.2360	0.59	0.8008	0.85	0.4258	1.03	0.9768	0.29
S*C*SD*RS	0.9964	0.13	0.0973	0.79	0.3853	1.79	0.8631	0.43	0.9457	0.40
Rep(S)	.	**10.42**	.	**16.26**	.	9.34	.	**12.57**	.	**20.51**
Residual	.	**43.95**	.	9.97	.	**38.53**	.	**23.52**	.	**33.26**

When seeded in canola stubble, spring wheat produced similar seed yields at 9.5 cm and 19 cm row spacings at Carman 2020, Howden 2019, and Howden 2020 (Figure 4.1). Stubble type did not influence spring wheat seed yield at Carman 2019 and Portage la Prairie 2019. These observations did not support the hypothesis that spring wheat grown in canola stubble would yield better at a slightly wider (19 cm) row spacing. The lack of seed yield difference between spring wheat seeded at the 9.5 cm and 19 cm row spacings indicates that no yield loss occurred using a narrow row (9.5 cm) spring wheat system in no-till canola stubble in these experiments. Spring wheat seeded in canola stubble at narrow row spacings of 9.5 cm or 19 cm consistently produced greater seed yields, on average improving seed yields by 27.3%, 16.8%, and 18.0%, compared with the widest row spacing (38 cm) at Carman 2020, Howden 2019, and Howden 2020, respectively.

When spring wheat was seeded into soybean stubble, the greatest seed yields were obtained at the 19 cm row spacing at Howden 2019 and Howden 2020 (Figure 4.1). At Howden 2019, spring wheat produced on average 10.7% and 19.3% greater seed yield at the 19 cm row spacing compared with the 9.5 cm and 38 cm row spacings, respectively. At Howden 2020, a 9.9% seed yield increase was observed when spring wheat was grown at the 19 cm row spacing compared with the 9.5 cm and 38 cm row spacings, with no seed yield differences occurring between the 9.5 cm and 38 cm row spacings. At Carman 2020, however, seed yields were greatest at the 9.5 cm row spacing, and as row widths increased to the 19 cm and 38 cm row spacings, seed yield decreased by 5.2% and 29.9%, respectively, compared with the 9.5 cm row spacing. Although, the interaction between stubble type*row spacing at Howden 2019 and 2020 contributed more to the total variation in seed yield within the site-year (4.7% to 7.0%) when compared with Carman 2020 (0.63%) (Table 4.3). These observations did not support the hypothesis that spring wheat grown in soybean stubble would yield better at a narrower (9.5 cm) row spacing. This result remains unexplained. It would be expected that because soybeans are a low-residue crop compared with canola in these experiments, with possibly reduced soil water reserves in previous soybean fields, more effective water uptake was expected to occur by spring wheat plants seeded in the narrowest (9.5 cm) row spacing resulting in greater seed yields.

Only two instances were observed where stubble type provided a seed yield advantage in the row spacing treatments. Soybean stubble provided a 13.7% yield increase when spring wheat was seeded at the 19 cm row spacing at Howden 2019 and a 12.8% yield increase when spring wheat was seeded at the 38 cm row spacing at Howden 2020 when compared with canola stubble (Figure 4.1).

A 4.7% and 23.3% average seed yield increase was observed when spring wheat was seeded at the 19 cm row spacing compared with the 9.5 cm and 38 cm row spacings, respectively at Carman 2019 (Figure 4.1). The contribution of this main effect to the total sum of squares at this site-year was large (36.5%) (Table 4.3).

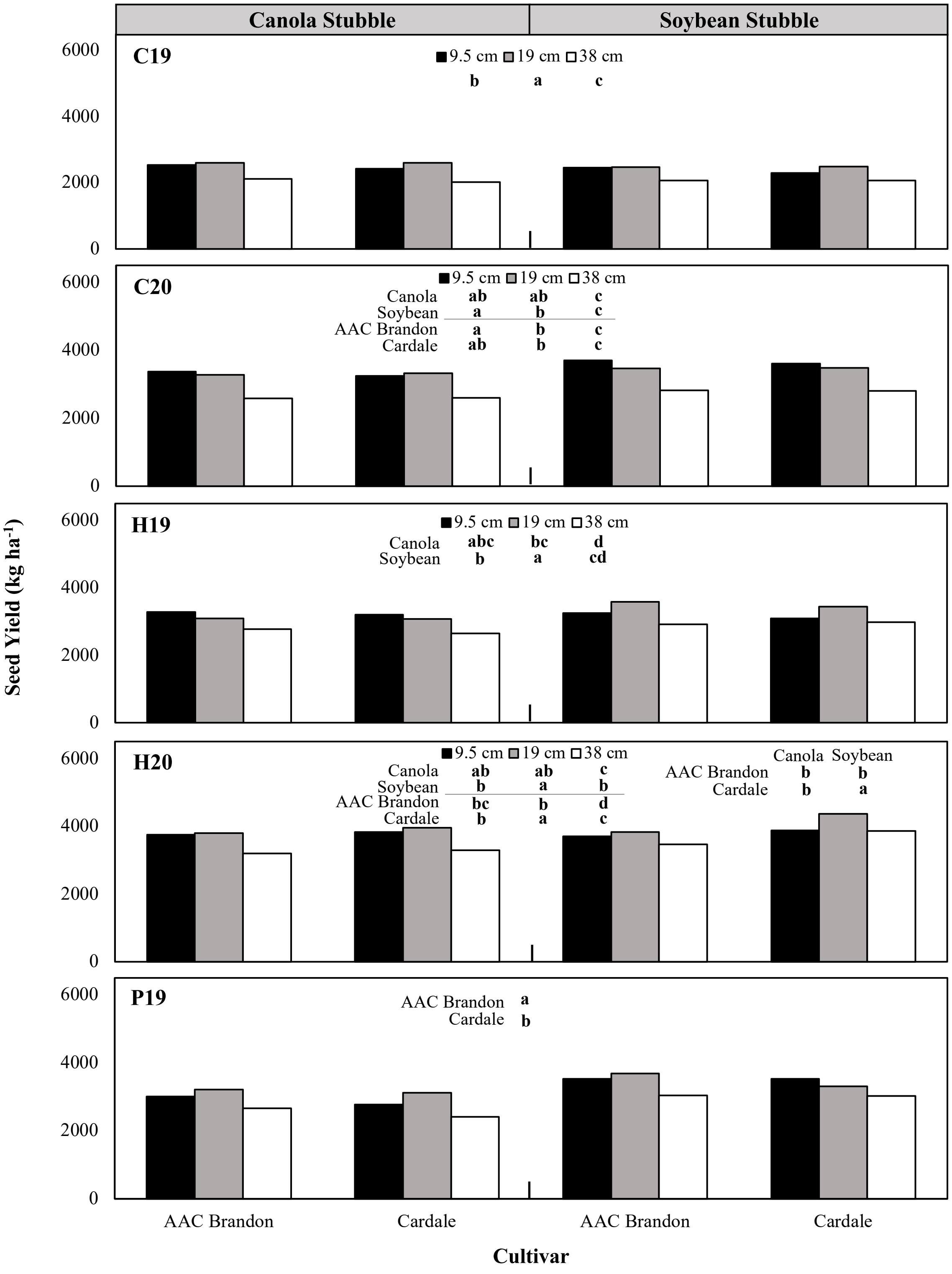

Figure 4.1 Seed yield (kg ha^{-1}) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on seed yield. An interaction effect is the effect of two or more independent variables on seed yield.

These results collectively support the hypothesis that spring wheat will yield better when seeded at a narrower (9.5 cm or 19 cm) row spacing compared with a wider (38 cm) row spacing. In addition, these results suggest that spring wheat seed yield is more responsive to changes in row spacing when seeded in soybean stubble compared with canola stubble.

4.1.2 Seed Yield Response to Cultivar

Cultivar had a smaller effect on the variation in seed yield, accounting for only 0.11% to 9.0% of the total sum of squares (Table 4.3). Nevertheless, seed yield was different between the two spring wheat cultivars at three of the five site years (Carman 2020, Howden 2020, and Portage la Prairie 2019). However, neither cultivar provided a consistent seed yield advantage over the other (Figure 4.1).

Where cultivar differences were observed, AAC Brandon produced greater seed yields when seeded at the 9.5 cm row spacing, while Cardale produced greater seed yields when seeded at the 19 cm row spacing (Figure 4.1). At Carman 2020, AAC Brandon seeded at the 9.5 cm row spacing produced 5.2% and 30.8% greater seed yields compared with seeding at row spacings of 19 cm and 38 cm, respectively. At Howden 2020, Cardale produced the greatest seed yield when grown at the 19 cm row width, improving average seed yield by 8.1% and 16.2%, compared with 9.5 cm and 38 cm row spacings, respectively. Otherwise, no seed yield differences occurred between the 9.5 cm and 19 cm row spacings in AAC Brandon and Cardale.

Generally, no differences occurred within the site-years when comparing the seed yield of both cultivars within each row spacing treatment (Figure 4.1). The one exception was at Howden 2020, where Cardale produced average seed yields that were 8.9% and 7.2% greater compared with AAC Brandon when seeded at the 19 cm and 38 cm row spacings, respectively. At Portage la Prairie 2019, AAC Brandon produced on average 5.2% greater seed yield (3192 kg ha^{-1}) than Cardale (3033 kg ha^{-1}).

AAC Brandon and Cardale seed yield was generally not influenced by stubble type, with one exception at Howden 2020, where Cardale seed yield was more responsive to changes in stubble type compared with AAC Brandon (Figure 4.1). Cardale produced on average 9.2% more seed yield when grown in soybean stubble compared with canola stubble, whereas AAC Brandon seed yield was not affected by stubble type.

In these experiments, it is evident that AAC Brandon and Cardale behaved similarly in yield response in each row spacing and stubble type treatment. While relatively rare, when differences did occur, these results suggest that Cardale demonstrated greater plasticity in response to wider (19 cm and 38 cm) row spacing treatments and stubble type. However, these observations deserve further study during growing seasons with more average or above-average precipitation.

4.1.3 Seed Yield Response to Seeding Density

Increasing seeding density from 200 to 500 target plants m^{-2} had a surprisingly small effect on spring wheat seed yield, contributing only 0.43% to 2.4% to the total variation in seed yield among the site-years (Table 4.3). Seeding density had no effect on seed yield in either wheat cultivar at three of the five site-years (Carman 2019, Carman 2020, and Howden 2019).

Where differences in response to seeding density were observed, seed yields generally decreased as seeding density increased (Figure 4.2). Surprisingly, spring wheat seed yield was more responsive to changes in seeding density when seeded at the narrow, 9.5 cm row spacing compared with the 19 cm and 38 cm row spacings at Portage la Prairie 2019. Spring wheat seeded at the 9.5 cm row spacing produced on average 16.8% greater seed yields at the lowest seeding density of 200 target plants m^{-2} compared with the highest seeding density of 500 target plants m^{-2}. At the intermediate seeding densities, seed yield was intermediate where no seed yield differences were observed at a seeding density of 300 or 400 target plants m^{-2} compared with a seeding density of 200 or 500 target plants m^{-2} at this row spacing. Spring wheat seed yield was not responsive to changes in seeding density from 200 to 500 target plants m^{-2} when seeded at the 19 cm or 38 cm row spacing. As expected, significant seed yield advantages were observed when spring wheat was grown at the narrower 9.5 cm or 19 cm row spacings. Spring wheat seeded at the 9.5 cm row spacing at a seeding density of 200 target plants m^{-2}, or the 19 cm row spacing at seeding densities of 200 or 300 target plants m^{-2}, produced on average 22.9% greater seed yields compared with spring wheat seeded at the 38 cm row spacing at any of the four seeding densities. As seeding density increased from 300 target plants m^{-2} in spring wheat seeded at the 9.5 cm or 19 cm row spacings, respectively, seed yield differences diminished when compared with the widest 38 cm row spacing at any of the four seeding densities. The lack of significant seeding density by row spacing interactions in these experiments, with the exception of at Portage la Prairie 2019 (Table 4.3), indicates that during a dry growing season in weed-free conditions, adjustments in seeding density may not be required with changes in row spacing.

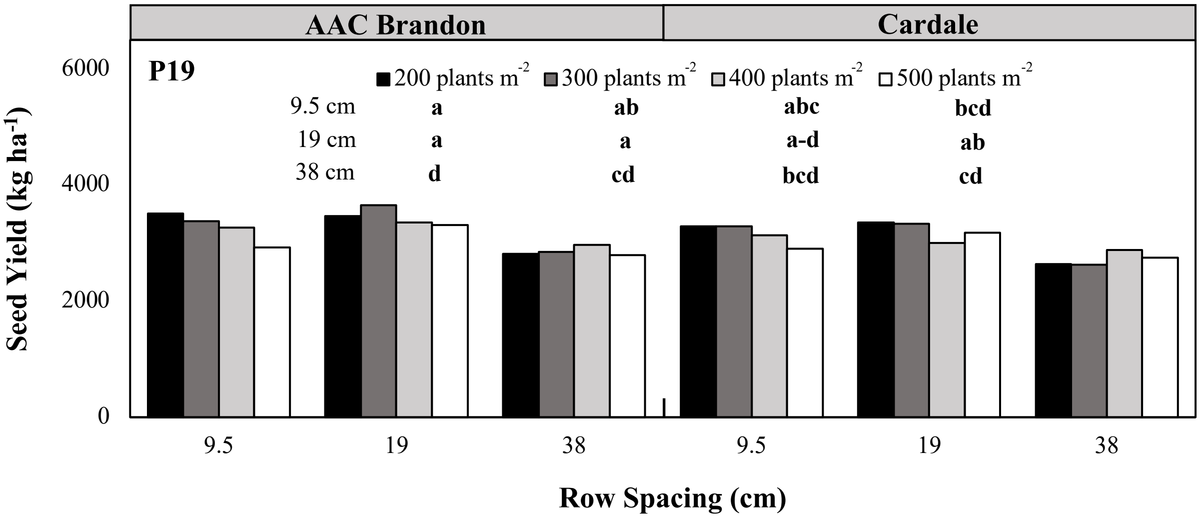

Figure 4.2 Seed yield (kg ha^{-1}) of AAC Brandon and Cardale spring wheat at three row spacings (9.5, 19, 38 cm) and four seeding densities (200, 300, 400, 500 plants m^{-2}) at Portage la Prairie 2019. Different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$).

At Howden 2020, where a seeding density main effect was observed, the greatest seed yields were observed at seeding densities of 200 or 400 target plants m^{-2} (combined average = 3794 kg ha^{-1}), with no significant differences in seed yield occurring between these two seeding densities (Table 4.3). The lowest seed yields occurred at a seeding density of 500 target plants m^{-2} (3650 kg ha^{-1}), while a seeding density of 300 target plants m^{-2} showed no significant yield difference (3739 kg ha^{-1}) compared with all other seeding densities. The contribution of this main effect to the total sum of squares within the site-year was only 2.4% (Table 4.3).

Collectively, these results were not expected and do not support the hypothesis that spring wheat will respond positively to increasing plant density. It is likely that the lack of seed yield response to increasing plant densities within the density range in these experiments was due to the below-average precipitation received throughout the growing season at all site-years (Table 4.2).

Seeding density did not influence AAC Brandon or Cardale seed yield differently at any of the five site-years (Table 4.3). Differences in seed yield responses between AAC Brandon and Cardale were thus more prominent within the row spacing treatments (two significant cultivar*row spacing interactions at Carman 2020 and Howden 2020) and stubble type treatments (one significant cultivar*stubble type interaction at Howden 2020) compared with the seeding density treatments (zero significant cultivar*seeding density interactions). In addition, the seed yield of spring wheat in canola or soybean stubble was not influenced by seeding density at any of the five site-years. The lack of significant seeding density*stubble type interactions was an indication that stubble type was not a limitation to seed yield in these experiments as seeding density increased from 200 to 500 target plants m^{-2}.

4.1.4 Seed Yield Response to Actual Plant Density

The influence of actual plant density on seed yield also was determined to account for differences in seedling emergence among treatments. While relatively rare, seed yield in Cardale (five significant relationships out of a possible thirty) was slightly more responsive to increasing plant densities than AAC Brandon (two significant relationships out of a possible thirty) (Table 4.4).

Interestingly, Cardale wheat was most responsive to plant density at the 19 cm row spacing when seeded in soybean stubble, where all site-years with the exception of Carman 2020, showed a negative yield response to increasing plant density (89 to 587 plants m^{-2} among the site-years) (Table 4.4). The only other yield response in Cardale to plant density was positive (129 to 337 plants m^{-2}) and was observed in canola stubble at the 19 cm row spacing at Carman 2020.

In AAC Brandon, seed yield responses to plant density were only observed in soybean stubble at Carman 2019 in the 19 cm row spacing treatment and at Howden 2020 in the 38 cm row spacing treatment (Table 4.4). Both seed yield responses were negative. The seed yield of AAC Brandon grown in soybean stubble at a row spacing of 19 cm (Carman 2019) and 38 cm (Howden 2020) decreased as plant density increased from 140 to 399 plants m^{-2} and from 119 to 562 plants m^{-2}, respectively. This pattern indicates that maximum seed yields in Cardale and AAC Brandon were obtained at lower seeding densities, and Cardale may be more responsive to changes in plant density, but only when certain other agronomic conditions are met. In addition, these observations further confirm that stubble type appears to have a greater influence on Cardale seed yield compared with AAC Brandon seed yield.

Table 4.4 Linear regression slopes and *p*-values for the dependent variable seed yield as influenced by actual plant stand densities of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) at each site-year. Linear slopes are reported only when significant (Tukey's HSD, $p < 0.05$).

Cultivar	Stubble Type	Row Spacing (cm)	Site-Years	Density Range (plants m^{-2})	Linear Slope	Linear Slope *p*-value
AAC Brandon	Canola	9.5	n.s.			
		19	n.s.			
		38	n.s.			
	Soybean	9.5	n.s.			
		19	Carman 2019	140 - 399	- 1.70	0.0378
		38	Howden 2020	119 - 562	- 1.54	0.0013
Cardale	Canola	9.5	n.s.			
		19	Carman 2020	129 - 337	+ 1.83	0.0089
		38	n.s.			
	Soybean	9.5	n.s.			
		19	Carman 2019	154 - 395	- 2.39	0.0056
			Howden 2019	89 - 587	- 2.23	0.0003
			Howden 2020	112 - 387	- 0.90	0.0483
			Portage la Prairie 2019	112 - 390	- 3.27	0.0126
		38	n.s.			

4.2 Yield Components

4.2.1 Yield Component Correlations

Plant density (plants m^{-2}) was negatively correlated with seed yield, while the number of seeds $head^{-1}$ was positively correlated with seed yield when significant (Table 4.5, Table 4.6). The number of heads $plant^{-1}$ and thousand-seed weight (TSW) generally correlated positively with seed yield, although some negative correlations were observed. The late yield components (seeds $head^{-1}$ and TSW) were more influential on AAC Brandon and Cardale seed yield compared with the early yield components (plant density and heads $plant^{-1}$). Seeds $head^{-1}$ and TSW had more significant correlations with seed yield among site-years compared with plant density and heads $plant^{-1}$. Precipitation was generally greater later in the growing season (July and August) compared with earlier in the growing season (May & June) in both 2019 and 2020 (Table 4.2), which likely was a main factor in later yield components having a greater influence on seed yield than earlier yield components. The plants were compensating for limitations to productivity earlier in the growing season.

Seeds $head^{-1}$ showed significant positive correlations with seed yield at four of the five site-years in spring wheat seeded in canola stubble (Table 4.5). The Pearson r values ranged from 0.58 to 0.78 and seeds $head^{-1}$ explained 34% to 61% of the variation in seed yield among the site-years. In spring wheat seeded in soybean stubble, seeds $head^{-1}$ showed significant positive correlations with seed yield at all five site-years (Table 4.6). Pearson r values were similar as in canola stubble, ranging from 0.54 to 0.75 and seeds $head^{-1}$ explained 29% to 56% of the variation in seed yield among the site-years.

A greater number of positive correlations between seeds $head^{-1}$ and seed yield were observed in spring wheat seeded in soybean stubble at the narrow, 9.5 cm or 19 cm row spacings (seven and five significant relationships out of a possible ten, respectively) compared with the wide, 38 cm row spacing (two significant relationships out of a possible ten) among the site-years (Table 4.6). This likely contributed to the increased seed yield response to row spacing, and the improved seed yields at the narrow, 9.5 cm and 19 cm row spacings, in soybean stubble (Figure 4.1). This correlation trend was less evident in spring wheat seeded in canola stubble (Table 4.5).

Thousand-seed weight (TSW) showed significant positive correlations with seed yield at two and three of the five site-years in spring wheat seeded in canola and soybean stubble, respectively (Table 4.5, Table 4.6). Pearson r values were similar in canola and soybean stubble, ranging from 0.50 to 0.66 in canola stubble and 0.51 to 0.73 in soybean stubble among the site-years. Thousand-seed weight explained 25% to 44% and 26% to 53% of the variation in seed yield among the site-years in canola and soybean stubble, respectively. All correlations between TSW and seed yield were positive, except at Carman 2020, where a negative correlation was observed in AAC Brandon spring wheat seeded in canola stubble at the 9.5 cm row spacing (Table 4.5). Row spacing did not consistently influence correlations between TSW and seed yield.

A yield component that is formed earlier during the growing season, heads plant^{-1}, only showed a significant positive correlation with seed yield at one of the five site-years in AAC Brandon and Cardale spring wheat seeded in canola stubble (Table 4.5). The Pearson r values ranged from 0.54 to 0.58 at this site-year (Portage la Prairie 2019), and heads plant^{-1} explained 29% and 34% of the variation in seed yield in AAC Brandon and Cardale, respectively. In spring wheat seeded in soybean stubble, heads plant^{-1} showed significant positive correlations with seed yield at two of the five site-years (Table 4.6). The Pearson r values ranged from 0.55 to 0.74, with heads plant^{-1} explaining 30% to 55% of the variation in seed yield among the site-years. All correlations between heads plant^{-1} and seed yield were positive, except at Howden 2020, where a negative correlation was observed in AAC Brandon spring wheat seeded in soybean stubble at the 19 cm and 38 cm row spacing. Row spacing did not consistently influence correlations between heads plant^{-1} and seed yield.

Table 4.5 Pearson's Correlation Coefficients (r) and *p*-values for the relationship between seed yield (kg ha^{-1}) and each yield component: plant density (plants m^{-2}), head number per plant (heads plant^{-1}), seed number per head (seeds head^{-1}), and thousand-seed weight (TSW) (g) in AAC Brandon and Cardale spring wheat seeded in canola stubble at three row spacings (9.5, 19, and 38 cm) at each site-year. Correlation coefficients are reported only when significant ($p < 0.05$).

	Seed Yield											
	Canola Stubble											
	AAC Brandon						Cardale					
	9.5 cm		19 cm		38 cm		9.5 cm		19 cm		38 cm	
	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value
	---------- **Carman 2019** ----------											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}												
TSW							0.58	0.0189	0.50	0.0468		
	---------- **Carman 2020** ----------											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}			0.67	0.0042								
TSW	-0.71	0.0022										
	---------- **Howden 2019** ----------											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}			0.63	0.0083			0.70	0.0024	0.56	0.0285		
TSW												
	---------- **Howden 2020** ----------											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}					0.64	0.0070	0.66	0.0051			0.58	0.0180
TSW												
	---------- **Portage la Prairie 2019** ----------											
Plants m^{-2}												
Heads plant^{-1}	0.54	0.0399					0.58	0.0224				
Seeds head^{-1}									0.66	0.0056	0.78	0.0004
TSW							0.66	0.0054			0.53	0.0357

Table 4.6 Pearson's Correlation Coefficients (r) and *p*-values for the relationship between seed yield (kg ha^{-1}) and each yield component: plant density (plants m^{-2}), head number per plant (heads plant^{-1}), seed number per head (seeds head^{-1}), and thousand-seed weight (TSW) (g) in AAC Brandon and Cardale spring wheat seeded in soybean stubble at three row spacings (9.5, 19, and 38 cm) at each site-year. Correlation coefficients are reported only when significant ($p < 0.05$).

	Seed Yield											
	Soybean Stubble											
	AAC Brandon						Cardale					
	9.5 cm		19 cm		38 cm		9.5 cm		19 cm		38 cm	
	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value
	Carman 2019											
Plants m^{-2}			-0.55	0.64					-0.61	0.0130		
Heads plant^{-1}					0.55	0.0287			0.61	0.0112		
Seeds head^{-1}									0.55	0.0286		
TSW	0.71	0.0019					0.58	0.0173	0.56	0.0255		
	Carman 2020											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}	0.67	0.0045	0.58	0.0196								
TSW	0.51	0.0451							0.57	0.0205	0.71	0.0022
	Howden 2019											
Plants m^{-2}									-0.54	0.0291		
Heads plant^{-1}	-0.51	0.0445			-0.65	0.0066						
Seeds head^{-1}	0.64	0.0071	0.55	0.0282			0.75	0.0008	0.70	0.0024		
TSW												
	Howden 2020											
Plants m^{-2}					-0.80	0.0002			-0.67	0.0088		
Heads plant^{-1}			0.74	0.0015	0.66	0.0052						
Seeds head^{-1}	0.59	0.0163			0.71	0.0022	0.61	0.0119			0.61	0.0161
TSW												
	Portage la Prairie 2019											
Plants m^{-2}												
Heads plant^{-1}												
Seeds head^{-1}	0.62	0.0097	0.54	0.0322			0.55	0.0267				
TSW											0.73	0.0014

The only yield component with a consistent negative correlation with seed yield was plant density (plants m^{-2}). Plant density was negatively correlated with seed yield at three of the five site-years in spring wheat seeded in soybean stubble (Table 4.6). Pearson r values ranged from -0.54 to -0.80, with plant density explaining 29% to 64% of the variation in seed yield among the site-years. The negative correlations between plant density and seed yield were generally observed in spring wheat seeded in the 19 cm row spacing (four significant relationships out of a possible ten), with one negative correlation occurring in the 38 cm row spacing. There were no significant correlations between plant density and seed yield in spring wheat seeded in canola stubble (Table 4.5). Plant densitys had the smallest influence on seed yield compared with the other management factors, so it was not surprising that plant density had a smaller influence on seed yield compared with other yield components.

The relationship between plant density and the other yield components was examined to better understand why higher seeding densities did not translate into increased spring wheat seed yields. AAC Brandon and Cardale plant density showed strong negative correlations with heads plant^{-1} at all five site-years in canola and soybean stubble in all three row spacing treatments (Table 4.7, Table 4.8). Pearson r values ranged from -0.52 to -0.94 and -0.64 to -0.94 among the five site-years in canola and soybean stubble, respectively. Spring wheat plants were compensating for the lower plant densities by increasing the number of heads plant^{-1} produced. Additionally, spring wheat seeded at higher seeding rate treatments (300, 400, and 500 target plants m^{-2}) would have suffered more from resource limitations, such as moisture limitations, which likely prevented increased head development. These observations help explain how the spring wheat plants obtained similar yields at different plant densities.

Plant density was negatively correlated with seeds head^{-1} at three site-years in canola stubble and four site-years in soybean stubble (Table 4.7, Table 4.8). The correlation with seeds head^{-1}, however, was slightly weaker when compared heads plant^{-1}, with Pearson r values ranging from -0.53 to -0.76 and -0.34 to -0.81, respectively, among the site-years. Thus, when yield differences due to plant density did occur, they were driven principally by seeds head^{-1}.

The correlations between thousand-seed weight (TSW) and plant density were inconsistent (Table 4.7, Table 4.8). Negative correlations with plant density were observed in spring wheat seeded in canola stubble at Carman 2019 and Howden 2020 ($r = -0.53$ to -0.71 among the two site-years), but in contrast, at Howden and Portage la Prairie 2019, positive correlations ($r = 0.57$ to 0.72 among the two site-years) were observed (Table 4.7). In spring wheat seeded in soybean stubble, a negative correlation between TSW and plant density was observed at Carman 2019 ($r = -0.76$), while at Howden and Portage la Prairie 2019, positive correlations ($r = 0.51$ to 0.54 among the two site-years) were observed (Table 4.8).

Table 4.7 Pearson's Correlation Coefficients (r) and *p*-values for the relationship between plant density (plants m^{-2}) and head number per plant (heads plant^{-1}), seed number per head (seeds head^{-1}), and thousand-seed weight (TSW) (g) in AAC Brandon and Cardale spring wheat seeded in canola stubble at three row spacings (9.5, 19, and 38 cm) at each site-year. Correlation coefficients are reported only when significant ($p < 0.05$).

	Plant Density											
	Canola Stubble											
	AAC Brandon						Cardale					
	9.5 cm		19 cm		38 cm		9.5 cm		19 cm		38 cm	
	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value
Carman 2019												
Heads plant^{-1}	-0.54	0.0374	-0.77	0.0005	-0.80	0.0002	-0.62	0.0110	-0.86	<.0001	-0.73	0.0012
Seeds head^{-1}							-0.59	0.0153				
TSW					-0.53	0.0350			-0.71	0.0021		
Carman 2020												
Heads plant^{-1}	-0.80	0.0002	-0.89	<.0001	-0.92	<.0001	-0.59	0.0163	-0.83	<.0001	-0.90	<.0001
Seeds head^{-1}												
TSW												
Howden 2019												
Heads plant^{-1}	-0.83	<.0001	-0.87	<.0001	-0.93	<.0001	-0.88	<.0001	-0.85	<.0001	-0.94	<.0001
Seeds head^{-1}												
TSW							0.72	0.0015				
Howden 2020												
Heads plant^{-1}	-0.66	0.0055	-0.89	<.0001	-0.85	<.0001	-0.72	0.0015	-0.76	0.0007	-0.82	0.0001
Seeds head^{-1}					-0.53	0.0330	-0.76	0.0006	-0.55	0.0287	-0.54	0.0294
TSW							-0.70	0.0026				
Portage la Prairie 2019												
Heads plant^{-1}	-0.52	0.0448	-0.79	0.0003	-0.88	<.0001	-0.77	0.0008	-0.78	0.0003	-0.94	<.0001
Seeds head^{-1}	-0.54	0.0372					-0.67	0.0062	-0.59	0.0169		
TSW			0.57	0.0202								

Table 4.8 Pearson's Correlation Coefficients (r) and *p*-values for the relationship between plant density (plants m^{-2}) and head number per plant (heads plant^{-1}), seed number per head (seeds head^{-1}), and thousand-seed weight (TSW) (g) in AAC Brandon and Cardale spring wheat seeded in soybean stubble at three row spacings (9.5, 19, and 38 cm) at each site-year. Correlation coefficients are reported only when significant ($p < 0.05$).

	Plant Density											
	Soybean Stubble											
	AAC Brandon						Cardale					
	9.5 cm		19 cm		38 cm		9.5 cm		19 cm		38 cm	
	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value	Pearson r	*p*-value
	-- **Carman 2019** --											
Heads plant^{-1}	-0.64	0.0103	-0.83	<.0001	-0.78	0.0004	-0.71	0.0022	-0.94	<.0001	-0.87	<.0001
Seeds head^{-1}												
TSW			-0.76	0.0006							-0.75	0.0008
	-- **Carman 2020** --											
Heads plant^{-1}	-0.86	<.0001	-0.89	<.0001	-0.94	<.0001	-0.68	0.0038	-0.93	<.0001	-0.94	<.0001
Seeds head^{-1}					-0.54	0.030	-0.57	0.0214	-0.59	0.0165		
TSW												
	-- **Howden 2019** --											
Heads plant^{-1}	-0.90	<.0001	-0.72	0.0016	-0.87	<.0001	-0.85	<.0001	-0.79	0.0003	-0.89	<.0001
Seeds head^{-1}									-0.75	0.0008	-0.81	0.0001
TSW							0.53	0.0338	0.51	0.0449		
	-- **Howden 2020** --											
Heads plant^{-1}	-0.73	0.0012	-0.88	<.0001	-0.89	<.0001	-0.81	0.0001	-0.90	<.0001	-0.85	<.0001
Seeds head^{-1}			-0.61	0.0166								
TSW												
	-- **Portage la Prairie 2019** --											
Heads plant^{-1}	-0.87	<.0001	-0.75	0.0009	-0.80	0.0002	-0.76	0.0006	-0.85	<.0001	-0.77	0.0005
Seeds head^{-1}											-0.34	0.2022
TSW							0.54	0.0324				

4.2.2 Effects of Row Spacing on Yield Components & Ground Cover

Row spacing was an important variable explaining differences among the four yield components - plant density (Table 4.9), head number per plant (Table 4.10), seed number per head (Table 4.11), and thousand-seed weight (Table 4.12). The response of these variables to changes in row spacing was assessed within each site-year to better understand the effect row spacing had on seed yield.

In addition, row spacing affected ground cover at the BBCH 31 developmental stage in wheat (from here on referred to as final ground cover) and the area under the ground cover curve (AUGCC) (Table 4.13). Ground cover image analysis from the final ground cover image collection was used to assess which spring wheat treatments produced the most complete ground cover (Figure 4.3). As ground cover approached 100%, Canopeo underestimated ground cover due to shadows from upper leaves on lower leaves resulting from the angle of the sun (Figure 4.4). Ground cover below 90% was generally observed with treatments that did not achieve full canopy closure (Figure 4.5). Consequently, percent ground cover greater than 90% was assumed to represent full canopy closure. When full canopy closure was achieved in two or more treatments, differences in the AUGCC reflected the speed at which full ground cover was achieved within these treatments. Final ground cover and AUGCC were analyzed within each site-year due to slight differences in the developmental stages of the wheat when images were collected among the site-years.

Table 4.9 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable plant density at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
Effect	2019		2020		2019		2020		2019	
	p-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS
Stubble Type (S)	0.7611	0.13	0.8614	0.00	0.9220	0.02	0.9617	0.00	0.3437	1.76
Cultivar (C)	**0.0465**	0.62	0.4394	0.08	**<.0001**	3.40	0.3705	0.20	**0.0128**	1.37
S*C	0.6289	0.04	0.8703	0.00	0.8642	0.01	0.9164	0.03	0.8675	0.01
Seeding Density (SD)	**<.0001**	**52.23**	**<.0001**	**72.25**	**<.0001**	**47.87**	**<.0001**	**36.19**	**<.0001**	**50.89**
S*SD	0.6939	0.22	0.6655	0.20	0.8178	0.09	0.4709	0.76	0.9822	0.03
C*SD	0.5704	0.31	0.9204	0.06	0.3766	0.52	0.6094	0.64	0.4390	0.59
S*C*SD	0.2175	0.70	0.0865	0.85	0.8708	0.19	0.5115	0.70	0.5783	0.43
Row Spacing (RS)	**<.0001**	**13.03**	**0.0002**	3.22	**0.0055**	1.97	**<.0001**	9.81	**0.0073**	3.36
S*RS	**0.0005**	2.47	**0.0440**	0.63	**0.0079**	1.82	0.0858	1.42	**0.0167**	2.14
C*RS	0.1270	0.64	0.9674	0.01	0.3185	0.41	0.4829	0.46	0.6983	0.20
S*C*RS	0.6765	0.12	0.2134	0.26	0.3492	0.38	0.1253	1.57	0.4557	0.37
SD*RS	0.9758	0.18	**0.0450**	2.09	0.8075	0.51	0.8653	0.64	0.8532	0.51
S*SD*RS	0.7381	0.54	0.8290	0.25	0.1068	1.95	0.8998	0.63	0.4501	0.81
C*SD*RS	0.9116	0.32	0.6788	0.51	0.7438	0.80	0.5292	1.73	0.6527	1.12
S*C*SD*RS	0.9777	0.18	0.0969	1.44	0.6289	1.14	0.3856	2.09	0.9024	0.33
Rep(S)	.	7.32	.	1.14	.	**14.33**	.	**10.41**	.	9.30
Residual	.	**20.95**	.	**17.01**	.	**24.59**	.	**32.74**	.	**26.80**

Table 4.10 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable head number per plant at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
Effect	2019		2020		2019		2020		2019	
	p-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS
Stubble Type (S)	0.8704	0.10	0.6407	0.10	0.3814	1.59	0.8834	0.03	0.1829	5.99
Cultivar (C)	0.6316	0.05	0.7235	0.03	**0.0258**	1.45	0.8008	0.02	**0.0032**	1.53
S*C	0.3119	0.22	0.6183	0.05	0.4808	0.14	0.5083	0.10	0.1858	0.30
Seeding Density (SD)	**<.0001**	**30.39**	**<.0001**	**53.34**	**<.0001**	**27.67**	**<.0001**	**28.91**	**<.0001**	**36.74**
S*SD	0.9557	0.07	0.6236	0.37	0.2613	1.15	0.2407	0.96	0.0835	1.53
C*SD	0.6017	0.39	0.4740	0.49	0.3083	1.03	0.8963	0.28	0.8477	0.10
S*C*SD	0.4126	0.60	**0.0356**	2.01	0.8589	0.22	0.7151	0.49	0.7137	0.12
Row Spacing (RS)	**<.0001**	**10.13**	**<.0001**	5.82	**0.0021**	5.17	**<.0001**	6.84	**0.0044**	1.96
S*RS	0.0641	1.18	0.4461	0.35	**0.0150**	1.82	0.8456	0.07	**0.0446**	1.10
C*RS	0.2977	0.51	0.6207	0.21	0.4171	0.42	0.4091	0.52	0.4808	0.24
S*C*RS	0.7586	0.11	0.2566	0.60	0.4802	0.23	**0.0067**	3.27	**0.0459**	1.06
SD*RS	**0.0165**	3.40	0.7774	0.50	0.5913	1.06	0.8604	1.00	0.5426	1.06
S*SD*RS	0.4019	1.31	0.7064	0.73	0.3924	1.76	0.6176	1.40	0.6072	0.97
C*SD*RS	0.7777	0.68	0.2214	1.32	0.8615	0.42	0.3076	2.21	0.7028	0.40
S*C*SD*RS	0.8995	0.46	0.3204	1.56	0.5946	1.12	0.2542	2.84	**0.0148**	1.62
Rep(S)	.	**22.21**	.	2.18	.	**16.56**	.	**10.10**	.	**23.39**
Residual	.	**28.22**	.	**30.34**	.	**38.19**	.	**40.97**	.	**21.90**

Table 4.11 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable seed number per head at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
Effect	2019		2020		2019		2020		2019	
	p-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS
Stubble Type (S)	0.5365	2.00	0.2627	1.36	0.4092	1.76	0.6134	0.36	0.6048	2.07
Cultivar (C)	0.0557	1.22	0.9810	0.00	**0.0043**	2.83	**0.0006**	4.69	**0.0205**	1.29
S*C	0.9305	0.00	0.8684	0.01	0.3166	0.33	0.7672	0.05	0.3516	0.20
Seeding Density (SD)	**0.0045**	4.45	**0.0003**	8.65	**<.0001**	**15.14**	**<.0001**	9.48	**<.0001**	8.00
S*SD	0.4079	0.94	0.3970	1.23	0.4414	0.90	**0.0270**	3.66	0.7823	0.24
C*SD	0.8658	0.23	0.4464	1.10	0.2753	1.30	0.1289	2.44	0.9627	0.07
S*C*SD	0.3914	1.00	0.0934	2.71	0.5066	0.78	0.0854	2.67	0.8879	0.15
Row Spacing (RS)	**0.0001**	6.49	**0.0005**	9.76	**0.0063**	2.88	0.9223	0.06	0.0550	1.57
S*RS	0.5107	0.45	0.2640	1.59	0.2765	0.49	**0.0078**	3.24	0.1432	0.61
C*RS	0.9486	0.04	0.9366	0.04	0.2899	0.73	0.3888	1.02	0.1630	0.97
S*C*RS	0.6008	0.34	0.9519	0.02	**0.0299**	2.58	0.7260	0.21	**0.0090**	1.53
SD*RS	0.1622	3.05	0.4135	2.53	0.7959	0.58	0.4174	2.46	0.0514	2.61
S*SD*RS	0.5883	1.51	0.5794	1.40	0.9622	0.56	0.2180	3.21	0.5781	0.78
C*SD*RS	0.5625	1.58	0.2673	3.62	0.5610	2.30	0.9067	1.05	0.1148	2.27
S*C*SD*RS	0.4624	1.86	0.8345	1.34	0.5445	1.26	0.5496	1.83	**0.0090**	2.89
Rep(S)	.	**31.03**	.	**10.54**	.	**22.80**	.	**10.41**	.	**45.01**
Residual	.	**43.79**	.	**54.09**	.	**42.81**	.	**53.15**	.	**29.74**

Table 4.12 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable thousand-seed weight at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
Effect	2019		2020		2019		2020		2019	
	p-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS	*p*-value	% SS
Stubble Type (S)	**0.0003**	4.16	0.6455	1.15	**0.0003**	**46.58**	**0.0002**	**48.17**	0.0744	6.27
Cultivar (C)	**<.0001**	**18.84**	**<.0001**	**18.62**	**0.0068**	0.98	**<.0001**	5.21	**<.0001**	**33.93**
S*C	0.1962	0.51	0.8767	0.01	0.5641	0.04	**0.0457**	0.69	**0.0109**	1.70
Seeding Density (SD)	**<.0001**	**15.75**	**0.0287**	2.21	**0.0189**	1.33	**<.0001**	6.19	**0.0064**	3.29
S*SD	0.6328	0.52	0.8167	0.22	0.8894	0.08	0.9593	0.05	0.7632	0.29
C*SD	0.3373	1.03	0.9784	0.05	**0.0386**	1.12	0.1464	0.92	0.7222	0.34
S*C*SD	0.4455	0.81	0.6983	0.34	0.6728	0.20	0.1069	1.05	0.1686	1.31
Row Spacing (RS)	**0.0020**	3.77	0.0954	1.42	**0.0002**	2.06	**<.0001**	3.72	0.1446	1.00
S*RS	0.1795	1.19	0.1384	1.21	**<.0001**	**19.22**	0.4835	0.24	**0.0068**	2.65
C*RS	**0.0027**	4.28	0.1059	1.33	0.4240	0.26	0.7209	0.11	0.5320	0.32
S*C*RS	0.5312	0.34	0.1789	0.67	0.4758	0.20	0.4946	0.23	0.0736	1.36
SD*RS	0.6938	1.24	0.3918	1.38	**0.0169**	2.16	0.0824	1.95	0.8633	0.64
S*SD*RS	0.4752	1.48	0.9093	0.47	0.7401	0.40	0.4477	0.94	0.9497	0.41
C*SD*RS	0.9060	0.64	0.3356	1.61	0.5745	0.60	0.4691	0.95	0.9689	0.34
S*C*SD*RS	0.3354	1.92	0.2833	2.16	0.0916	1.55	0.1440	1.71	0.9870	0.24
Rep(S)	.	0.29	.	**35.10**	.	5.62	.	4.49	.	**11.56**
Residual	.	**43.22**	.	**32.06**	.	**17.61**	.	**23.37**	.	**34.34**

Table 4.13 Significance (*p*-value) of the fixed effects for the dependent variables final ground cover (BBCH 31) and area under the ground cover curve (AUGCC) at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	BBCH 31	AUGCC	BBCH 31	AUGCC	BBCH 31	AUGCC	BBCH 31	AUGCC	BBCH 31	AUGCC
	---------------------- *p*-value ----------------------									
Stubble Type (S)	0.9551	0.2359	**0.0195**	0.8292	**0.0138**	0.0865	0.6630	**0.0140**	**0.0266**	**0.0015**
Cultivar (C)	0.8380	0.3712	**<.0001**	**0.0024**	**0.0038**	**<.0001**	**0.0008**	0.4726	**<.0001**	**<.0001**
S*C	0.8432	0.6608	0.6758	0.7790	0.9854	0.5970	0.3449	**0.0334**	0.5698	0.3027
Seeding Density (SD)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
S*SD	0.3029	0.5085	0.9481	0.8392	**0.0002**	**0.0031**	0.6298	0.7572	0.5452	0.6576
C*SD	0.1442	**0.0471**	0.8312	**0.0383**	0.6298	0.3265	0.1920	0.7719	0.4526	0.0530
S*C*SD	0.2210	0.8621	0.9550	0.7065	0.9447	0.9575	0.1217	0.7461	0.2702	0.3305
Row Spacing (RS)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
S*RS	0.7395	0.1977	**0.0051**	**0.0367**	**0.0092**	**0.0390**	0.4172	**0.0111**	**0.0097**	0.2175
C*RS	0.0668	0.3970	0.9969	0.8498	0.2569	0.2167	0.7534	0.4681	0.4019	0.5334
S*C*RS	0.3874	0.3230	0.2926	0.7871	0.4176	0.2475	0.3180	0.6818	0.3959	0.3612
SD*RS	0.1193	0.6609	0.1491	0.3608	**0.0024**	**0.0025**	0.8517	0.0639	**<.0001**	0.0905
S*SD*RS	0.8475	0.9513	0.9478	0.7663	0.0833	0.2148	**0.0445**	0.0508	0.8119	0.5218
C*SD*RS	0.7941	0.9743	0.8860	0.7902	0.9950	0.9780	0.2475	0.2760	0.9348	0.4794
S*C*SD*RS	0.9176	0.7819	0.9207	0.9192	0.5895	0.5140	0.3626	0.5470	0.3952	0.7468

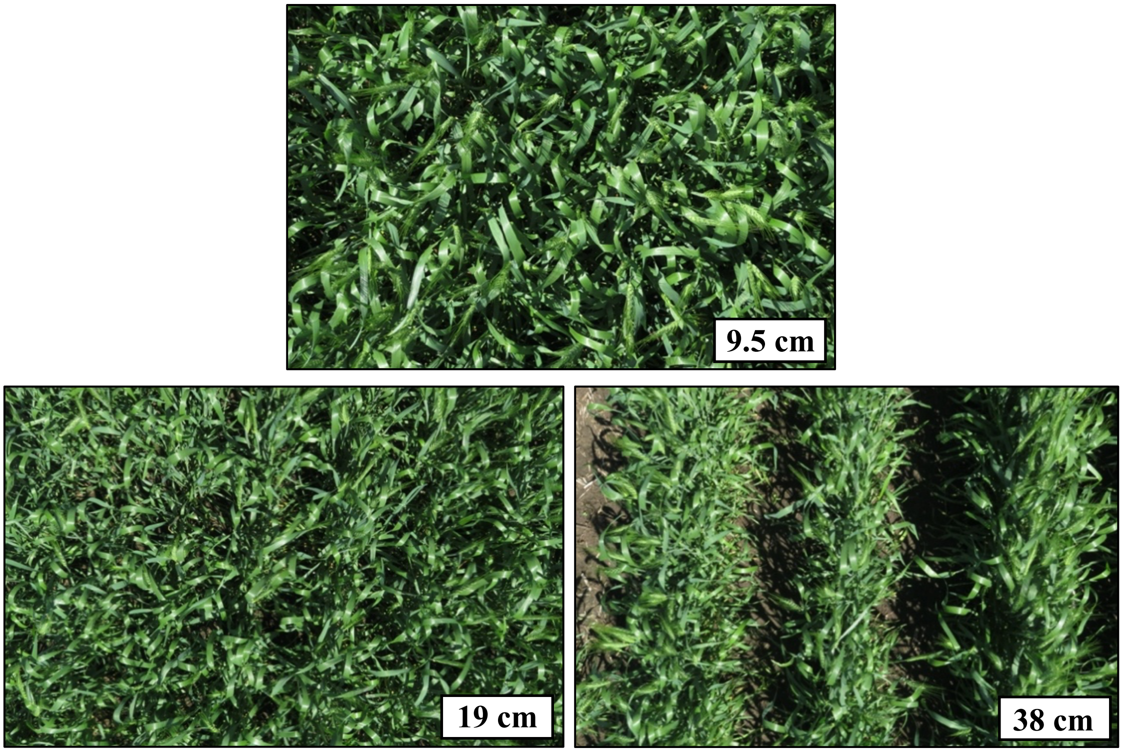

Figure 4.3 Ground cover images of spring wheat at BBCH 31 seeded at three row spacings, at a seeding density of 300 target plants m^{-2}.

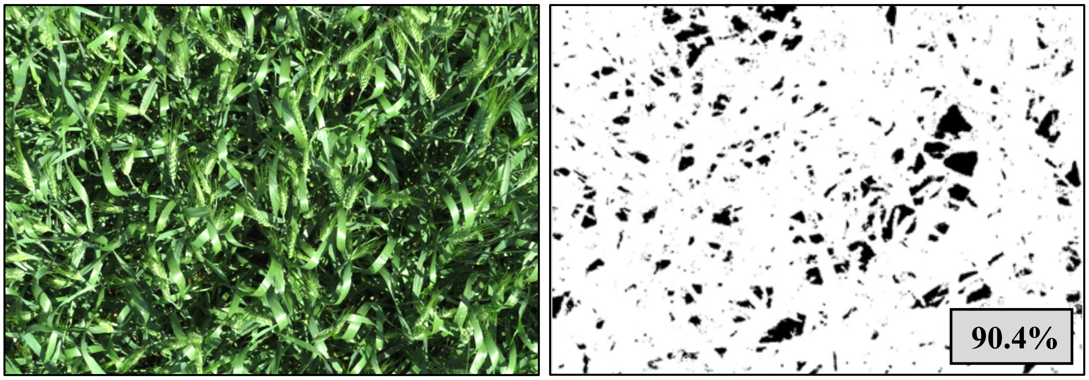

Figure 4.4 Full canopy closure image captured at BBCH 31 at Carman 2020 (left) and the percent ground cover value from Canopeo (right).

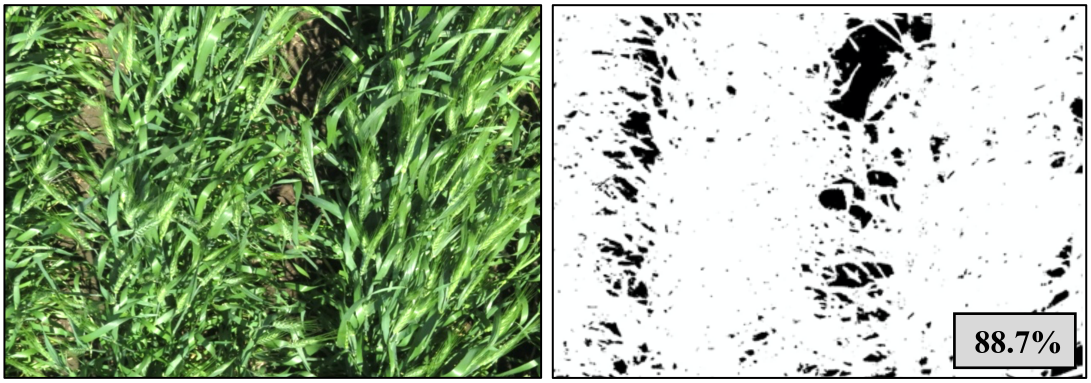

Figure 4.5 Incomplete canopy closure image captured at BBCH 31 at Carman 2020 (left) and the percent ground cover value from Canopeo (right).

Carman 2019. Seedling emergence in canola and soybean stubble gradually decreased as row spacing increased from 9.5 cm to 38 cm (Figure 4.6). Final ground cover at the 9.5 cm row spacing was 4% and 22% greater compared with the 19 cm and 38 cm row spacings, respectively (Figure 4.7). Although, all three row spacing treatments failed to achieve complete canopy closure. The number of heads plant^{-1} produced by spring wheat in each row spacing treatment was influenced by seeding density (Table 4.10). As row spacing increased from 9.5 cm to 38 cm at seeding density treatments of 200 and 300 target plants m^{-2}, the number of heads plant^{-1} gradually increased from 1.7 to 2.2 heads plant^{-1} and 1.3 to 1.9 heads plant^{-1}, respectively (Figure 4.9). This small increase in the number of heads plant^{-1} at the wide (38 cm) row spacing indicates that the wheat plants were compensating for the lower plant population, as indicated by the reduced seedling emergence. The below-average precipitation received in May and June likely limited the number of heads plant^{-1} produced. At greater seeding density treatments of 400 or 500 target plants m^{-2}, row spacing did not influence the number of heads plant^{-1}. There was a small decrease in the number of seeds head^{-1} produced by spring wheat (on average 1.8) as row spacing increased from 9.5 cm to 19 cm or 38 cm (Figure 4.10). The response of thousand-seed weight (TSW) to row spacing was influenced by cultivar, as Cardale TSWs were more responsive to changes in row spacing when compared with AAC Brandon TSWs (Figure 4.11). Cardale TSWs were on average 0.91 g greater when seeded at the wider 19 cm or 38 cm row spacings compared with the narrowest 9.5 cm row spacing. As more precipitation was received in July and August compared with May and June at Carman 2019, Cardale spring wheat was compensating for limitations to productivity at the wider row spacing earlier in the growing season. Row spacing did not influence AAC Brandon TSWs.

At Carman 2019, seed yield was the lowest at the widest (38 cm) row spacing (Figure 4.1). These results indicate that as row spacing increased in a drier than normal growing season, the reduction in plants m^{-2}, and to a lesser extent the reduction in the number of seeds head^{-1}, could not be compensated for by the increased number of heads plant^{-1} and TSW.

Carman 2020. Seedling emergence was greater at the 38 cm row spacing compared with the 19 cm row spacing in canola stubble, although at the 9.5 cm row spacing, seedling emergence did not vary compared with the other row spacing treatments (Figure 4.6). When spring wheat was grown in soybean stubble, the greatest seedling emergence occurred at the 38 cm row spacing compared with the 9.5 cm or 19 cm row spacings. These results remain unexplained as it would be expected that seedling emergence would decrease at wider row spacings due to safe site limitations for germination and emergence when seeds are more concentrated within each row. Final ground cover at the 9.5 cm or 19 cm row spacing was 15% greater in canola stubble and 13% greater in soybean stubble compared with the 38 cm row spacing (Figure 4.7). Full canopy closure was observed in canola and soybean stubble at the 9.5 cm or 19 cm row spacings. The rate of ground cover was the same when spring wheat was seeded at the 9.5 cm or 19 cm row spacings in canola stubble, whereas in soybean stubble, ground cover occurred more rapidly when spring wheat was seeded at the 9.5 cm row spacing compared with the 19 cm row spacing (Figure 4.8). As row spacing increased from 9.5 cm or 19 cm to 38 cm, the number of heads plant^{-1} decreased from 3.0 to 2.4 heads plant^{-1} (Figure 4.9). The greater number of heads plant^{-1} at the narrower (9.5 cm and 19 cm) row spacings indicates that the wheat plants were trying to compensate for the lower plant population as indicated by the reduced seedling emergence or the production of heads plant^{-1} was restricted at the widest (38 cm) row spacing. Precipitation levels were below-average in May and June and likely limited the number of heads plant^{-1} produced. Similar to Carman 2019, at Carman 2020, there was a small decrease in the number of seeds head^{-1} produced by spring wheat (on average 3.1) as row spacing increased from 9.5 cm to 19 cm or 38 cm (Figure 4.10). Row spacing did not influence TSW (Table 4.12). Carman 2020 received less precipitation in July and August than Carman 2019, which is likely why there was no late-season yield component compensation at the wide (38 cm) row spacing as observed at Carman 2019.

At Carman 2020, seed yield was the lowest in canola and soybean stubble at the widest (38 cm) row spacing (Figure 4.1). These results indicate that as row spacing increased in a drier than normal growing season, plants m^{-2} increased, but the following reduction in the number of heads plant^{-1} and seeds head^{-1} resulted in reduced seed yield at the 38 cm row spacing. In soybean stubble, the more rapid ground cover at the 9.5 cm row spacing compared with the 19 cm row spacing, likely contributing to the increased seed yield at this row spacing.

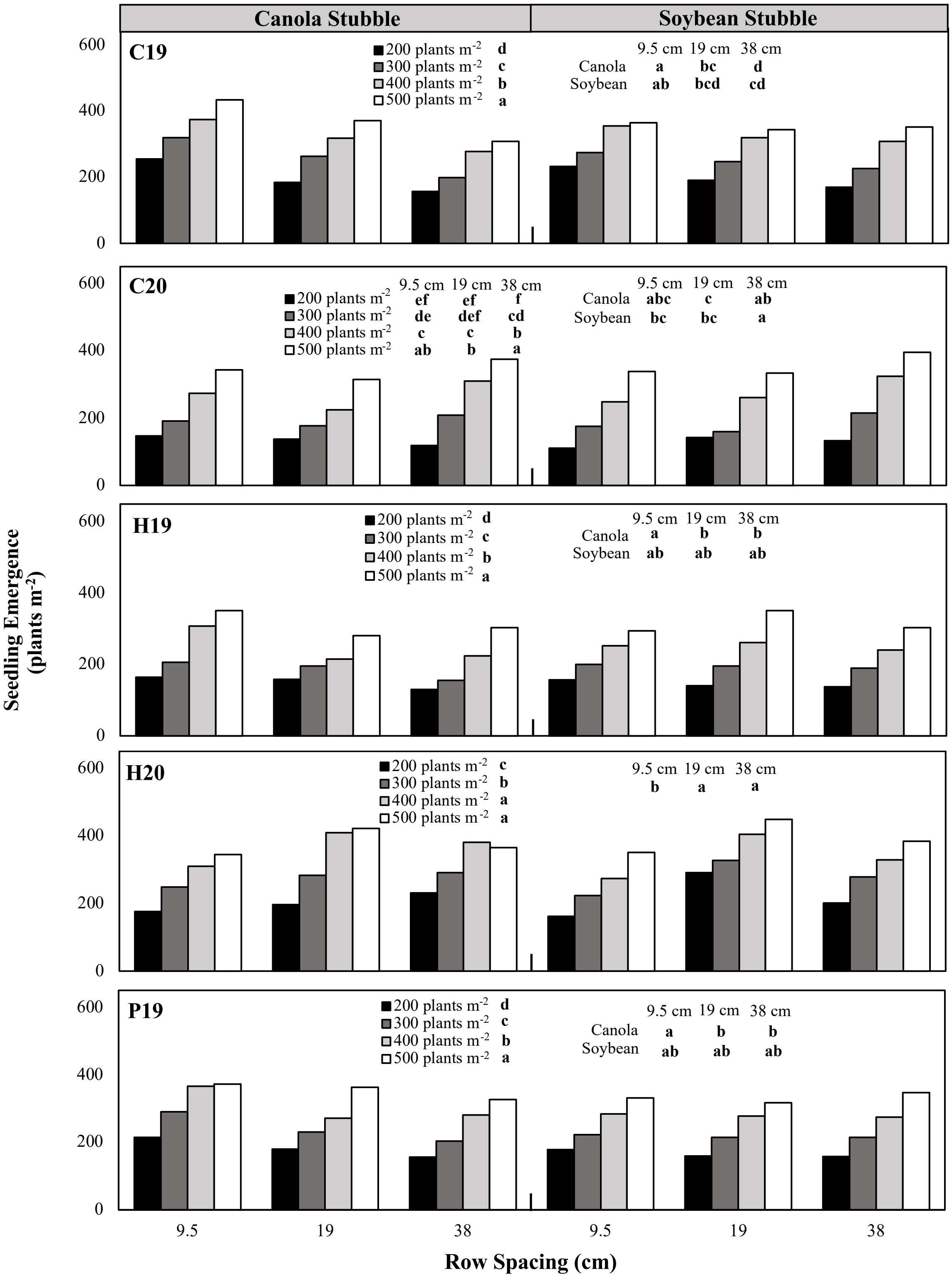

Figure 4.6 Seedling emergence (plants m^{-2}) across spring wheat cultivars seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) and four seeding densities (200, 300, 400, and 500 plants m^{-2}) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on seedling emergence. An interaction effect is the effect of two or more independent variables on seedling emergence.

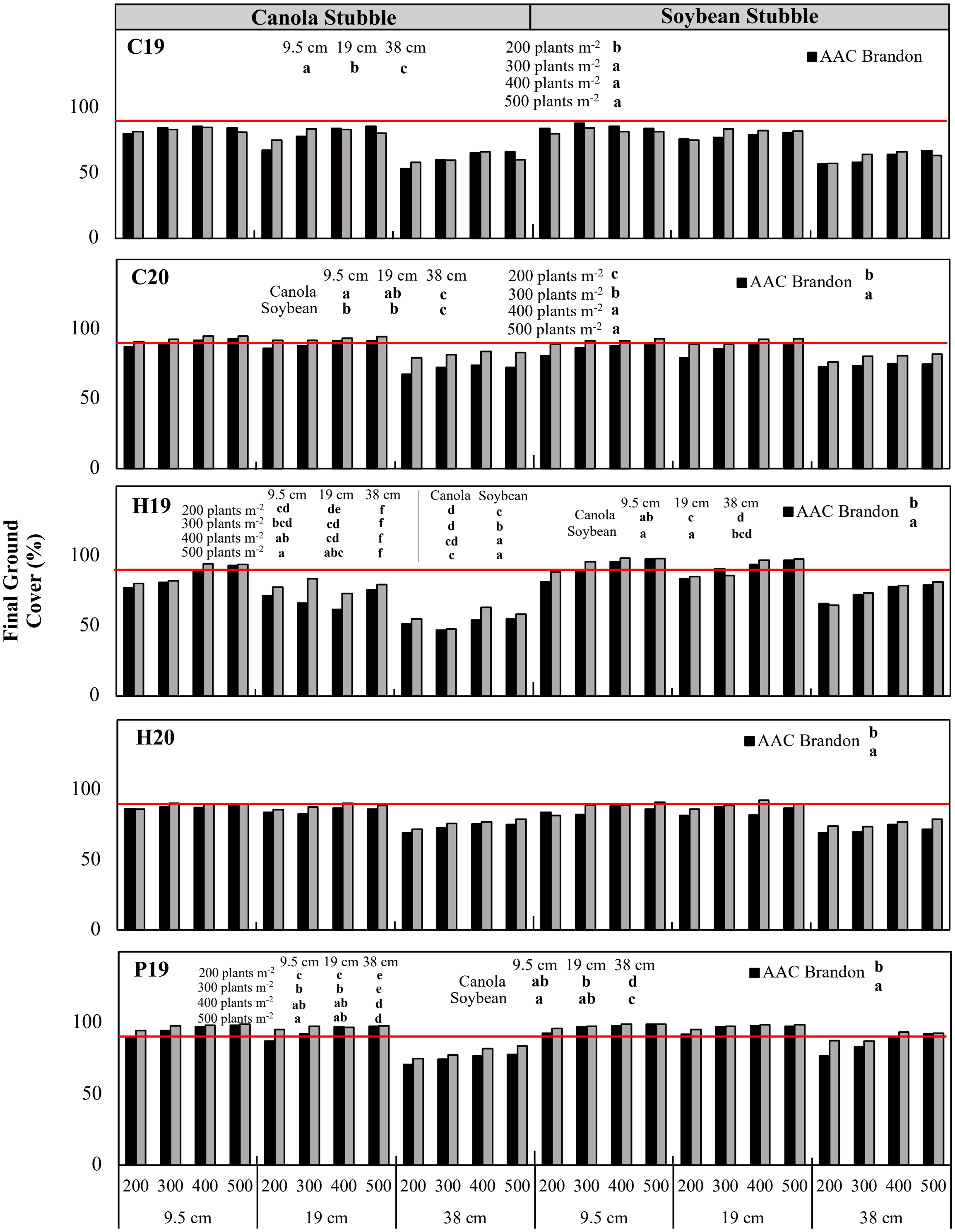

Figure 4.7 Final ground cover (%) (at BBCH 31) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at four seeding densities (200, 300, 400, and 500 plants m^{-2}) and three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on final ground cover. An interaction effect is the effect of two or more independent variables on final ground cover. The red line indicates 90% canopy closure indicating where "complete" canopy closure has been achieved.

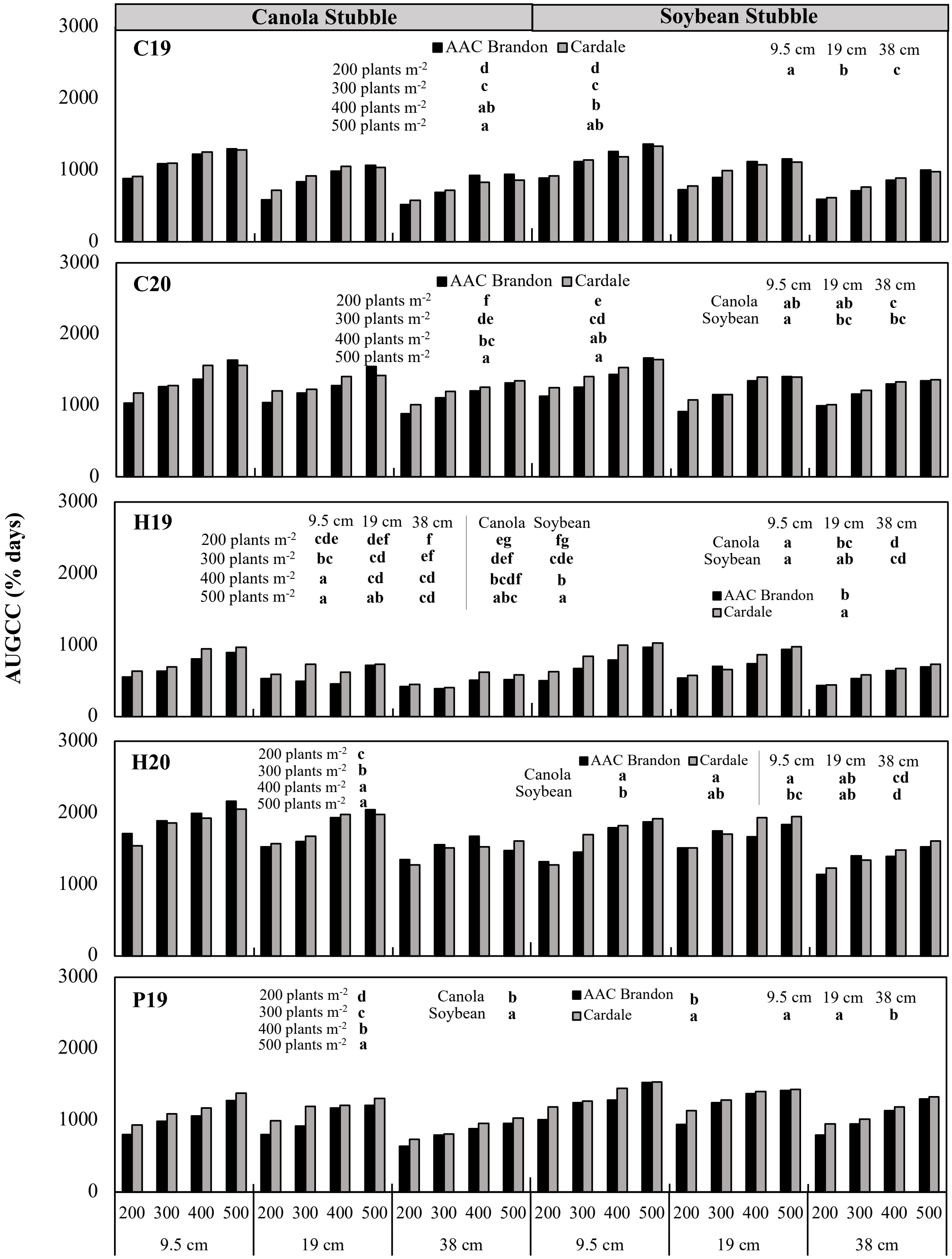

Figure 4.8 Area under the ground cover curve (AUGCC) (% days) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at four seeding densities (200, 300, 400, and 500 plants m^{-2}) and three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on AUGCC. An interaction effect is the effect of two or more independent variables on AUGCC.

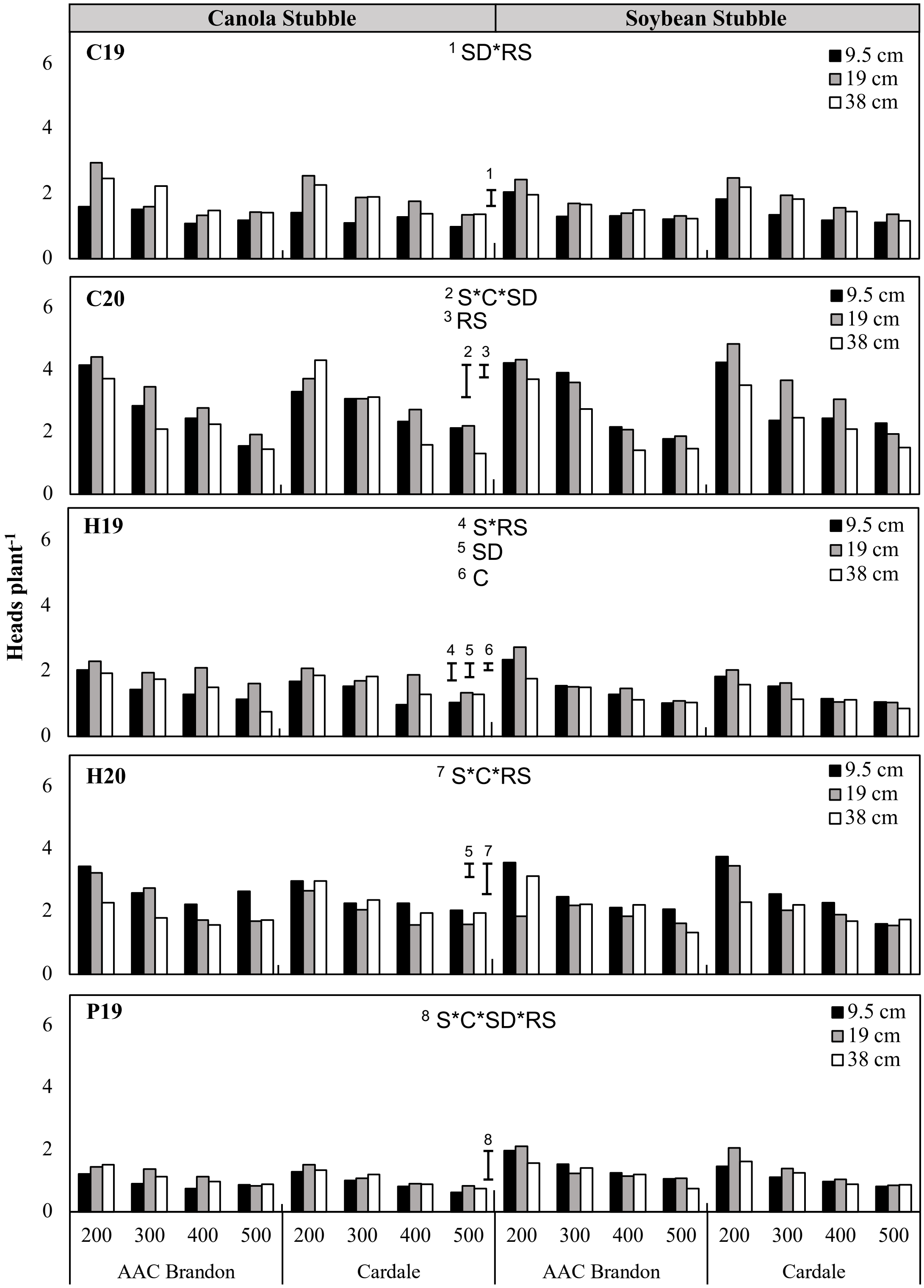

Figure 4.9 Heads plant^{-1} of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at four seeding densities (200, 300, 400, and 500 plants m^{-2}) and three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within each site-year, bold vertical lines indicate the mean difference of Tukey's HSD test ($p < 0.05$). The superscript above the line corresponds to the effect with the same superscript.

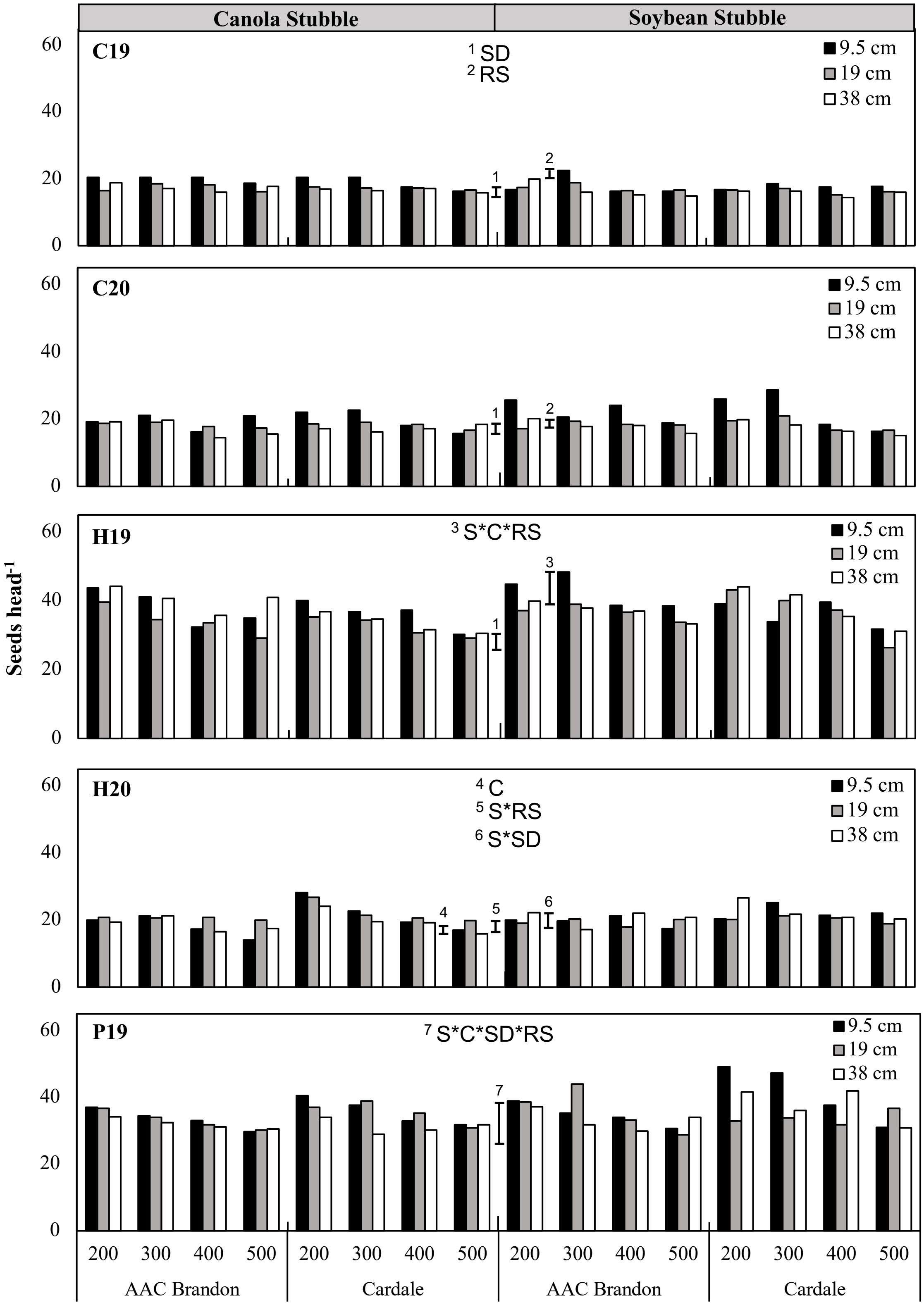

Figure 4.10 Seeds head^{-1} of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at four seeding densities (200, 300, 400, and 500 plants m^{-2}) and three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within each site-year, bold vertical lines indicate the mean difference of Tukey's HSD test ($p < 0.05$). The superscript above the line corresponds to the effect with the same superscript.

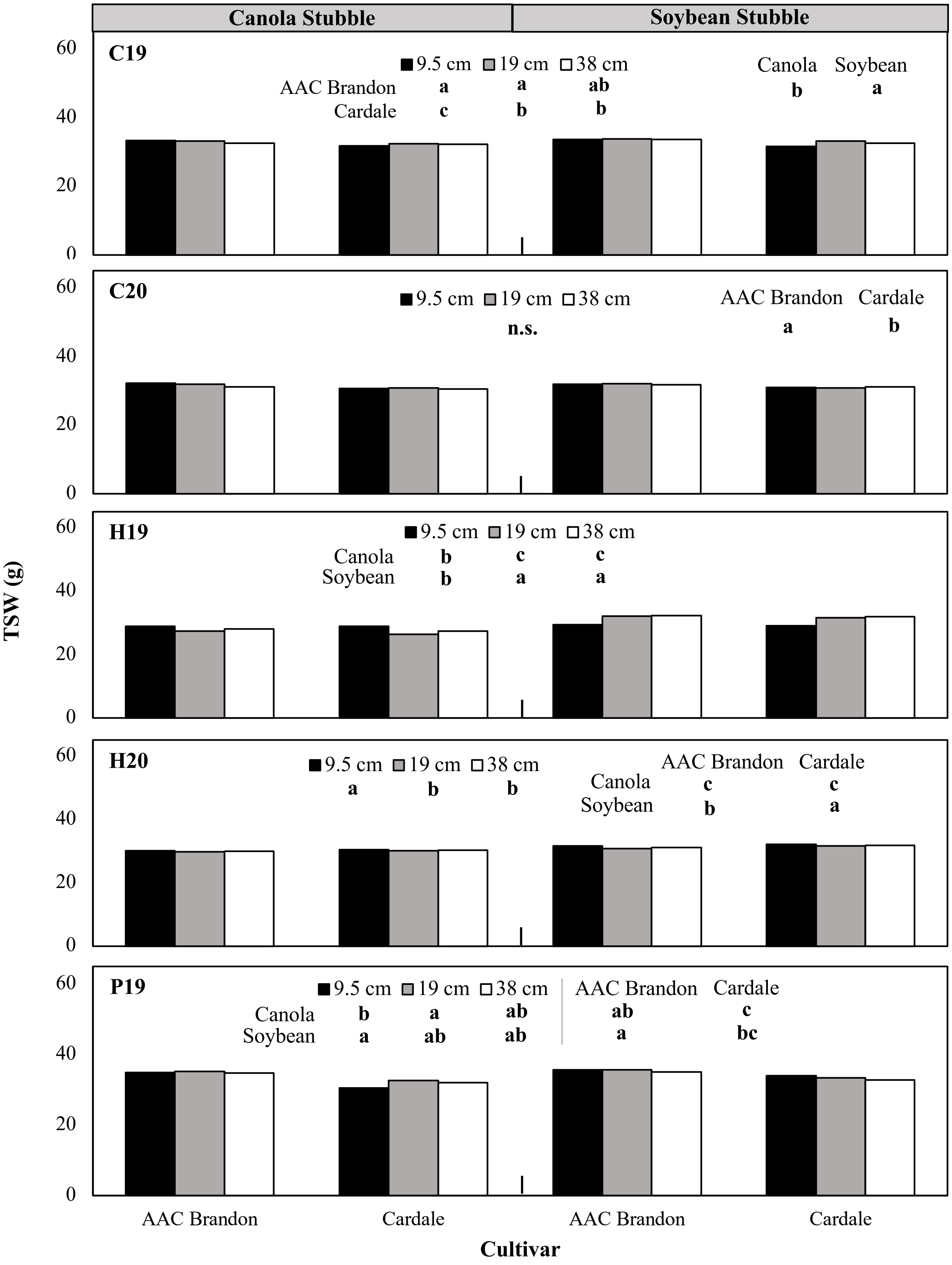

Figure 4.11 Thousand-seed weight (TSW) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on TSW. An interaction effect is the effect of two or more independent variables on TSW.

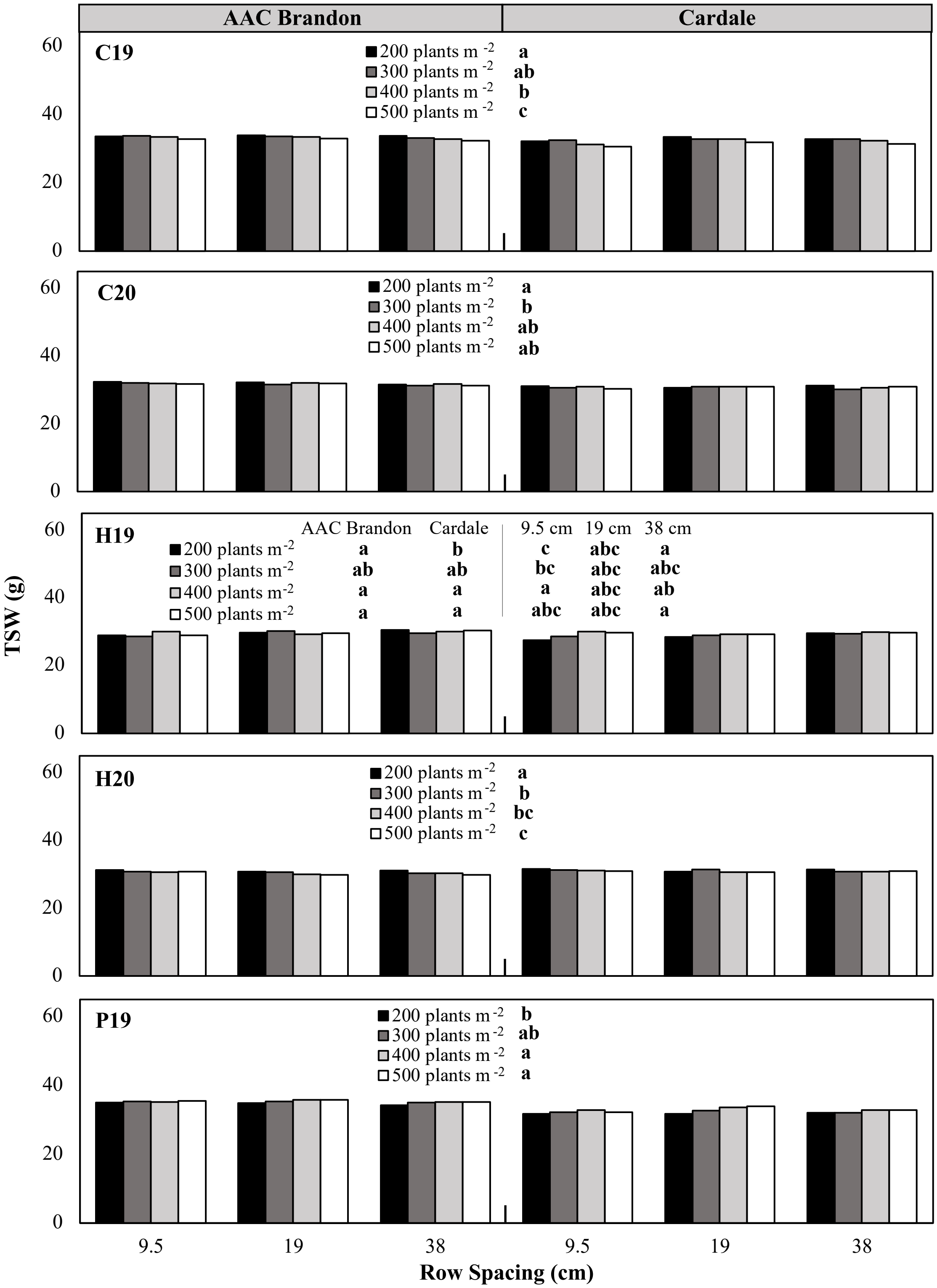

Figure 4.12 Thousand-seed weight (TSW) of AAC Brandon and Cardale spring wheat seeded at three row spacings (9.5, 19, and 38 cm) and four seeding densities (200, 300, 400, and 500 plants m^{-2}) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p <$ 0.05). A main effect is the effect of one independent variable on TSW. An interaction effect is the effect of two or more independent variables on TSW.

Howden 2019. Seedling emergence was the greatest in canola stubble when spring wheat was seeded at the narrowest (9.5 cm) row spacing compared with the 19 cm or 38 cm row spacings (Figure 4.6). When spring wheat was grown in soybean stubble, row spacing did not affect seedling emergence. Final ground cover in canola stubble at the 9.5 cm row spacing was 13% and 33% greater compared with the 19 cm and 38 cm row spacings, respectively (Figure 4.7). In soybean stubble, final ground cover was 19% greater at the 9.5 cm or 19 cm row spacings compared to the 38 cm row spacing. Full canopy closure was observed in soybean stubble at the 9.5 cm and 19 cm row spacings, but the rate of canopy closure was the same (Figure 4.8). In canola stubble, all three row spacing treatments failed to achieve complete canopy closure at BBCH 31. Spring wheat plants were compensating for the reduced plant density at the 19 cm row spacing in canola stubble by producing on average 0.48 more heads plant^{-1} at this row spacing compared with the 9.5 cm row spacing (Figure 4.9). In addition, in canola stubble AAC Brandon spring wheat produced on average 6.1 more seeds head^{-1} at the 38 cm row spacing compared with the 19 cm row spacing (Figure 4.10). When Cardale spring wheat was seeded in canola stubble, row spacing did not influence the number of seeds head^{-1}. In soybean stubble, the number of heads plant^{-1} and seeds head^{-1} produced by spring wheat did not vary with changes in row spacing (Figure 4.9, Figure 4.10). Howden 2019 received the least amount of precipitation in June among all site-years, which likely limited the number of heads plant^{-1} produced by spring wheat in canola stubble and contributed to the lack of response in soybean stubble. In July, Howden 2019 received the greatest amount of precipitation among all site-years, although a 1.7 g decrease in thousand-seed weights was still observed at the 19 cm or 38 cm row spacing compared with the 9.5 cm row spacing, likely due to the increased number of heads plant^{-1} and seeds head^{-1} at these two row spacings (Figure 4.11). The opposite occurred in soybean stubble, as TSWs were on average 2.7 g greater when spring wheat was seeded at a row spacing of either 19 cm or 38 cm, compared with when seeded at the narrowest row spacing of 9.5 cm.

At Howden 2019, seed yield was the greatest in canola stubble at the 9.5 cm or 19 cm row spacing compared with the 38 cm row spacing (Figure 4.1). These results indicate that as row spacing increased, the reduction in plants m^{-2} could not be compensated for by the increased number of heads plant^{-1} and seeds head^{-1}, even with the above-average precipitation received in July. In soybean stubble, seed yield was the greatest at the 19 cm row spacing and the lowest at the 38 cm row spacing. Row spacing did not influence the number of plants m^{-2}, heads plant^{-1}, or seeds head^{-1}, and TSW was greatest at the 19 cm and 38 cm row spacings, so the seed yield result remains unexplained. However, spring wheat failed to achieve complete canopy closure at the 38 cm row spacing, which may have contributed to the reduced seed yield, as complete canopy cover was achieved at the 9.5 cm and 19 cm row spacing treatments.

Howden 2020. This was the only site-year where the effect of row spacing on seedling emergence was not modified by stubble type (Table 4.9). Seedling emergence was unexpectedly greater at either 19 cm or 38 cm row spacings compared with the 9.5 cm row spacing (Figure 4.6). This result remains unexplained as it would be expected that emergence would decrease at wider row spacings, although precipitation received throughout the preceding fall and winter was above-average. Final ground cover results showed a three-way interaction among stubble type, seeding density, and row spacing (Table 4.10). This interaction contributed little to the interpretation of the results, as it was only marginally significant (p = 0.0445). As a result, the letter means separation was not displayed or discussed. See appendix for further details (Appendix 8.2a). Similar to Howden 2019, the number of heads plant^{-1} and seeds head^{-1} produced by spring wheat were more responsive to row spacing changes when spring wheat was seeded in canola stubble compared with soybean stubble. The number of heads plant^{-1} produced by AAC Brandon spring wheat seeded in canola stubble gradually decreased from 2.7 to 1.8 as row spacing increased from 9.5 cm to 38 cm (Figure 4.9). This greater number of heads plant^{-1} at the narrower (9.5 cm) row spacing indicates that the AAC Brandon plants were compensating for the lower plant population as indicated by the reduced seedling emergence or that under the more uniform spatial arrangement, these plants had sufficient resources to produce more heads. There were no differences in the number of heads plant^{-1} produced by spring wheat seeded into any other stubble type, cultivar, and row spacing combination. Spring wheat seeded in canola stubble at the 19 cm row spacing produced on average 2.2 more seeds head^{-1} compared with the 38 cm row spacing (Figure 4.10). At a row spacing of 9.5 cm, no significant differences in seeds head^{-1} were observed compared with the other row spacing treatments. In contrast, row spacing did not influence the number of seeds head^{-1} produced by spring wheat seeded in soybean stubble. Spring wheat thousand-seed weight (TSW) was on average 0.41 g greater when spring wheat seeded at the narrowest (9.5 cm) row spacing compared with at the wider, 19 cm or 38 cm row spacings (Figure 4.11).

At Howden 2020, seed yield was the greatest in canola stubble at the 9.5 cm or 19 cm row spacing compared with the 38 cm row spacing (Figure 4.1). These results indicate that as row spacing increased, even though plants m^{-2} increased, the following reduction in the number of heads $plant^{-1}$, seeds $head^{-1}$, and TSW ultimately caused a reduction in seed yield at the wide (38 cm) row spacing. In soybean stubble, seed yield was the greatest at the 19 cm row spacing and lowest at the 9.5 cm or 38 cm row spacing. Row spacing did not influence the number of heads $plant^{-1}$ or seeds $head^{-1}$ for spring wheat seeded in soybean stubble. In addition, seedling emergence was greatest at the 19 cm and 38 cm row spacing, and TSW was the lowest at the 19 and 38 cm row spacing, so this seed yield result remains unexplained.

Portage la Prairie 2019. This is the only site-year where the seed yield variable had a significant seeding density*row spacing interaction (Table 4.3), so the yield components will be discussed in Section 4.2.3.

General Results. Seedling emergence decreased as row spacing increased at all 2019 site-years, whereas the opposite was true at all 2020 site-years. This was likely due to the total precipitation throughout the preceding fall and winter being especially high prior to the 2020 growing season, leading to increased soil moisture recharge. Stubble type had a large influence on seedling emergence. Seedling emergence was more responsive to row spacing in canola stubble compared with soybean stubble. In addition, the number of heads $plant^{-1}$ and seeds $head^{-1}$ were generally more responsive to row spacing changes when seeded in canola stubble compared with soybean stubble. These results were unexpected as spring wheat seed yield was more responsive to changes in row spacing when seeded in soybean stubble compared with canola stubble. Spring wheat seeded at the widest (38 cm) row spacing consistently did not achieve full canopy closure among the site-years. This result was expected as plants at wider row spacings occupy a smaller portion of the soil surface when compared with plants at narrower row spacings.

4.2.3 Effects of Seeding Density on Yield Components & Ground Cover

Seeding density was an important variable explaining differences among the four yield components - plant density (Table 4.9), head number per plant (Table 4.10), seed number per head (Table 4.11), and thousand-seed weight (Table 4.12). The response of these variables to changes in seeding density was assessed within each site-year to better understand why seeding density had such a limited effect on seed yield.

In addition, seeding density was an important variable in explaining differences in final ground cover at BBCH 31 and the area under the ground cover curve (AUGCC) in these experiments (Table 4.10). As expected, increasing plant densities generally resulted in increased final ground cover (Figure 4.7). Ground cover also occurred more rapidly in the higher seeding density treatments when compared with the lower seeding density treatments (Figure 4.8).

The mean actual plant stand densities were similar to or slightly lower than the target plant densities at the lower seeding density treatments among the site-years (Figure 4.6). In the higher seeding density treatments, the mean actual plant stand densities were much lower than the target densities but still resulted in the greatest mean plant densities among the site-years. Thus, at all site-years, as seeding density increased from 200 to 500 target plants m^{-2}, seedling emergence increased.

Carman 2019. Final ground cover increased by 6% at seeding densities of 300, 400, or 500 target plants m^{-2} compared with 200 target plants m^{-2} (Figure 4.7), although all four seeding density treatments failed to achieve complete canopy closure at BBCH 31. As mentioned previously, the number of heads plant^{-1} produced by spring wheat in each row spacing treatment was influenced by seeding density (Table 4.10). Within each row spacing treatment, heads plant^{-1} gradually decreased as seeding density increased (Figure 4.9). This result indicates that the spring wheat plants were producing more heads plant^{-1} at the lower seeding density treatments to compensate for the reduced number of plants m^{-2}. The number of seeds head^{-1} did not vary considerably with increases in seeding density, as spring wheat seeded at 400 or 500 target plants m^{-2} only had 1.6 fewer seeds head^{-1} compared with being seeded at 300 target plants m^{-2} (Figure 4.10). At 200 plants m^{-2}, no significant differences in seeds head^{-1} were observed compared with the other seeding density treatments. Thousand-seed weight (TSW) gradually decreased by 1.3 g as seeding density increased from 200 to 500 target plants m^{-2} (Figure 4.12), and this seeding density main effect contributed to a large portion of the total variation in TSW within the site-year (15.8%) (Table 4.14).

At Carman 2019, seeding density did not influence seed yield. These results suggest that spring wheat plants directly compensated for the lower plant densities by increasing the number of heads plant^{-1}, seeds head^{-1}, and primarily increasing TSW. Carman 2019 received a greater amount of precipitation in July and August compared to May and June, which is likely why compensation was greater by this late-season yield component.

Carman 2020. Spring wheat seeded at a seeding density of 400 or 500 target plants m^{-2} had an average of 5% and 3% greater final ground cover compared with a seeding density of 200 and 300 target plants m^{-2}, respectively (Figure 4.7). Although, all four seeding density treatments failed to achieve complete canopy closure at BBCH 31. The number of heads plant^{-1} produced by spring wheat was influenced by cultivar and stubble type, although in each cultivar and stubble type combination, the number of heads plant^{-1} gradually decreased as seeding density increased from 200 to 500 target plants m^{-2} (Figure 4.9). Similar to Carman 2019, this result indicates that the spring wheat plants were producing more heads plant^{-1} at the lower seeding density treatments to compensate for the reduced number of plants m^{-2}. Also similar to Carman 2019, the number of seeds head^{-1} did not vary considerably with increases in seeding density, as spring wheat seeded at a seeding density of 400 or 500 target plants m^{-2} only had 2.8 fewer seeds head^{-1} compared with a seeding density of 200 or 300 target plants m^{-2} (Figure 4.10). The effect of seeding density on thousand-seed weight (TSW) was inconsistent, as spring wheat seeded at 200 target plants m^{-2} produced TSWs on average 0.39 g larger than at a seeding density of 300 target plants m^{-2}, but spring wheat at 400 or 500 target plants m^{-2} produced the same TSWs as spring wheat at 200 or 300 target plants m^{-2} (Figure 4.12).

At Carman 2020, seeding density did not influence seed yield. These results suggest that the spring wheat plants directly compensated for the lower plant densities by increasing the number of heads plant^{-1} and, to a lesser extent, the number of seeds head^{-1}. More precipitation was received in June than July and August, leading to this components seed yield response.

Howden 2019. Narrow row spacings combined with increased seeding densities resulted in significantly greater final ground cover and more rapid ground cover when compared with wide row spacings at lower seeding densities (Figure 4.7, Figure 4.8). Despite Howden 2019 receiving the greatest amount of growing season precipitation among all the site-years, primarily in July, heads plant^{-1} and seeds head^{-1} gradually decreased as seeding density increased, similar to Carman 2019 and Carman 2020. The number of heads plant^{-1} decreased from 2.0 to 1.1, and the number of seeds head^{-1} decreased by 6.7 as seeding density increased from 200 to 500 target plants m^{-2} (Figure 4.9, Figure 4.10). The significant effect of seeding density on heads plant^{-1} and seeds head^{-1} contributed to a large portion of the total variation with the site-year (27.7% and 15.1%, respectively) (Table 4.12, Table 4.13). As seeding density increased from 200 to 400 target plants m^{-2} for spring wheat seeded in the narrowest row spacing of 9.5 cm, thousand-seed weights (TSW) increased by 1.7 g (Figure 4.12). Thousand-seed weight was not influenced at 19 cm or 38 cm row spacings as seeding density increased from 200 to 500 target plants m^{-2}.

At Howden 2019, seeding density did not influence seed yield. These results suggest that spring wheat plants directly compensated for the lower plant densities and TSWs by an increase in the number of heads plant^{-1} and seeds head^{-1}.

Howden 2020. As mentioned previously (Section 4.2.2), final ground cover results showed a three-way interaction among stubble type, seeding density, and row spacing (Table 4.10). The letter means separation was not displayed or discussed. See appendix for further details (Appendix 8.2a). Similar to Carman 2019, Carman 2020, and Howden 2019, at Howden 2020 heads plant^{-1} gradually decreased as seeding density increased. The number of heads plant^{-1} decreased from 3.0 to 1.8 (Figure 4.9). The main effect of seeding density on heads plant^{-1} contributed to a large portion of the total variation within the site-year (28.9%) (Table 4.12). The number of seeds head^{-1} produced by spring wheat were more responsive to seeding density changes when spring wheat was seeded in canola stubble compared with soybean stubble at (Figure 4.10). As seeding density increased from 200 to 500 target plants m^{-2} for spring wheat seeded in canola stubble, seeds head^{-1} gradually decreased by 5.8. In contrast, the number of seeds head^{-1} produced by spring wheat seeded in soybean stubble did not vary with seeding density changes. Thousand-seed weight (TSW) gradually decreased by an average of 0.66 g as seeding density increased from 200 to 500 target plants m^{-2} (Figure 4.12).

At Howden 2020, the greatest seed yields were observed at seeding densities of 200 or 400 target plants m^{-2}, and the lowest seed yields occurred at a seeding density of 500 target plants m^{-2}, while a seeding density of 300 target plants m^{-2} showed no significant yield difference compared with all other seeding densities. These results indicate that spring wheat plants compensated for the lower plant densities by increasing heads plant^{-1}, seeds head^{-1}, and TSW. Although, the seed yield results at a seeding density of 300 and 400 target plants m^{-2} remain unexplained.

Portage la Prairie 2019. This is the only site-year where the seed yield variable had a significant seeding density*row spacing interaction (Table 4.3). Seedling emergence was the greatest in canola stubble when spring wheat was seeded at the narrowest (9.5 cm) row spacing compared with the 19 cm and 38 cm row spacings. Row spacing did not affect seedling emergence in soybean stubble. Narrow row spacings combined with increased seeding densities resulted in significantly greater final ground cover and more rapid ground cover when compared with wide row spacings at lower seeding densities (Figure 4.7, Figure 4.8). The results for the number of heads plant^{-1} and seeds head^{-1} showed four-way interactions among row spacing, seeding density, stubble type, and cultivar (Table 4.10, Table 4.11). These interactions were discussed briefly as they only accounted for 1.6% and 2.9% of the total variation within the site-year, respectively. When seeded in canola stubble, the number of heads plant^{-1} and seeds head^{-1} produced by AAC Brandon or Cardale did not vary as seeding density increased from 200 to 500 target plants m^{-2} in all three row spacings (Figure 4.9, Figure 4.10). In contrast, when seeded in soybean stubble, AAC Brandon produced a greater number of heads plant^{-1} at the lowest seeding density of 200 target plants m^{-2} at the 9.5 cm or 19 cm row spacing compared with the greatest seeding density of 500 plants m^{-2} at any of the three row spacing treatments (Figure 4.9). Cardale produced a greater number of heads plant^{-1} at the lowest seeding density of 200 plants m^{-2} at the 19 cm row spacing compared with a seeding density of 400 or 500 target plants m^{-2} at any row spacing treatment. The number of seeds head^{-1} produced by AAC Brandon spring wheat did not vary with changes in seeding density or row spacing in soybean stubble (Figure 4.10). Whereas Cardale spring wheat seeded in soybean stubble at the 9.5 cm row spacing at 200 or 300 target plants m^{-2} produced on average 17 more seeds head^{-1} compared with a seeding density of 500 target plants m^{-2} at the 9.5 cm or 38 cm row spacing. Spring wheat TSWs were on average 1.2 g greater when seeded in canola stubble at the 19 cm row spacing compared with the 9.5 cm row spacing (Figure 4.11). No significant differences in TSW were observed at the 38 cm row spacing compared with the 9.5 cm and 19 cm row spacings. In soybean stubble, row spacing did not influence TSW. As seeding density increased from 200 to 500 target plants m^{-2}, TSWs gradually increased by 1.0 g (Figure 4.12).

At Portage la Prairie 2019, seed yield was the greatest at 9.5 cm or 19 cm row spacings, specifically at the lower seeding densities of 200 or 300 target plants m^{-2}, compared with at the 38 cm row spacing at any seeding density (Figure 4.2). These results indicate that although plants m^{-2} increased as seeding density increased, the resulting decrease in seedling emergence at the wider (38 cm) row spacing, followed by a decrease in the number of heads $plant^{-1}$, could not be compensated for by the increase in seeds $head^{-1}$ and TSW.

General Results. Higher seeding density treatments resulted in greater plant densities, which translated into increased and more rapid ground cover, although this generally did not result in greater spring wheat seed yields in these experiments. The number of heads $plant^{-1}$ decreased as seeding density increased at all site-years. This result was expected due to the strong negative correlation observed between plant density and the number of heads $plant^{-1}$ (Table 4.7, Table 4.8). Additionally, the number of seeds $head^{-1}$ decreased as seeding density increased at most site-years. This result was also expected due to the negative correlation observed between plant density and the number of seeds $head^{-1}$ (Table 4.7, Table 4.8). The effects of seeding density on TSWs were inconsistent among the site-years, although this result was expected due to the inconsistent correlations between plant density and TSW. Thus, lower plant densities were principally compensated for by an increase in head density (heads $plant^{-1}$) and, to a lesser extent, by an increase in seed density (seeds $head^{-1}$). When decreases in seed yield were observed as seeding density increased, it was likely driven by a decrease in the number of seeds $head^{-1}$.

4.2.4 Cultivar Differences

Seedling Emergence. Cardale spring wheat had greater overall seedling emergence when compared with AAC Brandon spring wheat at three of the five site-years (Table 4.14). Both cultivars have a medium kernel size (Cuthbert et al., 2017; Fox et al., 2013). At Carman, Howden, and Portage la Prairie 2019, Cardale spring wheat seedling emergence was on average 4.9%, 15.9%, and 8.3% greater than AAC Brandon spring wheat seedling emergence, respectively. Seedling emergence at Carman 2020 and Howden 2020 was the same between both cultivars. Greater Cardale seedling emergence likely contributed to Cardale spring wheat achieving greater final ground cover at BBCH 31, and occasionally more rapid ground cover than AAC Brandon spring wheat (Figure 4.7, Figure 4.8). Cardale spring wheat achieved 2% to 5% greater final ground cover among all site-years, excluding Carman 2019, compared with AAC Brandon spring wheat (Figure 4.7). At Howden 2019 and Portage la Prairie 2019, Cardale spring wheat achieved canopy closure more rapidly than AAC Brandon spring wheat (Figure 4.8). However, greater seedling emergence and increased and more rapid ground cover generally did not result in greater seed yield in Cardale spring wheat (Figure 4.1).

Table 4.14 Mean plant density (plants m^{-2}) in each spring wheat cultivar at each site-year. Means followed by different letters within each column are significantly different (Tukey's HSD, $p < 0.05$).

	Carman		Howden		Portage la Prairie
Cultivar	2019	2020	2019	2020	2019
	------------------------- Plant Density (plants m^{-2}) -------------------------				
AAC Brandon	278 **b**	238 **a**	209 **b**	310 **a**	249 **b**
Cardale	292 **a**	233 **a**	242 **a**	299 **a**	270 **a**

Head Density (heads plant^{-1}) and Seed Density (seeds head^{-1}). AAC Brandon and Cardale produced a similar number of heads plant^{-1} and seeds head^{-1} within the majority of the site-years. Although, at Howden 2019, a cultivar main effect on the number of heads plant^{-1} was observed. AAC Brandon spring wheat produced on average 0.15 more heads plant^{-1} than Cardale spring wheat (Figure 4.9). At Howden 2020, a cultivar main effect on the number of seeds head^{-1} was observed. Cardale spring wheat produced on average 1.9 more seeds head^{-1} compared with AAC Brandon spring wheat (Figure 4.10).

Thousand-Seed Weight (TSW). The TSW of AAC Brandon spring wheat was generally greater than the TSW of Cardale spring wheat, likely due to genetic differences. The TSWs of AAC Brandon were on average 1.0 g greater than the TSWs of Cardale at Carman 2020 (Figure 4.11). At Portage la Prairie 2019, AAC Brandon TSWs were 3.2 g and 2.0 g greater than Cardale TSWs when grown in canola and soybean stubble, respectively. Cardale TSW was more responsive to seeding density changes compared with AAC Brandon TSW at Howden 2019 (Figure 4.12). Cardale TSWs were on average 1.2 g greater when seeded at higher seeding densities of 400 or 500 target plants m^{-2} compared with the lowest seeding density of 200 target plants m^{-2}. Seeding density did not influence AAC Brandon TSWs. Although, AAC Brandon TSWs were on average 1.3 g greater than Cardale TSWs at a seeding density of 200 target plants m^{-2}. No other differences in TSW occurred among cultivars at seeding densities of 300 to 500 target plants m^{-2}. The one instance where Cardale produced greater TSWs compared with AAC Brandon occurred at Howden 2020 (Figure 4.11). Cardale seeded in soybean stubble produced TSWs that were on average 0.65 g greater when compared with AAC Brandon TSWs. When seeded in canola stubble, cultivar did not influence TSW.

Plasticity. It is evident from the results in the present study that Cardale spring wheat is more plastic than AAC Brandon spring wheat. Among the site-years that received a greater amount of precipitation in July and August compared with May and June (Carman 2019, Howden 2019, Portage la Prairie 2019), the late yield components (seeds head^{-1}, thousand-seed weight) of Cardale were more responsive among row spacing and seeding density treatments, compensating for limitations to productivity earlier in the growing season. The late yield components of AAC Brandon remained constant among row spacing and seeding density treatments. At Carman 2019, Cardale produced greater TSWs at the 19 cm or 38 cm row spacing compared with the 9.5 cm row spacing, whereas AAC Brandon TSWs did not vary among row spacing treatments (Figure 4.11). At Howden 2019, Cardale produced greater TSWs at the higher seeding density treatments (400 or 500 target plants m^{-2}), but AAC Brandon TSWs remain constant among seeding density treatments (Figure 4.12). Additionally, at Portage la Prairie 2019, Cardale produced a greater number of seeds head^{-1} at the 9.5 cm row spacing at 200 or 300 target plants m^{-2}, whereas the number of seeds head^{-1} produced by AAC Brandon did not vary with changes in seeding density or row spacing (Figure 4.10).

4.3 Harvest Index

4.3.1 Harvest Index Response to Row Spacing

Row spacing was the most important variable in explaining differences in harvest indices within the site-years (0.86% - 26.0% of the total variation) (Table 4.15). The harvest index (HI) of spring wheat was generally greater when seeded at narrower, 9.5 cm or 19 cm row spacings, compared with the wider, 38 cm row spacing (Figure 4.13). As row spacing increased from 9.5 cm to 38 cm, HI gradually decreased by an average of 0.06 and 0.10 at Carman 2019 and Carman 2020, respectively. At Howden 2020, HI decreased by an average of 0.03 as row spacing increased from 19 cm to 38 cm. The HI of spring wheat seeded at the 9.5 cm row spacing did not vary from the 19 cm or 38 cm row spacings. Lower HI at the wider row spacing (38 cm) suggests that spring wheat was under greater stress, such as moisture stress. Moisture stress was evident among these three site-years, as indicated by the reduced number of seeds head^{-1} at the 38 cm row spacing compared with the 9.5 cm and 19 cm row spacings. Thus, spring wheat plants seeded at narrower (9.5 cm or 19 cm) row spacings were growing in an environment that promoted greater HI, translating into improved spring wheat seed yields (Figure 4.1).

Table 4.15 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable harvest index at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS
Stubble Type (S)	0.7344	0.31	0.3677	1.54	0.7024	0.69	0.9301	0.05	0.8085	0.56
Cultivar (C)	**0.0455**	1.54	0.5505	0.13	0.2680	0.49	**0.0328**	3.07	0.7488	0.02
S*C	0.8698	0.01	0.9372	0.00	0.1347	0.90	0.8036	0.04	**0.0055**	1.72
Seeding Density (SD)	**0.0327**	3.40	**0.0039**	4.37	**0.0262**	3.83	0.5437	1.30	**0.0028**	3.20
S*SD	0.8026	0.38	0.6649	0.42	0.6553	0.63	0.2193	3.04	0.7301	0.28
C*SD	0.6877	0.56	0.0679	2.23	0.3433	1.52	0.0944	5.23	0.2081	1.00
S*C*SD	0.1535	2.02	0.4116	0.96	0.7289	0.51	0.3249	2.59	0.6017	0.40
Row Spacing (RS)	**<.0001**	**13.97**	**<.0001**	**25.95**	0.5696	0.45	**0.0338**	4.76	0.1504	0.86
S*RS	0.5690	0.43	0.4116	0.60	0.2840	1.01	0.2007	2.09	0.1200	0.88
C*RS	0.5558	0.45	0.8638	0.10	0.9054	0.08	0.6832	0.50	0.1555	0.76
S*C*RS	0.4819	0.55	0.8124	0.14	0.1435	1.57	0.6443	0.62	**0.0119**	1.87
SD*RS	0.1615	3.55	0.2195	3.31	0.5614	1.86	0.1346	6.72	**0.0223**	3.48
S*SD*RS	0.2536	2.98	0.9332	0.61	0.8224	1.08	0.4450	4.35	0.5705	0.97
C*SD*RS	0.6638	1.55	0.9102	0.57	0.6414	1.92	0.8828	1.46	0.3104	1.63
S*C*SD*RS	0.7341	1.35	0.8130	1.10	0.6383	1.43	0.4794	3.55	**0.0059**	3.95
Rep(S)	.	**14.89**	.	9.31	.	**27.25**	.	**38.00**	.	**53.11**
Residual	.	**52.06**	.	**48.66**	.	**54.78**	.	**84.84**	.	**29.88**

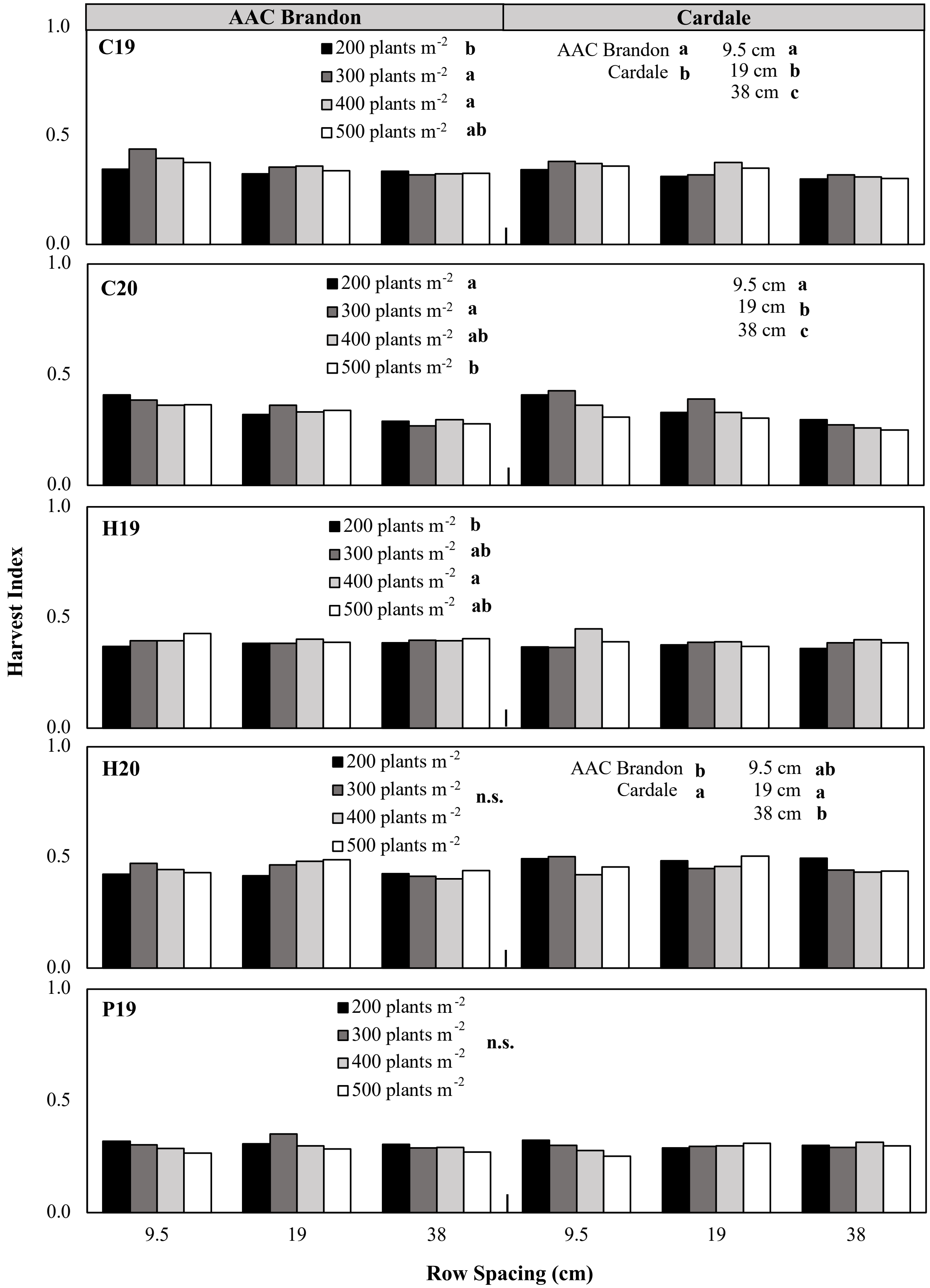

Figure 4.13 Harvest index (HI) of AAC Brandon and Cardale seeded at three row spacings (9.5, 19, and 38 cm) and four seeding densities (200, 300, 400, and 500 plants m^{-2}) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$).

4.3.2 Harvest Index Response to Seeding Density

The effects of seeding density on harvest index (HI) were inconsistent among the site-years (Figure 4.13). At Carman 2020, the HI was 0.04 greater when spring wheat was seeded at a seeding density of 200 or 300 target plants m^{-2}, compared with 500 target plants m^{-2}. The average HI of spring wheat seeded at a seeding density of 400 target plants m^{-2} did not differ from the other three seeding densities. In contrast, at Carman 2019, the HI was 0.03 greater when spring wheat was seeded at a seeding density of 300 or 400 target plants m^{-2}, compared with 200 target plants m^{-2}. The average HI of spring wheat seeded at a seeding density of 500 target plants m^{-2} did not differ from the other three seeding densities. At Howden 2019, the HI was 0.03 greater when spring wheat was seeded at a seeding density of 400 target plants m^{-2} compared with 200 target plants m^{-2}. The average HI of spring wheat seeded at a seeding density of 300 or 500 target plants m^{-2} did not differ from the other two seeding densities. The lack of a large or consistent effect of seeding density on harvest index likely contributed to the lack of a yield-density response in the present study.

4.3.3 Harvest Index Response to Cultivar

The effects of cultivar on harvest index (HI) were also inconsistent among the site-years (Figure 4.13). At Carman 2019, the harvest index (HI) of AAC Brandon spring wheat was 0.02 greater compared with Cardale spring wheat. In contrast, at Howden 2020, the HI of Cardale spring wheat was 0.02 greater compared with AAC Brandon spring wheat. At Portage la Prairie 2019, the HI of spring wheat was influenced by seeding density, row spacing, stubble type, and cultivar. This four-way interaction was discussed briefly as it only accounted for 4.0% of the total variation within the site-year (Table 4.15). Harvest index was more responsive to changes in seeding density, row spacing, and cultivar when spring wheat was seeded in soybean stubble compared with canola stubble. The HI of AAC Brandon spring wheat seeded in soybean stubble at a seeding density of 300 target plants m^{-2}, was on average 0.12 greater at a row spacing of 19 cm (HI = 0.38) compared with a 38 cm row spacing (HI = 0.26). As a result, increased seed yield was observed at Portage la Prairie 2019 when spring wheat was seeded at 300 target plants m^{-2} at row spacing of 19 cm compared with a row spacing 38 cm. No differences between the HI of spring wheat in any other seeding density, row spacing, stubble type, and cultivar combinations (average HI = 0.30) were observed.

4.4 Plant Biomass Production

4.4.1 Plant Biomass Response to Row Spacing

Row spacing, not seeding density, was the most important variable explaining differences in above-ground plant biomass among the treatments within the site-years (1.9% - 22.6% of the total variation) (Table 4.16). A positive relationship was observed within site-years between biomass accumulation and seed yield.

At Carman 2019, spring wheat produced on average 14.4% greater biomass when seeded in the 19 cm row spacing compared with the 9.5 cm or 38 cm row spacings, with no significant biomass differences occurring between the 9.5 cm and 38 cm row spacings (Figure 4.14). This increased biomass contributed to greater seed yield at the 19 cm row spacing compared with the 9.5 cm and 38 cm row spacings.

At Howden 2019, spring wheat seeded in canola and soybean stubble produced 20.2% and 11.9% greater biomass, respectively, when seeded at the narrower, 9.5 cm or 19 cm row spacings compared with the 38 cm row spacing (Figure 4.14). This increased biomass contributed to greater seed yield in canola and soybean stubble at the 9.5 cm or 19 cm row spacings compared with the 38 cm row spacing. Similarly, at Portage la Prairie 2019, spring wheat produced on average 16.3% greater biomass when seeded at the 9.5 cm or 19 cm row spacings compared with the 38 cm row spacing, with no significant biomass differences occurring between the 9.5 cm and 19 cm row spacings. This increased biomass contributed to greater seed yield at the 9.5 cm and 19 cm row spacings compared with the 38 cm row spacing.

At Howden 2020, spring wheat produced on average 10.5% greater biomass when seeded at the 19 cm row spacing compared with the 38 cm row spacing, and seed yield at the 19 cm row spacing was greater compared with the 38 cm row spacing (Figure 4.14). Spring wheat seeded at the 9.5 cm row spacings produced average biomass that did not differ from when seeded at the 19 cm or 38 cm row spacings.

Table 4.16 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable plant biomass at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS
Stubble Type (S)	0.8854	0.12	0.9254	0.02	0.5625	1.44	0.3894	1.12	0.1369	**12.20**
Cultivar (C)	0.5986	0.11	0.2586	0.56	0.9882	0.00	0.3668	0.40	**0.0085**	1.83
S*C	0.5475	0.15	0.7018	0.06	0.0858	0.78	0.2626	0.61	**0.0134**	1.61
Seeding Density (SD)	0.1559	2.18	**0.0279**	4.11	**0.0007**	4.70	0.1617	2.54	0.8768	0.18
S*SD	0.4108	1.18	0.4800	1.09	0.7619	0.30	0.8347	0.42	0.7086	0.36
C*SD	0.5027	0.96	**0.0043**	6.04	0.8254	0.23	0.0967	3.14	0.7375	0.32
S*C*SD	0.3575	1.33	0.3780	1.37	0.9836	0.04	0.1999	2.29	0.3856	0.79
Row Spacing (RS)	**<.0001**	**10.98**	0.1197	1.89	**<.0001**	**22.55**	**0.0007**	4.44	**<.0001**	**12.63**
S*RS	0.2711	0.53	0.5391	0.54	**0.0088**	2.19	0.4971	0.43	0.6117	0.25
C*RS	0.5871	0.64	0.8619	0.13	0.6063	0.19	0.6308	0.37	0.3231	0.58
S*C*RS	0.5198	0.65	0.3089	1.04	0.1733	0.86	0.9226	0.08	0.5767	0.28
SD*RS	0.2298	1.93	0.5532	2.17	0.3311	1.50	0.6456	1.57	0.2328	2.10
S*SD*RS	0.1892	3.14	0.6512	1.84	0.7103	0.79	0.1434	3.66	0.4751	1.43
C*SD*RS	0.2369	1.88	0.5814	2.07	0.5396	1.49	0.6467	1.44	0.2156	2.17
S*C*SD*RS	0.8126	0.87	0.2106	3.74	0.7232	1.15	0.9500	1.01	0.0933	2.86
Rep(S)	.	**21.67**	.	**12.79**	.	**26.35**	.	**10.76**	.	**25.06**
Residual	.	**51.68**	.	**60.52**	.	**35.43**	.	**65.74**	.	**35.35**

4.4.2 Plant Biomass Response to Seeding Density

Seeding density did not influence above-ground plant biomass at the majority of the site-years (Table 4.16). When significant, the effects of seeding density on biomass were observed to be influenced by precipitation. At Carman 2020, as Cardale spring wheat seeding density increased from 200 to 500 target plants m^{-2}, biomass increased by 18.2%, from 9490 kg ha^{-1} to 11217 kg ha^{-1}. Total precipitation throughout the preceding fall and winter was especially high prior to the 2020 growing season, including Carman 2020. This would have led to increased soil moisture recharge. In addition, Carman 2020 received the greatest precipitation in June compared with the other site-years. This likely contributed to the greater biomass observed at the higher plant densities. Although, this increased biomass at the higher plant densities did not increase seed yield. In addition, AAC Brandon biomass remained the same as seeding density increased from 200 to 500 target plants m^{-2}, averaging 9774 kg ha^{-1}. This observation further confirms that Cardale spring wheat is more plastic to agronomic conditions compared with AAC Brandon. At Howden 2019, as seeding density increased from 200 to 500 target plants m^{-2}, biomass decreased by 8.6%, from 8459 kg ha^{-1} to 7789 kg ha^{-1}. Total precipitation throughout the preceding fall and winter was low prior to the 2019 growing season, specifically at Howden 2019. In addition, Howden 2019 received the least amount of precipitation in June compared with the other site-years. The lack of a biomass response, or decrease in biomass, to increased seeding density likely contributed to the lack of a yield-density response in the present study.

4.4.3 Plant Biomass Response to Cultivar

Above-ground plant biomass at BBCH 83 did not differ between the cultivars at the majority of the site-years (Table 4.16). At the one site-year where cultivar did influence biomass (Portage la Prairie 2019), AAC Brandon spring wheat produced 10.1% greater biomass compared with Cardale spring wheat when seeded in soybean stubble (Figure 4.14). AAC Brandon seed yield was greater compared with Cardale seed yield at this site-year. When seeded in canola stubble, there were no significant differences in biomass between the two cultivars.

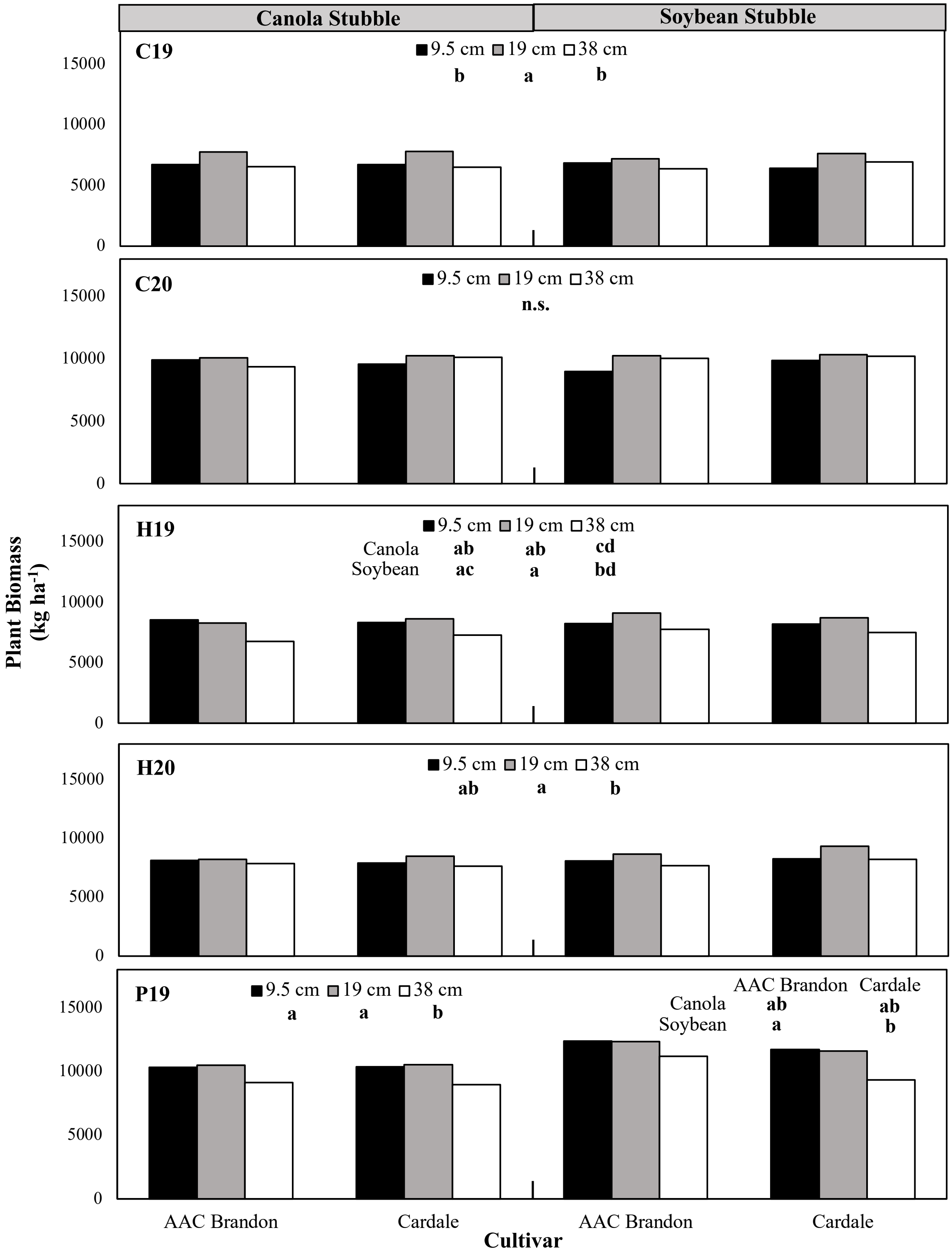

Figure 4.14 Plant biomass (kg ha^{-1}) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on biomass. An interaction effect is the effect of two or more independent variables on biomass.

4.5 Plant Height

4.5.1 Plant Height Response to Cultivar

Cardale spring wheat was consistently taller than AAC Brandon spring wheat (Figure 4.15). Cardale spring wheat was on average 1.9 cm and 6.7 cm taller than AAC Brandon spring wheat at Carman 2019 and Portage la Prairie 2019, respectively. Due to the inherent genetic differences in height between the cultivars, only differences within and trends among the cultivars will be examined (Seed Manitoba, 2021) (Table 4.17). Further observations on plant height can be found in the appendix (Appendix 8.2b).

Table 4.17 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable plant height at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing, and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the % SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS	*p*-value	%SS
Stubble Type (S)	0.2111	4.19	0.7814	0.30	0.1225	**11.67**	**0.0198**	5.71	0.3246	5.83
Cultivar (C)	**0.0125**	2.61	**<.0001**	**46.74**	**<.0001**	**16.57**	**<.0001**	**35.50**	**<.0001**	**35.76**
S*C	0.6534	0.08	0.3156	0.18	0.6954	0.03	0.5195	0.08	0.1179	0.29
Seeding Density (SD)	**0.0005**	7.75	0.7325	0.23	**<.0001**	**10.13**	**<.0001**	7.46	**<.0001**	4.23
S*SD	0.7670	0.47	0.7492	0.21	0.7673	0.20	0.3461	0.67	0.5484	0.25
C*SD	0.9138	0.21	0.3668	0.56	0.2269	0.77	0.1196	1.19	0.6988	0.17
S*C*SD	0.7034	0.57	0.8680	0.13	0.1356	0.98	0.2631	0.81	0.0547	0.91
Row Spacing (RS)	**0.0011**	5.85	0.1028	0.69	**<.0001**	3.77	**<.0001**	5.20	**<.0001**	3.06
S*RS	0.1427	1.61	0.3405	0.44	**<.0001**	4.52	**0.0002**	3.61	0.8339	0.04
C*RS	0.7743	0.21	0.7348	0.07	0.6242	0.16	0.0926	0.95	0.5056	0.16
S*C*RS	0.5801	0.45	**0.0060**	2.48	0.9231	0.03	0.8911	0.04	0.2362	0.34
SD*RS	0.8299	1.15	0.4105	1.37	0.2350	1.42	**0.0154**	3.23	0.4658	0.66
S*SD*RS	0.3495	2.76	0.6242	0.57	0.6429	0.74	0.5551	1.03	0.9245	0.23
C*SD*RS	0.5326	2.08	0.6825	0.67	**0.0266**	2.59	**0.0393**	2.76	0.2916	0.87
S*C*SD*RS	0.8738	0.99	0.6526	0.83	0.8141	0.51	0.7065	0.76	0.4747	0.65
Rep(S)	.	**12.82**	.	**20.36**	.	**21.90**	.	3.41	.	**30.38**
Residual	.	**56.20**	.	**24.18**	.	**24.00**	.	**27.59**	.	**16.16**

Cardale spring wheat height was more responsive to seeding density changes compared with AAC Brandon spring wheat height, another indication that Cardale spring wheat is more plastic to agronomic conditions. At Howden 2019, the height of Cardale spring wheat seeded in the narrowest (9.5 cm) row spacing decreased by an average of 6.7 cm as seeding density increased from 200 to 500 target plants m^{-2} (Figure 4.16). No significant differences in plant height occurred among seeding densities of 200, 300, and 400 target plants m^{-2}. The height of Cardale spring wheat seeded in 19 cm or 38 cm row spacings was not influenced by seeding density. AAC Brandon spring wheat plant height remained the same as seeding density increased from 200 to 500 target plants^{-2} at all three row spacings. At Howden 2020, the height of Cardale spring wheat seeded in the narrowest (9.5 cm) row spacing decreased by an average of 4.9 cm as seeding density increased from 200 to 500 target plants m^{-2}. When seeded in 19 cm row spacings, plant height decreased by 5.4 cm as seeding density increased from 300 to 500 target plants m^{-2}. The height of Cardale spring wheat seeded in 38 cm row spacings was not influenced by seeding density. AAC Brandon spring wheat plant height remained the same as seeding density increased from 200 to 500 target plants m^{-2} within all three row spacings.

Although Cardale spring wheat was observed to have a taller canopy (Figure 4.15) and greater final ground cover (Figure 4.7) compared with AAC Brandon spring wheat, this did not translate to improved seed yield (Figure 4.1). Lodging was not observed in these experiments.

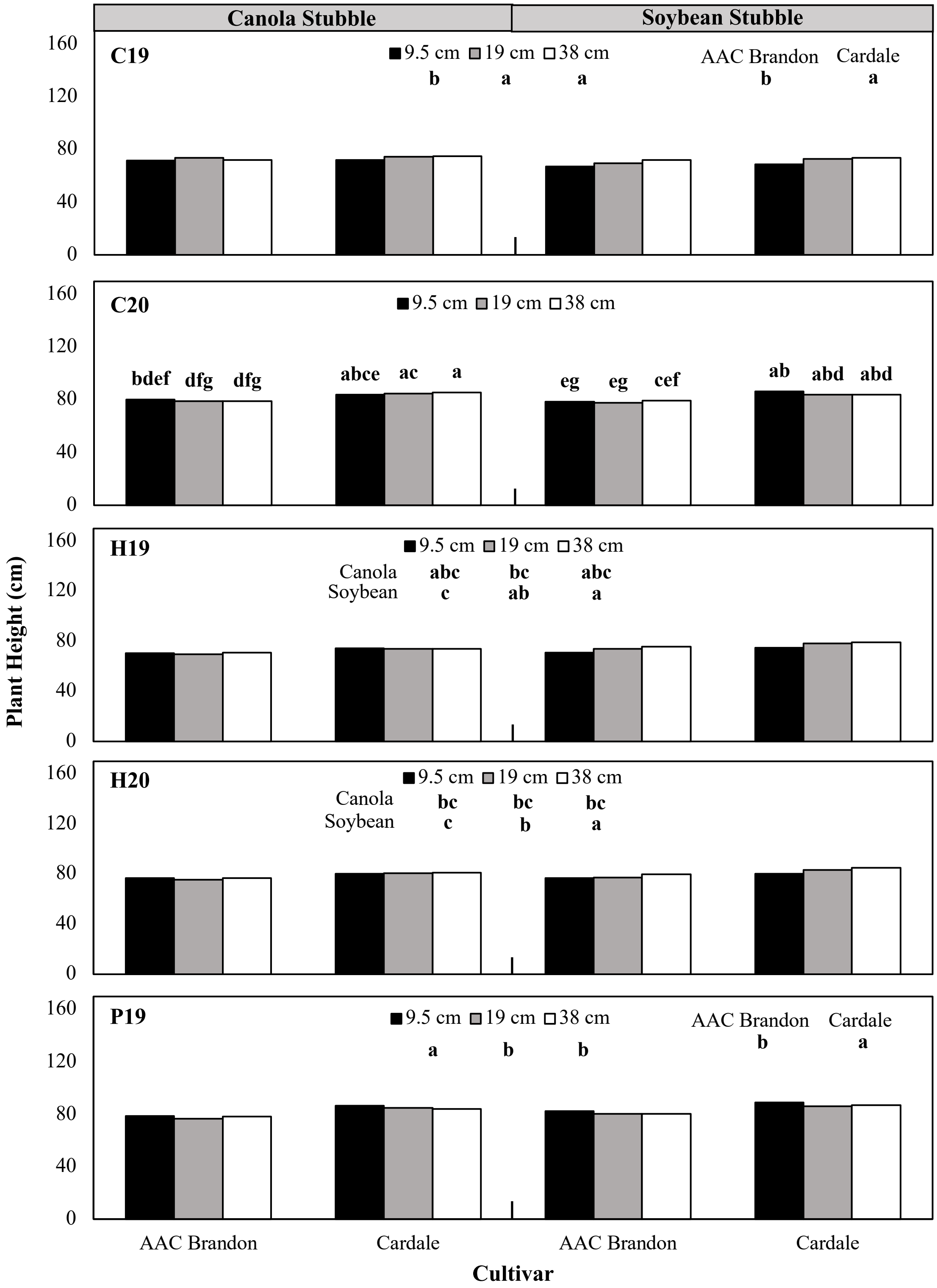

Figure 4.15 Plant height (cm) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) and three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on plant height. An interaction effect is the effect of two or more independent variables on plant height.

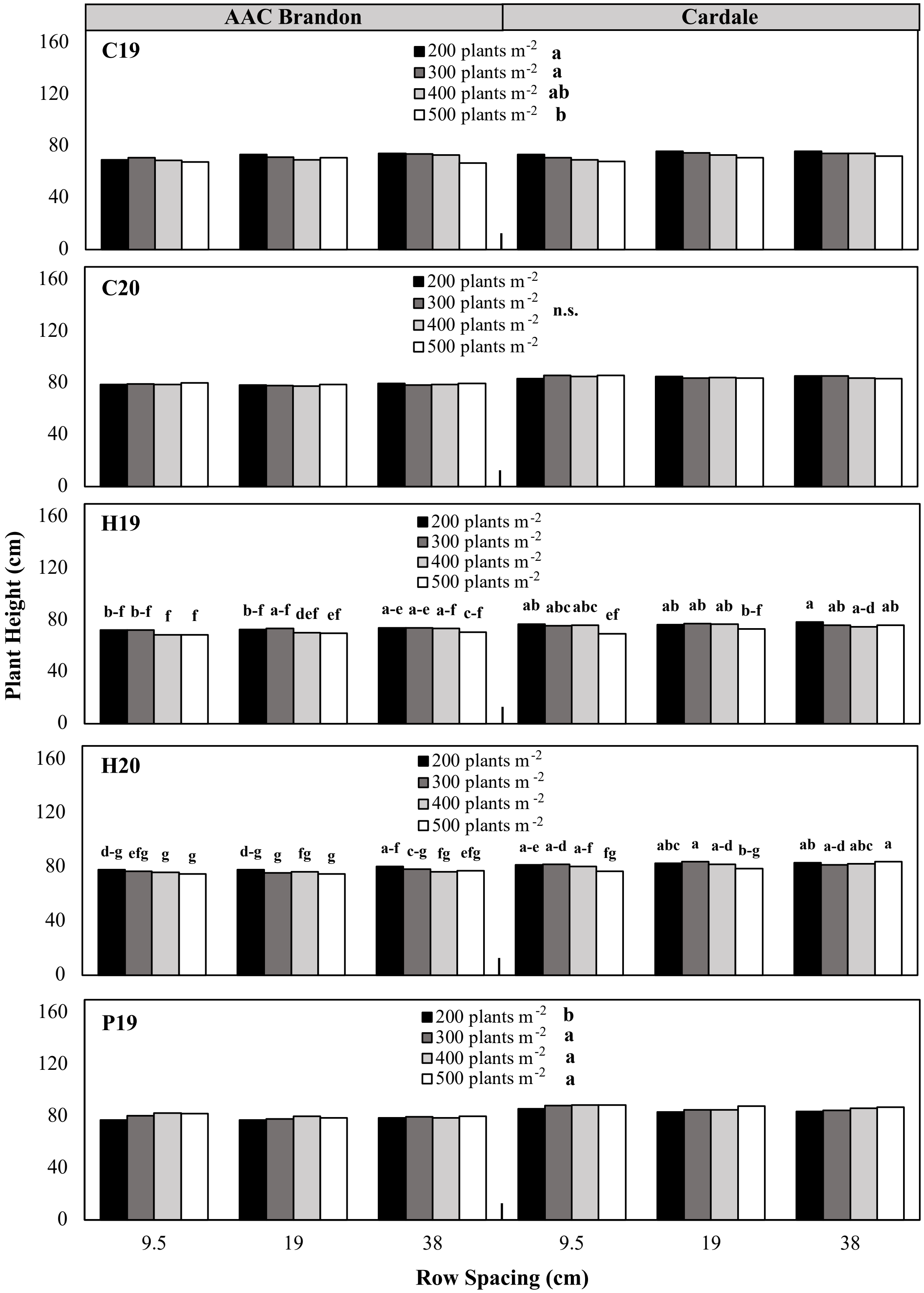

Figure 4.16 Plant height (cm) of AAC Brandon and Cardale spring wheat cultivars seeded at three row spacings (9.5, 19, and 38 cm) and four seeding densities (200, 300, 400, and 500 plants m^{-2}) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on plant height. An interaction effect is the effect of two or more independent variables on plant height.

4.6 Grain Protein

4.6.1 Grain Protein Response to Stubble Type

Stubble type was the most important management technique explaining protein concentration differences within the site-years (21.8% - 55.5% of the total variation) (Table 4.18). Spring wheat consistently produced larger grain protein concentrations at all five site-years when seeded in canola stubble compared with soybean stubble. At Carman 2019, 2020, and Howden 2020, seed protein concentration was 0.72%, 0.87%, and 0.81% greater, respectively, when spring wheat was seeded in canola stubble compared with soybean stubble (Figure 4.17). At Portage la Prairie 2019, AAC Brandon and Cardale spring wheat protein concentrations increased by 1.1% and 0.66%, respectively, when seeded in canola stubble compared with soybean stubble. At Howden 2020, seed protein concentrations were 1.2%, 0.84%, and 0.74% greater at 9.5 cm, 19 cm, and 38 cm row spacings, respectively, when spring wheat was seeded in canola stubble compared with soybean stubble.

Table 4.18 Significance (*p*-value) of the fixed effects and the percentage of the total sum of squares (% SS) for the dependent variable grain protein at each site-year. The model factors included: stubble type, cultivar, seeding density, row spacing and their interactions. Values indicated in bold were *p*-values considered significant at $p < 0.05$ or where the %SS contributed to more than 10% of the total sum of squares.

	Carman				Howden				Portage la Prairie	
	2019		2020		2019		2020		2019	
Effect	p-value	%SS	p-value	%SS	p-value	%SS	p-value	%SS	p-value	%SS
Stubble Type (S)	**0.0012**	**21.77**	**0.0012**	**48.34**	**0.0071**	**46.70**	**0.0001**	**55.51**	**0.0015**	**44.11**
Cultivar (C)	**<.0001**	**11.50**	**<.0001**	5.50	**<.0001**	4.64	**<.0001**	3.97	**<.0001**	4.80
S*C	0.8632	0.01	0.3723	0.11	0.6632	0.03	0.5629	0.03	**0.0477**	0.81
Seeding Density (SD)	0.7065	0.56	**<.0001**	3.83	**0.0009**	2.46	**<.0001**	2.83	**0.0223**	2.02
S*SD	0.8551	0.31	0.9905	0.02	0.9853	0.02	0.3123	0.36	0.8726	0.14
C*SD	0.9821	0.07	0.7804	0.15	**0.0008**	2.49	0.0691	0.74	0.9890	0.02
S*C*SD	0.8527	0.32	0.8572	0.11	0.3402	0.47	0.7674	0.11	0.5856	0.39
Row Spacing (RS)	0.4995	0.56	**<.0001**	8.54	**<.0001**	2.92	**<.0001**	**12.71**	**0.0001**	3.94
S*RS	0.6825	0.31	0.5613	0.17	0.1074	0.82	**<.0001**	3.21	0.1934	0.68
C*RS	0.4918	0.58	0.1224	0.61	0.6762	0.09	0.1845	0.35	0.2219	0.62
S*C*RS	0.9713	0.02	0.3159	0.33	0.2652	0.27	0.4482	0.17	0.3022	0.49
SD*RS	0.9852	0.40	0.3521	0.96	0.2329	1.14	0.1296	1.03	0.2195	1.71
S*SD*RS	0.8679	1.00	0.9044	0.31	0.6788	0.62	0.5875	0.48	0.7795	0.65
C*SD*RS	0.8616	1.02	0.3918	0.90	0.2319	0.86	0.5593	0.52	0.4434	1.19
S*C*SD*RS	0.9030	0.87	0.0785	1.66	0.7178	0.53	0.3919	0.64	0.8543	0.53
Rep(S)	.	5.43	.	8.82	.	**17.21**	.	3.54	.	**10.11**
Residual	.	**55.27**	.	**19.65**	.	**18.72**	.	**13.78**	.	**27.79**

4.6.2 Grain Protein Response to Cultivar

Where differences occurred, Cardale spring wheat consistently had increased grain protein concentrations compared with AAC Brandon spring wheat (Figure 4.17). At Carman 2019, Carman 2020, and Howden 2020, Cardale produced average protein concentrations of 14.5%, 16.6%, and 13.9%, respectively, which were greater than AAC Brandon protein concentrations of 14.0%, 16.4%, and 13.7%, respectively. Carman 2020 received the least amount of precipitation throughout the growing season compared with Carman 2019 and Howden 2020. The production of the high protein wheat at Carman 2020 was likely in response to lower levels of available moisture.

4.6.3 Grain Protein Response to Row Spacing

Small increases in spring wheat protein concentration were observed at wider row spacing treatments, indicating moisture limitations at these wider row spacings (Figure 4.17). At Carman 2020 and Howden 2019, spring wheat seeded at the widest row spacing (38 cm) had on average 0.38% and 0.20% greater protein concentration, respectively, compared with spring wheat seeded at the narrowest row spacings of 9.5 cm or 19 cm. No differences in protein content occurred between the 9.5 cm and 19 cm row spacings. Although, at Portage la Prairie 2019, spring wheat seeded in 9.5 cm and 38 cm row spacings produced the same protein content but had average protein contents that were 0.25% greater compared with spring wheat seeded at the 19 cm row spacing.

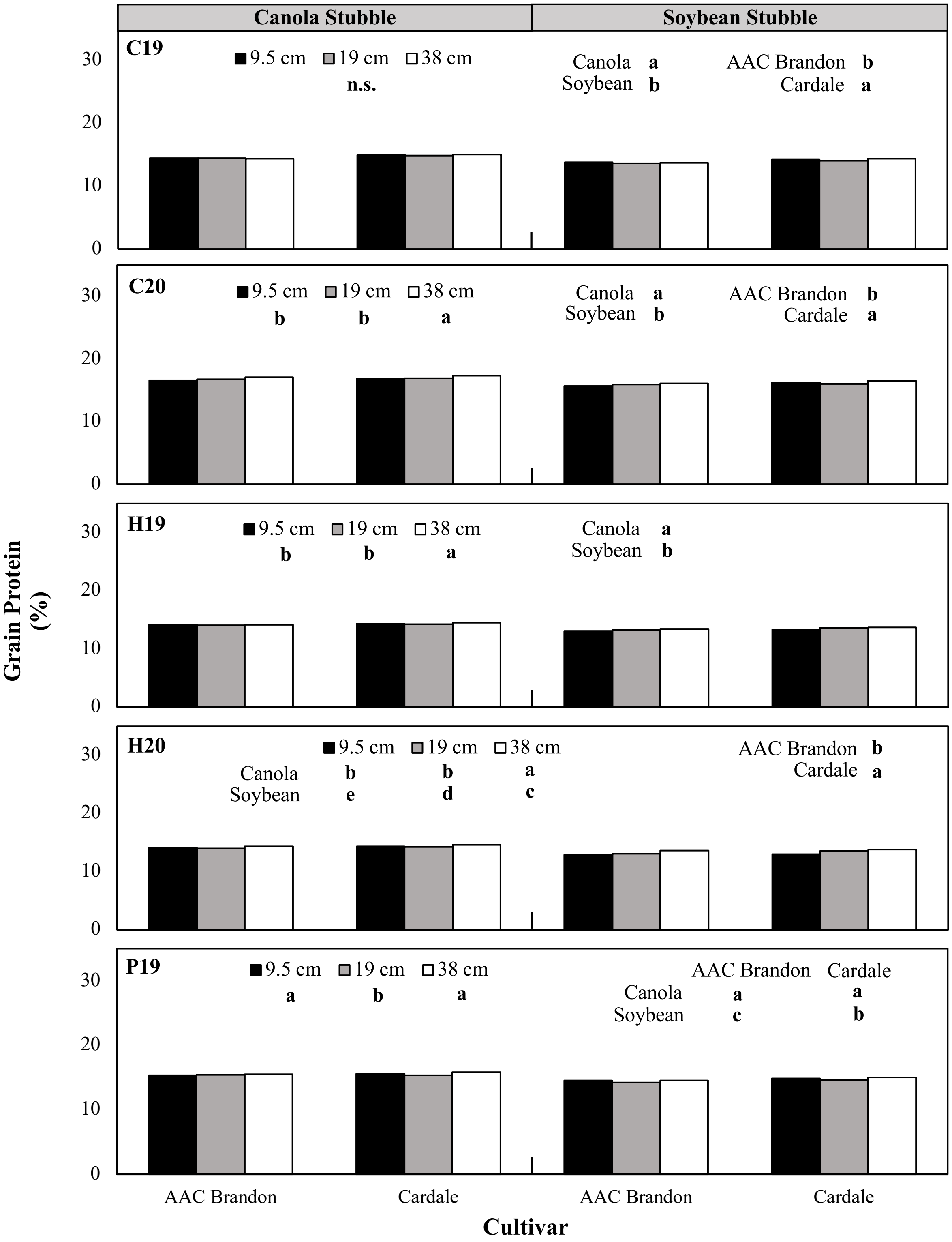

Figure 4.17 Grain protein (%) of AAC Brandon and Cardale spring wheat seeded in two stubble types (canola and soybean) at three row spacings (9.5, 19, and 38 cm) at each site-year (C19: Carman 2019, C20: Carman 2020, H19: Howden 2019, H20: Howden 2020, P19: Portage la Prairie 2019). Within site-year, main or interaction effects followed by different bold letters indicate significant differences (Tukey's HSD, $p < 0.05$). A main effect is the effect of one independent variable on protein. An interaction effect is the effect of two or more independent variables on protein.

4.6.4 Grain Protein Response to Seeding Density

A general decrease in protein concentration was observed as seeding densities increased from 200 to 500 target plants m^{-2} (Table 4.19), indicative of increased early growing season water use at higher plant densities. At Howden 2020, as seeding density increased from 200 to 500 target plants m^{-2}, protein concentration gradually decreased from 14.0% to 13.7%. Similar results were observed at Carman 2020, where the highest average protein content (16.7%) was observed at a seeding density of 200 or 300 target plants m^{-2}, and the lowest average protein content (16.3%) was observed at a seeding density of 400 target plants m^{-2}. At a seeding density of 500 plants m^{-2}, no difference in protein content was observed compared with seeding densities of 300 or 400 target plants m^{-2}. At Portage la Prairie 2019, spring wheat protein concentration was greatest when seeded at 200 target plants m^{-2} (15.2%) and lowest at 400 target plants m^{-2} (15.0%). The protein content of spring wheat at a seeding density of 300 or 500 target plants m^{-2} was not significantly different from the other two seeding density treatments. During the non-growing season (September to April), above-average precipitation was received at Carman 2020, Howden 2020, and Portage la Prairie 2019. This led to increased soil moisture recharge, which likely was a main factor in contributing to the increase in early growing season water use at higher plant densities at these site-years compared with Carman 2019 and Howden 2019.

The protein concentration of Cardale was more responsive to changes in plant density compared with AAC Brandon at Howden 2019. Cardale protein concentration increased from 13.8% to 14.2% as seeding density increased from 200 to 500 target plants m^{-2}. No significant differences in protein concentration were observed as seeding density increased from 200 to 300 target plants m^{-2} or from 400 to 500 target plants m^{-2}. In contrast, AAC Brandon protein content did not respond to increased seeding density, averaging 13.7%. This result further indicates that Cardale spring wheat is more plastic compared with AAC Brandon spring wheat.

Table 4.19 Mean grain protein (%) across spring wheat cultivars at four seeding densities (200, 300, 400, and 500 plants m^{-2}) at each site-year. Means followed by different letters within each column are significantly different (Tukey's HSD, $p < 0.05$).

Seeding Density (plants m^{-2})	Carman 2019	Carman 2020	Howden 2019*	Howden 2020	Portage la Prairie 2019
	Grain Protein (%)				
200	14.36	16.67 **a**	13.74	13.95 **a**	15.19 **a**
300	14.25	16.54 **ab**	13.75	13.82 **ab**	15.16 **ab**
400	14.21	16.33 **c**	13.88	13.78 **bc**	14.97 **b**
500	14.32	16.45 **bc**	13.96	13.65 **c**	15.02 **ab**

* Statistical separation is provided in text due to a significant C*SD interaction

5.0 DISCUSSION

5.1 Seed Yield

The average seed yields for AAC Brandon and Cardale among the site-years ranged from 2380 to 3627 kg ha^{-1} (35 to 54 bu ac^{-1}) and 2322 to 3861 kg ha^{-1} (35 to 57 bu ac^{-1}), respectively. These seed yields were below the average seed yields reported for these two cultivars in Manitoba in 2019 and 2020. The average seed yield for AAC Brandon was 4102 kg ha^{-1} (61 bu ac^{-1}) in 2019 and 4371 kg ha^{-1} (65 bu ac^{-1}) in 2020. For Cardale, the average seed yield was 3833 kg ha^{-1} (57 bu ac^{-1}) in 2019 and 4102 kg ha^{-1} (61 bu ac^{-1}) in 2020 (MASC, 2020a, 2021a). The precipitation received at Carman, Howden, and Portage la Prairie throughout the growing season was generally lower than in other areas of Manitoba, particularly in June 2019 and June 2020 (MAFRD, 2019, 2020). In addition, seeding occurred May 22nd or later at all site-years except at Carman 2019. Hard red spring wheat in Manitoba is typically seeded between May 1st and May 10th (MASC, 2020b). Earlier seeding results in greater yield potential due to better soil moisture utilization by plants throughout the growing season, reduced weed competition, reduced insect and disease pressure, and avoidance of heat stress during anthesis (Manitoba Agriculture and Resource Development, n.d.-e; MASC, 2020b). Thus, the lower seed yield averages obtained in this study were likely due to a combination of delayed seeding and low precipitation in June.

5.2 Plant Spatial Arrangement

5.2.1 Row Spacing

In dry growing season conditions, AAC Brandon and Cardale spring wheat consistently produced the greatest seed yield when seeded at the more narrow row spacings of 9.5 cm or 19 cm, compared with the wider, 38 cm row spacing. Where cultivar seed yield differences were observed, although generally rare, AAC Brandon produced a greater seed yield when seeded at the 9.5 cm row spacing, while Cardale produced greater seed yield when seeded at the 19 cm row spacing. Cardale spring wheat demonstrated greater plasticity in response to wider (19 cm and 38 cm) row spacing treatments than AAC Brandon spring wheat. These results add to previous research in the Northern Great Plains that confirmed a yield benefit to seeding spring wheat at narrower row spacings (May et al., 2020; Chen et al., 2008; McConkey & Miller, 1999; Briggs, 1975), but also provide new insight into row spacings that maximize seed yield for currently available spring wheat cultivars grown in the Manitoba environment.

Plant spatial arrangement was better optimized at the 9.5 cm and 19 cm row spacing treatments, resulting in a growing environment that facilitated better resource utilization. Greater and more rapid ground cover has been reported to occur when spring wheat is seeded at narrower row spacings (McConkey & Miller, 1999), and this was reflected in the current experiment. Rapid ground cover is beneficial in dry growing seasons as McConkey & Miller (1999) observed that soil water evaporation was reduced in the inter-row spaces. Below-average precipitation was received throughout the growing season at all site-years in the current experiment, so spring wheat plants would have experienced reduced moisture stress when seeded at the 9.5 cm or 19 cm row spacings compared with the 38 cm row spacing. Early canopy closure can also suppress weed seedling recruitment and seedling growth, as there is less space and fewer resources available for additional plants (Blackshaw et al., 2005; Fahad et al., 2015). Fahad et al. (2015) observed reduced weed biomass when wheat was seeded at a narrower (11 cm) row spacing compared with wider (15 cm and 23 cm) row spacings. Weed density was not determined in this present experiment. However, it was evident that weeds had better access to sunlight, water, and nutrients at the wide (38 cm) row spacing due to the absence of the wheat canopy in the inter-row spaces.

AAC Brandon and Cardale spring wheat produced greater shoot biomass per unit area when seeded at more narrow row spacings (9.5 cm or 19 cm) compared with the wider (38 cm) row spacing. Chen et al. (2008) and May et al. (2020) also observed greater biomass production at the narrow row spacing treatments in their studies. Rapid biomass accumulation in the more narrow row spacing treatments would have contributed to earlier and complete canopy closure. Increased biomass accumulation at narrow row spacings can be attributed to improved resource capture and utilization by each plant, which translated into increased seed yield.

Harvest index (HI) can be used to examine the relationship between above-ground biomass accumulation and grain yield. Increases in HI have been attributed to increases in grain yield (Duan et al., 2018; Porker et al., 2020; Siddique et al., 1989). The average HI among the site-years ranged from 0.30 to 0.45, which was generally below the typical HI range of 0.45 to 0.50 observed in spring wheat (Sierra-Gonzalez et al., 2021). Reduced HI values indicate proportionally less grain yield for the amount of biomass produced and indicate resource limitations. Below-average precipitation was received throughout the growing season, so these results were not surprising. Chen et al. (2008) previously reported that a terminal drought during a growing season reduced spring wheat HI values compared with a growing season with more average precipitation. Similar to the current experiment, Chen et al. (2008) reported greater HI values in the narrow (15 cm) row spacing treatment compared with the wide row spacing treatment (30 cm). Lower HI values at the wider row spacing (38 cm) further confirm that the spring wheat plants were under greater stress and ran out of resources during yield formation.

There are obstacles preventing growers from adopting a narrow row spring wheat system. Agricultural companies that manufacture seeding equipment typically offer row spacing options of 19 cm to 50 cm (7.5 in to 20 in). Thus, seeding equipment built for row spacings narrower than 19 cm is limited. Based on the research from this experiment, it is evident that the seeding equipment used by growers is potentially limiting their productivity. An additional challenge is potentially higher equipment costs. A seeder with narrow row spacings has additional parts, requiring more maintenance and parts to replace if needed. Pulling a seeder with narrower row spacings can also require more horsepower, increasing fuel costs. Further research on these constraints may lead to improved production and higher adoption by growers.

The effect of row spacing on spring wheat yield components can vary depending on available resources (Chen et al., 2008; Johnston & Stevenson, 2001; Lafond, 1994; May et al., 2020) and cultivar, and this was reflected in the current experiments. It was observed that Cardale spring wheat was more plastic than AAC Brandon spring wheat. When greater amounts of precipitation were received later in the growing season (July and August) compared with earlier in the growing season (May and June), there was often an increase in the late-season yield components (seeds head^{-1} or thousand-seed weight) by Cardale spring wheat seeded at the 38 cm row spacing. Cardale spring wheat plants were trying to compensate for limitations to productivity earlier in the growing season. In contrast, the late yield components of AAC Brandon remained constant among row spacing treatments. Although, due to the reduced seed yield at the 38 cm row spacings, it is evident that the initial decrease in seedling emergence at the

38 cm row spacings could not be directly compensated for by the increase in these late-season yield components by Cardale spring wheat. May et al. (2020) also found that seedling emergence decreased at the wider row spacing treatment during a growing season that received precipitation 30% below the long-term average and could not be compensated for by increases in the other yield components. Thus, improved distribution of plants within the row at narrow row spacings appears to have improved resource utilization in each spring wheat plant and potentially delayed the onset of intraspecific competition. This created a less stressful environment for a longer portion of the growing season. These results provide new insight into how Cardale spring wheat is more responsive to changes in environmental conditions compared with AAC Brandon spring wheat.

Limited research has been conducted on the effect of the preceding crop species on the ideal spatial arrangement and yield relationship in a subsequent spring wheat crop. In these experiments, spring wheat seed yield was more responsive to changes in row spacing when seeded in soybean stubble compared with canola stubble. Although, the yield components (seedling emergence, heads plant^{-1}, and seeds head^{-1}) were generally more responsive to changes in row spacing when seeded in canola stubble. Canola was a high-residue crop compared with soybeans in these experiments, and greater crop residue can cause poor seedling emergence, as excess residue can affect seed placement within the seedbed (Lockwood, 2000). In the current experiment, seedling emergence in canola stubble was negatively affected at the 19 cm and 38 cm row spacing treatments compared with the 9.5 cm row spacing treatments. The differences in seedling emergence among row spacing treatments in canola stubble may have contributed to the variable responses in the number of heads plant^{-1} and seeds head^{-1} in canola stubble. Based on these results, it was unexpected that spring wheat seed yield was more responsive to changes in row spacing when seeded in soybean stubble. Differences in water retention between soybean and canola may have contributed to these results. Unfortunately, soil moisture was not determined in my experiments. Further research is required to understand soil moisture differences when spring wheat is seeded in soybean versus canola stubble throughout the growing season.

5.2.2 Plant Density

In dry growing season conditions, increasing seeding densities from 200 to 500 target plants m^{-2} surprisingly did not influence AAC Brandon or Cardale seed yield at the majority of the site-years in these experiments. As seeding density increased, actual plant density increased at all site-years. Thus, seed yield was unresponsive to increasing plant densities within the density range in these experiments. Asymptotic yield-density models have been well documented in spring wheat in the Northern Great Plains, which represents a relationship where seed yield increases with increasing plant density to a maximum, and then becomes relatively constant at high densities (Chen et al., 2008; Lafond & Derksen, 1996; Lafond 1994; Guitard et al., 1961). The plant densities tested in those studies ranged from 75 to 490 plants m^{-2}. Parabolic yield-density models have also been reported, which describe a relationship where seed yield increases with increasing plant density to a maximum and then declines with increasing plant density (Carr et al., 2003; Faris & DePauw, 1981). The plant densities tested in those studies ranged from 50 to 1100 plants m^{-2}. Linear yield-density models describe a relationship where seed yield increases or decreases linearly as plant density increases, although only linear seed yield increases were reported (Baker, 1981; Briggs, 1975; Johnston & Stevenson, 2001). The plant densities tested in those studies ranged from 81 to 400 plants m^{-2}. Based on this previous research, the yield-density relationship in my experiments was expected to be positive, but the below-average precipitation received throughout the growing season at all site-years likely prevented this relationship.

Among the studies that reported below-average precipitation (Carr et al., 2003; Lafond, 1994; Baker, 1981; Faris & DePauw, 1981), the growing season precipitation was generally 5% to 25% below the long-term (30-year) average among site-years. In my experiments, growing season precipitation was 25% to 45% below the long-term average among site-years. Lafond (1994) conducted experiments over four years. The growing season that received the least amount of precipitation (23% below the long-term average) had the least-pronounced asymptotic yield-density relationship. The point at which yield became constant to increasing plant density occurred at a lower seeding density compared to the other three years. Among the other three years, growing season precipitation was 8% below- and 15% and 40% above- the long-term average. Based on these reports in the literature, it would be expected that AAC Brandon and

Cardale plant density would have a greater influence on seed yield during growing seasons with more average or above-average precipitation.

Previous spring wheat studies have reported that row spacing did not interact with seeding density (Chen et al., 2008; Johnston & Stevenson, 2001; Lafond, 1994; Lafond & Derksen, 1996), and this was reflected in the current experiment. This indicates that during a dry growing season in weed-free conditions, adjustments in seeding density are not required with changes in row spacing.

Plant density did not influence shoot biomass per unit area at the majority of the site-years. Typically, biomass conforms to an asymptotic curve, known as the law of constant final yield. Gooding et al. (2002) reported that shoot biomass in wheat followed an asymptotic curve as plant density increased from 75 to 600 plants m^{-2}, with a plateau occurring at densities beyond 350 plants m^{-2}. The current experiment's lack of biomass response to increased seeding density was likely attributed to the below-average growing season precipitation received at all site-years. An increase in biomass as plant density increased only occurred at Carman 2020. Carman 2020 received the greatest precipitation throughout the preceding fall and winter and in June compared with the other site-years. Chen et al. (2008) observed an increase in biomass as plant density increased from 89 to 388 plants m^{-2} in two experimental years where average growing season precipitation was received, although increases in biomass as plant density increased were much smaller in 2005 due to a terminal drought. In my experiments, the one other site-year where seeding density influenced biomass was at Howden 2019, where the lowest precipitation levels were received throughout the preceding fall and winter months and in June among the site-years in this study. At Howden 2019, wheat shoot biomass decreased as plant density increased. Increasing plant densities resulted in greater and occasionally faster ground cover, but this did not improve spring wheat seed yields in these experiments.

AAC Brandon and Cardale harvest index (HI) values had an inconsistent relationship with plant density in these experiments, with larger HI values occurring at lower or higher plant densities depending on the site-year. Previous literature has reported various types of relationships between HI and plant density. Chen et al. (2008) reported a negative relationship between plant density and HI during one growing season where average growing season precipitation was received. In contrast, plant density did not influence HI during the other growing season in which a terminal drought occurred. In contrast, Gooding et al. (2002) observed a positive relationship between plant density and HI. Precipitation conditions during this study were not reported. In my experiments, the greatest growing season precipitation occurred at Howden 2019, and the lowest precipitation occurred at Carman 2020 among the site-years. At Howden 2019, greater HI values were observed at higher plant densities, and at Carman 2020, greater HI values were observed at lower plant densities. Improvements in HI cannot be guaranteed by seeding at a particular seeding density. This likely contributed to the lack of a yield-density response in these experiments and indicates that HI is more driven by environmental conditions than agronomic management.

The relationship between plant density and the other yield components was examined to better understand why greater plant densities did not result in greater spring wheat seed yields. There was a strong negative relationship between plant density and the number of heads plant^{-1} in both cultivars. Thus, decreases in plant density were principally compensated for by an increase in the number of heads plant^{-1}, resulting in a similar number of heads m^{-2}, independent of plant density. In previous spring wheat studies that examined the relationship between plant density and head density, the majority observed that as plant density increased, head density (heads m^{-2}) increased (Chen et al., 2008; Gooding et al., 2002; Lafond, 1994; Faris & DePauw, 1981). Above-average, average, and below-average growing season precipitation was reported in these studies. However, the precipitation received in my experiments was lower than in these studies. Similar to my experiments, two studies reported that head density (heads plant^{-1}) was greater at the lower seeding density treatments (Gooding et al., 2002; Guitard et al., 1961), and an increase in seed density (seeds head^{-1}) also occurred. Precipitation conditions during these studies were not reported. Below-average precipitation, particularly at the beginning of the growing season (May and June), was likely a main factor contributing to a decrease in the number of heads plant^{-1} as plant density increased in my experiments. When soil moisture is limited, competition for moisture increases as plant density increases, limiting tiller development. Chen et al. (2008) also observed fewer heads plant^{-1} during a growing season that experienced drought, compared with a growing season with more average precipitation. Thus, during a growing season with more average precipitation, as plant density increases, there would be sufficient soil moisture for plants to tiller more and produce heads, increasing heads plant^{-1} as plant density increases to a certain extent. The yield-density relationship in my experiments was strongly influenced by the ability of plants to produce heads. This indicates that soil moisture limitations occurred quite early during the growing season during my experiments.

Plant density was also negatively correlated with the number of seeds head^{-1}. The correlation was slightly weaker when compared with the number of heads plant^{-1}. Previous spring wheat studies also observed a negative relationship between plant density and seed density (Faris & DePauw, 1981; Guitard et al., 1961; Lafond, 1994). Below-average precipitation was reported by Faris & DePauw, 1981 and Lafond, 1994. Precipitation conditions were absent in the study performed by Guitard et al. 1961.

AAC Brandon and Cardale thousand-seed weights (TSWs) had an inconsistent relationship with plant density in these experiments, with positive or negative relationships observed depending on the site-year. These results indicate that moisture ran out at different developmental stages among the site-years or the plants had previously allocated resources to early yield components that later impacted other yield components such as TSW. Drought stress can negatively affect seed size (Sehgal et al., 2018). At the site-years that received more precipitation in July during caryopsis development (Howden 2019; Portage la Prairie 2019), TSW gradually increased or remained constant as seeding density increased from 200 to 500 target plants m^{-2}. In contrast, at the site-years that received less precipitation in July (Carman 2019; Carman 2020; Howden 2020), TSW gradually decreased as seeding density increased, as there would be increased competition for the already limited moisture at increased plant densities. These results agree with Chen et al. (2008), who reported decreased individual seed weight during a growing season with a terminal drought compared with a growing season with a less severe drought. A negative relationship between plant density and seed weight in spring wheat was most commonly reported in literature (Faris & DePauw, 1981; Guitard et al., 1961; Johnston & Stevenson, 2001; Lafond, 1994). Although, two previous studies where above-average growing season precipitation occurred reported that plant density did not influence seed weight as resources were not limiting (Carr et al., 2003; Briggs, 1975).

Among the site-years that received a greater amount of precipitation in July and August compared with May and June (Carman 2019, Howden 2019, Portage la Prairie 2019), the late yield components (seeds head^{-1}, thousand-seed weight) of Cardale were more responsive among seeding density treatments, compensating for limitations to productivity earlier in the growing season. These results provide additional new insight into how Cardale spring wheat is more responsive to changes in environmental conditions compared with AAC Brandon spring wheat.

5.3 Cultivar Differences

Due to inherent genetic differences, Cardale spring wheat was consistently taller than AAC Brandon spring wheat in these experiments. Seed Manitoba (2021) further confirms this observation as they reported that mature plants of Cardale spring wheat are normally 3 cm taller than plants of AAC Brandon spring wheat. Lodging was not observed in these experiments.

Crop sequence, i.e. wheat after canola vs. wheat after soybean, had no effect on either AAC Brandon or Cardale spring wheat yield at most site-years. This was surprising as these observations contradict findings reported by Manitoba Agriculture Services Corporation (2021b). The Manitoba Agriculture Services Corporation gathered information on the yield response (percentage of 2011-2020 average) of Manitoba crops sown on large fields (>120 acres) of various previous crops (stubble) in rotation. Based on this data, it was reported that spring wheat has a 7% greater yield response when seeded in soybean stubble compared with canola stubble. Canola stubble soil moisture reserves may have been greater, as the canola stubble was taller and left more residue on the soil surface. This potentially resulted in increased snow capture and potentially reduced soil water evaporation (Caprio et al., 1985). Due to the dry growing season, this potential increased soil moisture for spring wheat when seeded in canola stubble may have contributed to the lack of yield gap between seeding spring wheat in canola versus soybean stubble. Unfortunately, soil moisture was not determined in my experiments.

Cardale spring wheat had greater overall seedling emergence and, although generally rare, produced slightly more seeds head^{-1} compared with AAC Brandon spring wheat. In contrast, AAC Brandon spring wheat produced heavier thousand-seed weights and, although generally rare, produced slightly more heads plant^{-1} compared with Cardale spring wheat when significant. These results suggest that AAC Brandon and Cardale spring wheat produce seed yields differently. These cultivars have different parent plants, likely explaining the difference in seed yield production. Cardale spring wheat was derived from the cross McKenzie/Alsen (Fox et al., 2013), whereas AAC Brandon spring wheat was derived from the cross Superb/CDC Osler//ND44 (Cuthbert et al., 2017).

Cardale spring wheat produced average protein concentrations that were 0.2% to 0.5% greater compared with AAC Brandon protein concentrations. This observation was expected because in Manitoba in previous years, the average protein concentration of Cardale spring wheat was always 0.2% to 0.3% greater than that of AAC Brandon spring wheat (Seed Manitoba 2019, 2020, 2021). These differences can be attributed to genetic differences between cultivars.

5.4 Grain Protein

The average protein concentrations among the site-years ranged from 13.7% to 16.4% in AAC Brandon and 13.9% to 16.6% in Cardale wheat. These values were within and above the average range for hard red spring wheat in Manitoba (13.9% to 15.5%) during this period. In addition, these values were both below and above the average concentrations reported for these two cultivars in Manitoba in 2019 and 2020 (AAC Brandon – 2019: 14.2%, 2020: 14.3%; Cardale – 2019: 14.5%, 2020: 14.5%) (Seed Manitoba, 2021). Protein premiums depend on supply and demand, but in recent years, Manitoba growers have typically received one cent per bushel per 1/10th percentage of protein above 13.5%, capping at 14.5%. Thus, spring wheat protein levels at Carman 2019, Howden 2019, and Howden 2020, averaging 13.8% to 14.3%, would have earned a premium price.

In comparison to all other management factors, stubble type had the greatest influence on seed protein in these experiments. Spring wheat produced greater protein concentrations when seeded in canola stubble compared with soybean stubble at all five site-years. This result was unexpected and contradicts research that found spring wheat produced 3% greater protein concentrations when grown on pulse stubble compared with oilseed stubble (Miller et al., 2002). It would be expected that reduced moisture and increased soil nitrogen availability in soybean would have increased protein concentration. The most limiting nutrient to wheat production is nitrogen (N), and if spring wheat protein content is less than 13.5%, it is considered that insufficient N was applied for maximum crop seed yield production (Manitoba Agriculture and

Resource Development, 2007). As the minimum protein concentration was 13.7% in these current experiments, it is evident that nitrogen was not limiting on either canola or soybean stubble. Although, it is possible soil moisture was so limiting in soybean stubble that it prevented nitrogen uptake by the spring wheat plants, resulting in lower protein concentrations. Soil moisture and nitrogen uptake were not evaluated in these experiments, but they may have influenced the results.

Small increases in spring wheat protein concentration were generally observed at wider (38 cm) row spacing treatments, indicating moisture limitations at these wider row spacings. Capouchová et al. (2008) and Hiltbrunner et al. (2005) also reported greater protein concentrations at wider row spacings compared with narrow row spacings, although these studies involved winter wheat. As seed yield was lowest at the 38 cm row spacing, it is evident that there was a negative relationship between protein concentration and seed yield. This result was not surprising as in dry growing seasons, seed yield response to available nitrogen is low, so the uptake of plant nitrogen by the crop will increase grain protein concentration (Fowler et al., 1990). The seed yields among the site-years were low relative to the provincial results, and as a result, increased protein levels were observed among site-years.

Small decreases in spring wheat protein concentration were generally observed as seeding density increased. This confirms findings from Chen et al. (2008), Gooding et al. (2002) and Kolb et al. (2012), who reported that protein content decreased as plant density increased, from 89 to 388 plants m^{-2}, 75 to 350 plants m^{-2}, and 400 to 600 plants m^{-2}, respectively. Gooding et al. (2001) evaluated the influence of plant population on wheat grain nitrogen concentration. They observed that higher seeding rates were associated with more rapid flag-leaf senescence, which can negatively impact grain protein.

6.0 CONCLUSIONS

The objectives of this research project were to determine row spacing and seeding density combinations in two modern spring wheat cultivars that maximize seed yield and if the preceding crop (canola or soybean) affects this relationship. Revisiting spring wheat plant spatial arrangements in the Manitoba environment represents a critical component of crop management and is necessary to maintain and improve wheat productivity as a whole. Below-average precipitation was received throughout the growing season at all site-years in this experiment. As a result, this research provides a comprehensive dataset under moisture limiting conditions.

Row spacing was the most important management factor leading to differences among spring wheat seed yields in these experiments. Spring wheat seeded at the narrower, 9.5 cm or 19 cm row spacings consistently resulted in greater seed yields when compared with the wider, 38 cm row spacing. Improved distribution of plants both within and between crop rows at the narrow row spacings created an environment that promoted greater biomass accumulation and more rapid ground cover. Further research on producer constraints, such as seeding equipment, may increase narrow row adoption.

Seeding density unexpectedly did not affect spring wheat seed yield in these experiments at the majority of the site-years. Where significant, increased seeding densities resulted in decreased seed yield. The yield-density relationship was strongly influenced by the ability of plants to produce heads. A strong negative correlation occurred between plant density and the number of heads plant^{-1}. This was an indication that soil moisture limitations occurred quite early during the growing season. Increasing plant densities resulted in greater and occasionally faster ground cover, but this did not improve spring wheat seed yields in these experiments. Further research is necessary to investigate the yield-density relationship during growing seasons that receive more average or above-average precipitation.

Where cultivar differences were observed, AAC Brandon produced greater seed yields when seeded at the 9.5 cm row spacing, while Cardale produced greater seed yields when seeded at the 19 cm row spacing. The late yield components (seeds head^{-1} and thousand-seed weight) of Cardale were more responsive among row spacing and seeding density treatments, compensating for limitations to productivity earlier in the growing season. The late yield components of AAC Brandon, on the other hand, were more consistent among row spacing and seeding density treatments.

Spring wheat seed yield was more responsive to changes in row spacing when seeded in soybean stubble compared with canola stubble. When seeded in canola stubble, spring wheat produced similar seed yields at the 9.5 cm and 19 cm row spacings. When seeded in soybean stubble, the greatest yields occurred at the 9.5 cm or 19 cm row spacing, depending on the site-year. Differences in water retention between soybean and canola may have contributed to these results. Unfortunately, soil moisture was not determined in my experiments. Further research is required to understand soil moisture differences when spring wheat is seeded in soybean versus canola stubble throughout the growing season.

In summary, this research indicates that spring wheat growers in Manitoba have the opportunity to increase seed yields by seeding at narrower row spacings, notably in dry growing conditions. AAC Brandon or Cardale spring wheat would be suitable to be seeded at these narrow row spacings. AAC Brandon might be better suited for very narrow row spacings (9.5 cm) compared with Cardale, but further research is needed to investigate this. Seeding spring wheat at narrower row spacings was suitable in both no-till canola and soybean stubble. This research also suggests that the seeding recommendations promoted by the Government of Manitoba of 250 to 300 plants m^{-2} (Manitoba Agriculture and Resource Development, n.d.-f) are sufficient during a dry growing season, as neither AAC Brandon nor Cardale seed yield responded to increased densities. Decreasing the seeding rate below 250 plants m^{-2} may have negative consequences not evaluated in this study. Lower seeding rates may result in non-uniform stands due to increased tillering and extended flowering and maturation periods, which make the timing of fungicide applications and harvest more challenging. In addition, decreased seeding rates may increase weed pressure concerns.

7.0 LITERATURE CITED

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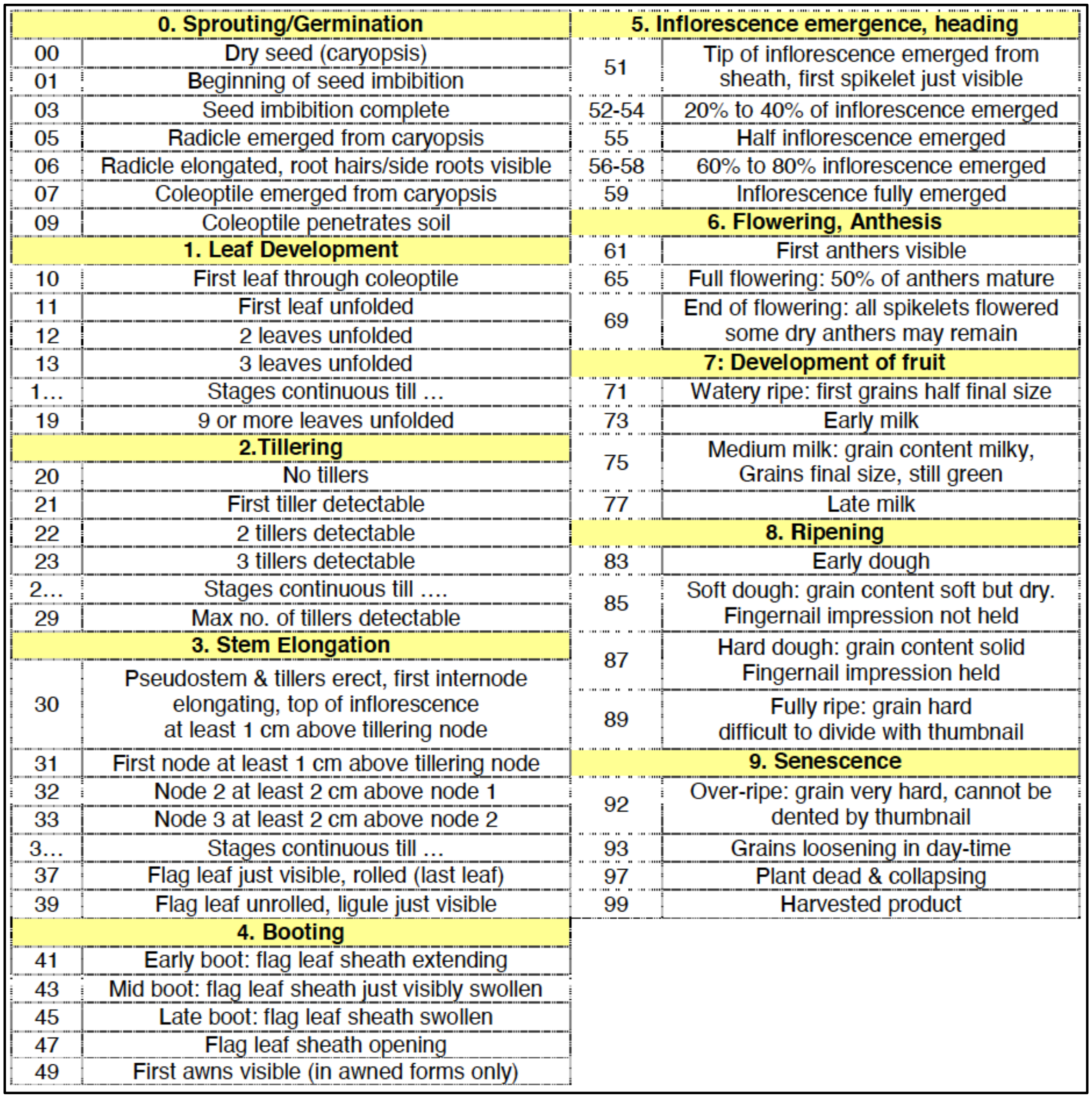
8.0 APPENDIX

8.1 BBCH developmental stages for cereals (Agriculture and Agri-Food Canada, 2012).



0. Sprouting/Germination	
00	Dry seed (caryopsis)
01	Beginning of seed imbibition
03	Seed imbibition complete
05	Radicle emerged from caryopsis
06	Radicle elongated, root hairs/side roots visible
07	Coleoptile emerged from caryopsis
09	Coleoptile penetrates soil
1. Leaf Development	
10	First leaf through coleoptile
11	First leaf unfolded
12	2 leaves unfolded
13	3 leaves unfolded
1…	Stages continuous till …
19	9 or more leaves unfolded
2.Tillering	
20	No tillers
21	First tiller detectable
22	2 tillers detectable
23	3 tillers detectable
2…	Stages continuous till ….
29	Max no. of tillers detectable
3. Stem Elongation	
30	Pseudostem & tillers erect, first internode elongating, top of inflorescence at least 1 cm above tillering node
31	First node at least 1 cm above tillering node
32	Node 2 at least 2 cm above node 1
33	Node 3 at least 2 cm above node 2
3…	Stages continuous till …
37	Flag leaf just visible, rolled (last leaf)
39	Flag leaf unrolled, ligule just visible
4. Booting	
41	Early boot: flag leaf sheath extending
43	Mid boot: flag leaf sheath just visibly swollen
45	Late boot: flag leaf sheath swollen
47	Flag leaf sheath opening
49	First awns visible (in awned forms only)
5. Inflorescence emergence, heading	
51	Tip of inflorescence emerged from sheath, first spikelet just visible
52-54	20% to 40% of inflorescence emerged
55	Half inflorescence emerged
56-58	60% to 80% inflorescence emerged
59	Inflorescence fully emerged
6. Flowering, Anthesis	
61	First anthers visible
65	Full flowering: 50% of anthers mature
69	End of flowering: all spikelets flowered some dry anthers may remain
7: Development of fruit	
71	Watery ripe: first grains half final size
73	Early milk
75	Medium milk: grain content milky, Grains final size, still green
77	Late milk
8. Ripening	
83	Early dough
85	Soft dough: grain content soft but dry. Fingernail impression not held
87	Hard dough: grain content solid Fingernail impression held
89	Fully ripe: grain hard difficult to divide with thumbnail
9. Senescence	
92	Over-ripe: grain very hard, cannot be dented by thumbnail
93	Grains loosening in day-time
97	Plant dead & collapsing
99	Harvested product

8.2 Expansion of Select Main and Interaction Effects

a. Final Ground Cover

Howden 2020. S*SD*RS. Final ground cover results at Howden 2020 showed a three-way interaction among stubble type, seeding density, and row spacing (Table 4.10). This interaction only occurred at one site-year and contributed little to the interpretation of the results, as it was only marginally significant ($p = 0.0445$). After removing the three-way interaction (stubble type*seeding density*row spacing) from the interpretation of the output, there was also a lack of significant two-way interactions (stubble type*seeding density, stubble type*row spacing, or row spacing*seeding density). In addition, this interaction was not significant in the area under the ground cover (AUGCC) at this site-year. The method used to obtain the sum of squares could not be used when modelling residuals to the beta distribution, so the amount of final ground cover variation this interaction explained within the site-year could not be identified. As a result, the letter means separation was not displayed or discussed.

b. Plant Height

Carman 2020. S*C*RS. When seeded in soybean stubble, Cardale spring wheat was on average 6.1 cm taller than AAC Brandon spring wheat at any of the three row spacings (Figure 4.15). No significant differences in plant height occurred between row spacings in Cardale or AAC Brandon spring wheat in soybean stubble. When seeded in canola stubble, Cardale spring wheat seeded at the 19 cm or 38 cm row spacings was on average 5.8 cm taller than AAC Brandon spring wheat seeded at any of the three row spacings. When seeded in canola stubble at the 9.5 cm row spacings, no significant differences in plant height were observed between Cardale and AAC Brandon spring wheat.

Carman 2019. Portage la Prairie 2019. SD. At Carman 2019, as seeding density increased from 200 to 500 target plants m^{-2}, plant height gradually decreased by 4.3 cm (Figure 4.16). In contrast, at Portage la Prairie 2019, as seeding density increased from 200 target plants m^{-2} to 300, 400, or 500 target plants m^{-2}, plant height increased by 3.0 cm.

Carman 2019. Portage la Prairie 2019. RS. At Carman 2019, spring wheat grew on average 2.9 cm taller when seeded in 19 cm or 38 cm row spacings compared with the narrowest, 9.5 cm row spacing (Figure 4.15). No significant plant height differences were observed between 19 cm and 38 cm row spacings. This observation as expected because at wider row spacings, plants within the rows are growing closer to one another compared with plants growing at narrower row spacings, likely resulting in taller plants as a shade-avoidance response. Although, at Portage la Prairie 2019, the opposite occurred. Spring wheat grew on average 2.1 cm taller when seeded at the 9.5 cm row spacing compared with the 19 cm and 38 cm row spacings. No significant differences in plant height were observed between 19 cm and 38 cm row spacings.

Howden 2019. Howden 2020. S*RS. At Howden 2019 and 2020, spring wheat plant height was more responsive to changes in row spacing when seeded in soybean stubble compared with canola stubble (Figure 4.15). As row spacing widened from 9.5 cm to 38 cm, the average plant height of spring wheat seeded in soybean stubble gradually increased by 4.5 cm and 4.0 cm at Howden 2019 and 2020, respectively. In contrast, the average plant height of spring wheat seeded in canola stubble was unresponsive to changes in row spacing at both site-years. At Howden 2020, spring wheat seeded in soybean stubble at the 38 cm row spacing was on average 4.0 cm taller than spring wheat seeded in canola stubble at any of the three row spacings.