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OPTIMAL SEEDING RATES AND DISEASE MANAGEMENT FOR YIELD AND QUALITY IN FABA BEAN (*Vicia faba* L. minor)

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By

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ABSTRACT

Faba bean (*Vicia faba* L.) production has remained extremely low, compared to pea and lentil, in the Canadian Prairies due to agronomic and economic barriers. These barriers can be overcome, if a consistent, high yielding and high quality faba bean crop is produced annually. This can be achieved by updating the best management practices for the dark brown and black soil zones of Saskatchewan, where faba bean is primarily produced. The objective of the first experiment is to identify the optimal seeding rate required to maximize yield in three faba bean varieties. The objective of the second experiment is to identify the optimal disease control practices required to minimize disease severity, and increase yield and quality, in two faba bean varieties. In the seeding rate experiment, CDC Snowdrop, CDC SSNS-1, and FB9-4 were seeded at 5 different rates between 20 and 100 viable seeds m^{-2} in 2015 and 2016, and 5 to 60 viable seeds m^{-2} in 2017. Results indicate that within the black and dark brown soil zones of Saskatchewan, maximum agronomic faba bean yields can be found between 49 and 54 viable seeds m^{-2}, while economic yields can be found at 45 viable seeds m^{-2}. There were no significant differences in the seeding rate required to achieve maximum yields of the three varieties tested. Therefore, results indicate that 50 viable seeds m^{-2} is required to maximize yield, quality, and profitability for all faba bean varieties and seed sizes cultivated in Saskatchewan. In the disease control experiment, chlorothalonil, fluxapyroxad + pyraclostrobin, fluopyram + prothioconazole, and penthiopyrad fungicides were applied at 10%, 50%, and 10+50% flower, and compared to an untreated control, on CDC Snowdrop and CDC SSNS-1 varieties. Due to the environmental conditions and low disease severity experienced throughout the experimental period, both varieties had minimal responses to fungicide application. Results suggest that all four fungicide products tested, can be equally effective to maintain or improve faba bean yield and quality when disease severity is low. Overall, the results of this thesis can be used to update two components in the set of best management practices for faba bean cultivation in Saskatchewan.

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DEDICATION

I dedicate this thesis to my parents, siblings, Dean, and friends. Thank you for providing an open ear and words of encouragement throughout the course of this emotional rollercoaster of post-secondary education. Your love, prayers, hugs, and constant reminders were the motivation I needed to complete my third and (hopefully) final degree.

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LIST OF ABBREVIATIONS

AIC	Akaike Information Criterion
ANOVA	Analysis of Variance
AUDPC	Area Under the Disease Progress Curve
G.A.E	Grams of Acid Equivalent
NA	Not Applicable
POST	After Fungicide Application at 50% Flowering
TKW	Thousand Kernel Weight

LIST OF EQUATIONS

1.0 INTRODUCTION

Faba bean (*Vicia faba* L.) has been cultivated since early Neolithic times (Cubero 1974). This annual legume crop is well adapted to both temperate and semi-arid growing regions which allows for its worldwide production (Lòpez-Bellido et al. 2005; Jensen et al. 2009). As a result of global production, faba bean is also referred to as: fava bean, broad bean, horse bean, field bean, and tick bean (Duc 1997). In 1972, the first commercial faba bean crop was grown in Western Canada (Graf and Rowland 1987). Originally, this crop was grown for livestock rations, as it is a high source of protein (30 to 35%) (Agriculture Canada 1975; El-Sayed et al. 2011). There are two market classes of faba bean in Canada: tannin and low-tannin. Generally, tannin varieties are destined for human consumption, while low-tannin varieties are directed into livestock feed (Saskatchewan Pulse Growers (SaskPulse) 2018).

During the 1980s, faba bean production remained extremely low in the Canadian Prairies due to a lack of accessible markets, low commodity prices, and low economic returns (Graf and Rowland 1987). These barriers are still relevant today and continue to support the lower cultivated acreage of faba bean compared to pea and lentil (S. Phelps Pers. Comm). The lack of accessible markets as a production barrier has the potential to be overcome if a high quality supply is consistently produced (S. Phelps Pers. Comm.). The low economic return of faba bean is largely attributed to inconsistent yields and lower average yield than field pea (1,800 versus 2,400 kg ha^{-1}, respectfully) (S. Phelps Pers. Comm; Saskatchewan Crop Insurance Corporation 2017). In order to produce a high quality and consistent crop supply, best management practices need to be established. The current best management practices for Western Canadian faba bean production were established 30 to 40 years ago. These practices may no longer be accurate as they were established using varieties, equipment, and production practices that have vastly changed over the years.

Due to the global diversity of faba bean, varieties come in a range of seed sizes, largely depending on its end use. Inopportunely, the majority of previous seeding rate recommendations were based on small-seeded varieties (<350 g 1000^{-1} $seeds^{-1}$). Therefore, these recommendations do not consider the implications posed on or by large-seeded (>650 g 1000^{-1} $seeds^{-1}$) types. Furthermore, there is little information surrounding the efficacy of fungicide application timing, as disease severity in the Canadian prairies has been relatively minor. Recently, faba bean management practices have been supplemented with information from other growing regions, as a means to update recommendations. Nevertheless, best management practices differ between and within growing regions (Lòpez-Bellido et al. 2005). However, this supplemental information may not be applicable to all Saskatchewan faba bean varieties and growing regions. Consequently, there is a need to re-evaluate the best management practices for faba bean production in Saskatchewan.

The first experiment of this thesis will specifically investigate optimal seeding rates for three *Vicia faba* L. *minor* varieties. As with other large-seeded pulse crops (ie. dry bean and chickpea), the optimal seeding rate is highly dependent on seed costs. This is due to seed costs comprising a substantial portion of the total cost of production and due to yield responses being small at higher plant densities (Graf and Rowland 1987; Loss et al. 1998). The seeding rate required to achieve targeted plant stands can be further exasperated by variations in percent germination and seed weight within and between varieties (Loss et al. 1998). Furthermore, commonly used seeding equipment cannot always apply the required seeding rate in one pass and multiple passes are required. These additional logistical factors (ie. additional supply deliveries to field, increased fuel costs, increased seeding time per field, etc.) can further increase the cost of seeding/production. Both seed costs and logistical issues can be reduced with the use of small-seeded varieties. However, large-seeded types are preferred by export markets and are often associated with higher prices, making them more economically attractive to grow than small-seeded types (Saskatchewan Pulse Growers 2018). Therefore, there is the need to explore the optimal seeding rate required by the various varieties and seed sizes cultivated in Saskatchewan, in order to obtain agronomically and economically sustainable faba bean production.

The second experiment of this thesis will investigate optimal fungicide products and application timings for *Vicia faba* L. *minor* varieties. Although Saskatchewan is semi-arid, the warm and humid conditions that occur periodically throughout the growing season, are conducive to the development of faba bean diseases. There are five fungal diseases that can infect faba bean: chocolate spot (*Botrytis fabae*), ascochyta blight (*Ascochyta fabae*), powdery mildew (*Microsphaera penicillta* var. *ludens*), rust (*Uromyces viciae-fabae*), and cercospora leaf spot (*Cercospora zonata*) (Stoddard et al. 2010). A recent, unpublished, survey across Saskatchewan found that 100% of faba bean fields had disease present (Chatterton 2018). Chatterton (2018) noted that despite high disease incidence, the average severity was 1.9 (small lesions on less than 2% of the leaf surface) and was more prevalent in the lower canopy. Cultured samples revealed, that the most commonly present pathogens were chocolate spot, *Alternaria* spp., and *Fusarium* spp. However, their physical symptoms were not always present. Although disease symptoms may not always be present, they still cause concern as they can develop into outbreaks. Moreover, as more faba bean crops are produced, disease inoculum will slowly build up, and an inevitable increase in disease incidence and severity will occur.

Chocolate spot and ascochyta blight are two of the most commonly discussed faba bean diseases. Moreover, both diseases have been known to produce physical damage to Saskatchewan's faba bean crop in the past. Globally, chocolate spot has been known to cause 40 to 50% yield loss, while ascochyta blight can cause up to 90% yield loss (El-Sayed et al. 2011; Omri Benyoussef 2012). Both can cause significant destruction to yield and quality when severe. In order to meet Canadian Grain Grading Standards, faba bean seed can only contain up to a maximum of 3% perforated seed (Canadian Grain Commission 2018). Thus, disease control, to protect against seed perforation, in conjunction with maintaining yield, is essential. Currently, there is noticeably limited agronomic research or information surrounding the best management practices for disease control in faba bean for Saskatchewan, as well as for the Canadian Prairies. Therefore, optimal fungicide products and their application timing(s) need to be identified in order to ensure the high-quality standards for export markets are met, as well as forming yield stability.

Overall, research using current varieties, management practices, and environmental conditions is warranted to ensure that stable, high yielding, and high quality faba bean crops can be produced in Saskatchewan. This research project was initiated to investigate the effects optimal seeding rates and disease management practices have on the various faba bean varieties cultivated in Saskatchewan.

The hypothesis for the first experiment is that the seeding rate required to reach maximum yield will differ between varieties (ie. tannin content) and varieties varying in seed size. The objective of this experiment is to identify the optimal seeding rate required to maximize yield in three faba bean varieties. It is hypothesized for the second experiment that disease control in faba bean, and subsequent effect on yield and quality, will differ between fungicide products, application timing(s), and varieties. The objective is to identify the optimal disease control practices required to minimize disease severity and increase yield and quality in two faba bean varieties. Overall, the objective of this thesis was to update two components in the set of best management practices for faba bean production in Saskatchewan, using information obtained from within the province.

2.0 LITERATURE REVIEW

2.1 Origin and Distribution

Faba bean (*Vicia faba* L.) cultivation first began in early Neolithic times and has thus occurred since the beginning of agriculture (Cubero 1974). Faba bean is an annual, cool season, legume grain crop that is well adapted to temperate and semi-arid growing regions (Jensen 2009; Köpke and Nemecek 2010; López-Bellido et al. 2005). This crop supports sustainable agriculture through its nitrogen fixation capabilities, support of arbuscular mycorrhizal fungi associations, and improvements to soil structure (Jensen 2009; Köpke and Nemecek 2010; Landry et al. 2015). Globally, faba bean is the third most grain legume produced; following after soybean (*Glycine max*) and pea (*Pisum sativum*) (Caracuta et al. 2015).

Since 1994, world faba bean production has ranged from 3.4 to 4.6 million tonnes (Food and Agriculture Organization of the United Nations (FAOSTAT) 2017). Currently, China, Ethiopia, and Egypt are the world's top three faba bean producing countries (FAO 2017). Australia, France, the United Kingdom, China, and Ethiopia are the top five exporting countries with a combined export of 0.02 to 0.16 million tonnes annually (FAO 2017). Conversely, Egypt, Italy, Spain, and the Sudan annually import a combined 0.05 to 0.23 million tonnes (FAO 2017).

For many years, the exact origin of faba bean was unknown. In 2015, charred faba bean remains were found in a Neolithic archeological site in Lower

Galilee (Northern Israel) (Caracuta et al. 2015). Based on radiocarbon dating and stable carbon isotope analysis, this study proposed that faba bean was first cultivated around 10,200 cal. BP and domesticated during the 11th millennium (Caracuta et al. 2015). During this time period, lentil (*Lens culinaris*) was also being domesticated. It was not until 2016, that the first remains of wild faba bean were discovered at Mount Carmel, Israel, and estimated to be 14,000 years old (Caracuta et al. 2016).

During the 10th millennium, the area cultivated to faba bean increased throughout Lower Galilee (Israel) (Caracuta et al. 2015). The area increased due to genetic selection and adaptation for drier growing environments (Caracuta et al. 2015). Cubero (1974) suggests three routes were used to spread faba bean cultivation throughout the world. These routes consist of movement into Greece and northward into Europe, movement into the Nile Delta and southward into Africa, and finally into India and further eastward into China (Cubero 1974). Due to regional preferences and geographic isolation over time, four classes of faba beans were developed (Serradilla et al. 1993).

2.2 Classification

There are four classes of domesticated faba bean: *major, minor, equine,* and *paucijuga* (Duc 1997). Differences between the classes largely consist of variations in phenotype, especially seed size. These characteristic changes are thought to have occurred during the pre-Pottery Neolithic period (Caracuta et al. 2015). *Vicia faba paucijuga* is considered the primitive form of faba bean, which can be found between Afghanistan, India, and Ethiopia (Cubero 1974; Duc 1997). This primitive form is short, small-leaved, and possess a thousand-seed weight less than 250 g (Duc 1997). *Vicia faba equina* seeds are medium-sized (500 g to 1 kg 1000^{-1} $seeds^{-1}$) and believed to have been developed between Egypt and the Middle East (Duc 1997). *Vicia faba major* is considered the largest-seed type with an average thousand kernel weight of 1 kg or more (Duc 1997). This class originates in the Southern Mediterranean and dispersed into China along the silk road (Duc 1997; Serradilla 1993; Cubero 1974). Serradilla et al. (1993) proposed that *major* developed from *equina* due to human preferences for larger seeds. *Vicia fabae minor* varieties are greater than 250 g but less than 500 g thousand-seed weight (Duc 1997). This small-seeded type originated between India and Ethiopia (Cubero 1974). Lastly, Serradilla et al. (1993) suggest that *major* and *minor* types are genetically distinct due to geographic isolation.

Vicia faba minor continues to be favored by Ethiopia, Europe, and specifically North America (Duc 1997). Therefore, this thesis will solely focus on this class. Within *minor* there are multiple types: winter, spring, tannin, low-tannin, large-, medium-, and small-seeded. Winter types are planted in sub-tropical areas due to their expression of photoperiod responses, whereas spring types are planted in northern latitudes (Duc 1997). These differences reflect the time when cool, moist environmental conditions are occurring in each region. Tannin varieties are often associated with colored flowers, dark seed coats, and 8 to 9% tannin content (Oomah et al. 2011). Tannins provide both beneficial (natural seedling defenses) and non-desirable (decreased protein digestibility in livestock) effects. Low-tannin varieties were developed for livestock markets as a solution to reduce digestive problems (Duc 1997). Low-tannin varieties often have white flowers, light-colored seed coats, and 1% or less in tannin content (Oomah et al. 2011). Although *minor* is one of the small-seeded classes, it can be further sub-divided into three categories: large (1 kg 1000^{-1} $seeds^{-1}$), medium (1 kg to 500 g 1000^{-1} $seeds^{-1}$), and small (<500 g 1000^{-1} $seeds^{-1}$) (López-Bellido et al. 2005).

2.3 Physiological Attributes

Faba bean emerges through hypogeal germination, which allows it to tolerate frost in early spring and initial insect pressures (Caracuta et al. 2015; SaskPulse 2018). Faba bean has a fibrous tap root containing many nodules. Inoculation with *Rhizobium leguminosarum v. viciae* is necessary to ensure sufficient nodulation (Duc 1997). This pulse crop is the most efficient grain legume for nitrogen fixation. It has been found to fix up to 648 kg N ha^{-1}; however, values of 130 to 160 kg N ha^{-1} are commonly cited (Caracuta et al. 2015; Köpke and Nemecek 2010; Singh et al. 2013). Furthermore, unlike other grain legumes, this crop can maintain nitrogen fixation when soil available nitrogen levels are elevated (Köpke and Nemecek 2010).

As the crop emerges, two leaflets are produced per node and as the plant develops, six or eight leaflets are created at each node (Duc 1997). Despite the indeterminate growth pattern, the average overall height ranges from 1 to 1.5 meters (Agriculture Canada 1970). After a minimum of five leaf-bearing nodes are produced, multiple flower and leaf-bearing nodes are produced. However, only a few flowers per node will bear pods when mature (Rowland and Bond 1983). Flowers can have a range of colors; however, they are most often white or purple depending on tannin content (Duc 1997). Faba bean is an out-crossing species which relies on pollinators such as bee (*Bombus*) (Duc 1997). The pods of *minor* are short and upright with an average of three to four seeds per pod (Duc 1997). Final seed size is dependent on genetics, available water, and environmental conditions (Caracuta et al. 2015).

2.4 Faba bean Cultivation in Canada

In the Western Canadian grain-growing region, pea, and lentil are the primary pulse crops produced (CGC 2017). However, these crops are not suitable for all grain growing regions due to environmental or disease restrictions. Unlike pea and lentil, faba bean can tolerate excess moisture, thrives under cooler temperatures, and is resistant to Aphanomyces (*Aphanomuces euteiches*) (Jensen 2009). Therefore, faba bean is a suitable alternative in cereal-oilseed-pulse cropping rotations, where pea and lentil may not be viable. However, unlike pea and lentil which have 80 to 110 days to maturity, faba bean matures on average in 110 to 130 days (SaskPulse 2018). This leaves the crop vulnerable to fall frost and is one of the last crops to combine, instead of first.

Faba bean was first commercially grown in Western Canada during 1972 (Graf and Rowland 1986). In 2017, there were approximately 27,000 hectares of faba bean seeded in Canada (CGC 2017). Of this area, 57% was seeded in Saskatchewan, 30% in Alberta, and 13% in Manitoba (CGC 2017). Across the three provinces, Snowbird (low-tannin, medium-sized variety) accounts for almost half of all cultivated faba bean acres, whereas CDC Snowdrop (low-tannin, small-seeded) accounts for 19% (CGC 2017).

Between 1982 and 2007, Canada produced between 4,600 and 25,200 tonnes of faba bean (FAO 2017). This is less than 4% of the world's total faba bean production (FAO 2017). Canadian faba bean production is primarily shipped as whole seeds into the human consumption (plant-based protein) or livestock feed markets. However, opportunities exist to domestically process faba bean prior to shipping. Protein Industries Canada (2018) anticipates that Canada will be able to increase its market share in plant-based protein products, inorder to meet the world's growing population needs. However, there must be a consistent supply before market share increases can be achieved. Re-evaluated and adapted agronomic recommendations, as well as new varieties, will be required to increase faba bean yield and quality and stabilize future supply levels.

2.5 Seeding Rate and Yield Responses

2.5.1 Law of Constant Final Yield

Seeding rate is an important agronomic factor that directly influences plant density, growth (biomass), and yield. It is also the first component of grain yield to be established and is directly manipulated by humans (López-Bellido et al. 2005). Seeding rate also indirectly influences light interception, duration of vegetative growth, weed and disease control, and finally grain quality (López-Bellido et al. 2005; Loss et al. 1998).

The way plant populations/densities can influence final biomass and grain yield can be described through the Law of Constant Final Yield (Weiner and Freckleton 2010). This law describes the common growth pattern of short-lived, annual plant species. It illustrates that at low plant populations, biomass growth is linear as plant density increases. However, after a maximum plant density is reached, the rate of biomass growth does not change as plant density further increases. (Weiner and Freckleton 2010). The similar growth rate at high densities is a reflection of available resources and how biomass is altered when plant populations are elevated.

Linear growth at low populations is achieved due to decreased plant competition and a proportional expansion in biomass (Weiner and Freckleton 2010). In faba bean, leaf area index and the number of additional stems increases, as seeding rate is increased until competition for light and resources are strained (López-Bellido et al. 2005). As plant density is further increased (past maximum) plant competition becomes so great it results in unproportioned biomass growth (Weiner and Freckleton 2010). With increasing competition, the plant's structural components become smaller, the number of side branches decline, and biomass is reduced (Weiner and Freckleton 2010; López-Bellido et al. 2005). Plant parts become smaller due to allometric growth, which is a natural response to resource changes (Shipley and Meziane 2002; Müller et al. 2000). Resources are transferred to newly growing tissues, which can change a plants ability to obtain more resources, often resulting in reduced plant size (Shipley and Meziane 2002; Müller et al. 2000).

Maximum biomass production occurs when the increases in plant density are equal to the decreases in average plant weight (Weiner and Freckleton 2010). At this point, the growth of individual plants becomes linear again due to self-thinning. Self-thinning begins when some plants are unable to sustain themselves due to negative growth rates (Aikman and Watkinson 1980). It may also be due to size-asymmetric competition where larger plants receive a disproportionate amount of resources (Aikman and Watkinson 1980; Weiner and Freckleton 2010). Conversely, self-thinning can assist in size-symmetric competition when total biomass does not decline and growth remains linear until density becomes limiting (Weiner and Freckleton 2010). Lastly, as time progresses and growth stages advance, the density at which maximum is reached is reduced and the slope of the linear portion of the growth curve becomes larger (Weiner and Freckleton 2010).

The Law of Constant Final Yield is based on biomass production throughout the entire plant lifecycle, yet does not reflect seed yield (Weiner and Freckleton 2010). However, seed yield of smaller plant species can follow the generalities of this law. This is due to a decrease in the reproductive portion of a plant when density is increased. Consequently, this reduces the amount of total harvestable material (seed) (Weiner and Freckleton 2010). Therefore, this law can be extrapolated to harvestable seed yield in agronomic studies (Weiner and Freckleton 2010). This extrapolation has been verified in studies with corn (*Zea mays* L.) where the amount of dry matter accumulation and harvest index decreases with increasing seeding rate, although seed yield increases until an upper limit is reached and then began to decline (Li et al. 2015).

The point at which constant final yield is reached is dependent on the species and individual varieties. This variability is due to a plant's innate maximum size and its corresponding ecological neighborhood (Weiner and Freckleton 2010). Larger plants have a greater neighborhood, which affects light interception and self-regulation, due to greater dry matter yield and larger leaf size (López-Bellido et al. 2005). These attributes allow for larger plants to compensate more efficiently when plant densities are lower (López-Bellido et al. 2005). Therefore, larger species/plants have smaller optimal plant population needs than medium or smaller species/plants (López-Bellido et al. 2005).

2.5.2 Variations in Yield Response

Yield response to seeding rate is either linear or quadratic. Generally, quadratic yield-density relationships occur when considering reproductive growth, while vegetative growth typically follows linear relationships (Holliday 1960). Linear yield responses occur when maximum yield is reached and further increases in plant density do not result in declining yield (Holliday 1960). This response occurs due to a decline in harvest index, where plant population increases compensate for harvestable material losses. This also occurs when there are enough resources available to sustain high plant populations. Due to the near zero growth rate of a linear relationship, it becomes nearly impossible to define optimal plant densities or seeding rates (Shirtliffe and Johnston 2002). Quadratic yield responses occur when maximum yield is reached at a particular plant population and any density below or above results in lesser yield (Shirtliffe and Johnston 2002; Holliday 1960). This response often occurs when there are not enough available resources to sustain all reproductive structures. Therefore, the addition of more plants causes a decline in yield after the sustainable level has been reached. In quadratic relationships, the optimal seeding rate can be easily identified as it occurs at the density in which maximum yield is reached (Shirtliffe and Johnston 2002).

2.6 Response of Larger Seeded Pulses to Seeding Rate

Optimal seeding rates, within a given crop, can vary due to differences in seeding date, variety, seed quality, seed size, and environment (López-Bellido et al. 2005). Therefore, the optimal plant density for each growing region should also be re-evaluated when new production practices are used and when new varieties are released (López-Bellido et al. 2005).

The optimal seeding rate for large-seeded pulse crops is highly dependent on seed costs (Graf and Rowland 1987). Therefore, differences between optimal agronomic and economic seeding rates can occur. The optimal agronomic seeding rate is determined by the seeding rate at which the highest yields are produced (López-Bellido et al. 2005). In contrast, the optimal economic seeding rate is the point at which marginal costs of increasing plant density is equal to the marginal return from increased yield (Graf and Rowland 1987). Therefore, the economic seeding rate tends to be lower than the agronomic rate. Nevertheless, Graf and Rowland (1987) caution that due to the reduced seeding rate required by faba bean to be economical, additional weed control may also be required, which is often not factored into economic value.

A Saskatchewan-based dry bean study found the optimal agronomic plant density was unidentifiable for this crop due to an linear yield relationship (Shirtliffe and Johnston 2002). Despite this, the authors were able to identify the optimal economic seeding rate for each cultivar tested. Shirtliffe and Johnston (2002), found that CDC Expresso was economically optimal at 50 plants m^{-2}, while CDC Camino was at 25 plants m^{-2}. This difference in optimal seeding rate was attributed to differing yield potentials and seed costs (Shirtliffe and Johnston 2002).

Optimal seeding rates for chickpea (*Cicer arietinum* L.) are also influenced by seed size, cultivar selection, and environmental conditions (Chang et al. 2007). In 2017, Chang et al. found that chickpea yield responses were linear as seeding rate increased between 14 and 40 plants m^{-2}. However, chickpea is highly sensitive to diseases, such as ascochyta blight, which can result in significant yield and quality losses. Chang et al. (2017) found that higher seeding rates were often associated with higher disease incidence and severity, when they were not managed with a fungicide application. The study suggested that reduced seeding rates can also be an effective tool for managing chickpea diseases in Western Canada. Therefore, optimal seeding rates, both agronomic and economic, should take into consideration both disease and weed control aspects.

In field pea (*Pisum sativum* L.), optimum agronomic seeding rate depends on the growing region and cultivar selected. In Saskatchewan, the recommended seeding rate for field pea is 75 to 85 plants m^{-2} (SaskPulse 2018). However, Johnston et al. (2002) found that semi-leafless upright cultivars did not have a yield response to three seeding rate treatments (50, 100, and 150 viable seeds m^{-2}); while leafy prostrate varieties obtained maximum yield in the 150 seeds m^{-2} treatment. This result demonstrates the importance of determining seeding rates, for not only individual crops, but among varieties, market classes, or structural types, as differences can exist.

2.7 Seeding Rate and Yield Response in Faba bean

2.7.1 Faba bean Yield Components

The primary yield components in faba bean are seed weight, seeds per pod, and pods per plant; with the largest factor of these three being pods per plant (Graf and Rowland 1987; López-Bellido et al. 2005; Seitzer and Evans 1973). The number of pods per plant is extremely sensitive to both biotic and abiotic stresses (Loss et al. 1998; McVetty et al. 1986; Adisarwanto and Knight 1997). Biotic stresses are factors such as the inability of pollinators to move in lower parts of the canopy when vegetative growth is excessive, and when vegetative organs outcompete reproductive structures for nutrients (López-Bellido et al. 2005; Duc 1997).

Plasticity is a resource allocation response to the growing environment and results in phenotypic variation (Weiner 2004). For example, soybean has a plastic response to increased competition as more root biomass is produced when not surrounded by other roots (Weiner 2004). On the other hand, kochia (*Kochia scoparia*) does not exhibit a plastic response to competition as the leaf area index does not change (Weiner 2004). In faba bean, the number of pods per plant is considered plastic as it has an inverse relationship with plants m^{-2} (López-Bellido et al. 2005; Loss et al. 1998). López-Bellido et al. (2005) confirmed that faba bean seed yield is plastic due to similarities (within a given area) in the number of pods per plant at both high and low densities. However, under non-ideal conditions, inter-plant competition is reduced and the number of pods per m^{-2} continues to increase with increasing plant density (López-Bellido et al. 2005). Therefore, under ideal conditions, yield increases are likely to be linear, whereas under non-ideal conditions yields are likely quadratic.

The other two primary yield components, number of seeds per pod and mean seed weight, have been found to be more sensitive to changes in the environment (abiotic stresses) than plant density (López-Bellido et al. 2005; Loss et al. 1998; Adisarwanto and Knight 1997). These components tend to be less sensitive to biotic stresses as they are the last components in the yield model to be set (López-Bellido et al. 2005). Seed weight is largely affected by water availability late in the growing season, while the number of seeds per pod is affected by available assimilates (López-Bellido et al. 2005). Conversely, McVetty et al. (1986) found that seed size declined after the maximum yield was reached, while seeds per pod remained constant. However, the authors attribute this decline in seed size to cultivar variation across multiple environments.

2.7.2 Seeding Rate and Yield Responses in Other Faba bean Growing Regions

Faba bean grain yield tends to have a linear relationship with increasing seeding rate (López-Bellido et al. 2005). However, quadratic responses can also be found in temperate climates (López-Bellido et al. 2005). These responses do not always occur year after year due to variations in environmental conditions. This is largely attributed to variations in soil moisture, even though optimal plant densities are achieved (López-Bellido et al. 2005; Adisarwanto and Knight 1997).

In Mediterranean climates, the ideal plant density for faba bean ranges from 30 to 63 plants m^{-2}, with a mean of 45 plants m^{-2} (Loss et al. 1998; Adisarwanto and Knight 1997). Moreover, in Australia, it has been found that the optimal seeding rate changes depending on the seeding date. When seeded in late April, yields tend to decline with increasing density. However, when seeding is delayed until June, yields tend to increase with increasing density (Adisarwanto and Knight 1997).

Although the optimal plant density for Mediterranean countries is a useful starting point, it is not completely ideal for the Canadian Prairies, as the climates contrast in total rainfall, day-length, etc. (Adisarwanto and Knight 1997). López-Bellido et al. (2005) note that the optimal plant density in temperate climates is slightly higher than in Mediterranean climates, ranging from 45 to 65 plants m^{-2}. Adisarwanto and Knight (1997) also note this difference in optimal plant density and attribute it to decreased emergence rates in temperate compared to Mediterranean climates.

2.7.3 Seeding Rate and Yield Responses in the Canadian Prairies

In Alberta during 1975, Kondra found that faba bean yields increased with seeding rate up to 150 kg ha^{-1} (approximately 33 to 40 seeds m^{-2}, depending on variety). In 1986, Graf and Rowland found that the optimal economic plant density for faba bean grown in Saskatchewan was 38 plants m^{-2}. Also, McVetty et al. (1986) found that the optimal plant density for faba bean grown in Manitoba was 35 plants m^{-2}. Therefore, the prior optimal plant density for faba bean production in the Canadian prairies averaged 37 plants m^{-2}.

More recently, Strydhorst (2003) concluded that the optimal plant population for faba bean in north central Alberta was 43 plants m^{-2}, although it varied based on environmental conditions. Under normal growing conditions, optimal yields were achieved at 32 plants m^{-2}. However, under drought conditions, yield continued to increase with seeding rate. In turn, higher seeding rates were required to achieve higher grain yields. Strydhorst also noted that agronomic practices should not differ between market classes but rather between innate varietal differences. In an additional study, Strydhorst et al. (2008) found that under higher weed competition, greater seeding rates (68 to 90 plants m^{-2}) are required to consistently achieve higher faba bean yields.

The use of optimal seeding rates does not only contribute to optimal yields but can also contribute greatly to integrated disease management (Chang et al. 2007). Optimal seeding rates can help to minimize dense crop canopies, which in-turn reduces the potential for the development of environments conducive to disease progression. Dense crop canopies also reduce fungicide efficacy by preventing air movement and chemical penetration within the canopy. Disease management is important for faba bean production as it can cause large variations in yield and seed quality from year to year. Together, this makes faba bean production economically variable and prevents the full adaptation of faba bean into cropping rotations.

2.8 Disease of Faba bean

Faba bean diseases, such as ascochyta blight (*Ascochyta fabae* Speg.) and chocolate spot (*Botrytis fabae* Sard.), can cause substantial yield and quality losses. Although less common, other fungal diseases can affect faba bean as well, such as downy mildew, rust, and cercospora leaf spot (Stoddard et al. 2010). The destruction these pathogens can induce is highly dependent on the growth stage at which disease onset occurs, initial inoculum levels, and environmental conditions (Harrison 1988). Together or alone, these pathogens can greatly contribute to yield instability and low economic returns, which are barriers towards successful faba bean production.

In 1973, the first faba bean disease survey was conducted in Saskatchewan. Chocolate spot (*B. cinerea*) was found to be primarily present in the early parts of the growing season, while ascochyta blight was found later (McKenzie and Morrall 1975). McKenzie and Morrall (1975) suggested that *Ascochyta fabae* Speg. was likely brought to Saskatchewan on European seeds, whereas *B. cinerea* was likely present prior to the arrival of faba bean as it has been found on native and other crop species.

Globally, chocolate spot is one of the most destructive faba bean diseases because it is found in almost all faba bean fields (Stoddard et al. 2010). Furthermore, this disease can cause between 5 and 100% crop loss when on-set is prior to pod fill (Harrison 1998). Chocolate spot is more predominate under high humidity (>80%) or wet conditions, along with average temperatures of 20°C (Harrison 1988; Stoddard et al. 2010). Ascochyta blight can be highly destructive as well, although it is not as predominant in the Canadian prairies as chocolate spot. Ascochyta blight is more prevalent after significant rainfall events, as it spreads with rain droplets, and when the average temperature is 15°C (Stoddard et al. 2010). In Africa, this disease can cause yield losses of 35 to 90% (Omri Benyoussef et al. 2012; El-Sayed et al. 2011).

Despite somewhat contrasting epidemiology, these two pathogens (*B. fabae* and *A. fabae*) can infect at the same time, within any given year and growing region, given the right environmental conditions. Fortunately, foliar fungicides can control or suppress these pathogens and diseases. However, the chemical control options differ between each disease. Therefore, it is important to understand the symptoms and epidemiology of each disease in order to determine the best control measures. By choosing the best control measures and developing an integrated disease management plan, the devastating impacts that these diseases can have on successful faba bean production can be mitigated.

2.8.1 Ascochyta Blight (*Ascochyta fabae* Speg.)

Ascochyta blight is a seed-borne disease and is primarily expressed in the asexual form (Wallen and Galway 1997; Omri Benyoussef et al 2012). Ascochyta blight's teleomorph (*Didymella fabae*) can produce ascospores which are dispersed by the wind and infect faba bean crops over a great distance (Stoddard et al. 2010; Omri Benyoussef et al. 2012; Davidson and Kimber 2007). *Ascochyta fabae* Speg. growth and symptomology is initiated at 15°C and is ideal at 20°C (Wallen and Galway 1997). Under ideal growth conditions, fruiting structures begin to develop 14 days after inoculation (Wallen and Galway 1997). Lesions develop on leaves and stems in round to elongated oblong shapes (Stoddard et al. 2010). Lesions are generally grey in color with concentric circles of black pycnidia. The pycnidiospores are dispersed through rain splash and wind (Stoddard et al. 2010; Omri Benyoussef et al. 2012). This allows for rapid disease spread during major rainfall and wind events (Stoddard et al. 2010; Davidson and Kimber 2007). Typically, this disease spreads from initial lesions on developing seedlings and moves towards higher leaves (Omri Benyoussef et al. 2012). If the infection is severe, lesions will begin to develop on stems, pods, and seeds (Omri Benyoussef et al. 2012).

Infected seeds are the primary source of pathogen inoculum, as the asexual form does not survive overwintering in cold climates (Omri Benyoussef et al. 2012). Wallen and Galway (1997) found that under field conditions, when 13% of planted seeds were infected with ascochyta blight, only 3% of seedlings showed initial infection symptoms. However, as plant growth continued, a maximum 10% infection level was found. The authors noted that despite the high number of initially infected seeds, environmental conditions were not favorable for ascochyta development. Thus, conducive environmental conditions are required for severe outbreaks to occur.

2.8.2 Chocolate Spot (*Botrytis fabae* Sard.)

Chocolate spot is an overwintering seed borne disease, first identified in Spain during 1929 (Harrison 1988; Wallen and Galway 1997). *Botrytis fabae* can be mistaken for *B. cinerea*, which has markedly similar symptomology (Harrison 1998). Nonetheless, *B. fabae* is the species most often isolated in cultures, produces more lesions, and is more aggressive than *B. cinerea* (Harrison 1998). It is also the species most often found in cultured samples in Canada.

Chocolate spot is produced by conidiophores. These conidiophores rapidly develop and facilitate disease movement as the developing conidia become easily airborne (Stoddard et al. 2010). Eight hours after inoculation, conidia produce hyphae which grow into the epidermal tissue (Harrison 1988). Within 12 hours of hyphal invasion, the plant's cell walls begin to degrade (Harrison 1988). The rate of degradation is proportional to the number of hyphae (Harrison 1988). However, when hyphal growth is slow, hyphae can begin to die and infection sites are contained to the epidermal region (Harrison 1988). Moreover, the age of the conidia can also have an effect on hyphae development. When suspended in water, conidia can live up to 40 days. Conversely, when in an arid environment, viability can be reduced to 1% (Harrison 1988). Leaking nutrients from thin or broken leaf cuticles, as well as aphid honeydew, can provide additional support for hyphae growth (Harrison 1988).

Lesion development begins on the leaf surface, where the dead epidermal cells merge together forming dark colored spots. Under continuous high humidity and temperatures between 15°C and 22°C, lesions can grow 3 to 4 mm per day (Harrison 1988). Lesions are often elliptical, ranging between red, black, and brown in color, and can be found on leaves, stems, and flowers (Harrison 1988). Lesions are more often found on lower leaf surfaces, where there is more shade and higher humidity (Harrison 1988). In the Canadian Prairies, lesion growth is often less than in other faba bean growing regions. This is due to drops in nighttime temperature when humidity is at its highest (Stoddard et al. 2010); thus, providing temporary relief from ideal conditions for disease development.

After the lesions have developed, necrosis spreads rapidly, resulting in leaf drop. Older leaves close to senescence can contain 80% of the plant's total lesions (Harrison 1988). Often, the most severe damage occurs at flowering when decaying flower petals provide nutrition for fungal growth. This allows for lesions to spread from flowers to pods and seeds, ultimately resulting in yield reductions (Stoddard et al. 2010; Harrison 1988). If conditions are right, total plant growth can be terminated in as little as two days (Stoddard et al. 2010; Harrison 1988). This is why it is critical for proactive disease management strategies to be developed. A recent field study found all faba bean fields surveyed in Saskatchewan tested positive for chocolate spot, albeit with low symptom severity (Chatterton 2018). Therefore, if the environmental conditions become favorable, in any given year, complete devastation of Saskatchewan's faba bean crops can occur within a short period of time.

2.9 Disease Management

Integrated disease management incorporates multiple aspects of agronomy to reduce the development and spread of diseases. Often the first recommended strategy is the use of certified, clean, and unblemished seed. This is especially true for *Ascochyta fabae*, as it can be carried under the seed coat (Stoddard et al. 2010). Seed treatments can be an effective control measures for seed-borne diseases; however, they must be compatible with rhizobium inoculant (Stoddard et al. 2010; Harrison 1988). There are some varieties with various levels of genetic resistance to both *Botrytis fabae* and *Ascochyta fabae* Speg. (Stoddard et al. 2010). Unfortunately, there are none available for production in the Canadian Prairies. Although, some evidence does suggest, varieties with higher levels of tannin, can provide some level of seed-born disease mitigation.

Crop residue management requires attention as a component in integrated disease management. In faba bean, residue management is imperative as common vetch (*Vicia sativa* L.), narbon bean (*V. narbonensis* L.), and lentil are alternative hosts for chocolate spot (Stoddard et al. 2010). Additionally, *B. fabae* can overwinter in previous crop residue (Stoddard et al. 2010). When *B. fabae* is found in the sexual state, crop rotation can effectively reduce inoculum levels. However, when found in the asexual stage, isolation and residue burial is more effective (Davidson and Kimber 2007). A three to four-year break between host crops has been found to effectively reduce the incidence of chocolate spot, ascochyta blight, rust, and cercospora leaf spot (Stoddard et al. 2010; Davidson and Kimber 2007). It is also suggested that several hundred meters between faba bean fields is required to prevent disease transmission (Stoddard et al. 2010; Harrison 1988).

The use of optimal seeding rates, plant populations, and weed and insect control can also help to effectively manage diseases. Optimal plant densities and reduced weed populations can work together to lessen the relative humidity of a crop canopy. This, in turn, reduces the incidence and severity of chocolate spot (Sahile et al. 2008). Disease risk can also be minimized by managing nutrient deficiencies, water-logging, and frost avoidance. Overall, any management strategy which promotes healthy plant vigor can be highly effective (Stoddard et al. 2010).

Stoddard et al. (2010) suggests that genetic resistance is the most effective disease control measure in faba bean production. This is due to the high cost of fungicide application in some growing regions. Unfortunately, there are a noticeably limited number of disease resistant cultivars available worldwide (Sillero et al. 2010; Beyene et al. 2018). Therefore, faba bean disease management primarily relies on foliar fungicide application(s) as an integral part of an integrated disease management system both in Saskatchewan and around the world (Stoddard et al. 2010; Harrison 1988).

2.9.1 Disease Management with Fungicides

Fungicides are chemical control compounds used to control pathogens and their associated diseases. They were first developed in China, as inorganic chemicals, around 2,500 to 1,500 BC (Oerke 2005). It was only 100 years ago that organic-based chemical fungicides were developed (Oerke 2005). The way fungicides work can be divided into multiple categories. These categories (placement, timing, movement, spectrum, composition, and biochemistry) can be defined as the fungicide's mode of action (Guide to Crop Protection 2018). Each of these categories can be further subdivided.

There are two types of fungicide placement: contact and systemic. Contact fungicides remain on plant surfaces and modify a pathogen's metabolic pathway(s) (Gossen et al. 2014). Systemic fungicides are transported within the plant to modify site-specific pathways within a particular pathogen (Gossen et al. 2014). Timing determines when fungicide(s) need to be applied in order to provide effective control. Contact fungicides need to be applied prior to infection and at multiple time intervals (they do not protect newly emerging tissues) (Gossen et al. 2014). Conversely, systemic fungicides require site-specific targets, and thus will control established infections (Oerke 2005). Therefore, they can be applied when needed. Lastly, fungicides can be classified based on their spectrum of control. Contact fungicides are typically broad spectrum and control a broad range of diseases.

Globally, there are multiple fungicide groups registered for the control of faba bean diseases. Generally, faba bean diseases are controlled by products in groups: 1 (benzimidazoles), 2 (dicarboximides), 11 (strobilurins), M3 (dithiocarbamates), and M5 (chloronitriles) (Stoddard et al. 2010; Omri Benyoussef et al. 2012). In Saskatchewan, products within groups 3 (demethylation inhibitors), 7 (carboxamides), and 11 are registered for the control of white mold, ascochyta blight, powdery mildew, and chocolate spot (Guide to Crop Protection 2018; Table 2.1). Furthermore, there are multiple products within each group registered for use. Each product is registered for the control of specific diseases, having both systemic and broad spectrum modes of action.

It is interesting to note that there are only seven fungicide products registered for the control of ascochyta blight and two for chocolate spot in Saskatchewan (Table 2.1). Furthermore, fluxapyroxad + pyraclostrobin is the only product registered for the control of three or more faba bean diseases

(Table 2.1). The limited number of registered products could potentially lead to product overuse. This further increases the risk of fungicide resistance as these products are primarily systemic-based. Systemic fungicides are considered medium- and high- risk mode of action groups, for selecting towards pathogen insensitivity (Gossen et al. 2014).

Table 2.1: Registered fungicide products for control of various faba bean diseases in Saskatchewan. Adapted from the 2018 Saskatchewan Guide to Crop Protection.

Group	Chemical Name	Mode of Action	Disease Controlled
3	propiconazole	Broad Spectrum Systemic	Powdery Mildew
3 & 7	prothioconazole fluopyram	Broad Spectrum Systemic	Ascochyta Blight and White Mold
3 & 7	boscalid prothioconazole	Broad Spectrum Systemic	White Mold
3 & 11	azoxystrobin difenconazole	Broad Spectrum Systemic	Ascochyta Blight
3 & 11	azoxystrobin prothioconazole	Broad Spectrum Systemic and Contact	Powdery Mildew
11	picoxystrobin	Broad Spectrum Systemic	White Mold
11	azoxystrobin	Broad Spectrum Systemic and Contact	Ascochyta Blight
11	pyraclostrobin	Broad Spectrum Systemic and Contact	Ascochyta Blight and Powdery Mildew
7 & 11	fluxapyroxad pyraclostrobin	Broad Spectrum Systemic and Contact	Ascochyta Blight and White Mold
7 & 11	azoxystrobin benzovindiflupyr	Broad Spectrum Systemic and Contact	White Mold
7 & 11	fluxapyroxad pyraclostrobin	Broad Spectrum Systemic and Contact	Ascochyta Blight, Chocolate Spot, Powdery Mildew and White Mold
7	isofetamid	Systemic	White Mold
7	boscalid	Systemic	White Mold
7	penthiopyrad	Broad Spectrum Systemic	Ascochyta Blight and Chocolate Spot

Fortunately, currently registered fungicide products can perhaps control other faba bean diseases currently not on the product's label. For example, there are four fungicide products that contain azoxystrobin. Two are registered for the control of ascochyta blight, one for white mold, and one for powdery mildew. Consequently, it is likely that all products containing azoxystrobin can control multiple faba bean diseases. However, additional diseases have yet to be added to the product label through the regulatory process. This is an issue for faba bean disease control. However, this issue is not covered within this thesis.

2.10 Faba bean Disease Control with Fungicide Application

The recommendation to apply a fungicide is based on whether or not the environment is conducive to disease development, the pathogen is present, and if full yield potential can be achieved (Stoddard et al. 2010; Oerke 2005). The decision to apply should also take into consideration whether or not the cost of application is less than or equal to the return on investment (yield or quality increases), as fungicide application is costly (El-Sayed et al. 2011; Oerke 2005; Stoddard et al. 2010). As quality plays a large role in the grade and subsequent price received for faba bean, fungicide application can be economical. However, in certain situations, fungicide application can be highly effective in reducing disease progression, yet, cannot be economical, depending on an array of factors (Beyene et al. 2018).

In the Canadian Prairies, when and how many applications of which fungicides has not been fully established for faba bean production. However, recent small-plot studies re-evaluated fungicide application timing for Saskatchewan. In 2015, pyraclostrobin was applied 10 days prior to a combination of fluxapyroxad and pyraclostrobin at three locations. Results indicated that under low disease pressure, faba bean yield was not responsive to fungicide application (Hall 2015; Holzapfel 2015; Pratchler 2015). However, it was noted that if disease was present, the onset was in later parts of the growing season and was likely too late to cause any significant yield reductions (Holzapfel 2015). Lastly, in the prairies, faba bean disease control has concentrated on controlling both primary pathogens. Therefore, product efficacy is measured independently from the fungal disease(s) present and controlled.

2.10.1 Optimal Fungicide Products

There is a benefit to testing multiple products per fungicide group, as efficacy varies amongst products within any given group (Harrison 1988). This is due to variations in the active chemical ingredient of each product (Harrison 1988). Furthermore, additional testing of registered fungicides is justified to ensure adequate disease control is being continued (Harrison 1988).

Strobilurin-based fungicides are ideal for the control of fungal diseases (ascochyta blight, anthracnose, etc.) in pea, lentil, and chickpea (Banniza et al. 2017). However, anecdotally, application of strobilurin-based fungicides has been cited to cause increased canopy greenness, resulting in delayed maturity. Banniza et al. (2017) found that strobilurin-based fungicides were more effective in preventing disease, in comparison to non-strobilurin based fungicides. Yet, they did not always result in yield increases (Banniza et al. 2017). Furthermore, the study found that any anecdotal greenness effects did not always occur when a single application was applied. Therefore, one needs to be cautious when applying strobilurin fungicides, as any positive effects (increased disease control efficacy) needs to be weighed against any potential negative effects (delayed harvest).

In dry bean, strobilurin fungicides have been found to increase yields up to 60%, due to broad-spectrum activity against multiple dry bean diseases (Gillard et al. 2012). In chickpea, application of a contact fungicide prior to a rainfall event, followed by a systemic fungicide application, is required to effectively control ascochyta blight (Banniza et al. 2011). Fungal diseases in dry bean and chickpea pose a much greater threat to yield than those of faba bean. Therefore, any significant yield increases due to effective fungicide application(s) in these two pulse crops, are likely greater than one might expect in faba bean. However, these significant effects can give an indication as to how other pulse crops may respond to fungicide application.

A Chinese field study found that mancozeb (group M3) provided 81% control of chocolate spot in faba bean, whereas pyraclostrobin controlled 89% (Gu Chunyan et al. 2013). This resulted in an 11 to 42% yield increase depending on the variety. In Australia, chlorothalonil is the most widely used fungicide for the control of ascochyta blight in all pulse crops (Davidson and Kimber 2007).

Overall, there is little information regarding fungicide product efficacy on specific faba bean diseases under Saskatchewan growing conditions. However, this investigation considers the total disease control provided by various registered products rather than the control of specific diseases. Also, this investigation considers fungicide application based on plant growth staging rather than probability or incidence of disease. This was done to standardize treatment applications across testing locations.

2.10.2 Optimal Fungicide Application Timing

The efficacy of fungicide application is determined based on the amount of loss prevented. This needs to take into consideration the plant's growth stage, the stage of the disease, and its progression (Gillard et al. 2012). In some regions, the timing of the first and number of applications is highly dependent on regional experience (Stoddard et al. 2010). Stoddard et al. (2010) note that due to the weather being the main driving factor for disease development, weather conditions prior to and after application should be the largest determining factors. Lastly, the authors note that the timing of the last fungicide application also needs to reflect any pre-harvest interval requirements.

In chickpea, Banniza et al. (2011) found that one application of fungicide was as effective as multiple applications, in most cases, for the control of ascochyta blight (*Phoma rabiei*). This finding suggests that fungicide application, prior to or shortly after initial infection, is critical for preventing further disease development. However, when disease pressure was high, multiple fungicide applications were required (Banniza et al 2011). Overall, the study found that, under Saskatchewan growing conditions, optimal application timing must coincide with growth stage and rainfall events. Furthermore, appropriate application timing was more effective than the particular fungicide product selected.

In Australia, fungicide for the control of ascochyta blight in faba bean is primarily applied as a preventative measure, prior to initial disease development or significant rainfall event (Davidson and Kimber 2007). It is suggested that in low rainfall locations, a single application at podding, is sufficient to protect yield (Davidson and Kimber 2007). In contrast, in Syria, a single application at the vegetative stage is sufficient for disease control (Ahmed et al. 2016). Also, systemic fungicides have been found to be more advantageous when applied post-infection or after a rainfall event, up to three days (Davidson and Kimber 2007).

If the onset of chocolate spot occurs during senescence, fungicide application can be uneconomical (Harrison 1988). This is due to the disease having little to no effect on yield and can potentially delay crop maturity. However, if the onset of the disease is early, fewer pods develop and fungicide application can be effective and economical. El-Sayed et al. (2011) found that in Ethiopia, fungicide application two days prior to the onset of disease can significantly reduce the severity of chocolate spot. In northern Europe, due to seasonal variation in normal weather patterns, rules for optimal fungicide timing do not exist (Harrison 1988). However, it is stressed that fungicide timing should occur at any time prior to when disease severity developes beyond the ability for a fungicide to control the pathogen adequately (Harrison 1988). Furthermore, the product selected should determine its application timing based on its mode of action. For example, chlorothalonil is a contact fungicide and is best applied at an early flower or early pod set (Davidson and Kimber 2007), thus helping to protect newly developing reproductive structures and maintain yield. Therefore, consequently, altering application timing based on the product's mode of action can lead to more economical returns.

The current fungicide recommendation given to Saskatchewan faba bean growers is to apply a fungicide only if the weather is favorable for disease development. Furthermore, to target fungicide application to the protection of healthy plant material, at the onset of flowering, or at the first sign of symptoms (SaskPulse 2018). In the 2018 Guide to Crop Protection, many fungicide products are registered for control when applied at the first bud or early flower, followed by a secondary application 10 to 14 days later. This endorsement for a second application contradicts the recommendation by SaskPulse (2018), which states that a well-timed application is sufficient for faba bean disease control.

3.0 OPTIMAL SEEDING RATES FOR VARIOUS FABA BEAN VARIETIES

3.1 Introduction

Determining the optimal seeding rate(s) for any crop is important as it is the first "building block" towards grain yield to be determined and is directly manipulated by humans (López-Bellido et al. 2005). Determining the optimal seeding rate for faba bean production, in Saskatchewan, is not a novel topic. Graf and Rowland, in 1986, determined the optimal economic plant density to be 38 plants m^{-2}. This recommendation was adequate for the time, but did not consider the impact it could have on the large-seeded varieties within *V. faba* L. *minor*, as it was determined using small-seeded varieties. In an attempt to update the recommendation, seeding rates from other faba bean growing regions have supplemented or modified the previous recommendation. Although this information is valuable, it may not be adequate for all seed sizes currently cultivated in Saskatchewan. This is due to vast changes in genetics, growing seasons, and production practices.

Seed costs comprise a large portion of the total cost of production for faba bean. These seed costs can be raised further, due to differences in thousand kernel weight (TKW) between and within varieties. Costs are raised due to more seed being required to achieve targeted plant densities (Loss et al. 1998). Furthermore, due to innate differences in seed volume compared to small-seeded crops, and the potential increase in seed volume due to TKW differences, there may be additional costs associated with the logistics of handling larger seed volumes. Further additional costs such as increased seeding time per field, fuel costs, man-power, can also increase the total cost of production for faba bean, further deterring the cultivation of this crop. Reducing production costs can be achieved using small-seeded varieties. However, large-seeded types are economically more attractive as they are preferred by export markets and often associated with higher prices (Saskatchewan Pulse Growers 2018). Additionally, small-seeded varieties can help to reduce the aforementioned logistical issues and in turn minimize associated additional costs. Furthermore, this crop is known to respond to higher plant densities with small yield increases. Therefore, determining the seeding rate(s) at which yield and the return on investment are maximized is essential for improving faba bean production (Graf and Rowland 1987; Loss et al. 1998). Therefore, there is a need to re-assess the optimal seeding rate required by the various faba bean varieties produced in Saskatchewan, in order to obtain economically sustainable faba bean production.

CDC Snowdrop and CDC SSNS-1 are the two smallest seed-size faba bean varieties grown in Saskatchewan. These two varieties are representative of the two tannin classes. Although FB9-4 is not commonly seeded, it is representative of the large-seeded varieties available in V. faba *minor* and for those cultivated in Saskatchewan. This study was conducted to determine seeding rate responses of various faba bean varieties, under two contrasting Saskatchewan environments. One site was located in the black soil zone which traditionally has cooler temperatures and more precipitation than the site located in the brown soil zone. Furthermore, this study was conducted using seeds m^{-2} instead of plants m^{-2}. This is due to seeds m^{-2} being directly manipulated by the grower, whereas plants m^{-2} is subjected to many external factors. Using viable seeds m^{-2} rather than plants m^{-2} can also help to reduce the cost of production by reducing seed and logistical costs, as mortality does not need to be accounted for. In this experiment, it is hypothesized that the seeding rate required to reach maximum yield will differ among varieties (ie. tannin content) and varieties that differ in seed size. The objective of this experiment is to identify the optimal seeding rate required to maximize yield in three faba bean varieties. This will be used to update one component in the set of best management practices for faba bean production in Saskatchewan.

3.2 Methodology

3.2.1 Experimental Design and Management

This experiment was conducted on conventional, no-till land in 2015, 2016, and 2017 in Melfort and Saskatoon, Saskatchewan. At Melfort, the study site was located at the Northeast Agriculture Research Foundation Research Farm (Melfort: 52°85'N, 104°63'W), in the black soil zone, in all three years. This location represents Saskatchewan's primary faba bean production area, where over half of the seeded acres are found (Specialty Crop Report 2018). The Saskatoon locations were managed by the University of Saskatchewan and were located in the dark brown soil zone. This location represents a less typical faba bean production area, with only 10% of the seeded acres to this crop are found (Specialty Crop Report 2018). In 2015, the study was located at the Goodale Research Farm (Saskatoon: 52°05'N, 106°48'W), in 2016 at the University's Main Campus (Saskatoon: 52°13'N, 106°63'W), and in 2017 at the Kernen Research Farm (Saskatoon: 52°15'N, 106°54'W). These two sites represent the more typical faba bean growing areas in the province. All sites were seeded into cereal stubble, except in 2016 at Saskatoon, which was chemical fallowed in the previous cropping year.

This experiment followed a three by five factorial treatment structure, in a randomized complete block design, with four replicates. The first factor was variety: CDC SSNS-1, CDC Snowdrop, and FB9-4. CDC SSNS-1 is a small-seeded (<360 g thousand kernel weight [TKW]) tannin variety, CDC Snowdrop is a small-seeded (<360 g TKW) low-tannin variety, and FB9-4 is a large-seeded (>650 g 1000^{-1} $seeds^{-1}$) tannin variety. The second factor was seeding rate: 20, 40, 60, 80, and 100 viable seeds m^{-2}. In 2017, the seeding rate treatments were modified to 5, 10, 20, 40, and 60 viable seeds m^{-2}. This was done in response to the 2015 and 2016 results, as it was apparent the original seeding rates were inadequate to elicit a yield response curve. Actual seeding rates were determined based on percent germination and TKW (Table 3.1).

Table 3.1: Percent germination and thousand kernel weight of CDC SSNS-1, CDC Snowdrop, and FB9-4 at all locations in 2015, 2016, and 2017.

Variety	Year	Germination (%)	Thousand Kernel Weight (g 1000^{-1} $seeds^{-1}$)
CDC SSNS-1	2015	100	316
	2016	100	316
	2017	100	316
CDC Snowdrop	2015	94	344
	2016	94	344
	2017	96	344
FB9-4	2015	99	695
	2016	99	695
	2017	98	695

Faba bean was seeded into moisture in early to mid-May (Table 3.2), approximately 3.8 to 7.6 cm deep, by a Fabro cone seeder with knife openers. In Melfort, the plots were 1.8 by 7 m with 10 rows 17.7 cm apart in 2015 and 6 rows 30.5 cm apart in 2016 and 2017. At Saskatoon, plots were 1.8 m by 6 m with 6 rows 30.5 cm apart in all three years. Due to mechanical difficulties during seeding, the large-seeded FB9-4 varieties were unseeded in all three years at Melfort.

Table 3.2: Seeding and harvest dates in 2015, 2016, and 2017 at Melfort and Saskatoon, Saskatchewan.

	Melfort		**Saskatoon**	
Year	**Seeded**	**Harvested**	**Seeded**	**Harvested**
2015	May 26	October 18	May 9	September 14
2016	May 9	November 7	May 4	September 6
2017	May 23	September 26	May 11	September 5

Prior to seeding, the seed was treated with Apron Maxx® RTA® (fludioxonil 0.73% + metalaxyl-M and S-isomer 1.10%, Syngenta Canada Inc., Guelph, Ontario, Canada) at 325 ml per 100 kg $seed^{-1}$. Tagteam® granular inoculant (*Penicillium bilaii* and *Rhizobium leguminosarum*, Monsanto Canada Inc., Winnipeg, Manitoba, Canada) was applied in-furrow with the seed at 3.0 kg ha^{-1}, except in Melfort during 2015 when it was applied at 5.3 kg ha^{-1}. Phosphorus was applied as monoammonium phosphate at 25 kg P_2O_5 ha^{-1} in 2015 and 2016 and at 40 kg P_2O_5 ha^{-1} in 2017 at Melfort. In Saskatoon, phosphorus was applied at 17 kg P_2O_5 ha^{-1} in all three years. Sulphur was only applied at Melfort, in 2015, as ammonium sulphate at 11.2 kg S ha^{-1}. Nitrogen and potassium fertilizers were not required. However, some nitrogen was applied due to nitrogen-containing fertilizers.

All herbicide, fungicide, insecticide, and desiccation products were applied as needed at each location, to provide non-limiting conditions (Table 3.3). Lastly, all plots were combined in late September to early November (Table 3.2).

Table 3.3: Herbicide, fungicide, insecticide, and desiccation products and rates for Melfort and Saskatoon, Saskatchewan in 2015, 2016, and 2017.

	Melfort		**Saskatoon**	
	Product	**Rate**	**Product**	**Rate**
2015				
Herbicide	Glyphosate 540 g.a.e. L^{-1}	1.7 L ha^{-1}	Glyphosate 540 g.a.e. L^{-1}	1.7 L ha^{-1}
	Bentazone 480 g.a.e. L^{-1}	2.3 L ha^{-1}	Imazamox 35% a.e. & Imazethapyr 35% a.e.	42.8 g ha^{-1}
			Clethodim 240 g L^{-1}	0.1 L ha^{-1}
Fungicide	Not Applied		Pyraclostrobin 250 g L^{-1}	0.4 L ha^{-1}
Insecticide	Not Applied		Lamda-cyhalothrin 120 g L^{-1}	0.1 L ha^{-1}
Desiccant	Not Applied		Diquat 240 g L^{-1}	1.7 L ha^{-1}
2016				
Herbicide	Imazamox 35% a.e. & Imazethapyr 35% a.e.	42.8 g ha^{-1}	Ethalfluralin 5%	22.0 kg ha^{-1}
			Glyphosate 540 g.a.e L^{-1}	1.7 L ha^{-1}
			Imazamox 35% a.e. & Imazethapyr 35% a.e.	42.8 g ha^{-1}
Fungicide	Pyraclostrobin 250 g L^{-1}	0.4 L ha^{-1}	Pyraclostrobin 250 g L^{-1}	0.4 L ha^{-1}
Insecticide	Not Applied		Lamda-cyhalothrin 120 g L^{-1}	0.1 L ha^{-1}
Desiccant	Not Applied		Diquat 240 g L^{-1}	1.7 L ha^{-1}
2017				
Herbicide	Imazamox 35% a.e. & Imazethapyr 35% a.e.	42.8 g ha^{-1}	Imazamox 35% a.e. & Imazethapyr 35% a.e.	42.8 g ha^{-1}
			Sethoxydim 450 g L^{-1}	0.5 L ha^{-1}
Fungicide	Picoxystrobin 350 g L^{-1}	0.85 L ha^{-1}	Not Applied	
Insecticide	Not Applied		Not Applied	
Desiccant	Glyphosate 540 g.a.e. L^{-1}	1.7 L ha^{-1}	Diquat 240 g L^{-1}	1.7 L ha^{-1}

3.2.2 Data Collection

Data collection consisted of plant density, above-ground biomass yield, harvested grain yield, and TKW. Density was measured approximately two weeks after first emergence was noted. Faba bean seedlings were counted in a minimum of two randomly selected 0.25 m^{-2} quadrats in the front and back of each plot. In 2016 and 2017, prior to physiological maturity, all above-ground biomass in two 0.25m^{-2} quadrats were collected. Faba bean biomass was oven-dried for approximately 48 hours prior to weighing. After maturity was reached, a minimum of four center rows per plot, were harvested with a small plot combine. After a drying period, the entire harvested sample was cleaned and weighed to calculate yield in kg ha^{-1}. A subsample was then taken and used to determine thousand kernel weight (g 1000^{-1} $seeds^{-1}$). Lastly, in order to identify the optimal economic seeding rate, an average seed price of $0.51 per kg and grain price of $0.22 per kg was assumed (Crop Planning Guide 2018). Furthermore, a 10% opportunity cost was also factored in to the cost of production (Loss et al. 1998; Shirtliffe and Johnston 2002).

3.2.3 Statistical Analysis

Due to mechanical difficulties at seeding resulting in spatially uneven plots, the 80 and 100 viable seeds m^{-2} seeding rate treatments of FB9-4, in Saskatoon, were removed for statistical analysis. Any explainable outlying data was removed from anaylsis, while non-explainable data points were retained (ie. plots seeded less than 3 meters were removed). Data were analyzed using “lme4” and “lmerTest” in R (Bates et al. 2015; Kuznetsova et al. 2016). Data was modeled using mixed-effects with seeding rate and variety as the fixed effects and site-year, replication within site-year, variety by site-year, seeding rate by site-year, and seeding rate and variety by site-year as random effects.

Data was modelled using both linear and quadratic regression analyses and assessed using ANOVA and AIC values. Random effects were assessed using the “ranova” command in R. All treatment effects were acknowledged as significant at $P < 0.05$.

3.3 Results and Discussion

All response variables, except plant density, had significant replicate nested within site-year interaction, while site-year was significant for all four response variables (Table 3.4). There was a significant variety by site-year interaction for plant density, yield, and thousand kernel weight (Table 3.4). The seeding rate by site-year interaction was significant for both plant density and yield as well (Table 3.4). The three-way random effect was insignificant for plant density, biomass, and yield and was consequently dropped from further analyses (Table 3.4). The three-way random effect was, however, significant for thousand kernel weight and therefore retained for further analysis (Table 3.4). These results indicate that treatment effects were dependent on the site-year and thus each location was analyzed separately. Despite, the non-significant treatment by site year interactions for biomass, it was also analyzed by site-year. This was done due to differences in treatments between years and to match the analyses of the other response variables.

Table 3.4: Random effect p-values for site-year and respective interactions between variety and seeding rate for plant density (plant m^{-2}), biomass yield (g m^{-1}), grain yield (kg ha^{-1}), and thousand kernel weight (g TKW).

	Plant Density (plant m^{-2})	**Biomass Yield (g m^{-1})**	**Grain Yield (kg ha^{-1})**	**Thousand Kernel Weight (g 1000^{-1} $seeds^{-1}$)**
Site-Year (SY)/Replicate	0.1890	<0.0001***	<0.0001***	<0.0001***
Site-Year	0.0018**	<0.0001***	<0.0001***	0.0012**
Variety (V) x SY	0.0288*	1.0000	<0.0001***	0.0477*
Seeding Rate (SR) x SY	<0.0001***	0.5614	<0.0001***	0.0723
V x SR x SY	1.0000	0.2984	0.7100	0.0017**

*** P < 0.0001; ** 0.0001< P >0.01; * 0.01< P >0.05

3.3.1 Environmental Conditions

May 2015 at Melfort and Saskatoon was cooler than their respective long-term averages, while June was warmer, and July was similar (Table 3.5). The remaining part of the 2015 growing season was warmer at Melfort. In Saskatoon, August and September were cooler, while October was warmer. May and June 2016 were warmer than the long-term average at both locations. July through October 2016 was much warmer than normal in Melfort, while the same period was much cooler in Saskatoon. May and June were similar to the long-term average in Melfort 2017, while the remainder of the growing season was warmer. In Saskatoon, May and October 2017 were warmer than the long-term average, whereas June through August was cooler, while September was similar. Overall, all three experimental periods were similar to each location's respective long-term climate normal (Table 3.5).

Table 3.5: Mean monthly temperatures (°C) and precipitation (mm) at Melfort and Saskatoon in 2015 – 2017.

Location	Year	May	June	July	August	September	October	Avg./Total
	---------- **Mean Temperature (°C)** ----------							
Melfort[x]	2015	9.9	16.4	17.9	17.0	11.9	6.6	13.2
	2016	13.6	17.1	18.1	16.3	12.0	1.7	13.1
	2017	10.8	15.2	18.7	17.2	11.9	4.3	13.0
	Long-Term[z]	*10.7*	*15.9*	*17.5*	*16.8*	*10.8*	*3.3*	*12.5*
Saskatoon[y]	2015	10.1	17.2	19.4	17.4	11.9	6.7	13.7
	2016	13.7	17.4	18.7	16.9	11.8	2.1	13.4
	2017	12.1	16.1	19.6	17.8	12.8	5.0	13.9
	Long-Term[z]	*11.8*	*16.1*	*19.0*	*18.2*	*12.0*	*4.4*	*13.6*
	---------- **Precipitation (mm)** ----------							
Melfort[x]	2015	7.1	54.8	149.8	57.4	70.0	33.0	372.1
	2016	16.8	53.2	128.7	80.8	41.3	57.7	378.5
	2017	46.4	44.1	33.3	3.1	70.0	43.5	240.4
	Long-Term[z]	*42.9*	*54.3*	*76.7*	*52.4*	*38.7*	*27.9*	*292.2*
Saskatoon[y]	2015	0.4	13.6	84.3	45.2	50.0	33.9	227.4
	2016	41.6	49.7	58.6	70.2	24.1	40.8	285.0
	2017	46.3	30.9	25.5	25.2	29.1	17.8	174.8
	Long-Term[z]	*36.5*	*63.6*	*53.8*	*44.4*	*38.1*	*18.8*	*255.2*

[x] Environment Canada weather station located at 52°49’00N; 104°36’00
[y] Environment Canada weather station located at 52°09’00N; 103°36’00
[z] Canadian Climate Normal by station 1981 to 2010.

The 2015 and 2016 growing seasons in Melfort received more precipitation than normal with a 49% increase in total rainfall in July 2015 and 40% in 2016 (Table 3.5). This contrasted with the 2017 growing season, where the total precipitation received was below average. This was largely due to only 3.1 mm of precipitation in August instead of the usual 52.4 mm (Table 3.5). Saskatoon in 2015 had slightly less than normal precipitation, while 2016 was slightly wetter more than normal (Table 3.5). The 2017 growing season differed greatly from the long-term average with a deficit of 80.4 mm less total precipitation (Table 3.5). Overall, total precipitation was the largest contrasting factor between the two sites. All three years Melfort received nearly 100 mm more precipitation than Saskatoon. Lastly, the 2017 experimental period provided a good contrasting environment to 2015 and 2016 periods.

3.3.2 Plant Population

As expected, plant density responded significantly to seeding rates in all six site-years (Table 3.6). Plant density was not significantly different between the varieties in any site-year (Table 3.6). Yet, there was a significant seeding rate by variety interaction in three out of six site-years (Table 3.6).

Table 3.6: Variety, seeding rate, and treatment interaction p-values for plant density (plants m^{-2}) at Melfort and Saskatoon, 2015 to 2017.

	Melfort			**Saskatoon**		
	2015	**2016**	**2017**	**2015**	**2016**	**2017**
Seeding Rate (SR)	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
Variety (V)	0.9662	0.4874	0.6909	0.4861	0.6530	0.5025
SR x V	0.0448*	0.0231*	0.5957	0.6103	0.1273	<0.0001 ***

*** P <0.0001; ** 0.0001< P >0.01; * 0.01< P >0.05

At each site-year, plant density increased linearly with increasing seeding rate (Figure 3.1). At Saskatoon 2015 and both 2016 locations, each seeding rate treatment was within 15% of the intended population. This response was similar to that found by Loss et al. in 1998. Plant density at Melfort 2015 and both 2017 locations, was only 50% of the intended population. Additionally, at these three site-years, as seeding rate increased the percent establishment decreased from 88 to 77%. This resulted in the slope of these lines to be smaller in than in the other three site-years (Figure 3.1).

This effect is likely due to inter-competition between seeds for available soil moisture (López-Bellido et al. 2005; Adisarwanto and Knight 1997). As the number of seeds within a given area increases, there is less water available for imbibition and the successful germination of all seeds. The low plant populations at Melfort 2015, were slightly unexpected as the high residual soil moisture from the fall of 2014 should have supplemented the minimal precipitation received in May 2015 (Table 3.5). However, this is only speculation as residual soil moisture was not measured. It is interesting to note that despite Saskatoon also being extremely dry in May and June 2015 the resulting plant populations were within the expected range (Table 3.5; Figure 3.1). Conversely, both 2017 locations had near-normal precipitation in May and above average precipitation in the fall of 2016. Therefore, it is unknown why 2017 plant populations were much lower than intended, as soil moisture levels should have been adequate. Additional data collection of days to emergence, soil temperature, seed vigor testing, etc., could have assisted in interpreting these unanticipated findings.

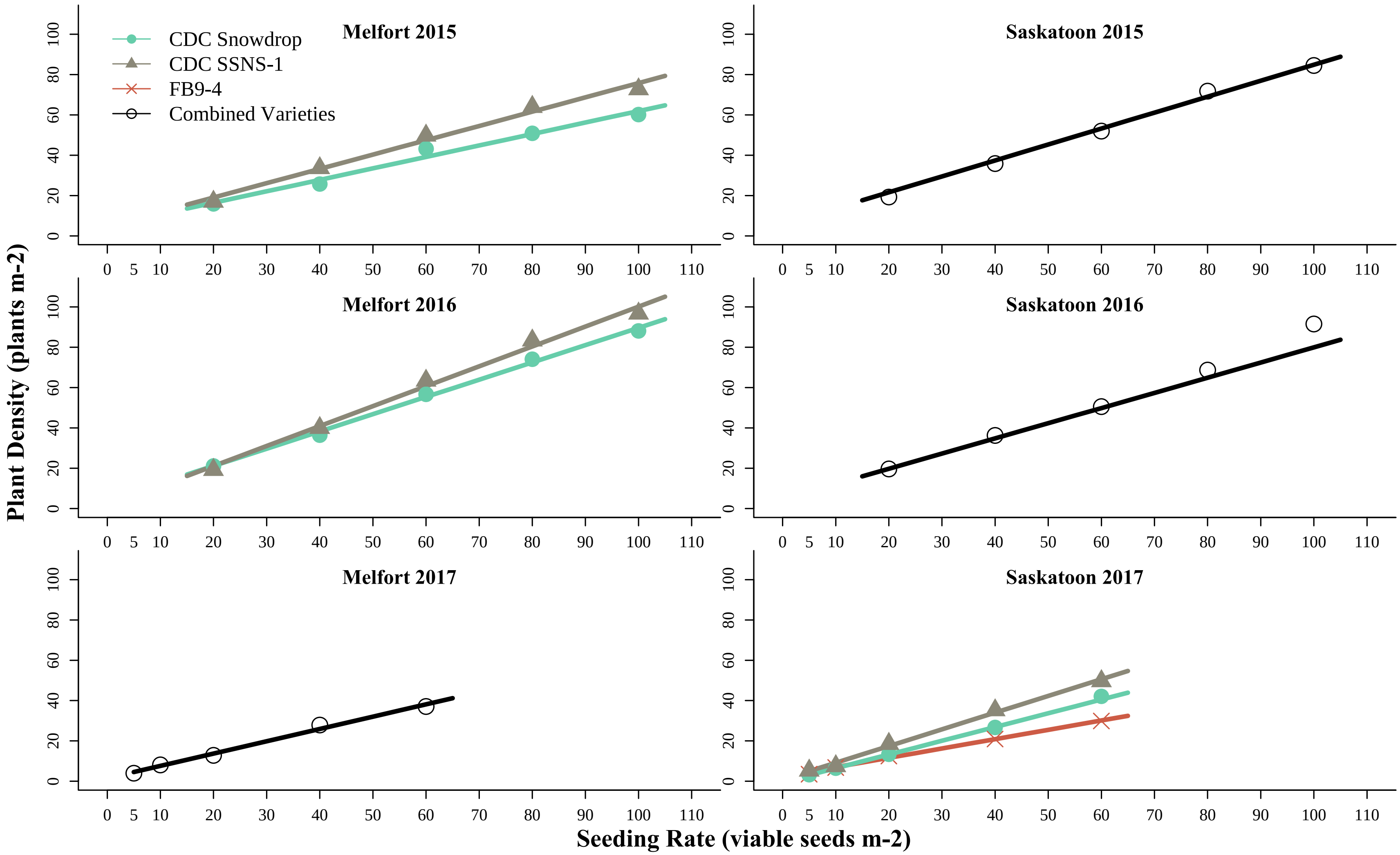

Figure 3.1: Seeding rate (viable seeds m^{-2}) effects on plant density (plants m^{-2}) of three faba bean varieties, at Melfort and Saskatoon 2015 to 2017.

At Melfort 2015 and 2016, along with Saskatoon 2017, CDC SSNS-1 had greater plant populations than CDC Snowdrop at each seeding rate treatment (Figure 3.1). Moreover, CDC Snowdrop and CDC SSNS-1 both had greater plant populations than FB9-4 (Figure 3.1). The difference between CDC SSNS-1 and CDC Snowdrop maybe due to variance in seed lot sizes, as CDC SSNS-1 was 316 g TKW, while CDC Snowdrop was 344 g TKW (Table 3.1). Therefore, CDC SSNS-1 could have required less moisture for imbibition, or had better seed vigor than CDC Snowdrop, contributing to its greater germination success. Furthermore, differences in germination may also be due to inherited seed coat differences, and initial seed moisture content (Rowland and Gusta 1976). Based on these considerations, it was expected that FB9-4 would have a lower population overall, compared to both small-seeded varieties, due to its innately larger size. In addition, this large-seeded variety is more susceptible to mechanical damage at seeding, which can further reduce germination success. Overall, plant density increased with increasing seeding rate as expected. Additionally, the resulting plant populations were adequate to proceed with further exploration.

3.3.3 Biomass Yield

Biomass yield significantly responded to seeding rate in two of four site-years (Table 3.7). There was only a significant difference in the biomass of each variety at Saskatoon 2017 (Table 3.7). Furthermore, in Saskatoon, there was a significant interaction between variety and seeding rate (Table 3.7). Lastly, Melfort 2016 was the only site-year to have biomass yield not be significantly affected by any treatment factor (Table 3.7).

Table 3.7: Variety, seeding rate, and treatment interaction p-values for biomass yield (g dry m^{-2}) at Melfort and Saskatoon, 2016 and 2017.

	Melfort		**Saskatoon**	
	2016	**2017**	**2016**	**2017**
Seeding Rate (SR)	0.1094	0.0205*	0.0016**	0.1359
Variety (V)	0.3783	0.5951	0.3850	<0.0001***
SR x V	0.6005	0.8464	0.0328*	0.0333*

*** p<0.0001; ** 0.0001<p>0.01; * 0.01<p>0.05

In general, biomass yield responded linearly to increasing seeding rate. At Melfort 2017, biomass yield increased significantly with increasing seeding rate (Figure 3.2). In Saskatoon 2016, the biomass of both CDC SSNS-1 and FB9-4 declined with increasing seeding rate; while biomass yield was similar across seeding rates for CDC Snowdrop (Figure 3.2). At Saskatoon 2017, CDC SSNS-1 followed the same trend as in 2016. However, both CDC Snowdrop and FB9-4 changed in response from the previous year, with both having increasing biomass yield in response to increasing seeding rate (Figure 3.2).

The lack of response by biomass to seeding rate in Melfort 2016, suggests that ideal growing conditions occurred during the vegetative period at this location. Under ideal conditions, total biomass accumulation (per unit area) becomes similar at both high and low seeding rates. This is because plant density and the number of stems is inversely related (López-Bellido et al. 2005). This result is similar to Adisarwanto and Knight (1997) who also found that biomass reaches a plateau at 20 plants m^{-2}. The results at Saskatoon 2016 suggest that growing conditions were nearly ideal as well. However, the declining biomass yield of two of the three varieties, suggests that growth may have been limited by competition for solar radiation (López-Bellido et al. 2005). The increasing biomass accumulation at both 2017 locations, is likely due to the lack of moisture, resulting in limiting or non-ideal growing conditions. However, if the two lowest seeding rates are disregarded at Melfort 2017,

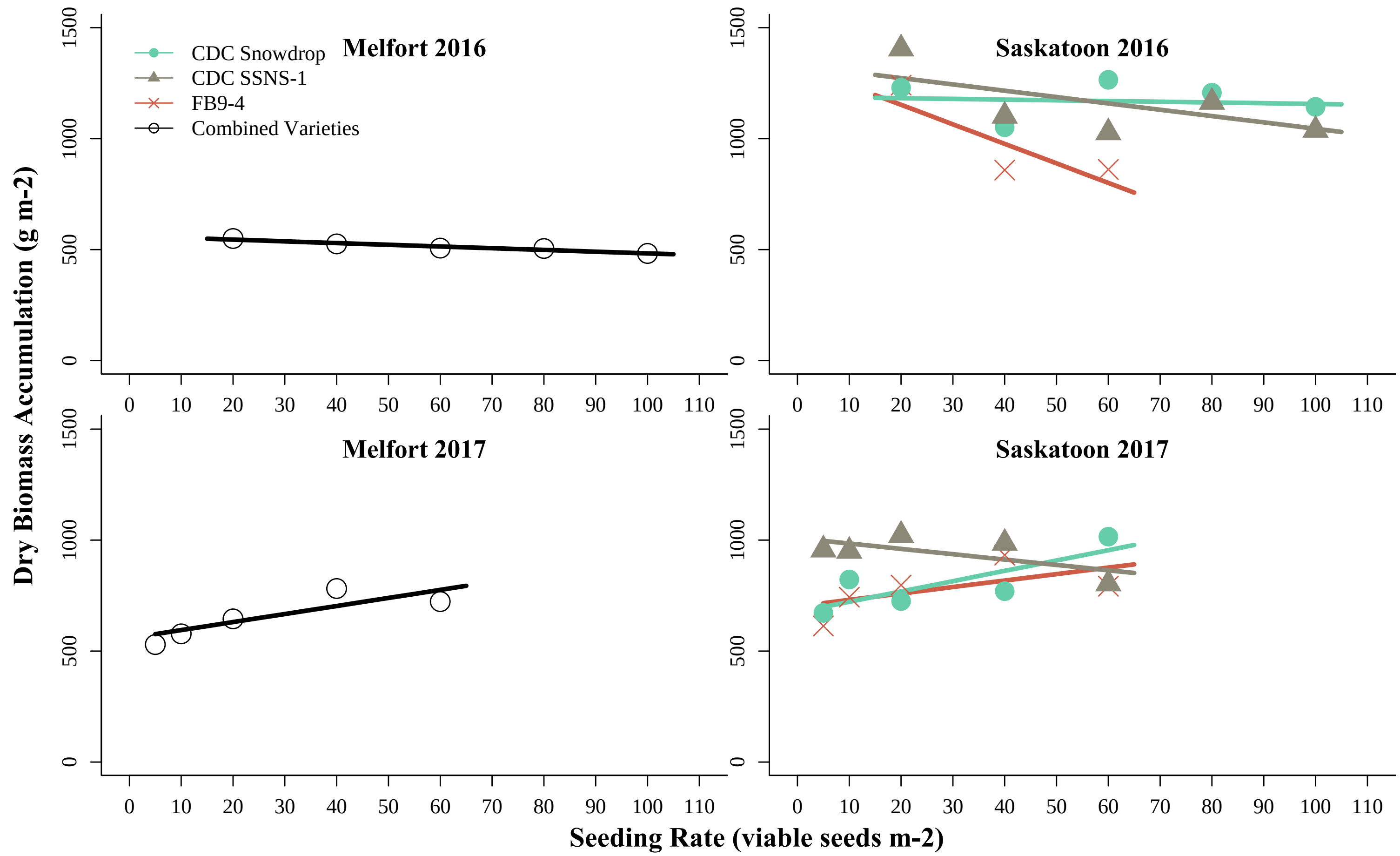

Figure 3.2: Seeding rate (viable seeds m^{-2}) effect on biomass yield (g m^{-2}) of three faba bean varieties in 2016 and 2017 at Melfort and Saskatoon. Multiply by a factor of 10 to get kg ha^{-1}. Melfort 2016 P = 0.4370; Melfort 2017 P = 0.0702; Saskatoon 2016 CDC Snowdrop P = 0.7689, CDC SSNS-1 P = 0.1222, FB9-4 P = 0.0155; Saskatoon 2017 CDC Snowdrop P = 0.0192; CDC SSNS-1 P = 0.5375, FB9-4 P = 0.0122.

biomass yield becomes relatively constant at 20 viable seeds m^{-2} and is thus similar to 2016 results (Figure 3.2).

It is hard to speculate as to why there was a significant difference between varieties in Saskatoon in both years. The significant differences between varieties in 2017 were likely confounded by the significant differences in the established plant population of each variety in that year (Figure 3.1). However, this suggestion is not supported by the 2016 data, where there were no significant differences in plant density, yet biomass differed. Therefore, these differences in biomass are likely driven by other factors other than any direct varietal or phenotypic differences. Overall, results were as expected, with ideal (wet) environments resulting in linear or decreasing biomass yield, while non-ideal (dry) environments saw biomass yield continuing to increase.

3.3.4 Grain Yield

Grain yield responded significantly to seeding rate at four of six site-years (Table 3.8). At three of six site-years, yield was significantly different between the varieties (Table 3.8). Yet, there was only a significant seeding rate by variety interaction at two of six site-years (Table 3.8). Lastly, Melfort 2015 and both 2017 locations had quadratic responses, while the other three site-years were linear (Table 3.8). Further to expectations, these are the locations where plant density was also significantly different between varieties.

Table 3.8: Variety, seeding rate, and treatment interaction p-values for grain yield (kg ha^{-1}) at Melfort and Saskatoon, 2015 to 2017.

	Melfort			Saskatoon		
	2015	**2016**	**2017**	**2015**	**2016**	**2017**
Seeding Rate (SR)	<0.0001 ***	0.0040 **	<0.0001 ***	0.1580	0.7958	<0.0001 ***
Variety (V)	0.0035 **	0.0129 *	0.3848	0.9365	0.9411	0.0017 **
Quadratic	0.0037 **	NA	<0.0001 ***	NA	NA	<0.0001 ***
SR x V	0.4593	0.0090 **	0.3145	0.4906	0.3416	0.0360*

*** P < 0.0001; ** 0.0001< P >0.01; * 0.01< P >0.05

NA – not applicable

The yield differences between the six site-years illustrates the considerable yield variability that occurs from year to year with faba bean production (Figure 3.3). This variability can be attributed to the amount of rainfall, soil moisture, air temperature between flowering and maturity from year to year, and differences between the soil zones (López-Bellido et al. 2005).

At Melfort 2015, CDC SSNS-1 yielded more than CDC Snowdrop, at all seeding rate treatments (Figure 3.3). This site-year received more precipitation than average, yet yield had a quadratic response to seeding rate. This could be a result of delayed seeding as it is known to decrease the plant competition effects (López-Bellido et al. 2005). Furthermore, this location only had 50% of the intended plant population at each seeding rate treatment. This likely had a large confounding effect on the response of yield to seeding rate. Quadratic yield responses can help to easily identify the optimal agronomic seeding rate, as it is the rate at which maximum yield is reached (Shirtliffe and Johnston 2002). If the seeding rate is increased past the point where maximum yield is reached, yield begins to decline (Shirtliffe and Johnston 2002; Holliday 1960).

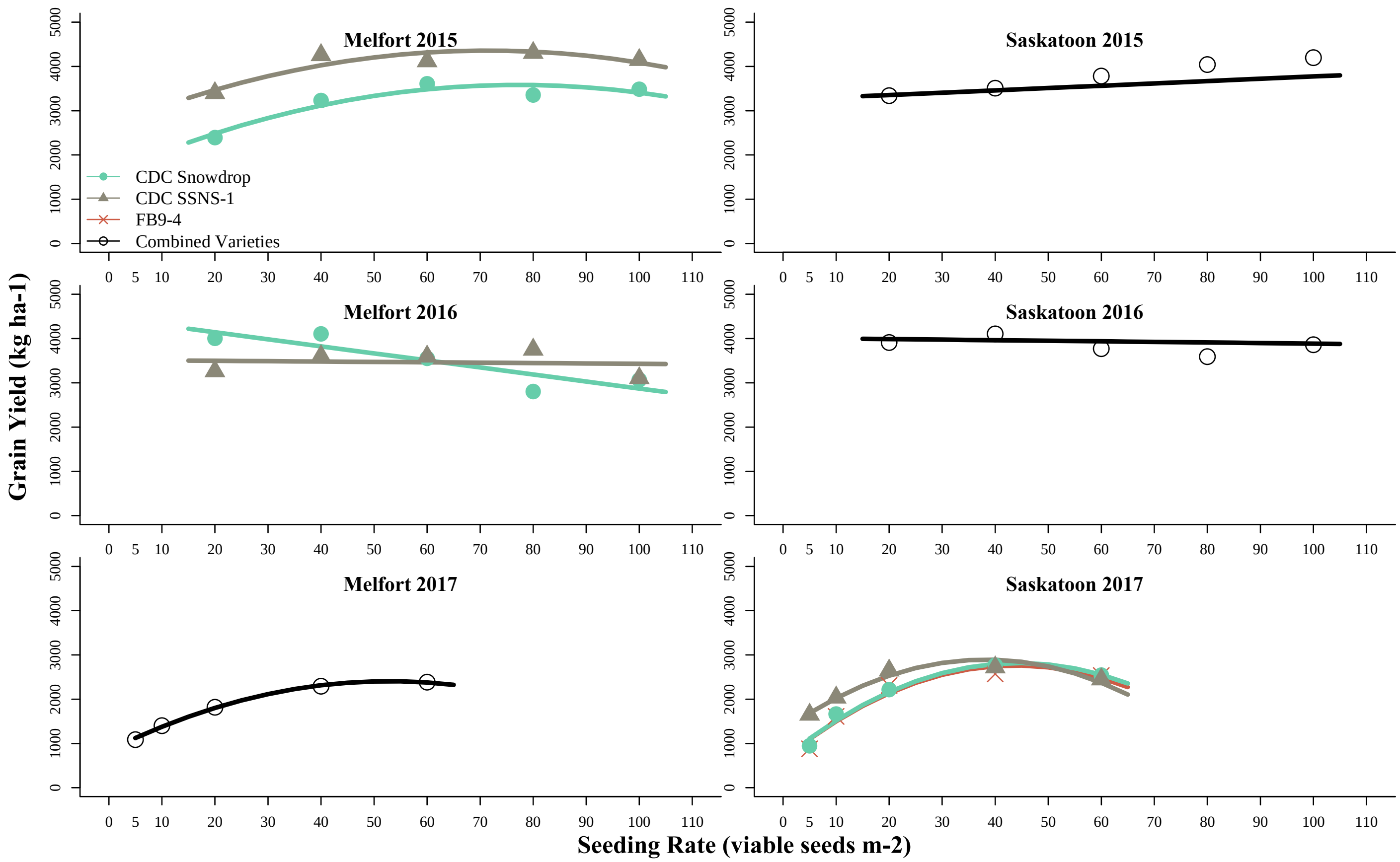

Figure 3.3: Seeding rate (viable seeds m^{-2}) effect on grain yield (kg ha^{-1}) of three faba bean varieties from Melfort and Saskatoon in 2015 to 2017. Melfort 2015 CDC Snowdrop $P < 0.0001$, CDC SSNS-1 $P = 0.4598$; Melfort 2016 CDC Snowdrop $P < 0.0001$, CDC SSNS-1 $P = 0.0090$; Melfort 2017 CDC Snowdrop $P < 0.0001$; Saskatoon 2015 $P = 0.1580$; Saskatoon 2016 $P = 0.8550$; Saskatoon 2017 CDC Snowdrop $P < 0.0001$, CDC SSNS-1 $P = 0.0188$; FB9-4 $P = 0.8320$.

Due to the quadratic response, maximum agronomic yield was identified at 77 viable seeds m^{-2} for CDC Snowdrop and 71 viable seeds m^{-2} for CDC SSNS-1 in Melfort 2015. This requirement for higher than recommended seeding rates contrasts the 2003 finding by Strydhorst who found that under non-ideal or drought-like conditions, higher seeding rates were required to maximize yield in Alberta (65 plants m^{-2}). Precipitation in Melfort 2015 was above average, yet there was a need for higher seeding rates. This further confirms that the established plant population had a confounding effect on yield.

With the drier conditions in 2017, both locations had quadratic yield responses to seeding rate. Both these locations also had only 50% of the intended plant densities, similar to Melfort 2016. At Melfort 2017, yield increased with seeding rate up to viable 53 seeds m^{-2}, where maximum agronomic yield was found (Figure 3.3). In Saskatoon, initially, CDC SSNS-1 had greater yield than CDC Snowdrop and FB9-4 which were similar (Figure 3.3). As seeding rate was increased, CDC Snowdrop and FB9-4 continued to have similar yields. All the while CDC SSNS-1 reached maximum yield earlier, resulting in the lowest numerical yield of the three varieties by the final seeding rate treatment (Figure 3.3). At this location, CDC Snowdrop and FB9-4 reached maximum agronomic yield at 44 viable seeds m^{-2}, while CDC SSNS-1 reached the maximum at 38 viable seeds m^{-2}.

The yield in the Saskatoon 2015 and both 2016 locations illustrate a linear response. Furthermore, it also suggests that the seeding rate treatments were not comprehensive enough to elicit a full response curve. Thus, only the upper limit portion of the response curve was illustrated, and thus a linear response is displayed. Therefore, the reduced seeding rate treatments in 2017, were introduced to mitigate this issue. The declining yield of CDC Snowdrop at

Melfort 2016, compared to CDC SSNS-1, could be due to differences in pod or seed retention. At this site-year, the plots were under heavy snow for approximately three weeks before combining. Thus, potentially contributing to the unexpected differences between the two varieties. However, as seed and pods were not measured, this is only a suggestion as to why this effect may have occurred.

In Saskatoon 2015, yield was similar across seeding rate treatments (Figure 3.3). The constant response, over a wide range of seeding rates, has also been found in Alberta when growing conditions were ideal (Strydhorst 2003). Although similar, yields increase by approximately 500 kg ha^{-1} between the lowest and highest seeding rate treatments at this site-year. The yield of the combined varieties, in Saskatoon 2016, slightly diminished as seeding rate increased with a 116 kg ha^{-1} difference between the lowest and highest rates. Graf and Rowland (1986) also found that faba bean yield had a tendency to slightly diminish with increasing seeding rate. In Melfort 2016, as seeding rate increased, the yield of CDC Snowdrop declined by approximately 1,400 kg ha^{-1} between the lowest and highest seeding rates (Figure 3.3). However, the yield of CDC SSNS-1 was similar across seeding rate treatments, with only a 50 kg ha^{-1} difference between the highest and lowest treatments (Figure 3.3). The declining yield of CDC Snowdrop was not expected. A possible explanation for this, could be due to the early snowfall in the fall of 2016. Plots remained under snow for three weeks, although not measured, the difference could be attributed to differences in pod or seed retention between the varieties.

At the site-years with linear responses, the minimal difference between seeding rate treatments is due to the plasticity of faba bean yield components, especially pods per plant. López-Bellido et al. (2005) confirmed that faba bean seed yield can be similar at both high and low densities, due to the number of pods per plant (within a given area) being similar. This is due to pods per plant and stems per plant having an inverse relationship. This response is supported by higher abscission rates when competition for assimilates are high, even in the absence of environmental stresses (López-Bellido et al. 2005). Furthermore, the number of pods per plant decreases with increasing seeding rate, due to a reduced number of stems (López-Bellido et al. 2005). This further contributes to the constant yield response across increasing seeding rates.

Generally, the three varieties tested had similar yield performance, when their established plant populations were also similar. This suggests that the ideal seeding rate for faba bean does not need to be altered between seed size classes other than accounting for natural differences in thousand kernel weight. Under ideal (wet) conditions, yield responded linearly to seeding rate and the maximum agronomic yield was obtained at 20 viable seeds m^{-2}. In drier (non-ideal) years, the seeding rate required to reach maximum yield was quite variable (30 to 77 viable seeds m^{-2}) and was highly dependent on the site-year. Variability in the optimal seeding rate, depending on environmental conditions, has also been cited in previous studies (Loss et al. 1998; Strydhorst 2003). At the locations where maximum yields were reached (sites with quadratic responses) had only 20 viable seeds m^{-2} had been sown, yields would have been 13 to 31% of the respective maximum. Overall results suggest that an average of 49 viable seeds m^{-2} is required to maximize the agronomic yield of faba bean in the black and brown soil zones of Saskatchewan. However, as seed costs comprise the largest portion of the total cost of production for faba bean, the economically optimal seeding rate may be lower. Thus, the agronomically ideal seeding rate needs to be weighed against the economic rate.

3.3.5 Thousand Kernel Weight

Seeding rate had a significant impact on thousand kernel weight at Melfort and Saskatoon 2016 and 2017 (Table 3.9). As expected, there was a highly significant difference between varieties at Saskatoon for all three years (Table 3.9). Furthermore, there was a significant seeding rate by variety interaction at three of six site-years (Table 3.9). Additionally, thousand kernel weight had a quadratic response at Melfort, while responses at Saskatoon were linear (Table 3.9).

Table 3.9: Seeding rate and variety treatment effects p-values for thousand kernel weight (g TKW) at Melfort and Saskatoon, 2015 to 2017.

		Melfort			**Saskatoon**	
	2015	**2016**	**2017**	**2015**	**2016**	**2017**
Seeding Rate (SR)	0.0028**	NA	0.0020**	0.3209	<0.0001 ***	<0.0001 ***
Variety (V)	0.3361	NA	0.3250	<0.0001 ***	<0.0001 ***	<0.0001 ***
Quadratic	0.0379*	NA	0.0097**	NA	NA	NA
SR x V	0.0186*	NA	0.2930	0.0433*	0.0020**	0.3494

*** P < 0.0001; ** 0.0001< P >0.01; * 0.01< P >0.05

The response of thousand kernel weight to seeding rate was for the most part similar across site-years. The thousand kernel weight of CDC Snowdrop tended to be greater than CDC SSNS-1; while FB9-4 had the largest thousand kernel weight, as expected. In Melfort 2015, the average thousand seed weight of both varieties declined slowly until 80 viable seeds m^{-2} and then began to increase (Figure 3.4). Seitzer and Evans (1973) also found that the TKW of faba bean had a tendency to decline with increasing seeding rate. However, they did not observe an increase as seeding rate was further increased. Furthermore, based

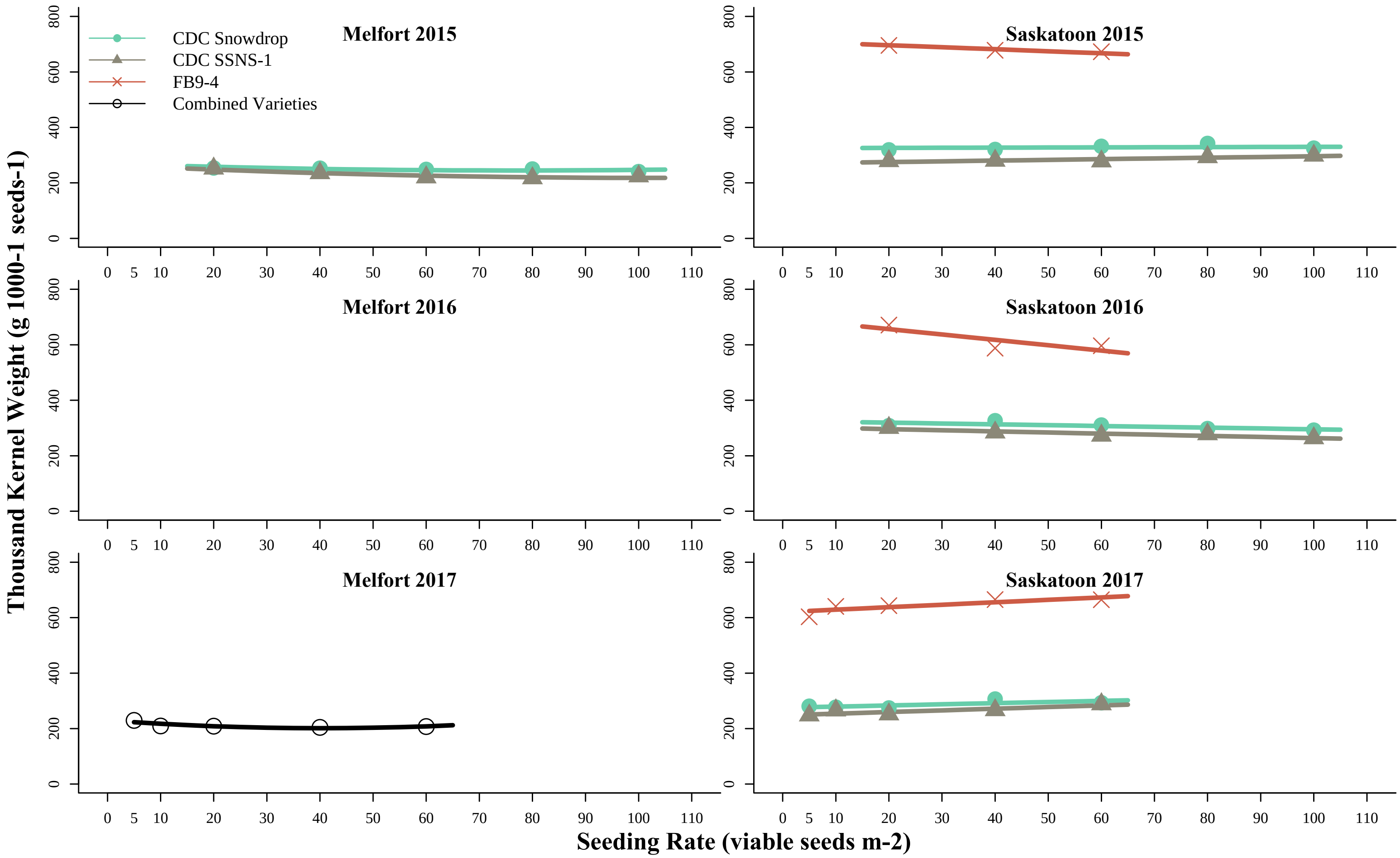

Figure 3.4: Effect of seeding rate (viable seeds m^{-2}) on thousand kernel weight (g TKW) from 2015 and 2017 in Melfort and 2015 to 2017 in Saskatoon. No TKW data was collected in Melfort 2016.

on experiences with dry bean in Saskatchewan, this decline is not likely to be agronomically or economically important (Shirtliffe and Johnston 2002). TKWs were not recorded in Melfort 2016, due to snowfall causing reduced quality and considerable variability. In Melfort 2017, the average thousand kernel weight declined as seeding rate increased up to 40 viable seeds m^{-2} and then was similar in size (Figure 3.4). Although relatively uncommon, López- Bellido et al. (2005) noted that declining TKW with increasing seeding rate had also been previously cited, with no suggestions as to why it occurred.

In Saskatoon, the thousand kernel weight response in each year and of each variety was different. The significant two-way interaction in Saskatoon is largely driven by innate differences in TKW between the three varieties. In 2015, the TKW of CDC SSNS-1 and CDC Snowdrop were similar across seeding rates tested, while FB9-4 declined (Figure 3.4). This result is interesting as the yield response at this site-year was similar among varieties and increased with seeding rate. In 2016, seed weight declined with increasing seeding rate (Figure 3.4). In 2017, seed weight increased across varieties with increasing seeding rate and corresponded to increasing yield (Figure 3.4).

Overall, the magnitude of response by thousand kernel weight to seeding rate were small across the range tested. Any significant treatment responses were for the most part dependent on the growing location. This is supported by the finding of Seitzer and Evans (1973), where thousand kernel weight was relatively unresponsive to changes in seeding rate and primarily a function of available water. Lastly, any changes to TKWs due to changes in seeding rate are likely to be of little an agronomic significance.

3.3.6 Summary

To summarize, as expected, faba bean production is highly impacted by the environment and specifically available moisture. When moisture was limiting, plant populations tended to be lower, biomass growth increased linearly, and maximum yield was obtained. Under higher moisture conditions, biomass growth and yield are similar despite significant increases in plant populations. Furthermore, the response of each variety was generally similar for each variable measured, with the largest differences existing between established plant populations. CDC SSNS-1 tended to have greater plant populations than CDC Snowdrop, while FB9-4 had the lowest populations of all three.

The seeding rate required to reach maximum agronomic yield ranged from 20 to 77 viable seeds m^{-2}, averaging 49 viable seeds m^{-2} when considering all environments. In growing seasons with more precipitation, maximum agronomic yields were reached at 20 viable seeds m^{-2} and either declined or remained similar across the range of seeding rates used. When the growing season was drier, maximum agronomic yield was reached between 30 and 77 viable seeds m^{-2}, averaging 54 viable seeds m^{-2}. The results of this experiment indicate that the current seeding rate recommendation of 44 plants m^{-2}, is slightly lower than adequate to produce a high yielding faba bean crop in the dark brown and black soil zones of Saskatchewan. Furthermore, elevated seeding rate recommendations can be a proactive management strategy to hedge against the environmental issues that cause yield variability from year to year (ie. reduced moisture). The suggestion use a higher seeding rates was also proposed by Loss et al. (1998). Therefore, based on the results of this experiment, 49 to 54 viable seeds m^{-2} should be used in order to achieve maximum agronomic yield under a wide range of Saskatchewan growing conditions.

In order to identify the optimal economic seeding rate, an average seed price of \$0.51 per kg and grain price of \$0.22 per kg was assumed (Crop Planning Guide 2018). Furthermore, a 10% opportunity cost was also factored in (Loss et al. 1998; Shirtliffe and Johnston 2002). Based on the results of this thesis, and the aforementioned assumptions, the average economic seeding rate was 45 viable seeds m^{-2} between varieties (data not shown). Coincidently, the average economic seeding rate is the same as the current recommended seeding rate in Saskatchewan. However, it is 7 seeds m^{-2} more than the previous Saskatchewan based economically optimal value of 38 plants m^{-2} (Graf and Rowland 1986). It should be noted that with near-ideal growing conditions, seeding rates above 20 viable seeds m^{-2} were uneconomical as yields were constant. Individually, CDC Snowdrop had an economically optimal seeding rate of 49 viable seeds m^{-2}, CDC SSNS-1 at 47 viable seeds m^{-2}, and FB9-4 at 35 viable seeds m^{-2}. Finally, the optimal economic seeding rate recommendation should be continuously modified, as the assumptions can change from year to year, and between farming operations.

Overall, based on the results of this experiment, 49 to 54 viable seeds m^{-2} should be used in order to achieve maximum agronomic yield. Conversely, these rates are slightly higher than the economically optimal seeding rate of 45 viable seeds m^{-2}. Therefore, on average, seeding rates of 50 viable seeds m^{-2} should be used to maximize yield and profitability of faba bean crops grown in the black and dark brown soil zones of Saskatchewan.

Determining the optimal seeding rate, both agronomically and economically, is a key step to producing a high yielding faba bean crop. Seeding rate is the first agronomic factor to affect grain yield and is directly manipulated by the grower. Results determined that the optimal seeding rate (average of agronomic and economic) for all three faba bean varieties tested was 50 viable seeds m^{-2}. This seeding rate is only required to be modified based on innate thousand kernel weight and germination values, rather than between specific varieties. Overall, this information can be used to update and supplement the best management practices for faba bean production in Saskatchewan.

Another component in the set of best management practices is disease control. Both chocolate spot and ascochyta blight have been known to significantly reduce yield and quality of faba bean crops grown in Saskatchewan. To meet Canadian Grain Grading Standards, faba bean seed can only contain up to 3% discolored or perforated seed (Canadian Grain Commission 2018). Thus, disease control, to protect against seed blemishing is essential. Determining the optimal disease control practices will also help to ensure that the optimal seeding rate defined earlier, will produce a high yielding and high quality faba bean crop. Ultimately these two agronomic components will aid in sustainable faba bean crop production for Saskatchewan and help to achieve export market standards.

4.0 OPTIMAL DISEASE MANAGEMENT WITH FUNGICIDE PRODUCTS AND APPLICATION TIMING FOR VARIOUS FABA BEAN VARIETIES

4.1 Introduction

A recent unpublished survey from across Saskatchewan found that 100% of faba bean fields surveyed had some disease present (Chatterton 2018). Although physical symptoms were minimal (less than 2%), culture samples revealed additional fungi were present beyond those that induced symptoms. While there are many diseases that can affect faba bean, chocolate spot and ascochyta blight are the two most often discussed because they have been known to cause significant yield and quality losses in faba bean crops across Saskatchewan. Consequently, there is a need for improved disease control practices for this crop in order to protect against seed blemishing, in conjunction with maintaining yield. This will help to stabilize the inconsistencies in yield and quality from year to year and ultimately help to make faba bean production in Saskatchewan more profitable.

Currently, there is noticeably limited agronomic research or information surrounding the best management practices for disease control in faba bean for Saskatchewan. As with the current recommended seeding rates, disease control recommendations have been supplemented with information from other growing regions. Although this information can provide a basis, it does not necessarily provide the best control measures for the dry, warm days, and humid, cool nights experienced throughout the growing season in Saskatchewan. Therefore, optimal fungicide products and their application timing(s) need to be identified in order to ensure the high-quality standards for export markets are met, as well as establishing yield stability. Although the primary diseases targeted in this experiment are chocolate spot and ascochyta blight, disease control was assessed based on total foliar disease severity.

This investigation was also conducted to determine if different varieties within *Vicia faba minor* require different disease management practices. Specifically, this investigation compared strobilurin-based fungicide products with a non-strobilurin product and untreated control. Furthermore, it will compare two multiple active ingredient fungicide products against two single active ingredient products. For this experiment, it is hypothesized that disease control in faba bean, and its subsequent effect on yield and quality, will differ between fungicide products, application timing(s), and varieties. The objective is to identify the optimal disease control practices required to minimize disease severity and increase yield and quality in two faba bean varieties. Overall, this will help to update one component in the set of best management practices for faba bean production in Saskatchewan.

4.2 Methodology

4.2.1 Experimental Design and Management

This experiment was conducted in and near Saskatoon, Saskatchewan on conventional, no-till managed land in 2015, 2016, and 2017. In 2015, sites were located at the University of Saskatchewan's Goodale Research Farm (Goodale: 52°95'N, 106°48'W) and on a producer's field near Osler, Saskatchewan (Osler: 52°36'N, 106°54'W). In 2016, the experiment was located at Kernen Research Farm (Kernen: 52°13'N, 106°63'W) and the Main University

Campus (Campus: 52°13'N, 106°63'W). In 2017 test sites were once again located at the Kernen Research Farm (Nasser and Lower Nasser). All sites were located within the Dark Brown soil zone and seeded into chemical-fallow or cereal stubble.

The experimental design followed a two by four by three treatment factorial structure, in a randomized complete block design, with four replicates. The first factor was faba bean variety, consisting of CDC SSNS-1 and CDC Snowdrop, which differed in their tannin content. The second factor was fungicide product with four chemical products being applied at their respective recommended rates. Fungicide products and applications rates were: fluxapyroxad 14% + pyraclostrobin 29% (Priaxor) (BASF Inc., Mississauga, Ontario, Canada) at 0.45 L ha^{-1}, fluopyram 200 g L^{-1} + prothioconazole 200 g L^{-1} (Propulse) (Bayer CropScience Inc., Calgary, Alberta, Canada) at 0.74 L ha^{-1}, penthiopyrad 200 g L^{-1} (Vertisan) (E.I. Dupont Canada Company, Mississauga, Ontario, Canada) at 1.5 L ha^{-1}, and chlorothalonil 500 g L^{-1} (Bravo) (Syngenta Canada Inc., Guelph, Ontario, Canada) at 2.97 L ha^{-1}. These products were selected as they are all or were registered for use in faba bean. In addition, Priaxor and Propulse are fungicide products with two active ingredients, whereas Bravo and Vertisan only have one active ingredient. Furthermore, Priaxor, Propulse, and Vertisan are all strobilurin-based products, whereas Bravo is not. Fungicide products were applied at 10%, 50%, and 10 + 50% flowering. The 10% flowering stage was defined as the time when one flower was open on the first node of at least 50% of plants; 50% flowering was considered when one flower was open on the fourth node of 50% of plants. In addition, an untreated (no fungicide at any application timing) treatment was included in every replicate and variety for comparison.

A cone seeder was used to seed plots of 1.8m by 6m, with 6 crop rows 30.5 cm apart. Faba bean was seeded between 3.8 to 7.6 cm deep in early May (Table 4.1). The recommended seeding rate of 45 plants m^{-2} was adjusted for 5% seedling mortality, percent germination, and thousand kernel weight. CDC SSNS-1 was 316 g TKW with 100% germination and CDC Snowdrop was 343 g TKW and 94% germination. Prior to sowing, the seed was treated with Apron Maxx®RTA® at 325 mL per 100 kg $seed^{-1}$. TagTeam® granular inoculant was applied with the seed at 3.0 kg ha^{-1}. Nitrogen fertilizer was not directly applied, but some nitrogen was provided from other nitrogen-containing fertilizers. Phosphorus was applied in a side-band at 17 kg P_2O_5 ha^{-1} as monoammonium phosphate. Lastly, potassium and sulphur fertilizers were not required.

Table 4.1: Seeding, fungicide application, and harvest dates in 2015, 2016, and 2017.

		Fungicide Application		
Site-Year	**Seeded**	**10% Flower**	**50% Flower**	**Harvested**
		2015		
Goodale	May 19	June 30	July 14	September 29
Osler	May 9	June 30	July 14	September 14
		2016		
Kernen	May 2	June 27	June 30	September 6
Campus	May 4	June 21	June 27	September 6
		2017		
Nasser	May 4	June 27	July 19	August 30
Lower Nasser	May 11	June 30	July 19	September 5

In the fall of 2015, ethalfluralin 5% was applied at 22.0 kg ha^{-1} for pre-emergence weed control. In addition, prior to seeding in the spring of every year, glyphosate 540 g.a.e. L^{-1} at 1.7 L ha^{-1} was applied to assist in pre-emergence weed control. After the faba beans had emerged and around the 3 to 6 node stage, 42.8 g ha^{-1} of imaxamox 35% a.e. + imazethapyr 35% a.e. were applied for broadleaf weed control. In 2015 and 2016, clethodim at 100 mL ha^{-1} was applied for grassy weed control, while in 2017 sethoxydim 450 g L^{-1} was applied at 0.5 L ha^{-1}. All fungicides were applied at the treatments respective timing on the dates listed in Table 4.1. Lambda-cyhalothrin 120 g L^{-1} insecticide at 1.7 L ha^{-1} was applied to control aphids and blister beetles in 2015 and 2016. After physiological maturity, the crop was desiccated with 1.7 L ha^{-1} of diquat 240 g L^{-1} to ensure dry down. After a final dry down period, plots were harvested throughout September (Table 4.1).

4.2.2 Data Collection

Data was collected on plant density, disease incidence and severity, above-ground biomass yield, grain yield, and TKW. Plant density was counted approximately two weeks after field emergence was noted. Faba bean seedlings were counted in a minimum of two randomly selected 0.25 m^{-2} quadrats in the front and back of each plot. Prior to the first and second fungicide applications, and every two weeks after the second application, disease ratings were recorded. In each plot, five plants were randomly selected to be rated. Ratings were based on the Faba bean Foliar Disease Severity Key (0 to 10 scale) where 0 represented no disease and 10 represented 91 to 100% disease symptom coverage (Boechler and Sayer 2016). Symptoms were not distinguished between chocolate spot and ascochyta blight as ratings were recorded as the total amount of disease present. To assess disease severity over time and across site-years, disease ratings were transformed into the area under the disease progress curve (AUDPC) (American Phytopathological Society [APS] 2018). The AUDPC was calculated as follows:

$$AUDPC = \sum\{[(R_i + R_{i+1})/2] * (T_{i+1} - T_i)\}$$ **(Equation 4.1)**

Where R_i is the initial or prior disease rating followed by the subsequent disease rating. T is the Julian date when the disease rating occurred. For the final AUDPC, all individual AUDPCs were summed.

Prior to physiological maturity, all the above-ground biomass from two 0.25 m^{-2} quadrats per plot were collected. To determine biomass yield, the samples were oven-dried in paper bags, for approximately 48 hours, prior to weighing. After maturity was reached a minimum of 4 rows, in the center of each plot, was collected using a small plot combine. After a drying period (to achieve equal moisture content) the entire sample was cleaned and weighed to calculate yield in kg ha^{-1}. A subsample was then used to determine average seed size (g 1000^{-1} $seeds^{-1}$).

4.2.3 Statistical Analysis

Any outliers, with known causes were removed from analysis, while those with no known cause were retained. A one-way ANOVA with all treatments and site-years combined was conducted for all response variables. Contrasts between the untreated control and the three timing, four products, and two variety treatments, were performed, as well as contrasts within timing, products, and variety factors. For plant density, a single-factor ANOVA was performed. For biomass yield, grain yield, and thousand kernel weight a two-factor ANOVA was performed (product and timing including the control). A three-factor ANOVA was also performed, without the control, for the aforementioned response variables. All factorial ANOVA analyses were modeled using the mixed-effects packages “lme4” and “lmerTest” in R (Bates et al. 2015; Kuznetsova et al. 2016). Variety, product, and timing were considered fixed effects and site-year, replication within site-year, variety by site-year, product by site-year, timing by site-year, and the associated two- and three-way interactions were considered random effects (where applicable). Data was tested for homogeneity of variances and transformations were used to correct for heterogeneous variances. All data points were subjected to square-root transformation, except plant density at Osler 2015 which was transformed by the natural logarithm. All data was then back-transformed for presentation. Finally, means were separated using the "emmeans" command giving the Least-Squares mean values (Lenth 2018). All data was considered significant at $P < 0.05$.

4.3 Results and Discussion

Specific random effect interactions for each measured variable are listed within each sub-section for clarity. Overall, there were significant replicate nested within site-year and site-year interactions for almost all response variables. There was a significant variety by site-year effects for plant density, disease ratings, and three-way biomass analyses. Product by site-year effects were significant for the disease ratings as well. Timing, the two- and three-way interactions by site-year were not significant for any variable tested. Therefore, some data was analyzed by site-year and some was combined across site-years. These results indicate that treatment effects were dependent on the site-year for some variables and were similar across site-years for others.

4.3.1 Environmental Conditions

Chocolate spot occurs when humidity is high (>80%) or when conditions are wet, with average temperatures of 20°C (Harrison 1988; Stoddard et al. 2010). Ascochyta blight occurs largely after significant rainfall events and when the average temperature is 15°C (Stoddard et al. 2010). Saskatoon experienced a significant rainfall event in July 2015 when 54.1 mm of the month's total (84.3 mm) was received on one day (Environment Canada 2018). In August 2016, there were two smaller albeit significant rainfall events that occurred five days apart. Between these two events, 37.4 mm of precipitation occurred, accounting for 47% of the month's total precipitation (Environment Canada

2018). During these months, the average daily temperature ranged between 18°C and 19°C, with daily highs between 20°C and 30°C. This combination of temperature and precipitation were conducive to the development of both chocolate spot and ascochyta blight in 2015 and 2016. Although temperatures were adequate for disease development in 2017, the lack of precipitation produced less than ideal environmental conditions. Overall, due to the conducive environmental conditions in 2015 and 2016, there is a greater probability of fungicide responses to occur in these site-years than in 2017. Lastly, the Osler location is approximately 30 km north of Saskatoon. As there was no weather measurements taken directly from the site, an assumption was made that the weather events were similar to the ones recorded in Saskatoon.

4.3.2 Plant Density

There was a significant difference between the plant density of CDC SSNS-1 and CDC Snowdrop, based on the one-way ANOVA ($F_{1,611}$=91.2, $p<0.0001$). On average, CDC SSNS-1 had 6 more plants m^{-2} than CDC Snowdrop (Figure 4.1). The two varieties also responded differently within each site-years, except both 2016 locations (Table 4.2). The greatest differences between the two varieties occurred in 2017, which is likely a result of the drier spring conditions (Figure 4.1). In 2015, the mean difference between the two varieties was 6 plants m^{-2} (Figure 4.1). It is interesting to note that plant densities were lowest in 2016, despite it being the wettest year. Overall, the plant densities in this experiment were adequate but could contribute to significant differences in disease levels and yields between the six site-years.

Table 4.2: Varietal effects on plant density in Saskatoon, 2015 to 2017.

	Goodale 2015	Osler 2015	Campus 2016	Kernen 2016	L. Nasser 2017	Nasser 2017
Variety	<0.0001***	0.0304*	0.2694	0.3469	<0.0001***	<0.0001***

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

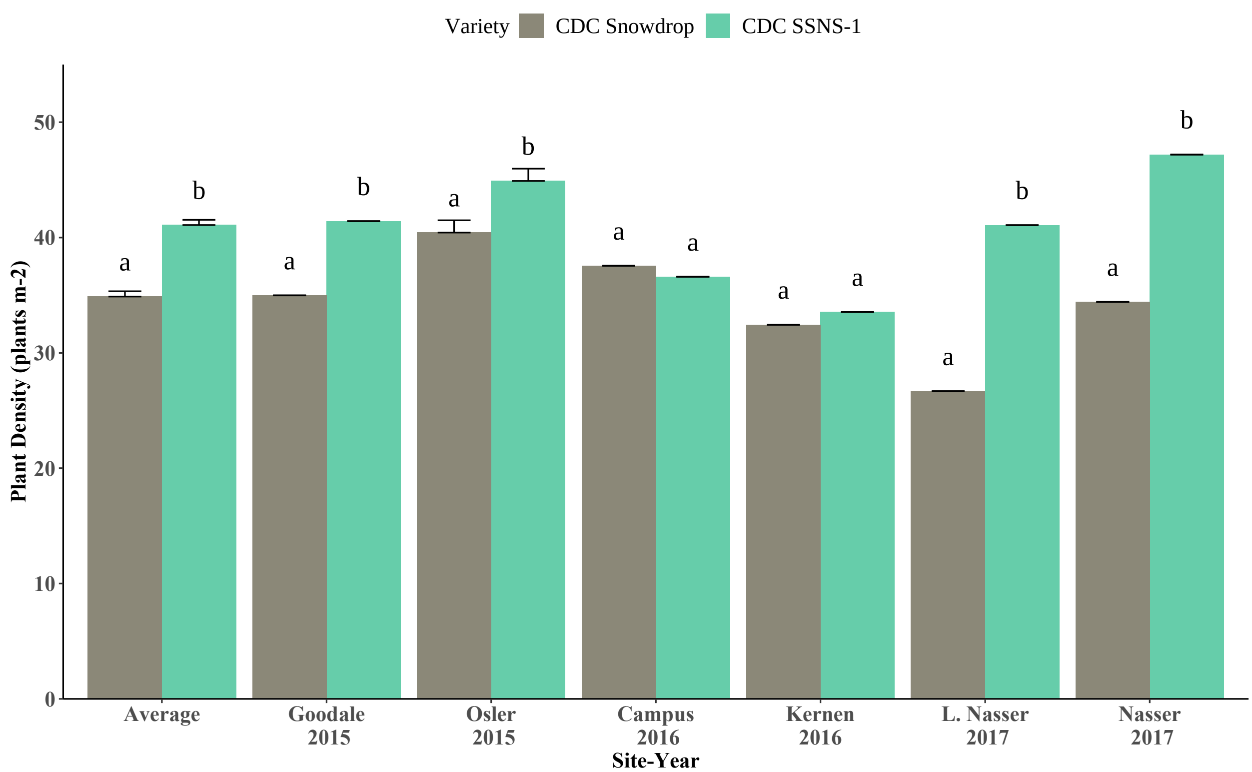

Figure 4.1: Varietal effects on plant density (plants m^{-2}) at six Saskatoon locations from 2015 to 2017 and the combined site-year average. Values with the same letter are statistically similar at P < 0.05.

4.3.3 Disease Ratings and Area Under the Disease Progress Curve

4.3.3.1 Disease Severity in the Untreated Control

As expected, the amount of disease in the control treatments varied between site-years (Figure 4.2). The most precipitation was received in 2016, yet disease ratings were lowest (Figure 4.2). It is possible that this effect is due to the inherent downfall of small plot disease control studies. With small plot studies, there are large alleyways between replicates, which allowed for increased airflow. This reduces canopy moisture, which is a key component in integrated disease management, but is necessary for disease development. Furthermore, as faba bean is a minor crop in Saskatchewan, the source of natural inoculum was likely low at the individual study locations. Contrary to expectation, in 2017 when only half of the normal precipitation was received, the disease ratings were the highest of the experimental periods (Figure 4.2). Unfortunately, each year, there was a different person responsible for recording disease levels. Consequently, the variation between site-years can likely be attributed to both human differences and differences in the relative humidity at each location (not recorded).

Generally, disease ratings were similar before and after fungicide application at 10% flowering and then began to slowly progress (Figure 4.2). However, in Nasser 2017, disease severity grew by 10% between the two fungicide applications timings. The large increase between 4- and 6- week after the second fungicide application, may have been confused with natural senescence. This resulted in Nasser 2017 having 80% disease severity overall (Figure 4.2). In 2015, disease steadily progressed after fungicide application at 50% flowering. However, disease only increased by 10% resulting in 20% disease severity overall (Figure 4.2). In 2016, there was no disease recorded at Campus. In Kernen 2016, faba bean disease slowly increased between POST 2 weeks and the final rating, for an overall disease severity of 30% (Figure 4.2). At Lower Nasser 2017, disease severity doubled between two and four weeks after fungicide application, with POST 4 weeks having similar levels at the time of the final disease rating (50%).

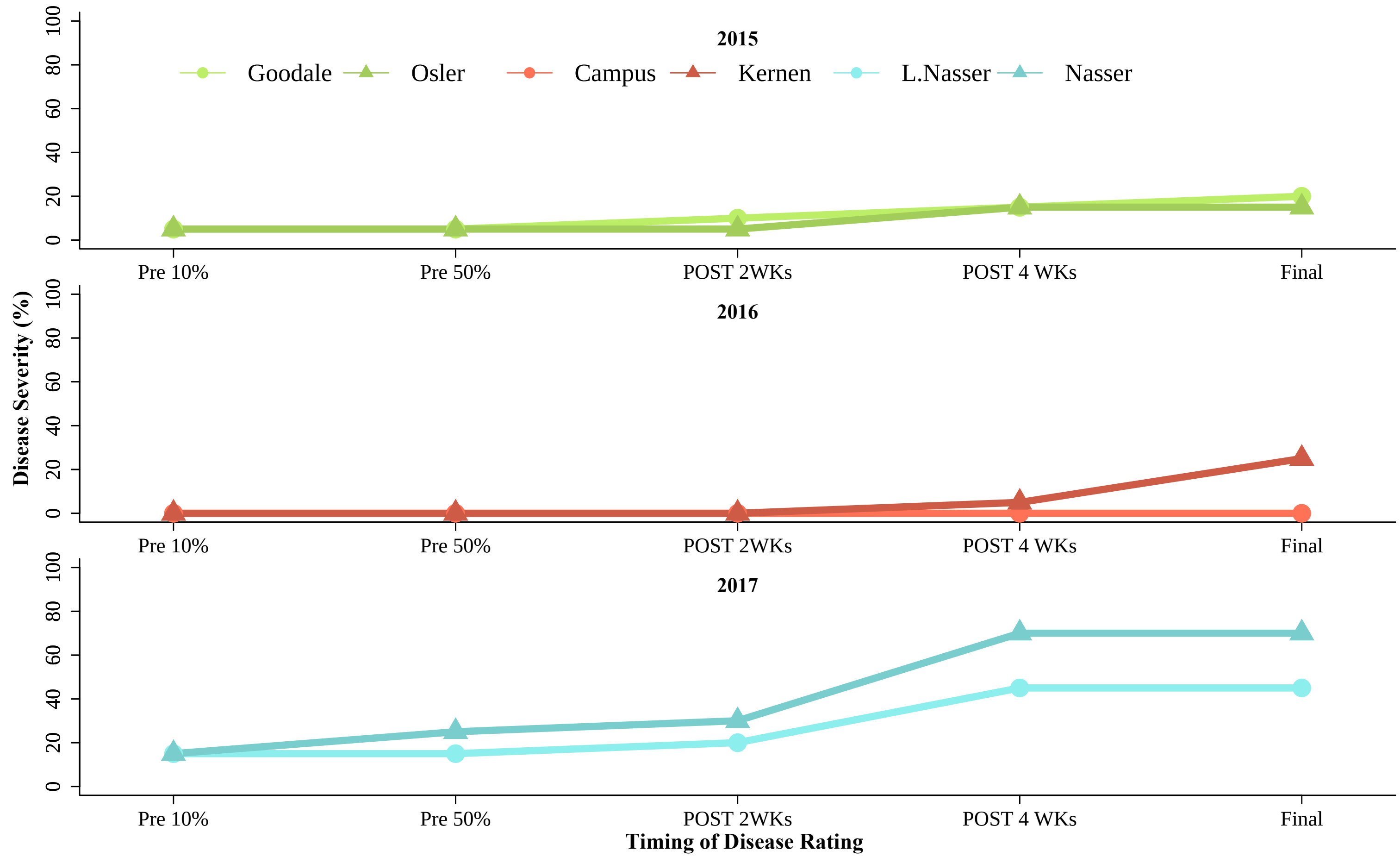

Figure 4.2: Disease progression in the untreated control, from prior to fungicide application until the final disease rating, at six site-years between 2015 and 2017. The final disease rating coincided with 6 weeks POST fungicide application at 50% flowering and prior to senescence.

Overall, there was minimal disease symptoms in the control treatments during 2015 and 2016, therefore responses to fungicide application are likely to be minimal. However, due to disease severity of 50% and higher in the 2017 control treatments, application of a fungicide may elicit a response. This is contrary to the expectations based on the environmental conditions mentioned previously. Overall, disease development was minimal until two-weeks after fungicide application at 50% flowering. Therefore, it is likely fungicide application may have occurred too early to elicit any meaningful responses.

4.3.3.2 Treatment Effect on Disease Severity and AUDPC

4.3.3.2.1 Prior to 10% and 50% flowering applications

Prior to fungicide application, the mean disease severity in the treatments was 1-10%. Initial disease severity in 2015 was <1% at both Goodale and Osler (Figure 4.3). In Campus 2016, there was no disease recorded throughout the duration of the ratings. While initial disease severity was 0% at Kernen 2016 (Figure 4.3). Finally, in 2017 both locations were rated at 11-20 % initial disease (Figure 4.3). Therefore, as expected, the amount of disease in the treatments prior to fungicide application, was similar to the levels found in the untreated control for each location.

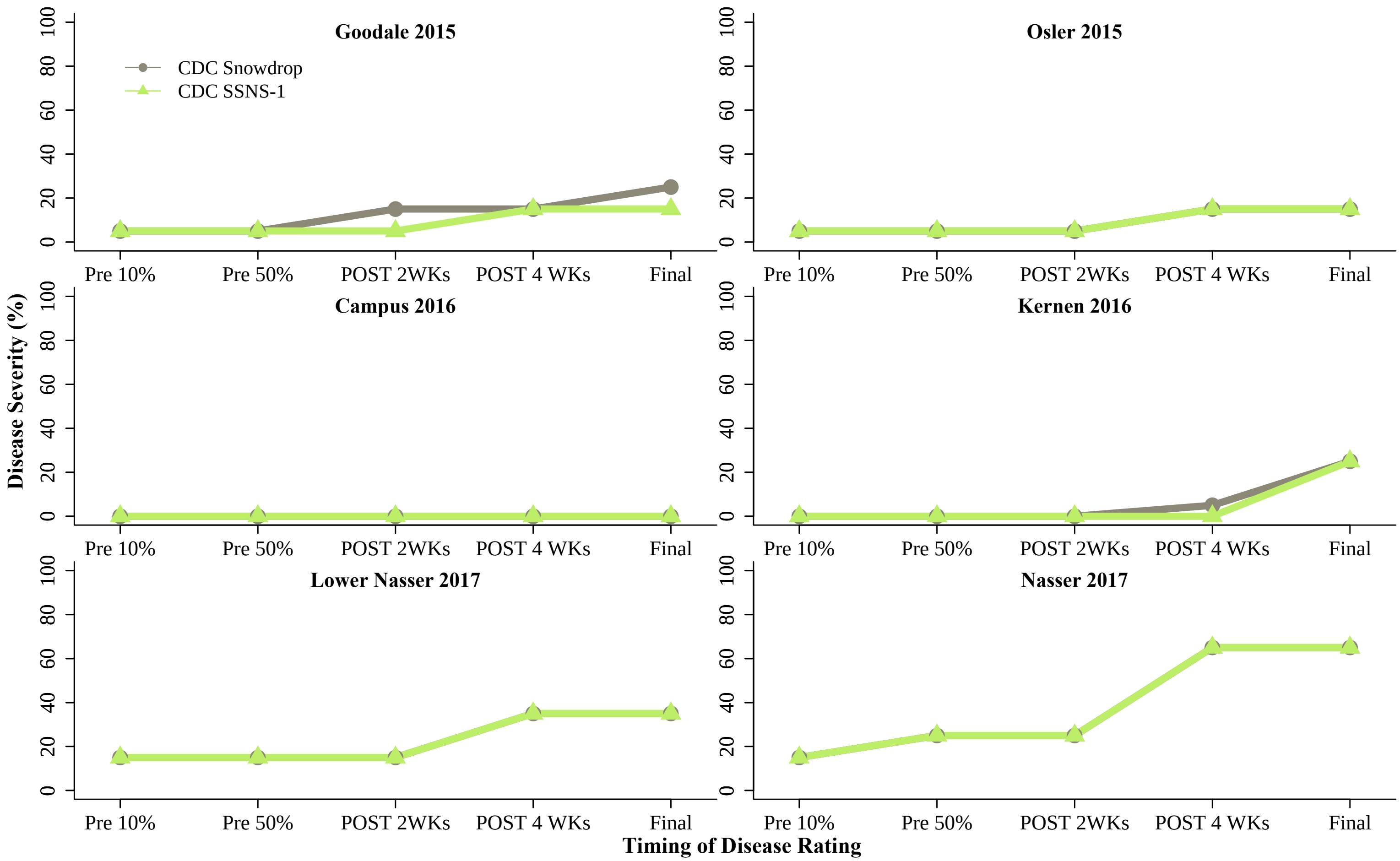

Figure 4.3: Disease progression within the applied treatments, between CDC Snowdrop and CDC SSNS-1, from prior to fungicide application until the final disease rating at six 2015 to 2017 Saskatoon sites.

Prior to fungicide application at 50% flowering, there was a significant difference in disease progression occurring between site-years (Table 4.3). Although there were no significant fixed by site-year interactions, each site was analyzed individually (Table 4.3). Overall, variety, product, nor their interaction significantly impacted disease progression after fungicide was applied at 10% flowering (Table 4.3). This result was anticipated, as there were few disease symptoms found prior to fungicide application. Furthermore, at some locations there were as little as three days between fungicide applications.

Disease ratings were not recorded two and four weeks after fungicide application at both 2015 locations. However, ratings were recorded about six weeks later to determine the total amount of disease that occurred within the study period. Therefore, these site-years were dropped from analysis at two and four weeks, but re-appear for the final AUDPC. At Campus 2016, only two plots contained disease symptoms. The site was retained for combined analysis but was not explored during individual analyzes.

Table 4.3: Random and treatment effects for AUDPC prior to fungicide application at 50% flowering, two and four weeks after fungicide application, and final AUDPC in Saskatoon, 2016 to 2017.

	PRE 50%	**POST 2 Wks**	**POST 4 Wks**	**Final**
	Random Effects			
Replicate	0.0601	1.0000	0.0031**	<0.0001***
Site-Year (SY)	<0.0001***	<0.0001***	<0.0001***	<0.0001***
Variety (V) x SY	0.5261	0.0416*	<0.0001***	<0.0001***
Product (P) x SY	0.4914	0.0418*	0.0319*	0.4509
Timing (T) x SY	NA	1.0000	1.0000	0.6547
	Fixed Effects			
Variety	0.5565			
Product	0.3964	See Table 4.4	See Table 4.6	See Table 4.8
V x P	0.5302			

*** p<0.001; ** 0.001<p>0.01; * 0.01<p>0.05

There continued to be a significant difference between the disease progression at each site-year, up to 6-weeks after fungicide was applied (Table 4.3). Furthermore, there was a significant varietal response between site-years for all POST fungicide application rating timings (Table 4.3). There was also a significant difference within the applied products between the site-years two and four weeks after application (Table 4.3). Consequently, each site-year was analyzed individually for disease progression based on AUDPC.

4.3.3.2.2 Two weeks POST Fungicide Application

Two weeks after fungicide was applied, disease progression was significantly affected by multiple treatment factors. In Kernen 2016 and Nasser 2017, there was a significant difference between the two varieties (Table 4.4). At Kernen 2016, disease progression was also significantly different between the four applied fungicides (Table 4.4). At Lower Nasser 2017 AUDPC was significantly impacted by fungicide application timing, the interactions between variety and product, and product and timing (Table 4.4).

Table 4.4: Fixed effects for AUDPC 2 weeks POST fungicide application at 50% flowering, in Saskatoon, 2016 to 2017.

	Kernen 2016	**L. Nasser 2017**	**Nasser 2017**
Variety (V)	0.0104*	0.6741	0.0188*
Product (P)	0.0159*	0.8057	0.0802
Timing (T)	0.3289	0.0340*	0.1124
V x P	0.3243	0.0031**	0.1350
V x T	0.3142	0.0623	0.5965
P x T	0.6816	0.0230*	0.6694
V x P x T	0.3349	0.4595	0.2859

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

Two weeks after the final fungicide application, Kernen 2016 had <1% disease, Lower Nasser 2017 had less than 20%, and Nasser 2017 had less than

30% (Figure 4.3). In Kernen 2016, CDC Snowdrop had a greater AUDPC than CDC SSNS-1 over the same period (Table 4.5). The same trend was observed at Nasser 2017 (Table 4.5). At Kernen 2016, fluopyram + prothioconazole application caused the least amount of disease development of the four applied products (Table 4.5).

Table 4.5: Variety, fungicide product, and timing effects on AUDPC at two weeks after fungicide application, at three Saskatoon locations 2016 to 2017.

	Kernen 2016[z]	**L. Nasser 2017**[z]	**Nasser 2017**[z]
Variety			
CDC Snowdrop	1.5 b	34.2 a	40.9 b
CDC SSNS-1	0.4 a	34.5 a	38.5 a
Product			
Chlorothalonil	1.0 b	34.5 a	41.2 a
Fluxapyroxad + Pyraclostrobin	1.7 b	33.9 a	37.7 a
Fluopyram + Prothioconazole	0.1 a	34.1 a	40.4 a
Penthiopyrad	1.1 b	34.9 a	39.5 a
Timing			
10% flowering	0.7 a	33.6 a	41.0 a
50% flowering	1.3 a	35.9 b	39.6 a
10% + 50% flowering	0.6 a	33.5 a	38.5 a

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05
[z] values with the same letter are statistically similar at P < 0.05

At Lower Nasser 2017, application of fungicide at 10% and 10% + 50% flowering resulted in less disease development than when only applied at 50% flowering (Table 4.5). This is not surprising, as the earlier application would have had a longer time period to provide disease control or it was when applied during initial disease development. However, although this response was statistically significant, it likely has little biological impact. The improved response at 10% + 50% flowering is likely driven by the application at 10% flowering.

The variety by fungicide product interaction was a unique result, as fluopyram + prothioconazole resulted in better disease control in CDC SSNS-1 than CDC Snowdrop (Figure 4.4A). The interaction between product and timing in Lower Nasser 2017 was interesting as well. Chlorothalonil and Fluopyram + prothioconazole, applied at either 10% or 50% had similar effects on disease control (Figure 4.4B). However, when applied at 10% + 50% flowering, disease control provided was less effective. This effect is not expected, as it should be similar to either or both single applications. This this is likely a type I error and thus of little agronomic significance. Furthermore, fluxapyroxad + pyraclostrobin and penthiopyrad were equally effective across application timings (Figure 4.4B). Overall, at Lower Nasser 2017, a single application of fungicide was just as effective as multiple applications two weeks after spraying. Furthermore, it did not appear that there was a benefit from using a strobilurin over a non-strobilurin variety.

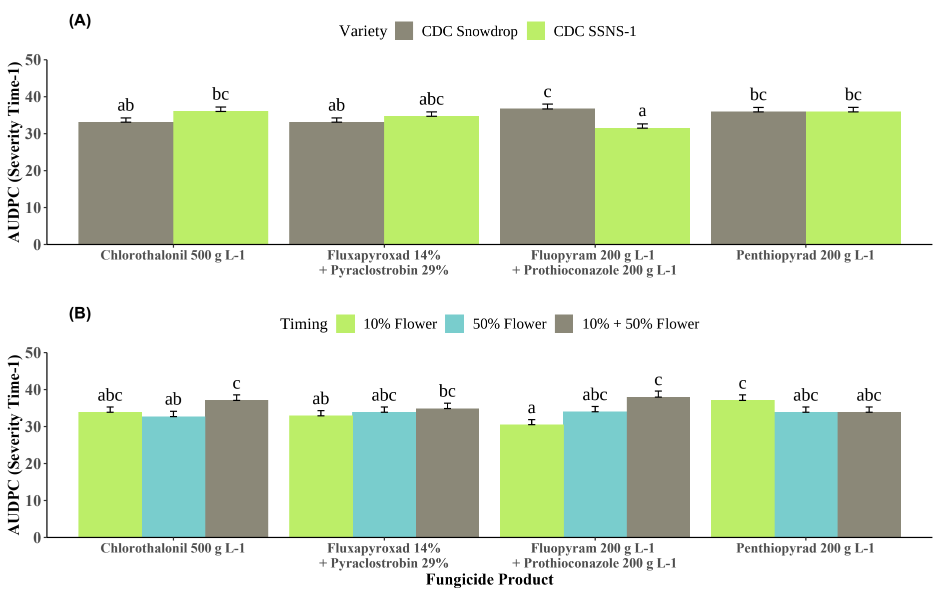

Figure 4.4: Effect of variety and fungicide product (A) and fungicide product and timing (B) on AUDPC 2 weeks after fungicide application at Lower Nasser, 2017. Values with the same letter are statistically similar at $p<0.05$.

4.3.3.2.3 Four weeks POST Fungicide Application

Four weeks after fungicide was applied, there continued to be a significant difference in the AUDPC of the two varieties at Kernen 2016 and Nasser 2017 (Table 4.6). Applied products continued to have an effect on disease progression at Kernen 2016; while product differences did not appear in Nasser 2017 until 4 weeks after the second fungicide application (Table 4.6). As well, the variety by product interaction continued to have an effect at Lower Nasser 2017 (Table 4.6).

Table 4.6: Fixed effects for AUDPC 4 weeks POST fungicide application at 50% flowering, in Saskatoon, 2016 to 2017.

	Kernen 2016	**L. Nasser 2017**	**Nasser 2017**
Variety (V)	0.0022**	0.9615	0.0049**
Product (P)	0.0155*	0.0913	0.0110*
Timing (T)	0.2372	0.0677	0.4894
V x P	0.2241	0.0106*	0.6124
V x T	0.2561	0.2948	0.4817
P x T	0.4711	0.1252	0.8544
V x P x T	0.8777	0.2142	0.4430

*** p<0.001; ** 0.001<p>0.01; * 0.01<p>0.05

In Kernen 2016, disease progression nearly doubled over this two week period; however, mean disease severity was still under 10% at four weeks after fungicide application (Figure 4.3). CDC Snowdrop had nearly double the amount of disease development than CDC SSNS-1 (Table 4.7). In Nasser 2017, disease severity significantly increased resulting in nearly 70% of the total plant area being infected (Figure 4.3). Here, CDC Snowdrop had less disease progression than CDC SSNS-1, contrary to the previous findings (Table 4.7). Again, this finding may not be biologically relevant.

Table 4.7: Variety and fungicide product effects on AUDPC at four weeks after fungicide application, at three Saskatoon locations 2016 to 2017.

	Kernen 2016[z]	**L. Nasser 2017[z]**	**Nasser 2017[z]**
Variety			
CDC Snowdrop	6.2 b	47.7 a	72.0 a
CDC SSNS-1	2.9 a	47.7 a	76.6 b
Product			
Chlorothalonil	6.2 b	49.5 a	78.2 b
Fluxapyroxad + Pyraclostrobin	6.3 b	47.0 a	71.2 a
Fluopyram + Prothioconazole	2.9 a	45.9 a	72.5 a
Penthiopyrad	2.8 a	48.5 a	75.3 ab

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05
[z] values with the same letter are statistically similar at P < 0.05

In Kernen 2016, fluopyram + prothioconazole and penthiopyrad reduced disease progression the greatest, while fluxapyroxad + pyraclostrobin and chlorothalonil reduced progression the least (Table 4.7). In Nasser 2017, the two two-active ingredient products reduced disease progression greater than the two single active ingredient products (Table 4.7). Although in Nasser 2017, penthiopyrad reduced disease similarly to fluopyram + prothioconazole (Table 4.7). However, penthiopyrad was also similar to chlorothalonil. At Lower Nasser 2017, each product provided similar disease control in CDC Snowdrop (Figure 4.5). Fluopyram + prothioconazole provided the best control in CDC SSNS-1 (Figure 4.5). Generally, the largest treatment difference occurred with fluopyram + prothioconazole, where it provided significantly better disease control in CDC SSNS-1 than CDC Snowdrop (Figure 4.5).

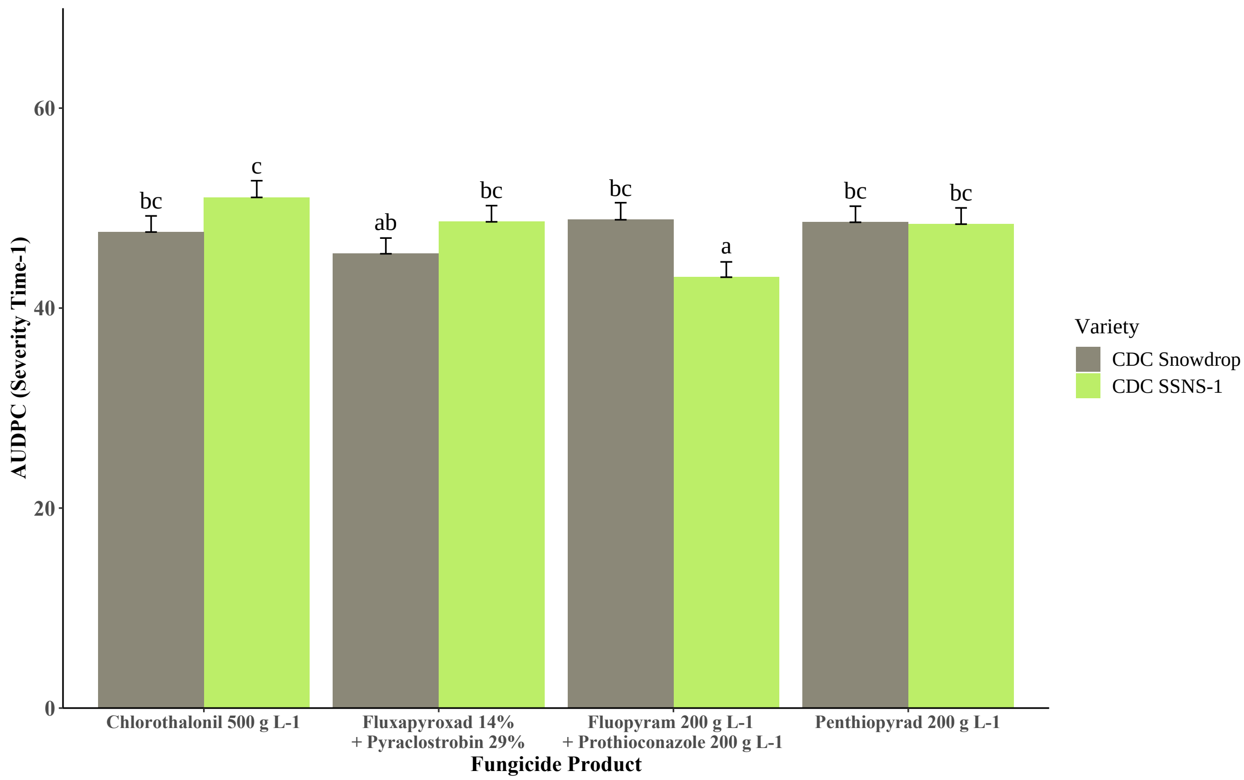

Figure 4.5: Varietal response to four fungicide products and their effect on AUDPC four weeks POST fungicide application at Lower Nasser, 2016. Values with the same letter are statistically similar at $P < 0.05$.

4.3.3.2.4 Six weeks POST Fungicide Application (Final)

Six weeks after fungicide application, there was a significant difference between disease progression in the two varieties at three of the six site-years (Table 4.8). Differences in AUDPC by product and by timing were significant at only one of six site-years each (Table 4.8). Interactions between the factors gave mixed results. There was a highly significant interaction between variety and product at Lower Nasser 2017 (Table 4.8). At Kernen 2016, the variety by timing effect was significant (Table 4.8). At Kernen 2016 and Lower Nasser 2017, the product by timing effect was significant (Table 4.8). Finally, at Goodale 2015, the three-way interaction was significant (Table 4.8).

Table 4.8: Fixed effects for the final AUDPC (6 weeks) POST fungicide application at 50% flowering, in Saskatoon, 2015 to 2017.

	Goodale 2015	Osler 2015	Kernen 2016	L. Nasser 2017	Nasser 2017
Variety (V)	<0.0001***	0.0043**	<0.0001***	0.3805	0.4496
Product (P)	0.3864	0.1386	0.0550	0.3449	0.0041**
Timing (T)	0.4004	0.1792	0.0976	0.0295*	0.1254
V x P	0.0690	0.7356	0.3709	<0.0001***	0.2884
V x T	0.8770	0.1720	0.0027**	0.0996	0.8196
P x T	0.0318*	0.2047	0.0227*	0.0196*	0.9854
V x P x T	0.0056**	0.0390	0.9814	0.3807	0.3887

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

By the time of the final rating, both 2015 locations had less than 20% disease (Figure 4.3). In 2016, there was still no considerable disease symptoms at the Campus location, while at Kernen disease was less than 30% (Figure 4.3). In 2017, Lower Nasser had less disease than Nasser, with less than 40% and 70%, respectively (Figure 4.3). Once again, CDC Snowdrop had greater disease progression than CDC SSNS-1 in 2015 and Kernen 2016 (Table 4.9). At Nasser, the products with two active ingredients significantly reduced disease in comparison to products with one (Table 4.9). However, fluopyram + prothioconazole was also similar to the two-single active ingredient products (Table 4.9). At Lower Nasser, there was better disease control when fungicide was applied at 10% flowering then 50% flowering (Table 4.9).

Table 4.9: Variety, fungicide product, and timing effects on final AUDPC six weeks after fungicide application, at five Saskatoon locations 2015 to 2017.

	Goodale 2015[z]	Osler 2015[z]	Kernen 2016[z]	L. Nasser 2017[z]	Nasser 2017[z]
Variety					
CDC Snowdrop	84.7 b	78.2 b	43.3 b	98.9 a	158.9 a
CDC SSNS-1	73.9 a	71.1 a	32.5 a	100.4 a	156.8 a
Product					
Chlorothalonil	80.0 a	75.0 a	42.4 a	101.7 a	163.8 b
Fluxapyroxad + Pyraclostrobin	81.3 a	73.7 a	36.8 a	98.2 a	149.8 a
Fluopyram + Prothioconazole	76.6 a	71.0 a	35.6 a	98.2 a	157.4 ab
Penthiopyrad	79.0 a	78.9 a	36.3 a	100.6 a	160.5 b
Timing					
10% flowering	78.8 a	73.0 a	37.3 a	97.2 a	160.8 a
50% flowering	81.0 a	73.1 a	40.5 a	102.8 b	158.7 a
10% + 50% flowering	77.9 a	77.8 a	35.4 a	99.1 ab	154.0 a

*** P <0.001; ** 0.001< P >0.01; * 0.01< P >0.05

[z] values with the same letter are statistically similar at P <0.05

In Lower Nasser 2017, fluxapyroxad + pyraclostrobin reduced disease progression greater than fluopyram + prothioconazole in CDC Snowdrop (Figure 4.6). In CDC SSNS-1, fluopyram + prothioconazole reduced disease progression greater than the other three products (Figure 4.6). Otherwise, all products had similar effects towards managing disease development at this location.

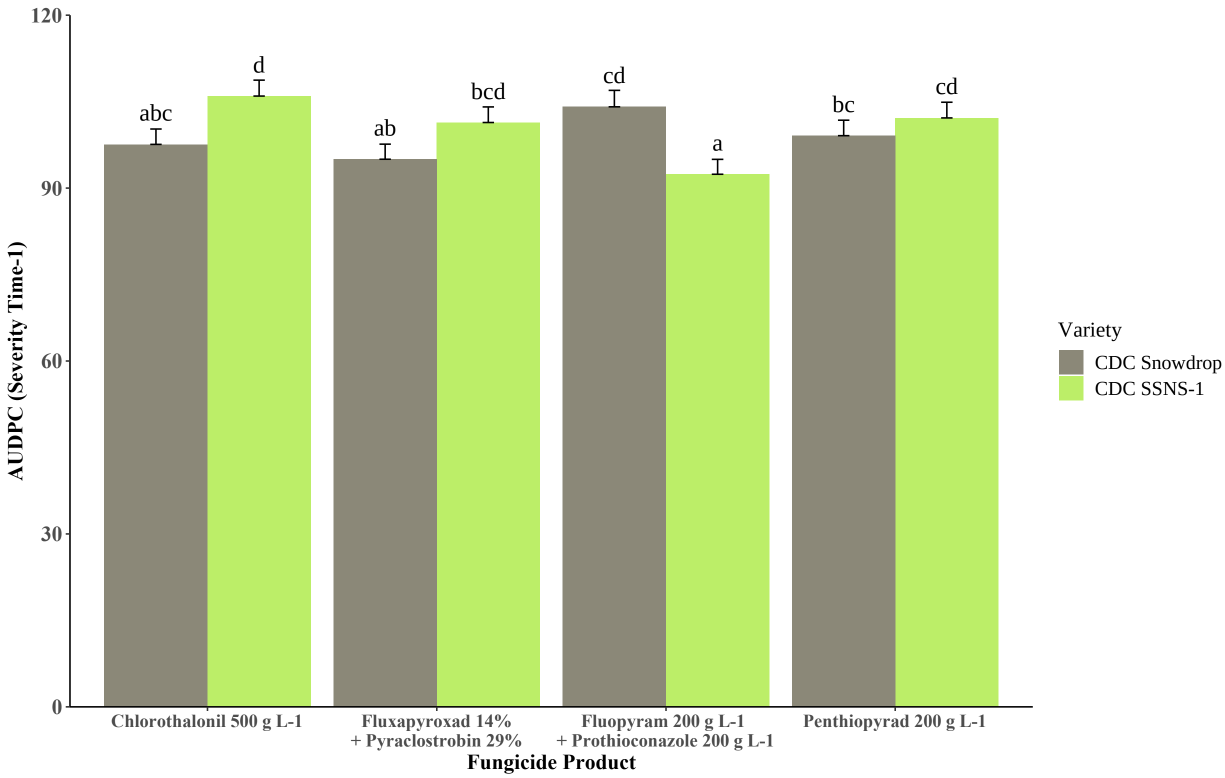

Figure 4.6: Varietal response to four fungicide products and their effect on final AUDPC six weeks POST fungicide application at Lower Nasser, 2017. Values with the same letter are statistically similar at $P < 0.05$.

In Kernen 2016, disease progression was significantly reduced when fungicide was applied at 50% flowering compared to 10 + 50% flowering in CDC Snowdrop (Figure 4.7). This is unique, as it would be expected that when the fungicide is applied twice, the result would be more similar to when it was applied once, which is not the case here. However, this effect is minor and of relatively little agronomic importance. It largely reflects the variability in disease ratings. In CDC SSNS-1 all application timings provided similar levels of disease control (Figure 4.7). Furthermore, earlier and two applications reduced the AUDPC greater in CDC SSNS-1 than CDC Snowdrop (Figure 4.7).

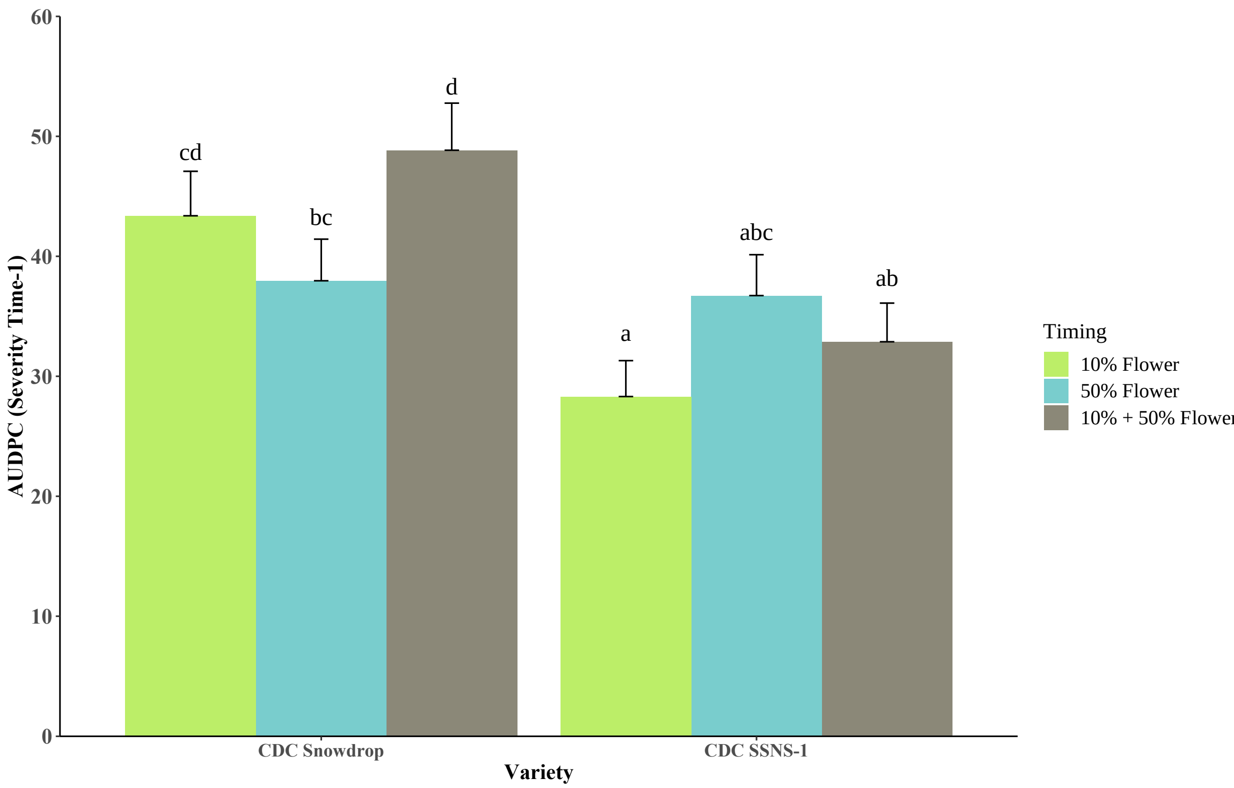

Figure 4.7: Varietal response to fungicide application timing and their effect on final AUDPC six weeks POST fungicide application at Kernen, 2016. Values with the same letter are statistically similar at $P < 0.05$.

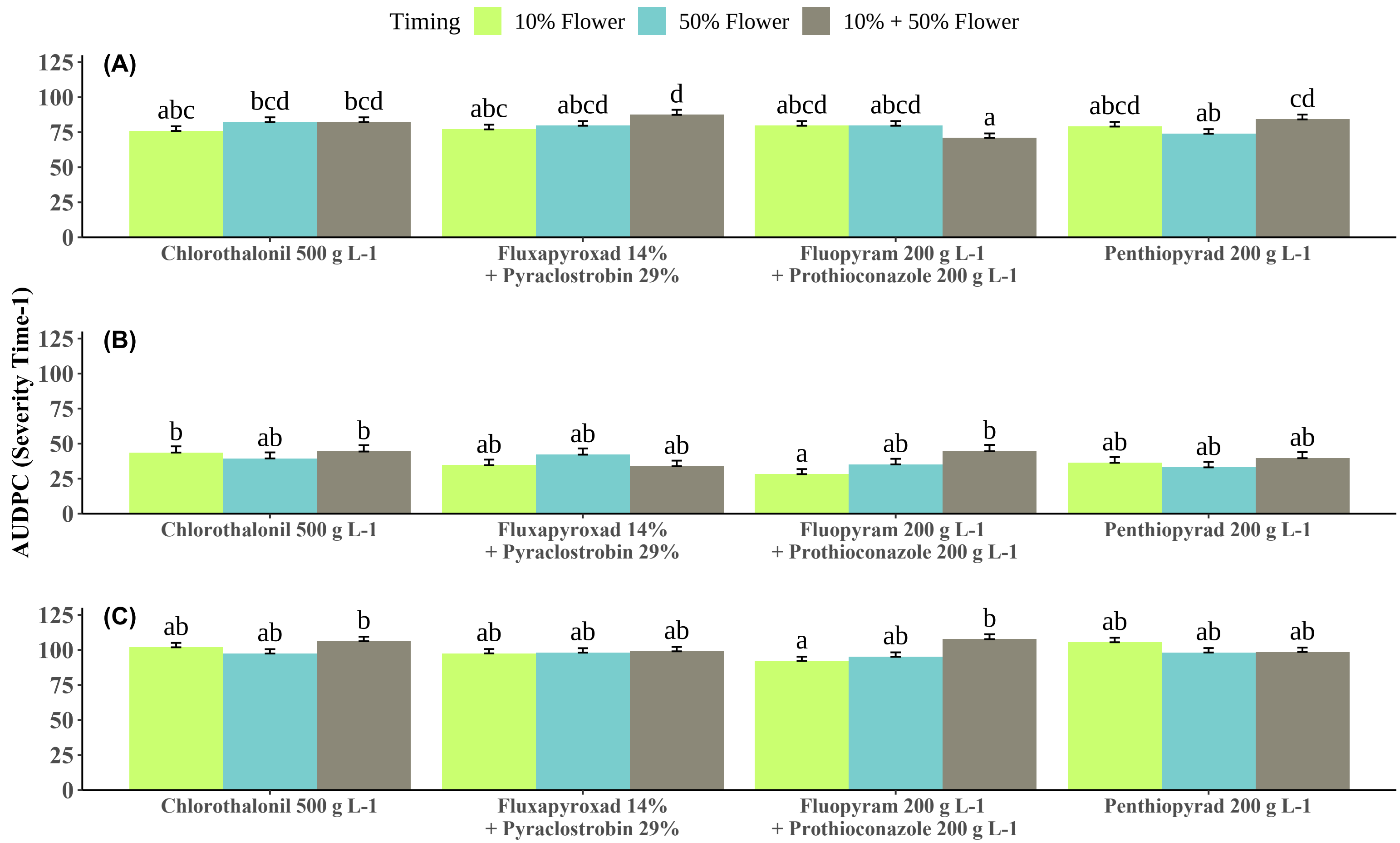

Figure 4.8: Fungicide products and application timing effect on final AUDPC six weeks POST fungicide application at (A) Goodale 2015, (B) Kernen 2016, and (C) Lower Nasser 2017. Values with the same letter are statistically similar at $P < 0.05$.

In Goodale 2015, fluxapyroxad + pyraclostrobin reduced AUDPC more when applied at 10% flower than 10 + 50% flower (Figure 4.8A). Furthermore, penthiopyrad reduced disease greater when applied at 50% flowering then when applied twice (Figure 4.8A). At Kernen 2016 and Lower Nasser 2017, fluopyram + prothioconazole reduced AUPDC significantly when applied at 10% flowering then when applied twice (Figure 4.8B and Figure 4.8C). This unexpected result is likely due to a type I error and is likely of little agronomic importance. Otherwise, as a whole, all products and application timings were equally effective in lowering AUDPC.

The final significant interaction to affect AUDPC 6 weeks POST was variety, product, and timing, at Goodale 2015 (Figure 4.9). In CDC Snowdrop, fluopyram + prothioconazole at 10% + 50% flower significantly reduced the AUDPC in comparison to chlorothalonil at 50% flower, fluxapyroxad + pyraclostrobin at 10% + 50% flower, and penthiopyrad at 10% + 50% flower (Figure 4.9A). In CDC SSNS-1, there were no significant differences among AUDPC of any of the treatments (Figure 4.9B). Overall, the largest significant differences between AUDPC at 6-weeks POST fungicide occurred within CDC Snowdrop. However, these differences largely occurred between application timing of specific products, and no considerable trends were identified.

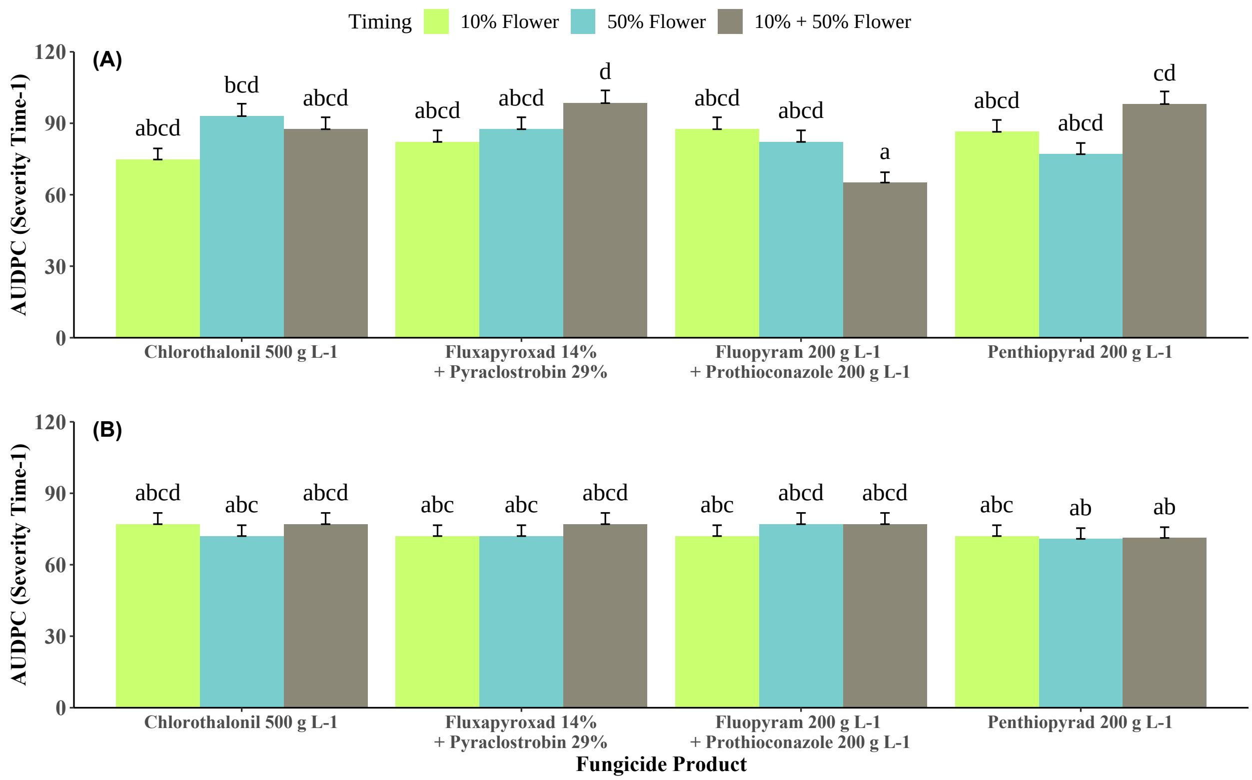

Figure 4.9: Variety, fungicide product, and application timing effect on AUDPC six weeks (final) POST fungicide application at Goodale 2015. (A) CDC Snowdrop (B) CDC SSNS-1. Values with the same letter are statistically similar at P < 0.05.

By the end of the rating period, disease severity in the untreated control and fungicide treatments were relatively similar. This suggests that there was not enough disease severity to elicit a large fungicide response. It also suggests that fungicide was applied too early in cases where disease severity was elevated. There was a general trend for CDC Snowdrop to have greater disease than CDC SSNS-1, yet this effect is likely of little biological significance. There were various products, application timings, and interactions that significantly affected disease severity and progression. Overall, the magnitude of these responses was relatively minor and thus have no real agronomic importance.

However, it does suggest that all four products, provide similar levels of disease control, regardless of timing, when disease severity is low.

4.3.4 Biomass Yield

Overall, there were no significant differences ($F_{25,389}$=0.74, P = 0.8112; data not shown) between the biomass yield of any treatment. Contrasts indicated that biomass yield was similar between the applied products and the control (P = 0.9930; data not shown), between the non-strobilurin and three strobilurin fungicides (P = 0.1220; data not shown), between the two multi-active ingredient products (P = 0.2200; data not shown), and between the two single active ingredient products (P = 0.8930; data not shown). Contrasts also indicated that there were no significant differences between the biomass yield when fungicide was applied at any timing (P = 0.9930; data not shown), 10% vs.50% flowering (P = 0.8720; data not shown), and 50% vs. 10 & 50% flowering (P = 0.9150; data not shown). However, contrasts did indicate that there was a significant difference between the two varieties (P = 0.0026; data not shown). On average, CDC SSNS-1 produced 720 kg ha^{-1} more biomass than CDC Snowdrop.

Each product and its respective application timing (including the control) responded similarly across site-years, yet biomass accumulation varied between individual locations (Table 4.10). Therefore, data was combined across site-years for the Two-way ANOVA. Furthermore, there was no significant difference between the applied treatments and their timings (Table 4.10). However, when the untreated control was removed and treatment means were factored over variety, there was a significant difference between the responses at each site-year (Table 4.10). Therefore, these years were analyzed independently.

Table 4.10: Random and fixed effects of the two- and three-factor ANOVA for biomass (g m^{-2}) in Saskatoon, 2016 to 2017.

	P * T	**V * P * T**
	Random Effects	
Replicate	<0.0001***	<0.0001***
Site-Year (SY)	<0.0001***	<0.0001***
Variety (V) x SY	NA	0.0353*
Product (P) x SY	1.0000	1.0000
Timing (T) x SY	1.0000	1.0000
	Fixed Effects	
Product	0.1709	NA
Timing	0.9598	NA
P x T	0.8677	NA

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

In 2017, at both locations, there was a significant difference between the biomass of each variety, while product and application timing did not have a significant effect (Table 4.11). This result indicates that the differences in plant density in 2017, had a confounding effect on biomass yield in that year. Furthermore, it reflects the results of the one-way ANOVA contrasts. Overall, in 2017, CDC SSNS-1 had approximately 1300 kg ha^{-1} greater biomass than CDC Snowdrop (Table 4.11).

Table 4.11: Treatment effects on biomass (g m^{-2}) in Saskatoon, 2016 to 2017. Multiply treatment means by a factor of 10 to get kg ha^{-1}.

	Campus 2016	**Kernen 2016**	**L. Nasser 2017**	**Nasser 2017**
			Pf>r	
Variety	0.2913	0.7468	<0.0001***	<0.0001***
Product	0.2700	0.8380	0.2155	0.0905
Timing	0.6148	0.4758	0.8973	0.8336
V x P	0.4912	0.9050	0.2373	0.7536
V x T	0.4818	0.8057	0.4342	0.9578
P x T	0.6120	0.5298	0.7299	0.6669
V x P x T	0.6847	0.4126	0.0861	0.2130
			Means	
CDC Snowdrop	1079.6a	1168.6a	1007.7a	725.7a
CDC SSNS-1	1115.4a	1157.5a	1149.3b	848.1b

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

[z] Values with the same letter are not significantly different from each other

4.3.5 Grain Yield

Across all six site-years, there was no significant difference ($F_{25,576}$=0.3098, P = 0.9996; data not shown) between the grain yield of any treatment. Contrasts also indicated that there was no significant difference in the grain yield between the applied products and control (P = 0.9540; data not shown), non-strobilurin and three strobilurin fungicides (P = 0.4330; data not shown), two multi-active ingredient products (P = 0.7470; data not shown), and the two single active ingredient products (P = 0.3040; data not shown). Furthermore, contrasts revealed that grain yield was similar when fungicide was applied at any timing compared to the control (P = 0.9540; data not shown), 10% and 50% flowering (P = 0.9840; data not shown), and 50% and 10 & 50% flowering (P = 0.9720; data not shown). Contrasts also indicated there was no significant difference between the grain yield of each variety (P = 0.2560; data not shown).

Each product and its respective application timing, including the control, responded similarly across site-years, yet yield varied between site-years (Table 4.12). Once again, when the untreated control was removed and treatment yields were factored over variety, yields varied between site-year but treatment response was similar across locations (Table 4.12). Therefore, combined site-year analyses were completed for both the two- and three-way ANOVAs.

Table 4.12: Random and fixed effects of the two- and three-factor ANOVA for yield (kg ha^{-1}) in Saskatoon, 2015 to 2017.

	P * T	**V * P * T**
	Random Effects	
Replicate	<0.0001***	<0.0001***
Site-Year (SY)	<0.0001***	<0.0001***
Variety (V) x SY	NA	0.0942
Product (P) x SY	1.0000	1.0000
Timing (T) x SY	1.0000	1.0000
	Fixed Effects	
Variety	NA	0.3184
Product	0.0674	0.0195*
Timing	0.9790	0.9498
V x P	NA	0.6254
V x T	NA	0.3359
P x T	0.3018	0.3017
V x P x T	NA	0.0059**

*** P < 0.001; ** 0.001< P >0.01; * 0.01< P >0.05

There was no significant yield difference between the applied products and their various timings (Table 4.12). This finding was expected based on disease control effects of the various treatments. However, there were significant differences between the applied products and the three-way factor interaction when the control plots were removed (Table 4.12). Overall, the two multi-active ingredient fungicides resulted in a modest (100 kg ha^{-1}) yield increase over the two single active ingredient products (Figure 4.10).

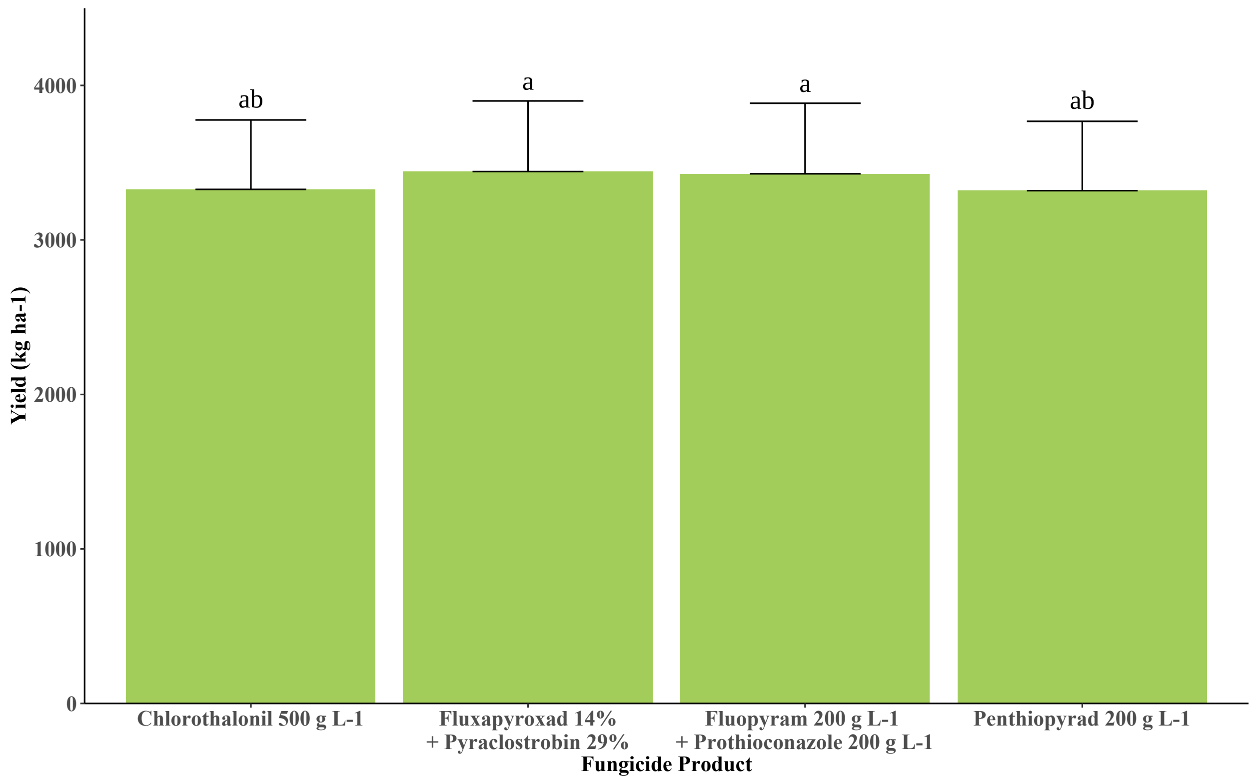

Figure 4.10: Applied product effects on yield (kg ha^{-1}) averaged across 6 Saskatoon locations from 2015 to 2017. Values with the same letter are statistically similar at P < 0.05.

When the three-way interaction was significant, the two varieties showed mixed responses to fungicide application and timing. In CDC Snowdrop, chlorothalonil at 50% failed to improved or maintain yield over application at 10% + 50% flowering (Figure 4.11A). Furthermore, the double application of fluopyram + prothioconazole resulted in a 200 to 300 kg ha^{-1} yield increase (Figure 4.11A). The greatest difference between the yields of CDC Snowdrop occurred when penthiopyrad was applied at 10% + 50% flower in comparison to chlorothalonil and fluopyram + Prothioconazole at 10% + 50% flowering (Figure 4.11A). In CDC SSNS-1, fluopyram + prothioconazole applied twice did not result in a yield increase in comparison to when applied once at 10% flower (Figure 4.11B). Furthermore, the two active ingredient products increased yield greater at 10% flowering than the single active ingredient products (Figure 4.11B). All products resulted in similar yields when applied at 50% and 10% + 50% flowering in CDC SSNS-1 (Figure 4.11B). Overall, in both varieties, all products and application timings resulted in similar yields. Any treatment effects are therefore of little agronomic significance.

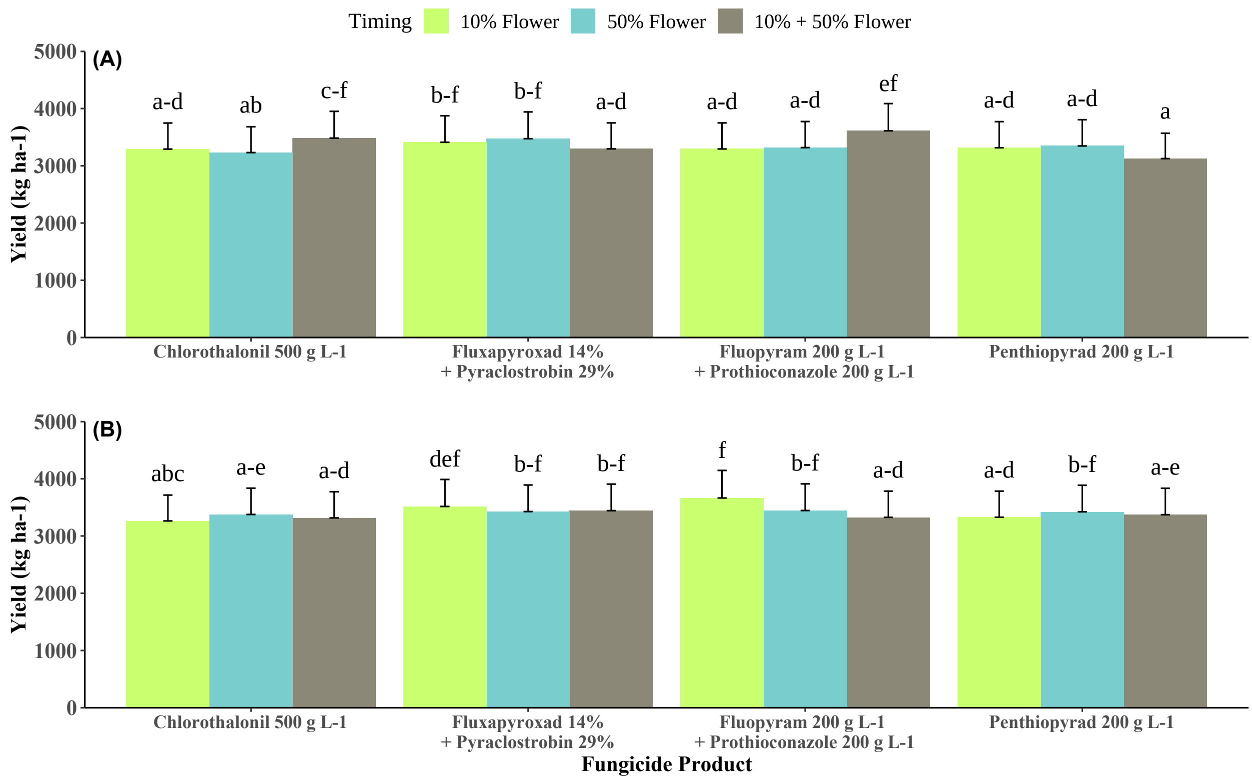

Figure 4.11: Product and timing effects on yield (kg ha-1) of CDC Snowdrop (A) and CDC SSNS-1 (B) averaged across 6 Saskatoon locations from 2015 to 2017. Values with the same letter are statistically similar at P < 0.05.

4.3.6 Thousand Kernel Weight

There was a significant difference ($F_{25,594}$=6.48, P < 0.0001; data not shown) between the thousand kernel weights of the treatments. Contrasts revealed that the largest TKW differences occurred between the varieties, as expected. CDC SSNS-1 had a smaller thousand kernel weight than CDC Snowdrop (270.1 g TKW vs. 292.2 g TKW, respectively). Contrasts also indicated that there was no significant difference in the TKW of the applied products and control (P = 0.9692; data not shown), non-strobilurin and three strobilurin fungicides (P = 0.7787; data not shown), two multi-active ingredient products (P = 0.3181; data not shown), and the two single active ingredient products (P = 0.0579; data not shown). Furthermore, contrasts revealed that TKW was similar when fungicide was applied at any timing compared to the control (P = 0.9690; data not shown), 10% and 50% flowering (P = 0.5120; data not shown), and 50% and 10 & 50% flowering (P = 0.7340; data not shown).

For both the two- and three-way factorial ANOVAs, datasets were combined across locations (Table 4.13). Furthermore, the various products and their various timings did not significantly affect thousand kernel weight (Table 4.13). When factored over variety and the untreated control was removed, variety, product, and the three-way factor interaction all significantly affected thousand kernel weight (Table 4.13).

Table 4.13: Random and fixed effects of the two- and three-factor ANOVA for thousand kernel weight (g TKW) in Saskatoon, 2015 to 2017.

	P * T	V * P * T
	Random Effects	
Replicate	0.4257	0.00105*
Site-Year (SY)	<0.0001***	<0.0001***
Variety (V) x SY	NA	0.0505
Product (P) x SY	1.0000	0.4409
Timing (T) x SY	1.0000	0.8537
	Fixed Effects	
Variety	NA	<0.0001***
Product	0.0953	0.0419*
Timing	0.5837	0.4930
V x P	NA	0.3317
V x T	NA	0.7140
P x T	0.9331	0.8558
V x P x T	NA	0.0322*

*** p<0.001; ** 0.001<p>0.01; * 0.01<p>0.05

As expected, CDC Snowdrop had a greater thousand kernel weight than CDC SSNS-1, by approximately 22 g 1000^{-1} $seeds^{-1}$ (data not shown). Generally, the four fungicide products did not significantly alter the thousand kernel weight when averaged across varieties (Figure 4.12). However, there was a significant difference between fluopyram + prothioconazole and penthiopyrad by 6 g TKW(Figure 4.12).

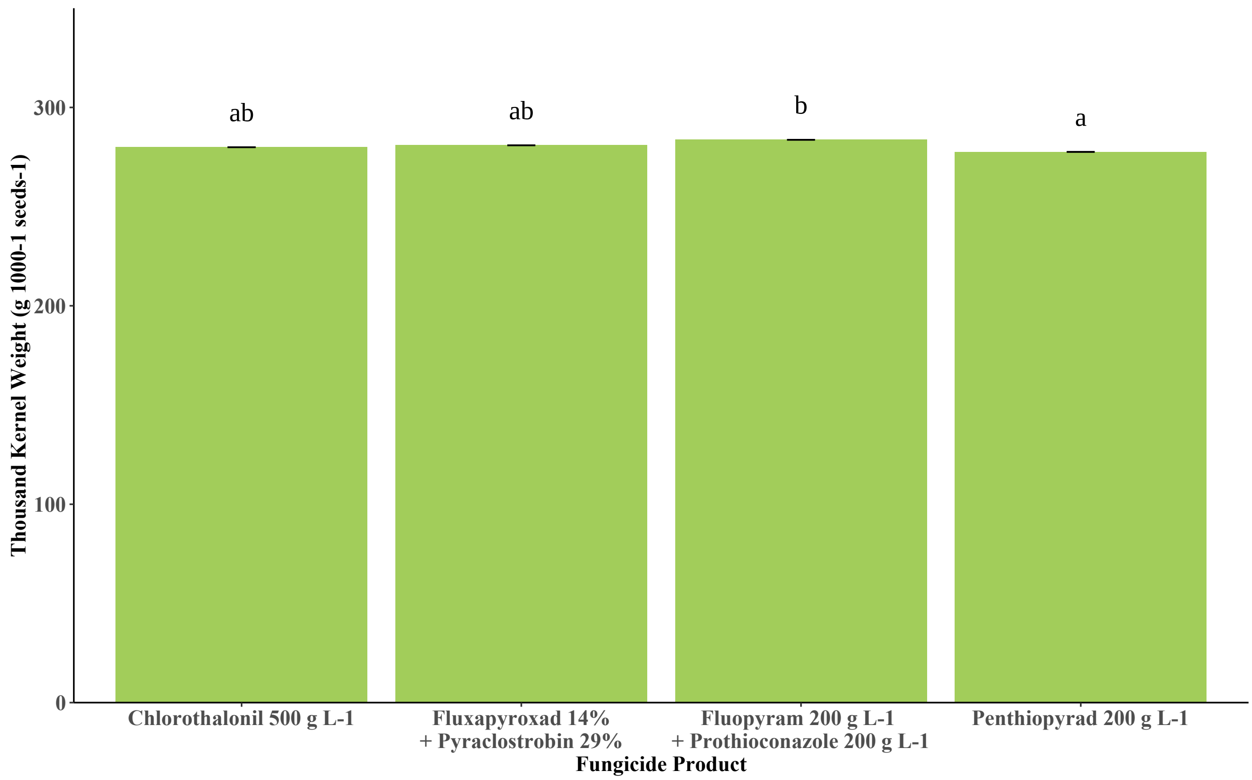

Figure 4.12: Applied product effects on thousand kernel weight (g TKW) averaged across 6 Saskatoon locations from 2015 to 2017. Values with the same letter are statistically similar at $P < 0.05$.

Overall, there were no significant differences between kernel weights of the applied treatments in either variety (Figure 4.13). Therefore, the largest driving factor for the statistical significance was innate TKW difference between the two varieties.

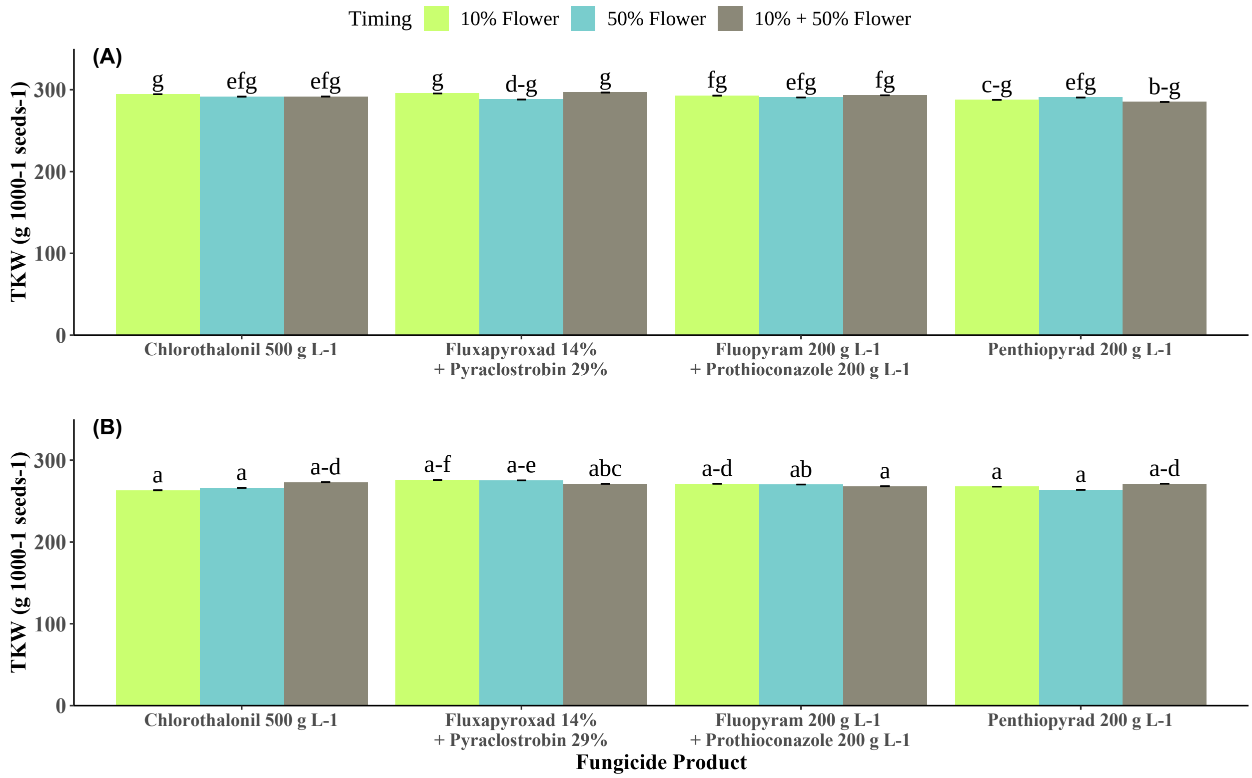

Figure 4.13: Product and timing effects on thousand kernel weight (g TKW) of CDC Snowdrop (A) and CDC SSNS-1 (B) averaged across 6 Saskatoon locations from 2015 to 2017. Values with the same letter are statistically similar at $P < 0.05$.

Overall, varietal differences were the largest influencer affecting thousand kernel weight in this experiment, as product and application timing caused mixed results. This is to be expected, as there was little disease throughout the experimental period. Additionally, yield was largely unaffected by the applied treatments as well. Therefore, one would not expect thousand kernel weight to also be significantly affected. Lastly, differences between the treatments were negligible and therefore, do not likely have any real agronomic significance.

4.3.7 Summary

Overall, the mixed results between each site-year proved difficult to summarize. Generally, CDC SSNS-1 had a greater plant density that CDC Snowdrop. Despite 2016 having the most precipitation of the experimental period, both 2016 sites had lower plant densities. In 2017, there was a significant difference between the establishment of the two varieties. This was likely due to reduced moisture and had effects on both biomass and grain yield.

Disease symptoms were minimal in 2015 and 2016, despite wet conditions. Unexpectedly, there were high rates of disease symptoms in 2017 compared to the other two years. This may be related to differences between the people rating disease rather than actual disease symptoms, as the year was fairly dry. Largely, disease symptoms were minimal until 4 to 6 weeks after fungicide application. In most circumstances, disease levels reacted similarly in both the untreated control and treatment plots. CDC Snowdrop tended to have greater disease levels than CDC SSNS-1, with all products, and application timings having similar effects on disease control. By large, fungicide application, regardless of its timing, had little effect on reducing disease severity. Therefore, disease severity was either not significant enough or fungicides were applied at too early of a growth stage to elicit any meaningful responses.

It is not surprising that yield and thousand kernel weights were largely unaffected by fungicide application and timing due to the minimal changes in disease severity responses. The elevated disease ratings with minimal yield response in 2017, coincides with a recent finding by Holzapfel in 2015. The author noted that when disease onset was later in the growing season it was likely too late to cause any significant yield reductions (Holzapfel 2015). There was a slight tendency for products with two active ingredients to have a modest yield response over the single active ingredient products as well. Moreover, this result was not surprising as using products with multiple active ingredients have a better chance of providing control than fewer. Lastly, the largest differences in thousand kernel weight were due to innate seed weight differences between varieties.

Due to the minimal disease levels that occurred throughout the experimental period, it is reasonable for minimal differences to occur between treatments. It is fully anticipated that if the disease pressure was higher or the diseases occurred earlier, larger differences between fungicide products and application timings would have occurred. Overall, it was suggested that the hypothesized differences between products, would be due to the number of active ingredients or product-base. These results suggest that there is no significant benefit to using a strobilurin-based fungicide over one that is not. However, there may be a slight benefit from using a multi-active ingredient product over a single active ingredient product. Furthermore, there does not appear to be a significant difference between application timings, when fungicide is applied during early growth stages and when disease severity is low. Lastly, results also suggest that under the low disease conditions of this study, the two varieties did not require different disease management practices. Overall, results indicate that the four fungicide products are equally effective towards controlling faba bean diseases in Saskatchewan. However, when disease severity is low and infection is delayed, there may not be a benefit to applying fungicide.

5.0 GENERAL DISCUSSION

Overall, the environmental variability between the site-years provided good insight into the issues that surround successful faba bean production in Saskatchewan. This thesis is also part of a larger research project. At the same time the experiments in this thesis were being conducted, a sub-set of treatments were trialed at five Agri-ARM locations across Saskatchewan. For the seeding rate experiment, CDC Snowdrop was the only variety seeded, at the same rates (20, 40, 60, 80, and 100 viable seeds m^{-2} in 2015 and 2016, then 5, 10, 20, 40, and 60 viable seeds m^{-2} in 2017). For the disease control experiment, CDC Snowdrop was the only variety seeded, with applications of the four fungicide products] only at 10% or 50% flowering. When these results and those of the smaller experiments are combined, they can be used to expand the inference space this thesis. Therefore, inference can move from beyond the black and brown soil zones and can be used to update the best management practices for faba bean cultivation throughout Saskatchewan.

5.1 Optimal Faba bean Seeding Rates for Saskatchewan

The hypothesis for the first experiment is that the seeding rate required to reach maximum yield will differ between varieties and varieties differing in seed size. Results indicate that there is no need to modify faba bean seeding rates beyond innate thousand kernel weight differences. Therefore, the hypothesis of this experiment was rejected. In this investigation, the seeding rate required to reach maximum agronomic yield, ranged from 20 to 77 seeds

m^{-2}, averaging 49 seeds m^{-2}. This result is only slightly greater than the current 44 plants m^{-2} recommendation. Loss et al. (1998) suggest that if variability is found between the optimal seeding rate at each site-year, the recommendation should be modified to higher rates. Increasing the seeding rate recommendation is also a proactive management strategy to hedge against environmental issues, which cause yield variability from year to year.

Higher plant densities can be beneficial towards hedging variability losses, as they alter the canopy in order to increase weed control, hasten maturity, and increase harvestability (López-Bellido et al. 2005). It is well known that higher plant densities increase competition against weeds. Personal field experience suggests that although 20 seeds m^{-2} can maximize agronomic yield, it may not be as efficient for providing additive weed control. This was especially noted in circumstances where herbicide resistant weeds were present and when late flushes of weeds occurred. As faba bean is a late season crop, with 104 to 109 days to maturity, earlier maturity can help prevent fall frost damage on the seed. Frost damage on the seed results in black to grey discoloration, resulting in downgrading, and consequently economic losses. Personal field experience also indicates that seeding rate can be effective in reducing discoloration, but will not eliminate it. This effect was also noticed in dry beans grown in Saskatchewan (Shirtliffe and Johnston 2002). Nevertheless, any simple agronomic modification that can reduce downgrading is beneficial. López-Bellido et al. (2005) also found that higher plant densities can also result in taller plants, with pods higher off of the ground, easing harvestability. However, although higher seeding rates can have significant benefits for faba bean production, higher rates need to be weighed against the increased risk of lodging and disease development.

As the optimal seeding rate for large-seeded pulse crops is highly dependent on seeding costs, the optimal agronomic seeding rate should be weighed against the optimal economic seeding rate. This is due to seed costs comprising a substantial portion of the total cost of production and due to yield responses being small at higher plant densities (Graf and Rowland 1987; Loss et al. 1998). The optimal economic seeding rate can be found in almost all yield-density relationships. This is because it takes into account the cost of sowing more seed and the additional grain yield gained, assuming some additional funds are required (Loss et al. 1998). Therefore, the economic seeding rate tends to be lower than the agronomic rate. Nevertheless, Graf and Rowland (1987) caution that if seeding rates are reduced in order to be economically feasible, the cost of additional weed control also needs to be considered. Conversely, as exemplified in chickpea, lower seeding rates can be an effective tool for disease management (Chang et al. 2007). This is due to a reduction of canopy moisture, increased chemical penetration, and increased air flow within the canopy. Therefore, the pros and cons of higher and lower seeding rates needs to be balanced.

Based on the results of this experiment, the optimal economic seeding rate was 45 seeds m^{-2}, across varieties. Individually, CDC Snowdrop had an economical seeding rate of 49 viable seeds m^{-2}, CDC SSNS-1 at 47 viable seeds m^{-2}, and FB9-4 at 35 viable seeds m^{-2}. Although seeding rates of 20 viable seeds m^{-2} optimized agronomic yield at 50% of locations, faba bean production at these sites were uneconomical. This was due to yield being constant over the entire range of seeding rates tested. However, as economics can change between years and individual farming operations, there may be some circumstances where seeding at 20 viable seeds m^{-2} can be economical. Therefore, as a way to hedge risk against less than ideal conditions and the added agronomic benefits provided by higher seeding rates, 50 viable seeds m^{-2}

should be the recommended seeding rate for all faba bean varieties cultivated in Saskatchewan. This seeding rate is a balance (average) between the rate required to maximize agronomic and economic yields. Overall, this recommendation should be used to update the best management practices for growing faba bean in Saskatchewan.

5.2 Optimal Disease Control for Faba bean Production in Saskatchewan

It was hypothesized for the second experiment that disease control in faba bean and its subsequent effect on seed yield and quality will differ between fungicide products, application timing(s), and varieties. Based on these results, the hypothesis was rejected. Although there were significant differences in disease severity between the site-years, all fungicide products and applications timings were equally effective in controlling disease development. In addition, although CDC Snowdrop was slightly more responsive to the various disease control measures than CDC SSNS-1, results were not always biologically or agronomically significant.

The recommendation to apply fungicide is based on whether or not the environment is conducive to disease development, the pathogen is present, and if full yield potential can be reached (Stoddard et al. 2010; Oerke 2005). Furthermore, the cost of fungicide application, the number of fungicide products available, and the increased risk of resistance should also be considered (El-Sayed et al. 2011; Oerke 2005; Stoddard et al. 2010). Results of this thesis suggest that foliar fungicide may not always be warranted, due to minimal disease development even under conducive environmental conditions, and in the presence of pathogens. Therefore, faba bean disease control should primarily focus on integrated disease control measures. Thus, clean, unblemished seed, at the recommended seeding rate, with adequate nutrition and weed control should be integral practices for disease management of faba bean in Saskatchewan.

As quality plays a large role in the grade and subsequent price received for faba bean, fungicide application can be economical. However, it is hard to speculate whether or not fungicide application played a role in grade retention, as it was not measured in this investigation. Overall, a maximum of 100 kg ha^{-1} (1.5 bu/ac) yield increase occurred with the application of fluopyram + prothioconazole and fluxapyrad + pyraclostrobin. If the average cost of fungicide is $151.73 ha^{-1} and an average $0.22 kg^{-1} grain price of is received, based on these results, fungicide application was not economical (Crop Planning Guide 2018). Uneconomical fungicide application also occurs in other faba bean growing regions, even where diseases are more common (Beyene et al. 2018). In other growing areas, this occurs when the onset of chocolate spot starts to develop during senescence (Harrison 1988). This is due to the disease having little to no effect on yield and fungicide application can potentially delay crop maturity (Harrison 1988). Based on personal field experience, if disease occurs during senescence it can actually be beneficial as it can hasten maturity, as long as it is not severe enough to reduce quality.

Furthermore, results indicate that under low disease pressure all four fungicide products are equally effective towards controlling faba bean diseases in Saskatchewan. However, when disease severity is low and infection is delayed, there may not be a benefit to applying fungicides. Furthermore, in this investigation, non-strobilurin based fungicides were equally effective as strobilurin based products. Although Bravo (chlorothanil) is no longer registered for use in faba bean, it does indicate that other non-strobilurin based fungicides can be used. This can help with fungicide resistance, as a way to reduce dependence on strobilurin-based fungicides which are at high risk.

These results also suggest that application timing at either 10% or 50% flowering may be too early, as disease progression did not escalate until nearly 6 weeks after first flowering occurred. However, there were some cases in which one application of any fungicide product, did result in disease control. However, the better of the two timings was dependent on the site-year. This finding is supported by the recommendation from the Saskatchewan Pulse Growers (2018), which states that a well-timed application is sufficient for faba bean disease control. Therefore, the consistently late onset of disease over the three-year study period, suggests that ideal application timing for disease control in faba bean may be more likely associated with the time after seeding, or rainfall events, rather than the growth stage. However, this is an area that needs further research, as later applications can result in later maturity, increased canopy 'greenness', and interfere with pre-harvest intervals. Furthermore, optimal application timing may have to more closely follow Australian recommendations, where the application is primarily preventative rather than curative (Davidson and Kimber 2007).

Overall, integrated disease management is the most effective disease control option for faba bean production in Saskatchewan. However, if a fungicide application is warranted the timing of the first and number of applications will be highly dependent on the grower's experience. This is similar to finding and suggestions made by Stoddard et al (2010). Lastly, as there was no significant difference using a strobilurin-based fungicide over a non-strobilurin fungicide and multi- over single active ingredient product, application timing and the diseases present, should be the largest driver for product selection.

5.3 Future Areas of Research

As corn and soybean gain more acreage in the prairie provinces, as well as more seed sales moving toward seed count selling units, the use of planters for seed singulation will become more prevalent. This provides an exciting opportunity for faba bean production. As mentioned earlier, current solid seeding equipment cannot always apply the targeted seeding rate in a single pass. With planters, seeds are more evenly spaced within the seed row, resulting in the use of less seed. This, in turn, may reduce the logistical issues currently associated with seeding faba bean and consequently decrease the cost of production. Ultimately, this may make faba bean production more profitable. To my knowledge, a small trial has been conducted at the University of Saskatchewan looking at the use of planters for faba bean production. Results seem promising; however, experimentation was not vigorous enough to provide new recommendations. Therefore, a more in-depth analysis is required to determine optimal seeding rates required for the use of planters.

Disease management in faba bean continues to be under-researched. Therefore, there are many routes further research could be directed. As mentioned earlier, small plots are not ideal for conducting disease research due to large pathways between replicates, resulting in increased air movement. Furthermore, plot equipment ensures the product is being applied at optimal application height. This does not reflect the abilities of field equipment, where application heights are suboptimal. Therefore, more disease control research should be conducted on-farm and with the use of field scale equipment.

Another area of research in disease management should look at the interaction between plant populations and fungicide use. As mentioned previously, reduced humidity in the canopy can minimize the development of ideal environments conducive to disease. This work would ideally be completed under high disease conditions and could potentially be well demonstrated on a field scale.

Lastly, as the results of this thesis indicate, disease incidence and its progression tend to occur during later parts of the Saskatchewan growing season. Therefore, ideal fungicide application timing could potentially be in the later parts of the season. Therefore, research should investigate fungicide timing as a function of weeks after planting, in conjunction with growth staging, in order to determine optimal timing. This needs to keep in mind any increased 'greening' effects that are often associated with fungicide use and pre-harvest interval restrictions on product labels.

5.4 Updating the Best Management Practices for Faba Bean Cultivation in Saskatchewan

In conclusion, the results of this thesis suggest that the best management practices for faba bean production in the dark brown and black soil zones of Saskatchewan should be updated. The new recommendation for faba bean seeding rate should be increased to 50 viable seeds m^{-2}. This rate accounts for the variability between the optimal agronomic and economic seeding rates. Furthermore, this recommendation is tailored to all varieties and solid-seeding practices. The recommendation to apply fungicide, when needed under conditions favorable disease development, is still valid. If required, one well-timed application of any registered product will provide adequate control. The optimal product and timing to use will depend on whether or not the product is a broad-spectrum fungicide and the current state of disease severity. Overall, this research using currently varieties, management practices, and environmental conditions will help ensure a stable, high yielding, and high quality faba bean crop can be continuously produced in Saskatchewan.

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