SHADE AVOIDANCE AND THE YIELD-DENSITY RESPONSE IN TWO NAVY BEAN (PHASEOLUS VULGARIS L.) VARIETIES UNDER WEED-FREE AND WEEDY CONDITIONS

BY

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A Thesis Submitted to the Faculty of Graduate Studies of
The University of Manitoba
In Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE

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Acknowledgements

To Dr. Robert Gulden, my M.Sc. advisor: Thank you for your patience, knowledge, and support through the years, and for always leaving your door open.

My committee members, Dr. Belay Ayele and Dr. Ivan Oresnik: Your constructive criticism and feedback has been vital, thank you.

Manitoba Pulse and Soybean Growers: Thank you for funding this project. Without it, my thesis would not have come to life.

The Weeds Lab research technician, Becky Dueck: Your personality and positive attitude brightens everyone around you and makes the most difficult tasks achievable. Thank you for the support and hard work over the years.

The summer students of the Weeds Lab: I don’t think I can ever express how grateful I am for your help during hand seeding, hand weeding, and hand counting everything else in my plots. I wouldn’t have asked for better hands to get the job done, thank you.

Fellow graduate students: Thank you for the coffee chats, the encouragement, and helping me decipher the language of SAS. But most importantly, thank you for helping to hand seed my plots.

Dr. Claudio Stasolla: Thank you for your endless care for graduate students in the department.

Hal: I’ve learned much about myself through this experience, but mostly that there is still much to learn. Thank you for opening my eyes.

My family: For accepting what I was doing, even when you may not have understood what I was doing. You told me to grasp the power of knowledge, so I did.

Русалка: Мої друзі, моя родина, моє серце. Your encouraging words meant the world to me. Thank you to those who gave their honest support when it was so needed.

My partner, Jim Hyde: My rock in a raging river. Thank you for holding steady when my world was turbulent.

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Abstract

Koroscil, Leanne J., M.Sc., The University of Manitoba, August 2020. Shade avoidance and the yield-density response in two navy bean (*Phaseolus vulgaris L.*) varieties under weed-free and weedy conditions. Major Professor: Robert H. Gulden

Field bean (*Phaseolus vulgaris L.)* production in Canada is limited to few regions, mainly Manitoba and Ontario. For being one of the main producers of field bean in Canada, Manitoba research has been limited in comparison to other major crops grown in the region. Few effective herbicides are registered in field bean and other methods of weed control must be used to enhance crop protection. This study was conducted to enhance the knowledge around the effect of spatial arrangement on field bean development and seed yield, which can simultaneously be used as an Integrated Weed Management (IWM) strategy against weed competition. The specific strategies examined were planting densities, planting date, and cultivar selection. The premise of the study focused on aspects of previous research conducted by Schmidt (2020) based out of the University of Manitoba, which were not found to conform to the 'law of constant final yield' (LCFY), an occurrence theorized by Weiner and Freckleton (2010) wherein at low plant densities crop yield is directly dependent on plant density while at increased densities, crop yield forms a plateau and becomes independent of plant density. This was not apparent in the navy bean experiments conducted by Schmidt (2020). To further examine this, two experiments were established at Carman, Manitoba in 2017 and 2018 at an early and a late seeding date with two navy bean cultivars, T9905 and Envoy, in each experiment. One experiment was kept weed-free, and the other included weed interference. Field bean seed yields in the weed-free experiment were greater at increased planting densities. Increasing planting densities in the weed-free experiment also enhanced certain shade avoidance characteristics, creating thinner stems, reduced branch numbers, longer first internodes and increased pod clearance. Interestingly, plant height did not significantly change with increasing planting densities in the weed-free experiment. Increasing planting densities did little to reduce weed biomass in all weedy experiments but one, late-seeded Envoy in 2018. Additionally, the increase in plant density did not improve seed yield outcome against weed competition when the natural weed community was allowed to interfere with the beans for the entire growing season. Over both experiments, the T9905 Type II navy bean cultivar experienced better seed yield results than the Envoy Type I navy bean cultivar.

1.0 Introduction

Manitoba is an important province in field bean production in Canada and research to broaden producer knowledge of advantageous practices for controlling weeds and increasing yield is both beneficial and necessary. Weeds also can maintain disease inoculum and can act as hosts to pests that could affect related crops, making crop rotations difficult. Crop competition as a form of Integrated Weed Management (IWM) using optimal seeding rates and densities may be cost effective if it implies reduced reliance on herbicides (Swanton and Weise 1991). This not only saves time and money for producers, but also plays an active role in weed management. One of the methods used in IWM is optimizing plant spatial arrangement to compete against weeds for nutrients, light, and water. Narrow row spacing and increased plant density have a competitive impact on weeds in crops (Blackshaw et al. 2000; Holmes and Sprague 2013), yet local research on field bean agronomy and weed management is scarce or outdated.

Preliminary research in our lab by Laura Schmidt in 2015 and 2016 on two varieties of navy and two varieties of pinto bean across four site-years in Manitoba showed somewhat unexpected results (Schmidt 2020). A decrease in yield with increasing plant densities was observed at the narrow 20 cm row spacing indicating that at this row spacing, bean yield did not appear to conform to the ‘law of constant final yield’ (LCFY) (Weiner and Freckleton 2010). The LCFY states that as plant density increases, yield also increases until a yield plateau that is independent of density is reached. In wider row spacing (40-80 cm) in Schmidt's study (2020), a yield plateau (= conformation to the LCFY) occurred at very low plant densities. A similar study in Saskatchewan did not show the same results (Shirtliffe and Johnston 2002). In addition, noticeable differences were observed between navy bean varieties with a different growth habit.

Studies described in this thesis were initiated to determine what caused these unexpected results. It was hypothesized that:

1. Under a weed-free environment, the indeterminate cultivar (T9905) will express greater shade avoidance characteristics and seed yield production than the determinate cultivar (Envoy) in response to plant spatial arrangement.
2. The plant density-yield response of both T9905 and Envoy field bean cultivars will conform to a rectangular hyperbola under weed interference.

2.0 Literature Review

2.1 The History and Global Production of Field Bean

It is unclear and a common debate whether bean (*Phaseolus vulgaris L.*) production originated from Mesoamerica or the Andes. In either case, beans are an important staple food for human consumption (Cortés 2013). Broughton et al. (2003) deems that “beans are the most important grain legume for human consumption in the world”. This is due to a variety of factors including the high nutritional content found in beans that provides a cost-effective source of fibre, minerals and protein to those in impoverished and malnourished regions (Bitocchi et al. 2012). For millennia, field bean has been an important staple food in the Americas but only in the past 20 years has field bean begun to expand into trade and export markets as their popularity has increased in other cultural circles (Broughton et al. 2003). The top producer of field bean worldwide in 2017 was India, producing approximately 5,796,910 metric tonnes of field bean (Food and Agriculture Organization of the United Nations 2017) while in comparison Canada produced approximately 232,996 metric tonnes during the same year. Canada falls in the 20th position for dry bean production worldwide, yet field bean is still considered a major commodity in Canada and production has increased substantially since the 1980s.

In Canada, pulse crops, which include field bean, peas, chickpeas and lentils, represented 6% of the area seeded to annual crops in 2011, which is relatively small compared with wheat and canola which, when combined, represent nearly 50% of the annual seeded acreage (Bekkering 2014). Field bean alone was seeded to 143,000 hectares in Canada in 2018 compared to the combined 10,073,500 seeded hectares of spring, durum and winter wheat and 9,232,200 seeded hectares of canola (Table 2.1; Statistics Canada 2020). Despite the differences in seeded hectares between field bean and other annual crops, the seeded area of coloured and white field bean, nevertheless, increased by 3.7 times between 1980 and 2018, from 38,400 to 143,000 seeded hectares respectively (Statistics Canada 2020). Over a dozen different market classes of field bean are currently grown in Alberta, Saskatchewan, Manitoba, Ontario, and Quebec including black turtle, pink, great northern, dark red kidney, light red kidney, pinto, white kidney, dutch brown, small red, and cranberry (Holmes 2012; Navabi et al. 2014; Government of Manitoba 2020). Among the types of field bean grown are white pea beans, also known as navy beans, which are a popular field bean market class grown in Manitoba. Currently, twelve varieties of navy bean are registered in Canada, with three more proposed to be registered in Canada (Manitoba Agriculture 2018).

2.2 Field Bean Production in Manitoba

The majority of field bean production in Canada occurs in Manitoba and Ontario. Other provinces involved in field bean production include Saskatchewan, Alberta and Quebec, yet they do not compare to the production capacity of Manitoba and Ontario (Table 2.1).

Table 2.1 Production of white and coloured field bean, canola, soybean, and spring wheat across Canada and the prairie provinces in 2018 (Statistics Canada 2020).

Type of crop	Canada	Ontario	Manitoba	Alberta	Saskatchewan
			Metric tonnes		
Bean, dry white	88,500	62,600	23,100	2,900	– [a]
Bean, dry coloured	252,600	70,800	83,600	69,900	14,200
Canola	20,342,600	66,700	3,318,400	5,870,600	10,927,100
Soybean	7,266,600	4,200,500	1,581,600	11,600	231,800
Wheat, spring	23,510,500	120,400	4,600,400	8,771,600	9,659,100

[a] Too unreliable to be published

Agronomic and scientific resources for field bean production in Manitoba have been insufficient. Current agronomic research has mainly been conducted in neighbouring states and provinces. Certain environmental conditions such as annual precipitation, frost-free days and soil type can vary substantially within a 100-kilometer range. The field bean production region of south-eastern Manitoba is relatively short compared to other provinces; an average of 105 to 125 frost-free days (Manitoba Agriculture Food and Rural Initiatives 2001) compared to southern Ontario, where the field bean growing season ranges from 125 to 190 frost-free days (Ontario Ministry of Agriculture Food and Rural Affairs 2016). The lack of knowledge in field bean production relative to Manitoba's local conditions provides reason for local field bean research. In order for Manitoba to remain a leading province in field bean production, research must focus directly on the conditions relevant to the province, not be borrowed from neighbouring regions with different environments.

2.2.1 Diseases in Field Bean

Field bean is susceptible to many diseases both above and below ground. Incidence and severity of typical field bean diseases such as *Colletotrichum lindemuthianum* (anthracnose), *Xanthomonas campestris pv. phaseoli* (common bacterial blight), Uromyces phaseoli (leaf rust), *Fusarium solani*, *Rhizoctonia solani* and *Pythium* spp. (root rot), mosaic virus, and *Sclerotinia sclerotiorum* (white mould) all rely on moist conditions to thrive (Goodwin 2005). These common diseases can cause up to 100% yield loss if severe (Venette and Lamey 1998; Singh and Schwartz 2010), yet it is impossible to predict if future seasonal moisture will be great enough to cause disease incidence. In addition, the few viable options that are available for control can protect against some but not all diseases, and can be unreliable (Singh and

Schwartz 2010; Conner et al. 2014). The knowledge that the occurrence of field bean diseases is highly variable in a season, that no field bean crop is guaranteed to be disease free, and that disease control options can be unreliable, emphasizes the importance of introducing an integrated pest management strategy with multiple areas of control (Venette and Lamey 1998). Various cultural management practices can be implemented in an effort to reduce susceptibility to diseases. These include increasing crop rotations (Park 1993), using seed treatments (Conner et al. 2014), selecting resistant cultivars or cultivars with an upright growth habit (Blad et al. 1978; Schwartz et al. 1978), and improving tillage to increase soil drainage (Park 1993; Singh and Schwartz 2010; Conner et al. 2014). It is also important to implement row spacing and planting densities that encourage airflow beneath the crop canopy without sacrificing competition against non-crop species (Schwartz et al. 1978; Conner et al. 2014). Using a variety of cultural control methods increases crop protection in the event that one or more of the methods fail, which would otherwise lead to reduced market quality or yield losses. Two of the most common field bean diseases in the south-eastern region of Manitoba are white mould and root rot, both of which have the potential to cause devastating losses to yield and quality.

2.2.1.1 White Mould

White mould (*Sclerotinia sclerotiorum)* is a common field bean disease in Manitoba that thrives in dense field bean canopies. The pathogen overwinters in the soil before becoming a mushroom-like apothecium in the moist and cool microclimate below the canopy. The spores from the apothecium land on petals which fall onto the leaves of the plant where they destroy plant tissues. Control methods exist, including fungicidal applications or crop rotations. However, major yield losses still occur from the lack of resistant varieties (Ando et al. 2007;

Schwartz and Singh 2013), the vast range of hosts (Schwartz et al. 1978), and the long dormancy of the disease (Harding and Chatterton 2019). Field bean yield losses vary drastically between seasons and can reach up to 100% for this disease (Vieira et al. 2010; Schwartz and Singh 2013).

2.2.1.2 Root Rot

Field bean root rot belongs to a range of species, including *Fusarium* spp., *Pythium* spp., and *Rhizoctonia solani* (Tan and Tu 1995; Conner et al. 2014). Symptoms in field bean vary depending on the fungal strain but mainly involve plant stunting, discolouration of the plant mainly at the stem or roots, and plant death (Harveson et al. 2005; Chaudhary et al. 2006). The symptoms of root rot can lead to diminished field bean plant stands that can increase weed interference in the field as a result (Harveson et al. 2005; Conner et al. 2014). Root rot symptoms may also result in up to 100% yield loss, depending on the severity of the disease and the species of root rot (Schwartz 2011). Control methods for root rots are not widely effective (Conner et al. 2014), thus multiple cultural and chemical controls should be used in field bean. Current methods of control include crop rotations, selecting treated seed, and tilling the field before seeding (Schwartz 2011). One of the main reasons for root rot is soil compaction (Tan and Tu 1995), which can be alleviated with tillage to increase water drainage and proper root formation. In addition to cultural and chemical controls, resistance to root rot would be a beneficial addition to an integrated pest management strategy for field bean. Resistance to root rot has been researched by many (Schneider et al. 2001; Román-Avilés and Kelly 2005; Miklas et al. 2006) but only partial resistance has been achieved (Conner et al. 2014). Implementing an integrated pest management strategy is important since root rot has been found in 100% of field surveyed in Manitoba in recent years (Henriquez et al. 2015; McLaren et al. 2016; Kim et al. 2017, 2019; Elmhirst 2018).

2.2.2 Weed Control in Field Bean

Weeds are competitors for critical resources such as water, light, and nutrients. They can also act as hosts to biological pests (Capinera 2005) and have the potential to lower crop quality and value by contamination during harvest. The 'law of the minimum' states that yield will be directly affected by the nutrients in the shortest supply (Brady and Weil 2007). Weed competition significantly impacts yield if the crop is deprived of light, soil moisture, and nutrients absorbed by a competitive weed canopy or root system. With strategic herbicide use, yield can increase due to the added benefit of eliminating or reducing other competitive vegetation through herbicide applications, assuming that herbicide injury to the crop is minimal (Swanton and Weise 1991; Blackshaw et al. 2000).

An alternative method to herbicide application involves understanding the critical period of weed control (CPWC) and therefore Integrated Weed Management (IWM). The CPWC is a period of time a crop must be free of weeds to avoid yield loss and has been identified in a multitude of crop types. The CPWC involves two main components as described by (Weaver and Tan (1983). The first component being the amount of time a crop can tolerate weeds before the effects of weed interference are irreversible, and the second component involves the determination of the point where late recruiting weeds, if unmanaged, no longer influence crop yield (Weaver and Tan 1983). Herbicide applications can be reduced if the CPWC is well understood and implemented. The CPWC is an example of a method used in IWM which aims at minimizing or eliminating chemical exposure through biological controls such as pathogens, parasites, or predators, and cultural controls such as strategic cultivation or other farming methods (Horne and Page 2008). In field bean, cultural methods of IWM typically involve between-row cultivation in wider rows or increasing plant stand density and population in narrow rows. However, the optimal plant spacing for field bean yield has not yet been studied closely in Manitoban environments, hence the purpose of this study.

2.3 Field Bean Growth Habits

There are three different growth habits of field bean common to Canada, namely Type I, II and III. The main distinction between growth habits is whether or not the field bean has a bushy determinate growth - meaning no vegetative growth occurs after flowering, or a vining indeterminate growth - meaning they will continue vegetative and reproductive growth so long as the environment is favourable (Singh 1981). A Type I growth habit is best described as a determinate bush, a Type II growth habit is an indeterminate upright short vine, and a Type III growth habit an indeterminate semi-prostrate vine (Singh 1981; OMAFRA 2017). Type IV growth habit bean is an indeterminate vining plant requiring stem support, but these are not common to Canadian field bean production. Growth habits can affect disease incidence (Schwartz et al. 1978), weed control (Saberali et al. 2012), and harvestability (Kelly 2010). The growth habit also has the potential to alter production decisions for different systems and for this reason Type I and II field bean are frequently used in Manitoba production. Field bean is typically grown in a row-crop system using a special seeder with pre-determined row spacing ranging from 30-36 inches apart, or a solid-seeded system which places the seeds into the soil in narrow 5-8-inch rows and is more uniformly distributed compared to row-cropping (Government of Manitoba 2020). Type I determinate-type field bean is better adapted to narrow-row or solid-seeded production systems since they have a determinate growth habit, while Type II bean has an indeterminate growth habit which fills void spaces between wider rows as they grow.

The Type II indeterminate growth habit and high yield of the T9905 cultivar is favoured among navy bean producers, ranking third among field bean varieties grown in Manitoba after Windbreaker pinto bean and Eclipse black bean (Manitoba Agricultural Services Corporation 2019). T9905 was planted to 5,531 hectares of a total 42,708 hectares dedicated to field bean production in Manitoba in 2016 (Manitoba Agricultural Services Corporation 2017) and in 2018, the number of T9905 seeded hectares rose to 5,814 hectares out of 48,110 total hectares in Manitoba (Manitoba Agricultural Services Corporation 2019). In comparison the Envoy navy bean cultivar had 455 seeded hectares in 2018 (Manitoba Agricultural Services Corporation 2019). Annual variety comparison trials across Manitoba have used Envoy navy bean as a local control variety for the last 51 site years. Envoy is a Type I determinate bush-type bean with a slightly shorter maturity period of 100 days compared to the 105 days for T9905.

2.3.1 Field Bean Growth Habit and its Effect on Disease

The growth habit of field bean can influence the relative humidity retained within the canopy which may influence the incidence and severity of plant pathogens. Indeterminate, vining plants in solid seeded stands typically have increased disease incidence due to humidity trapped under the canopy, while an open canopy can result in reduced apothecia, less humidity collected on plant material, and overall decreased disease incidence at harvest (McDonald et al. 2013). *Sclerotinia sclerotiorum* (white mould), one of the most devastating diseases in field bean, is influenced by the level of relative humidity under the canopy (Goodwin 2005). Reduced airflow and dense canopy cover encourage sclerotinia development which can cause 100% yield loss depending on the cultivar (Singh and Schwartz 2010; Schwartz and Singh 2013). The life cycle of the disease begins on the soil surface as apothecia, which release ascospores into the plant canopy. When flower petals fall into the canopy and trap spores on the plant surface, the spores germinate, enter the plant and pathogenesis begins. A Type I determinate growth habit of field bean may be less susceptible to white mould than Type II or III indeterminate growth habits due to increased access to airflow under the canopy, albeit not immune (Blad et al. 1978; Schwartz et al. 1978; Park 1993). Indeterminate growth habits have been shown to produce more flowers than determinate Type I bean (Schwartz et al. (1978), which suggests increased risk for greater disease development. However, a study by Schwartz et al. (1978) found that the density of the canopy, as measured using leaf area, dry weight and plant height, was the factor that determined the level of disease severity rather than the indeterminate versus determinate growth habit, since many field bean varieties offer partial or no resistance to sclerotinia (Schwartz & Singh 2013). Another study in southern Ontario found that certain indeterminate cultivars were less affected by sclerotinia than determinate cultivars (Park 1993). The reduced airflow within the canopy can increase disease development; however, the potential for increased weed interference exists when field bean is grown at wider row spacing.

2.3.2 Field Bean Growth Habit and its Effect on Weeds

Field bean is a weak competitor against weeds and can suffer high yield losses from weed interference. Rapid canopy closure enables the crop to absorb more sunlight and nutrients, diminishing their availability for weeds present in the same field, thus reducing weed competition (Marín and Weiner 2014). Multiple studies in field bean (Holmes 2012), corn (Mohammadi et al. 2012), organic wheat (Drews et al. 2009), and rice (Chauhan and Johnson 2011) have shown that row spacing and plant stand density can aid in controlling weed populations and thereby increase yields, while simultaneously reducing the need for pesticide application or other means of weed control. This can be supplemented further by selecting varieties with growth habits appropriate for the production system in use, whether it be row- or solid-seeded. Indeterminate growth habit field bean varieties are better suited to wider row spacing due to their nature of canopy spreading more than a determinate bean; the latter are more successful at canopy closure in narrow seeded systems (Holmes 2012). A balance between row spacing for minimized disease incidence and row spacing for enhanced weed competition must be considered when selecting bean varieties of different growth habits. A dense canopy may create natural weed competition but can also encourage disease development and progression.

2.4 The Effect of Spatial Arrangement and Planting Density on Field Bean and Pests

Row spacing and plant density are important factors in field bean production and can influence plant disease severity and weed competition, thus resulting in potential yield losses. Field bean is typically grown in a row-crop system but can be grown in a solid-seeded system. A row-crop system uses specialized equipment that seeds with wide space between the rows, allowing for future inter-row cultivation, while a solid-seeded system uses narrow rows with no inter-row cultivation (Shirtliffe and Johnston 2002). The choice depends on the traditional production practices of the producer since they are unlikely to invest in new equipment for only one of their rotational crops. Both systems have unique benefits and challenges to disease incidence, weed control, and harvest methods. Narrow row spacing has been acknowledged as an Integrated

Weed Management (IWM) practice, which attempts to incorporate multiple techniques of pest management (chemical, mechanical, natural) to reduce the reliance on chemical use alone (Capinera 2005). Field bean in particular is a poor competitor against weeds and with fewer registered, effective herbicide choices compared to popular conventional crops in Manitoba such as canola and wheat. Using IWM in the form of increased plant densities has been shown to be beneficial for weed control and yield; however, a balance between narrow row spacing and uniformity must also be considered to achieve successful results. The intent of uniform plant spatial arrangement is to optimize airflow and light capture to create a naturally competitive environment against weed species with reduced reliance on herbicides, but if plants are overpopulated then there is a risk for lost yield from disease incidence or nutrient competition (Heard et al. 1990).

2.4.1.1 The Effect of Spatial Arrangement on Weeds

Past studies have shown that plant density and row spacing influence competition between the crop and any weeds present in the field, in particular under conditions with narrow row spacing (Malik et al. 1993; Blackshaw et al. 2000; Holmes and Sprague 2013). Research in Michigan by Holmes and Sprague (2013) has shown that narrow row spacing in Type II black bean decreases the population sizes of weeds. The narrow rows spacing of 15 inches (38 cm) was established in their experiment using a split-row planter. It was found that in two of the four site years, weed populations were reduced, and in all site years except one the bean biomass was reduced (Holmes and Sprague 2013). Blackshaw et al. (2000) performed a weed management study involving row spacing, plant density, and herbicide combinations in dry bean in Alberta and found that weed biomass was less in narrow rows and higher plant densities than in wider rows and lower plant densities. In both studies, the addition of herbicides strengthened the crop competition against weed species affected by the herbicides, but the increased crop density enhanced the effect of the herbicides. Malik et al. (1993) have also shown that narrow rows increase crop competition; however, at plant densities of 25 to 38 plants m^{-2}, weed biomass did not decrease. Work by Marín and Weiner (2014) on the density and uniformity of maize and its relation to weed management suggested density and uniformity play a role in managing weed populations and thus reducing the need for herbicides and the time needed to use mechanical weed control. This is an ideal situation, as herbicides are expensive, application can be time consuming, and the long-term use of herbicides can be detrimental to the environment (Swanton et al. 1993; Blackshaw et al. 2000). The study by Blackshaw et al. (2000) in Alberta showed that decreased plant densities or narrow row spacing increased the yield of dry bean, yet without weed management strategies such as herbicides, the yields remained low.

2.4.1.2 The Effect of Spatial Arrangement on Harvest

In Manitoba, the method of harvesting field bean is dependent on the row width, whether narrow or wide. Upright, determinate growth habit varieties should be chosen for narrow row systems to ensure compatibility with direct harvesting (OMAFRA 2017), whereas vining, indeterminate varieties are well suited for wide row cropping systems. Wide row crops are harvested by being pulled or undercut beneath the soil surface with specialized equipment, then collected in windrows to dry before being harvested with a pickup header (Goodwin 2005). This additional handling during harvest raises the risk of harvest losses through pod shatter, and also increases the number of field visits required during the harvest season (Helm et al. 1990; Kandel and Endres 2019). Narrow row or solid seeded determinate field bean can be direct harvested with a combine, but bean pod clearance must be sufficient to ensure that the majority of field bean pods are harvested by the pickup header. Unlike pulling, undercutting, and windrowing, direct harvesting is highly efficient and reduces the time spent in the field by only requiring one pass (Kandel and Endres 2019) while eliminating the requirement for specialized equipment (Kelly 2010).

During either method of harvest, field bean can experience damage to the seed coat which can reduce seed quality and viability. Cracks in the seed coat can reduce market quality for canned beans and increases the risk of baldhead, a condition that causes seedling death at the cotyledon stage shortly after emergence, thus reducing plant density and yields (Helm et al. 1990). Seed coat damage can be reduced by ensuring a seed moisture level of 15-20% is maintained, and by handling beans gently during harvest and grain transfers (Helm et al. 1990; OMAFRA 2017).

2.4.1.3 Plant-Plant Interactions

Plants naturally compete with each other for valuable nutrients and resources, both above and below ground. The competitive intensity of plants depends on variables including but not limited to resource availability, plant size, and “area over which these resources are depleted” (Weiner and Freckleton 2010). Competitive characteristics can be triggered through the detection of neighbouring plants via resource dependent means such as water and nutrients, or resource independent means such as light and hormonal signalling (Page et al. 2010; Green-Tracewicz et al. 2011). These competitive characteristics are a result of physiological and morphological changes from non-resource limiting effects, otherwise known as shade avoidance characteristics (Ballaré et al. 1987; Page et al. 2010; Casal 2012). One of the most important factors responsible for influencing competitive plant growth are light signals detected by photoreceptors (Ballaré 2014). Once light interference is detected through signals such as the red to far-red ratio (R:FR), a plant may begin to exhibit signs of shade avoidance including elongation of the stem, apical dominance, and reduced root and shoot biomass (Page et al. 2010; Afifi and Swanton 2011). These physiological and morphological shade avoidance changes lead to increased focus on growth in an attempt to overcome the neighbouring competing plants (Ballaré 2009; Casal 2012) and may be detrimental if the shade avoidance characteristics continue to influence growth (Yang and Li 2017). Afifi and Swanton (2012) studied the effects of the Red (670 nm) to Far Red (730 nm) ratio (R:FR) light reflected from weeds on maize, and a similar study was also conducted by Mckenzie-Gopsill et al. (2016) on soybean seedlings. Both studies found that plant stress pathways were activated when the crops detected R:FR light from neighboring plants. Abnormal growth from shade avoidance responses mediated through plant hormones, gene expression, and stomatal closure were triggered by the detection of decreased R:FR light, modifying the growth characteristics of plants. These modifications can lead to early flowering, lowered defences against pests, decreased branch numbers and decreased yield (Yang and Li 2017). The resulting morphological and physiological adaptions from interactions between plants affect how well field bean adapts to narrow compared to wider row spacing, though is not widely studied in navy bean and will be examined in this study.

2.4.1.3.1 Intraspecific Interactions

One of the most important decisions a producer will make in a season involves row spacing and plant density. If the plant stand density is thin, there are more opportunities for weeds to populate, but in contrast if the plant stand density is too thick, problems such as overpopulation may occur. Overpopulation can cause self-thinning, which is what Chu et al. (2010) describes as "density-dependent mortality". This phenomenon occurs in dense plant stands where plants compete for limited resources, eventually leading to individual death from the lack of resources needed to survive (Morris 2002). Plant size also influences self-thinning since it allocates the most energy toward light interference due to higher leaves shading lower leaves (Weiner and Freckleton 2010). Uncompetitive crops such as field bean struggle with weed competition (Dawson 1964) and would benefit from a self-thinning weed population caused by a dense crop canopy. Weeds grow rapidly compared to field bean which can lead to a shading disadvantage and yield loss; however, the crop may try to overcome this competition for light with shade avoidance characteristics (Afifi and Swanton 2012; Green-Tracewicz et al. 2012). Optimizing the row spacing and density can reduce or eliminate the risk of overpopulation by establishing an enhanced canopy cover to compete against inter- and intraspecific competition for valuable nutrients like light, especially with field bean which is characterized by its uncompetitive abilities (Dawson 1964).

The effects of increasing plant density in a given area over time is described in an asymptotic relationship known as the 'law of constant final yield' (LCFY). The LCFY states that as plant density increases relative to plant biomass, the yield eventually becomes independent of density and plateaus (Weiner and Freckleton 2010). As shown in Figure 2.1, the initial linear slope near the origin represents plant growth with no competition, then develops into a plateau once yield become insensitive to planting density. A study by Nienhuis and Singh (1985) showed that the response curves can vary between growth habits; indeterminate field bean types such as II and III followed a parabolic relationship, while determinate type I plants followed an asymptotic relationship. This asymptotic function was found to fit best in a black and pinto bean (Type I determinate) study in Saskatchewan by Shirtliffe and Johnston (2002). The optimal spatial arrangement in field bean required to achieve the LCFY is a key factor in field bean production. Field bean are poor competitors, especially during the first six weeks of establishment (Dawson 1964; Blackshaw 1991), and the LCFY shows that the advantages of early establishment could improve the outcome of the crop.

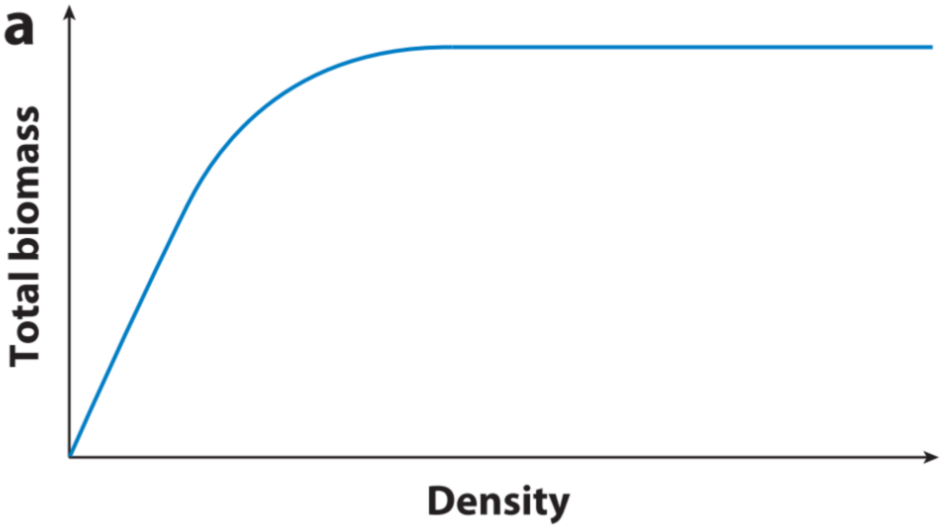

Figure 2.1 The ‘law of constant final yield’ adapted from Weiner and Freckleton (2010).

2.4.1.3.2 Interspecific Interactions

From a production perspective, a crop is ideally free from weeds and may only experience competition from plants of the same crop type. However, if given adequate resources to survive with lack of control, weeds may also thrive in the same environment or space. This competition for space, water, light and nutrients creates a situation with potentially detrimental effects including shade avoidance characteristics and yield loss. However, it can be difficult for a producer to decide if weed control is economically worth the time and effort. To aid in determining if weed control is necessary in a crop, Cousens (1985) developed a hyperbolic model to describe yield loss in response to increasing weed density. As shown in Figure 2.2, the yield loss plateau (A) as d approaches ∞ and the percent yield lost per unit weed density (I) as d approaches 0 are likely to change with other variables such as crop density, relative time of emergence of weed and crop, and soil type. Linear or sigmoidal models do not describe the relationship between weed density and yield as well as the hyperbolic model by Cousens (1985), where:

Y_L = Percent yield lost from competition due to weeds

d = Weed density

I = Percent yield lost per unit weed density as d approaches 0

A = Percent yield loss between 0 and 100% as d approaches ∞. Yield loss can never be more than 100%.

$Y_L = Id$ is the slope at which one weed plant affects yield loss.

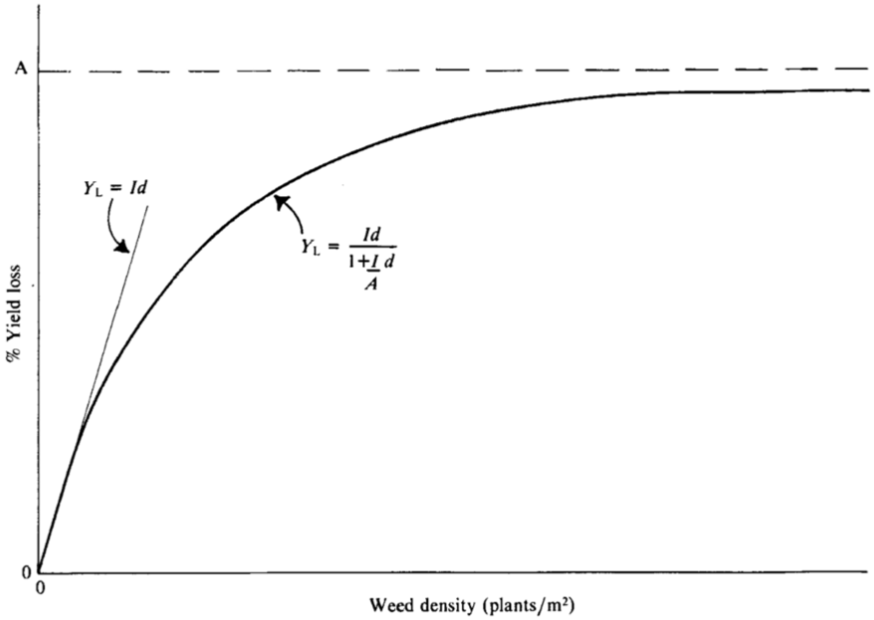

Figure 2.2 Cousens hyperbolic model depicting the relationship between yield loss and weed density (Cousens 1985).

2.5 Research Objectives

Manitoba is one of the top producers of field bean in Canada, yet there are many research gaps surrounding field bean production in Manitoba. Research on the effect of spatial arrangement on field bean yield is particularly insufficient. Work by Schmidt (2020) from the University of Manitoba examined row spacing and planting densities in field bean in an attempt to address this research gap, and instead observed a lack of conformation to the 'law of constant final yield' (LCFY). The intent of this research is to examine the lack of conformation of field bean to the LCFY by testing the following objectives:

1) Determine the yield and shade avoidance response in two navy bean cultivars at different spatial arrangements and relate this to the LCFY under weed-free conditions
2) Determine the navy bean density-yield response and the effect of increasing bean density on weeds under weed interference

3.0 The Effect of Spatial Arrangement on the Law of Constant Final Yield in Field Bean (*Phaseolus vulgaris L.*)

3.1 Abstract

Research on the effect of field bean spatial arrangement within the row is deficient in Manitoba. Previous research in field bean from the University of Manitoba studied the relationship between row spacing and yield with two navy bean cultivars and found the yield did not appear to conform to the 'law of constant final yield' (LCFY). Field experiments were conducted in 2017 and 2018 at Carman, Manitoba to explore these results and determine the effect of spatial arrangement on the LCFY on two different cultivars of navy bean, T9905 and Envoy, and two planting dates in May (early) and June (late). Field bean was hand seeded in rows 20 cm apart, with either 10, 20, or 40 cm intra-row spacing to further examine the LCFY in narrow row spacing. The LCFY was observed in both cultivars in 2017 and in late-planted Envoy in 2018, though was not observed in T9905 in 2018, or in early-planted Envoy in 2018. This failure to resemble the LCFY in 2018 was attributed mainly to precipitation during the growing season, as shade avoidance characteristics may have been enhanced in response to the increased precipitation levels in 2018. Alternatively, the increased precipitation in 2018 may have influenced disease incidence, in particular root rots which were not rated in this study. T9905 had greater yields than Envoy in addition to reduced shade avoidance responses, suggesting that type II growth habit was not as affected by environmental changes. For both cultivars regardless of growth habit, the spatial arrangement with the narrowest intra-row spacing in 2017 resulted in increased yields as was anticipated by the LCFY, and further solidifies evidence that wide row spacing is less productive.

3.2 Introduction

Field bean is an important commodity in Canada and is exported worldwide. Field bean production in Canada is often overshadowed by major conventional crops such as canola or wheat (Table 2.1) and as a result the research in field bean is lacking, especially in Manitoba. In 2018, 106,600 metric tonnes (MT) of field bean were produced in Manitoba, second only to Ontario which produced 133,300 MT. In other terms, Manitoba produced 31% and Ontario 39% of the total 341,100 MT Canadian production. To maintain and improve current field bean production standards in Manitoba, additional exploration is required to improve field bean agronomic practices that influence yield. Neighbouring provinces or states have studied field bean, but the results are outdated or were conducted in areas with environmental conditions different to those of the field bean growing regions in southeastern Manitoba. The agricultural regions of Manitoba consist of various environmental conditions with properties unique to other neighbouring provinces or nearby states. Local research relevant to Manitoba's environmental conditions is required to withhold its position as one of the top field bean producers in Canada and would encourage producers to introduce field bean in their rotations more frequently.

An experiment was conducted by the University of Manitoba to address research gaps in the area of spatial arrangement and its effect on field bean yield with navy and pinto field bean Schmidt (2020). Row spacing in Manitoba is typically wide row (30-36"), however it is well known that crops experience a yield benefit with increased planting densities (Drews et al. 2009; Chauhan and Johnson 2011; Holmes 2012; Mohammadi et al. 2012; Marín and Weiner 2014), and narrow row spacing (5-8") is encouraged (Government of Manitoba 2020). In addition to increased yields, narrow row spacing is an integral part of integrated pest management by closing the canopy and shading weeds, thus reducing the reliance on herbicides alone (Heard et al. 1990; Capinera 2005). Spatial arrangement can trigger shade avoidance responses such as stem elongation (Ballaré 2009; Page et al. 2010; Afifi and Swanton 2011), apical dominance (Page et al. 2010; Yang and Li 2017), reduced branching (Ballaré 2009; Yang and Li 2017), and reduced root and shoot biomass (Afifi and Swanton 2011) and have been found in other studies to affect plant development and yield (Page et al. 2010; Afifi and Swanton 2011; Yang and Li 2017). With increasing planting densities, yield increases up to a certain point in density where the yield reaches a plateau, which is described as the 'law of constant final yield' (LCFY) (Weiner and Freckleton 2010). Yet, Schmidt (2020) found that navy bean varieties T9905 and Envoy did not appear to conform to the LCFY; instead the yields decreased at low planting densities.

To further investigate the effects of spatial arrangement and shade avoidance response on yield in navy bean, this study was conducted to compare the performance of T9905 and Envoy navy bean planted at three different spatial arrangements, and early and late planting dates over two years. The intent of this research was to examine the lack of conformation of field bean to the LCFY by testing the following objectives:

1) Determine yield response in field bean plants at different spatial arrangements at narrow row spacing and relate this to the LCFY under weed-free conditions
2) Relate the shade avoidance response to the LCFY under weed-free conditions

3.3 Materials and Methods

3.3.1 Experimental Locations

Experiments were conducted at the Ian N. Morrison Research Farm in Carman, Manitoba (49° 30' 05.6" N, 98° 01' 43.1" W) in 2017 and 2018. The experiment was established in 2017 on the Rignold (RGD) soil series. In 2018, the experiment was moved to a location in the same field with soil consisting of both the Rosebank (RBK) and the Elm Creek (EEK) soil series (Manitoba Agriculture Food and Rural Initiatives 2010). Average climatic data were gathered from the weather station located on the research farm in addition to the annual spring soil nutrient analysis. Soil was sampled to a 24” depth on April 19th, 2017 and April 24th, 2018 and analysed by Agvise Laboratories (Northwood, North Dakota). In 2017, the organic matter (OM) was 2.8%, and pH was 5.2 in the 0-6” range, while in 2018, the OM was 2.6 and pH was 5.9. Nitrogen fertilizer was applied at 85.4 kg ha^{-1} (76.1 lb ac^{-1}) in both 2017 and 2018. The experiments were fertilized on May 15th, 2017 (early- and late-planted), May 25th, 2018 (early-planted), and May 28th 2018 (late-planted).

3.3.2 Establishment and Experiments

Two varieties of navy bean with contrasting growth habits were used in this experiment; Envoy (Type I determinate bush) and T9005 (Type II indeterminate vine). Intra-row plant spatial arrangement was varied to be lower (10 cm), equal (20 cm), or greater (40 cm) than the space between rows which was fixed at 20 cm (Figure 3.1, Figure 3.2). To determine the effect of seeding date on field bean performance, experiments were established two weeks apart at an early (June 6th, 2017 and May 23rd, 2018) and late (June 16th, 2017 and June 6th, 2018) seeding date, making this experiment a two-way factorial (cultivar x spatial arrangement) with an early and late seeding date, randomized complete block design with four replicates.

Weeds were controlled throughout the season to eliminate inter-specific resource competition as the study focused on intra-specific interference only. Pesticide application and manual weeding was conducted as needed to control early season pests and facilitate navy bean establishment (

Table 3.1). A bicycle sprayer equipped with a 2m wide boom and 80015 TeeJet nozzles (TeeJet Technologies, Wheaton, IL, USA) was used for pesticide applications at a pressure of 40 psi to apply a carrier volume of 80.55 L ha^{-1}.

Table 3.1 Summary of weed-free experiment pesticide application dates, rate, and crop stage

Date	Experiment	Formulation	Rate	Development Stage [a]
2017				
May 20	Early	480 g L^{-1} sulfentrazone	291.46 mL ha^{-1}	PRE
		915 g L^{-1} s-metolachlor	1.729 L ha^{-1}	
June 8	Late	480 g L^{-1} sulfentrazone	291.46 mL ha^{-1}	PRE
		915 g L^{-1} s-metolachlor	1.729 L ha^{-1}	
		540 g ae L^{-1} glyphosate	2.47 L ha^{-1}	
June 9	Early	240 g L^{-1} clethodim	185.25 mL ha^{-1}	V1
		Phosphate ester surfactant	0.5 L/100L	
June 12	Early	200 g L^{-1} chlorantraniliprole	249.47 mL ha^{-1}	V1-V2
June 12	Late	200 g L^{-1} chlorantraniliprole	249.47 mL ha^{-1}	VE
June 26	Early	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	900 mL ha^{-1}	V2
		Urea Ammonium Nitrate (28-0-0)	2.0 L ha^{-1}	
June 26	Late	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	900 mL ha^{-1}	V2
		Urea Ammonium Nitrate (28-0-0)	2.0 L ha^{-1}	
July 17	Early	240 g L^{-1} clethodim	185.25 mL ha^{-1}	V6-V11
		Phosphate ester surfactant	0.5 L/100L	
July 17	Late	240 g L^{-1} clethodim	185.25 mL ha^{-1}	V3-V5
		Phosphate ester surfactant	0.5 L/100L	
July 20	Early	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	900 mL ha^{-1}	V6-V11
		Urea Ammonium Nitrate (28-0-0)	2.0 L ha^{-1}	
July 20	Late	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	900 mL ha^{-1}	V3-V5
		Urea Ammonium Nitrate (28-0-0)	2.0 L ha^{-1}	
2018				
June 4	Early	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	900 mL ha^{-1}	VE
		Urea Ammonium Nitrate (28-0-0)	2.0 L ha^{-1}	
June 4	Late	480 g L^{-1} sulfentrazone	291.46 mL ha^{-1}	PRE
		915 g L^{-1} s-metolachlor	1.729 L ha^{-1}	
		540 g ae L^{-1} glyphosate	2.47 L ha^{-1}	
June 13	Early	480 g L^{-1} bentazon	2.2477 L ha^{-1}	V1
June 27	Early	240 g L^{-1} clethodim	185.25 mL ha^{-1}	V3-V5
		Phosphate ester surfactant	0.5 L/100L	

[a] = For descriptions of the developmental stages, refer to the dry bean development guide (Figure A1 in the appendix)

Custom wooden boards were designed to ensure accurate plant spatial arrangement (Figure 3.3). Holes were drilled at the 10, 20, or 40 cm intra-row spacing oriented perpendicular to the front of the plot with 20 cm rows oriented parallel to the front of the plot. A bolt was secured within each hole to ensure a consistent seeding depth of approximately 3 cm was achieved. Boards positioned on the appropriate plots measured 2.4 meters wide by 3.6 meters long, and three navy bean seeds were placed by hand in each depression created by the bolts. Initially only one seed was placed in each depression, but due to concerns over germination and establishment, this was increased to three seeds per depression. After emergence, seedlings were hand-thinned to one seedling per depression. Due to poor seedlot quality and cutworm damage to emerged seedlings in 2017, re-seeding of the early-seeded experiment was required. The early-planted experiment was seeded initially on May 19th, 2017 and then re-seeded on June 6th, 2017. In 2018, the early-planted experiment was planted on May 23rd, 2018. Late-planted experiments were seeded on June 16th, 2017, and June 6th, 2018.

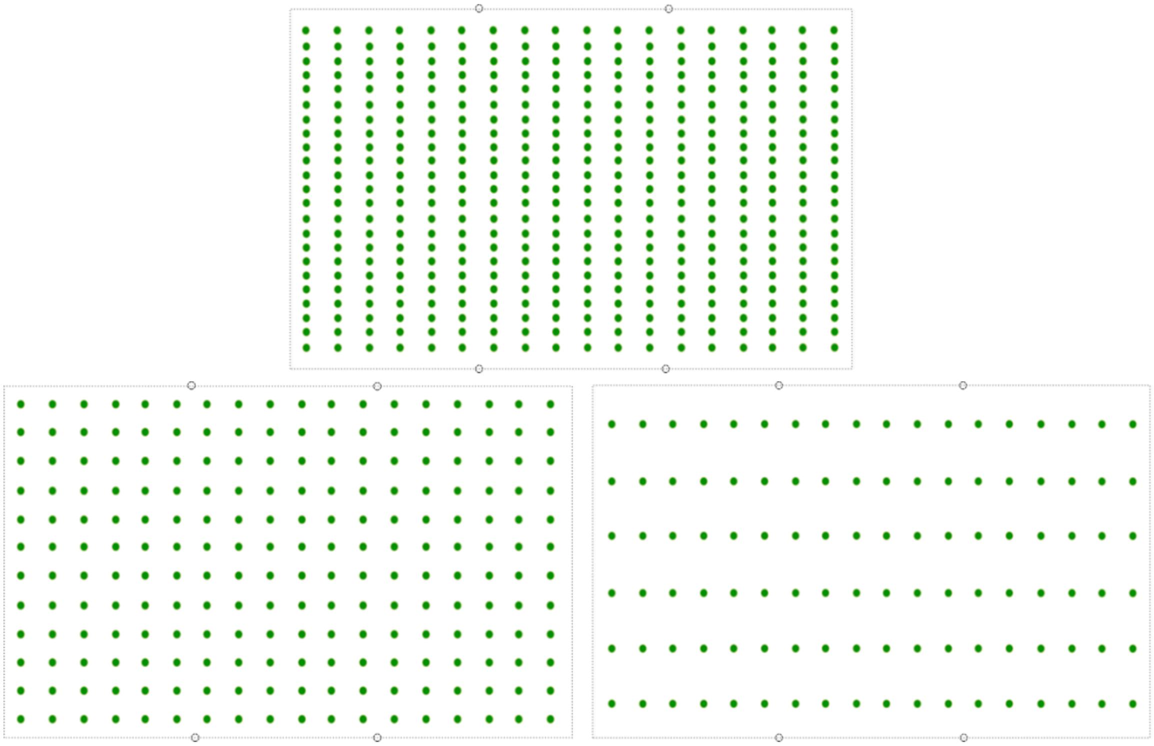

Figure 3.1 Intra-row spacing of 10 cm (top), 20 cm (bottom left), and 40 cm (bottom right). Plant densities are 48 plants m^{-2}, 24 plants m^{-2}, and 12 plants m^{-2}, respectively.

Figure 3.2 Intra-row spacings of 10 cm (top), 20 cm (bottom left), and 40 cm (bottom right). Plant densities are 48 plants m^{-2}, 24 plants m^{-2}, and 12 plants m^{-2} respectively. The above cultivar is T9905 in the late-seeded plots on August 30th, 2017.

Figure 3.3 Custom planting templates with bolts were used to ensure precise seed placement in every plot. Shown here is the 10 cm intra-row spacing.

3.3.3 Data Collection

Total emergence was recorded between the emergence (VE) and the third trifoliate (V3) stages.

In all experiments, shade avoidance responses were recorded during early and late vegetative, and the reproductive stages (Table 3.2).

Table 3.2 Recorded measurements in early and late hand seeded experiments with respective dates and bean developmental stages

Measurement	Date	Experiment	Development Stage [a]
	2017		
Emergence	June 22	Early	VE-V3
Emergence	July 6	Late	V1
Plant Height	August 11	Early	R1-R2
Plant Height	August 11	Late	R2
Stem Thickness	August 22	Early	R8
Stem Thickness	August 22	Late	R5
Internode Length/Pod Clearance	August 29	Late	R7
Internode Length/Pod Clearance	August 30	Early	R8
Branch Number	August 31	Early	R9
Branch Number	October 4	Late	R9
	2018		
Emergence	N/A	Early	N/A
Emergence	July 2	Late	V2-V3
Plant Height	July 18	Early	R1
Plant Height	July 13	Late	V5-V11
Stem Thickness	July 9	Early	V6-R1
Stem Thickness	July 13	Late	V5-V11
Internode Length /Pod Clearance	August 23	Early	R9
Internode Length /Pod Clearance	August 23	Late	R9
Branch Number	August 24	Early	R9
Branch Number	September 21	Late	R9

[a] = Refer to Figure A1 in the appendix for the dry bean development guide (Manitoba Pulse & Soybean Growers 2017)

During the early vegetative, flowering and reproductive stages of the field bean experiments (Table 3.3), three digital images were captured in each plot at arm’s length perpendicular to the ground to determine ground. The images were processed using the Canopeo app (Oklahoma State University, Stillwater, Oklahoma) and MATLAB software (The MathWorks Natick, Massachusetts) to determine ground cover within individual plots.

Table 3.3 Canopeo sampling dates for 2017 and 2018 hand seeded experiment

Date	Experiment	Development Stage [a]
2017		
July 10/13	Early	V6-V11
July 17/18	Late	V3-V6
July 24/25	Early	R1
August 1/3	Late	V8 to R1
August 14/15	Late	R1
2018		
July 2/3	Early	V6
July 12/13	Late	V5
July 16/17	Early	R1
July 23/24	Late	R1
July 31/August 1	Early	R4
August 8/9	Late	R4

[a] = Refer to Figure A1 in the appendix for the dry bean development guide

Plant and shade avoidance response was measured, including plant height, stem thickness, length of the first internode, pod clearance, and the number of primary branches (see Figure 3.4 for reference). Plant height was recorded from 5 randomly selected plants per plot and measured from the soil surface to the base of the most distal trifoliate without disturbing the plant. Stem thickness was measured on five random plants per plot using a caliper on the widest part of the bean stem at the base of the stem. The distance from the soil surface to the most proximal node, or “first internode length”, and the distance from the soil surface to the distal end of the lowest pod, or “pod clearance”, was determined on five randomly chosen plants per plot.

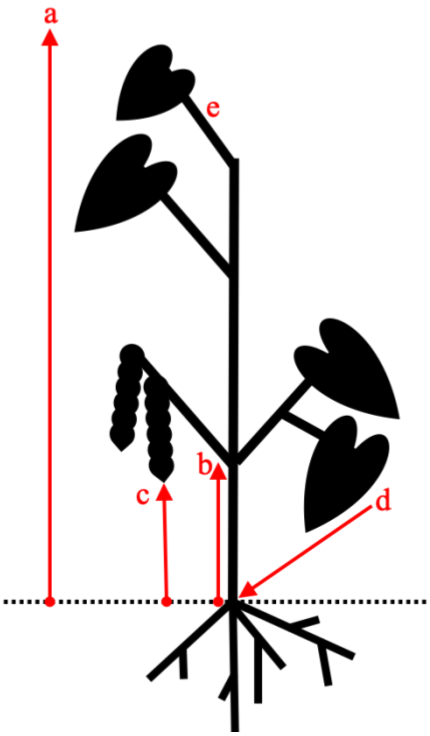

Figure 3.4 Diagram of bean plant depicting measurements taken throughout the season. Measurements included plant height (a), first internode length (b), pod clearance (c), stem thickness (d), and branch number (e).

At maturity, 20 plants were removed from each plot to determine seed yield, and branch numbers were determined from 5 of these plants. The 20 plants were placed in labelled cloth bags and then stored on a drying bed. Once air dry, the harvested field bean was threshed using an Agriculex LBT-2 belt thresher (1-59 Suburban Ave. Guelph, Ontario, Canada N1E 6B4). Remaining debris was removed by hand sieving, then clean field bean seed was weighed to determine yield. Thousand kernel weight (TKW) was determined using a seed counter. A sample from the harvested beans was saved from each plot and oven dried to calculate moisture-corrected yield with the following equation:

$$\%\ seed\ moisture\ content = \left(\frac{wet\ seed\ weight\ (g) - dry\ seed\ weight\ (g)}{wet\ seed\ weight\ (g)}\right) * 100$$

3.3.4 Statistical Analysis

Statistical analysis was performed using with the SAS University Edition (SAS Institute Inc., Cary, NC, USA). Each site year was analyzed as a two-way factorial (cultivar and row spacing) with an early and a late seeding date. Using the Univariate procedure (PROC UNIVARIATE), the results from the Shapiro-Wilk test were examined to test normality of the residuals. The heterogeneity of variance was corrected and tested using the repeated statement. Moisture-corrected yield, plant height, stem thickness, first internode length, pod clearance and branch numbers were compared via analysis of variance (ANOVA) using the mixed model procedure (PROC MIXED) (Littell et al. 2006). Denominator degrees of freedom were computed using the Kenward-Roger method. The fixed effects included year, time of planting, cultivar and spatial arrangement and all their interactions. Random variables included replicates nested within year by time. Means were separated using Fishers protected difference (α=0.05) using least square means with year, time of planting, cultivar and spatial arrangement, and further sliced by year and time to examine the interaction.

Canopy cover data were recorded using Canopeo (Oklahoma State University, Stillwater, Oklahoma; Patrignani and Ochsner 2015) and analyzed with the GLIMMIX procedure on SAS University Edition (SAS Institute Inc., Cary, NC, USA). The convergence method was laplace. The beta distribution and logit link function were used to model the error distribution. Model fixed effects were crop stage, cultivar, spatial arrangement, and their interactions. Random effects included replicates. The repeated measures analysis consisted of crop stage as the repeated measure, and included replicates as a subject nested within crop stage, cultivar, and spatial arrangement. The covariance structure was a first-order autoregressive structure. Means were separated using Fishers protected least square means with crop stage, cultivar, and spatial arrangement.

3.4 Results

3.4.1 Cultivar Differences

The response in field bean seed yield differed between the two years of study, though visually appeared to conform to the ‘law of constant final yield’ (LCFY). In 2017, field bean seed yield increased with increasing plant densities in both cultivars (T9905 and Envoy) and at both planting dates (early and late), though T9905 appeared to reach the yield plateau sooner (at 24 plants m$_{-2}$) compared with Envoy (at 48 plants m$_{-2}$). In 2018, however, a positive response in seed yield to increasing plant density only occurred in late-planted Envoy (Figure 3.5) with no changes or decreasing yield with increasing density in the late-planted T9905 treatments. In addition, the greatest seed yield was reached at different plant densities in Envoy and T9905 in 2017. In T9905, the yield response was approaching the plateau (greatest yield) typical of the LCFY at the 24 plants per m$_{-2}$ densities at both planting dates. In the same experiments, the greatest seed yield in Envoy was observed in the 48 plants m$_{-2}$ treatment, with the 24 plants m$_{-2}$ density producing intermediate seed yields at both planting dates (Figure 3.5). Yield increases between the lowest and average of the medium and high plant densities in Envoy and T9905 were 27.2% and 38.4%, respectively, in the early-planted and 19.5% and 16.4%, respectively, in the late-planted experiment. Not only was the greatest response to planting density observed in early-planted T9905 in 2017, but T9905 also yielded greater than Envoy (about 12%) throughout these studies. The response in late-planted Envoy to increasing densities in 2018 was similar to that observed in T9905 in 2017 with maximum seed yield achieved at the 24 plants m$_{-2}$ density rather than the 48 plants m$_{-2}$ density (Figure 3.5). This yield increase between the 12 plants m$_{-2}$ density and the average of the 24 and 48 plants m$_{-2}$ densities, however, was relatively small (16.7%) compared to those observed in 2017. When maximum yield in 2018 was observed at the lowest densities (12 plants m^{-2}), the LCFY plateau yield response was reached at this density suggesting a leftward shift of the curvilinear response of the LCFY to densities below those studied. Taken together, a LCFY response was observed within the three densities examined in these experiments in some, but not in all instances and the results of these studies suggest that study year, bean cultivar and time of planting all influence the LCFY in field bean.

In 2018, plant density had no effect on seed yield in T9905 at either planting date, or in early-planted Envoy (Figure 3.5). In the early-planted 2018 experiment, high variability in seed yield amongst the replicates contributed to the absence of statistical separation of the results. A broad range of yields was recorded within treatments among the replicates in the early-planted 2018 experiment. In the early-planted 2018 experiment, for example, seed yield ranged from 488.8 to 2405.2 kg ha^{-1} in the T9905 48 plants m^{-2} treatment, and from 547.2 to 3607.7 kg ha^{-1} in the Envoy 48 plants m^{-2} treatment (Figure 3.5). There is no apparent reason for that level of variation in seed yield in 2018. Different growing season precipitation was likely the most important contributor to the differences in results observed between the two years of the study.

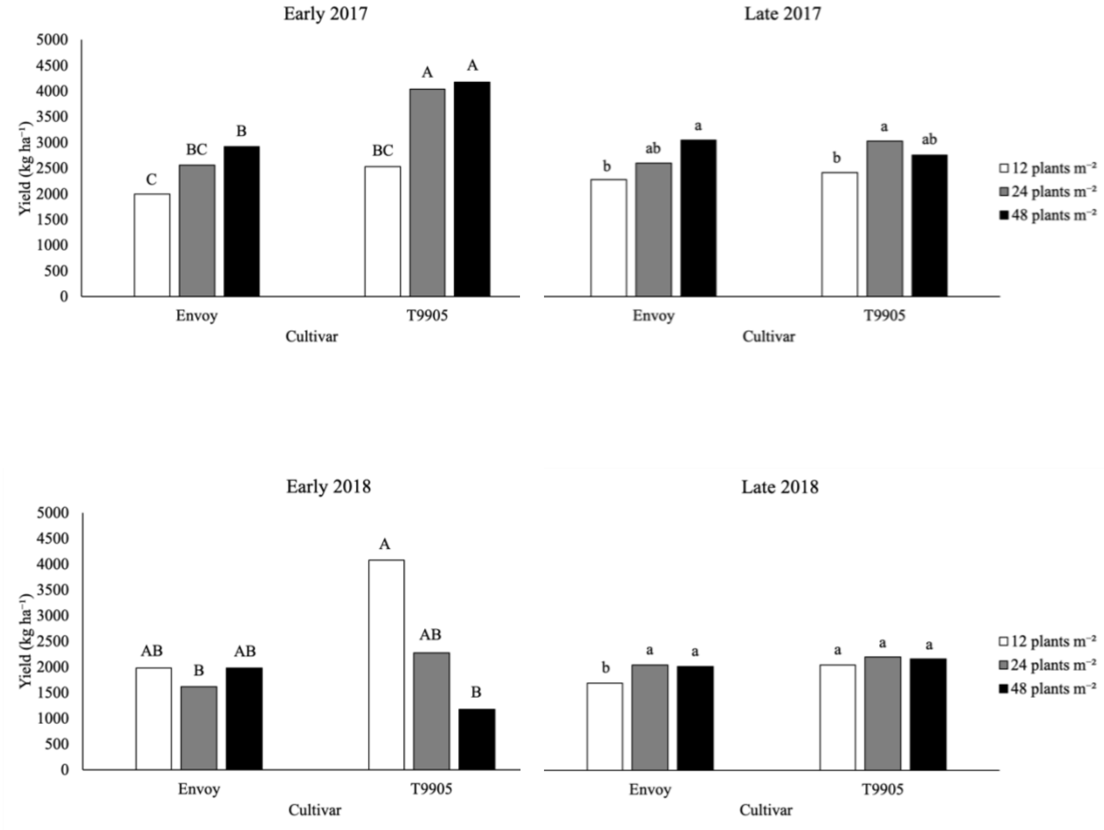

Figure 3.5 The moisture-corrected yield in two cultivars (Envoy and T9905) of field bean at three planting densities (12, 24, and 48 plants m$_{-2}$) in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

3.4.2 Environment

Monthly precipitation in 2018 exceeded that of 2017 in five out of the seven months, excluding April and September (Figure 3.6). The early- and late-planted experiments were sown on May 23rd and June 6th 2018, respectively, during which the total precipitation was at its greatest point of the two experimental years. In particular, the greatest monthly precipitation was recorded during June 2018 (98.1 mm), which coincided with the time of planting.

Table 3.4 The mean temperature and total precipitation from April to October for Carman, Manitoba between 2015 and 2018, and the Long Term Average from 1981-2010 (Government of Canada 2019a)

Month	2015	2016	2017	2018	LTA[a]
	Mean temperature (°C)				
April	5.5	2.4	5.3	0.6	4.5
May	10.7	13.6	12.1	14.8	11.6
June	17.5	17.1	17.1	18.8	17.2
July	19.9	19.4	19.4	19.9	19.4
August	18.3	18.4	17.7	19	18.5
September	15.8	14.1	13.7	10.5	13.4
October	7.2	6.7	6.4	2.8	5.4
Month	2015	2016	2017	2018	LTA[a]
	Total precipitation (mm)				
April	17.5	55.3	18.6	3.8	20.2
May	98.8	108.1	25.2	47.9	67.7
June	75.3	95.4	64.4	98.1	96.4
July	109.3	78.7	23.3	42.9	78.6
August	47.3	57.7	22.8	31	74.8
September	42	64.7	74.6	43.2	49
October	37.3	36.5	13.5	36.5	38.2

[a] = Long Term Average (LTA; 1981-2010)

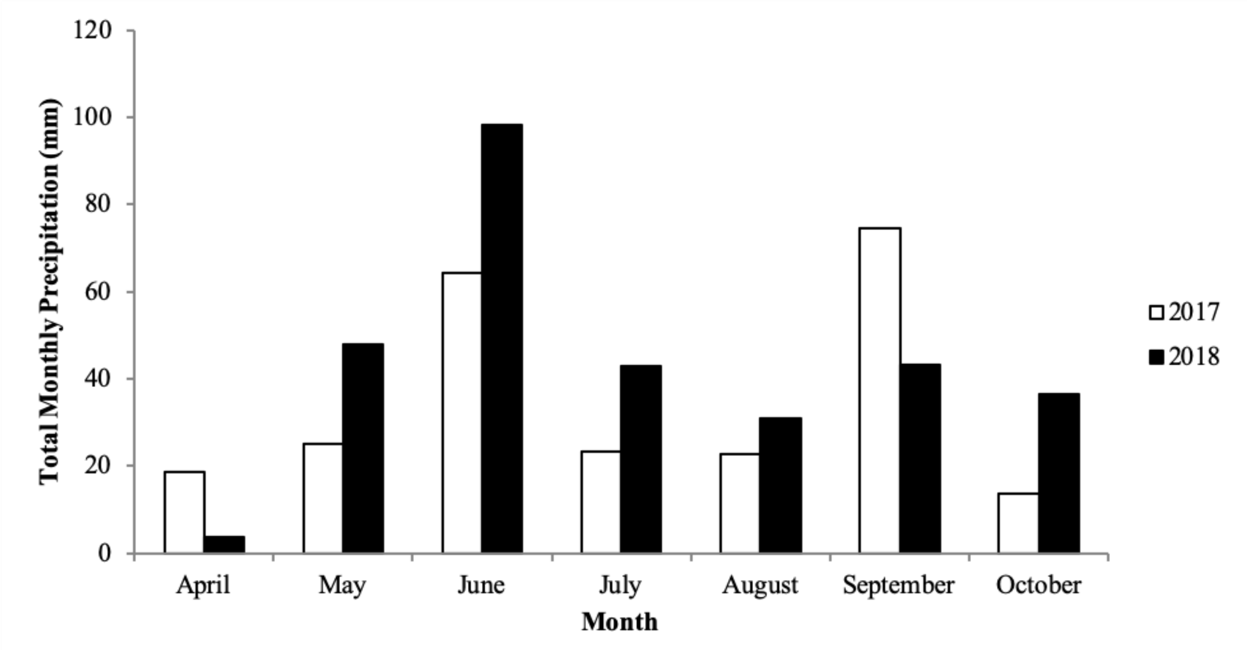

Figure 3.6 Total monthly precipitation at Carman, Manitoba from April to October in 2017 and 2018 (Government of Canada 2019b).

While cumulative precipitation from April to October in 2018 was 20.1% (61 mm) greater than in 2017, precipitation in both experimental years was lower than the long-term average (LTA) from 1981 to 2010 (Figure 3.7). The greater precipitation levels in 2018 versus 2017 likely influenced field bean growth and yield during the experimental years and emphasized morphological characteristics linked to shade avoidance.

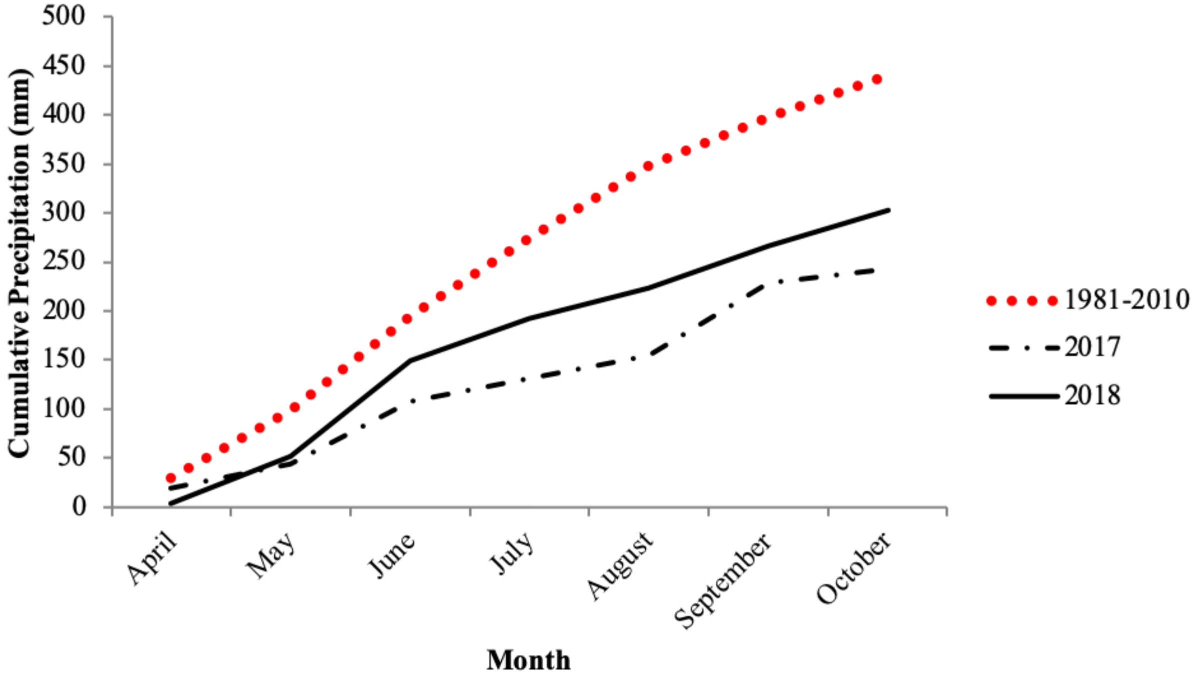

Figure 3.7 The accumulated precipitation at Carman, MB from April to October for 2017 and 2018, and the current climate Long Term Average (LTA; 1981-2010) (Government of Canada 2019b).

3.4.3 Field Bean Morphology

Changes in plant morphology related to shade avoidance were observed in both experiments, in particular at the greatest planting density (48 plants m^{-2}). Field bean stem thickness in the medium and low plant density treatments was not significantly different in most cases, even though stem thickness tended to be greater in the low plant density treatment (Figure 3.8). In the late-planted 2017 experiment, however, the difference in stem thickness between low and medium density field bean (about 12%) was significantly different in T9905 only. The reduction in field bean stem thickness between the high density treatment, and the average of the medium and low density treatments, was similar in both cultivars and ranged from 15.0 to 19.3% in Envoy, and from 14.5 to 19.9% in T9905. These results suggest that the plants were exhibiting shade avoidance characteristics in response to increasing densities. Over all the experiments, however, Envoy stems were 10.6% (or 0.67 mm) thinner than the stems of T9905.

Field bean stem thickness was affected by year and time of planting, but this effect was not consistent between the two years (Figure 3.8). In 2017, early-planted field bean produced thicker stems than late-planted field bean (about 8% or 0.58 mm), whereas in 2018, early-planted field bean stems were on average about 10% (or 0.58 mm) thinner than those in the late-planted experiment (Figure 3.8). While the yield response to planting density was most pronounced between the low and the medium field bean density treatments, the planting density effect on stem thickness was most pronounced between the medium and high plant density treatments.

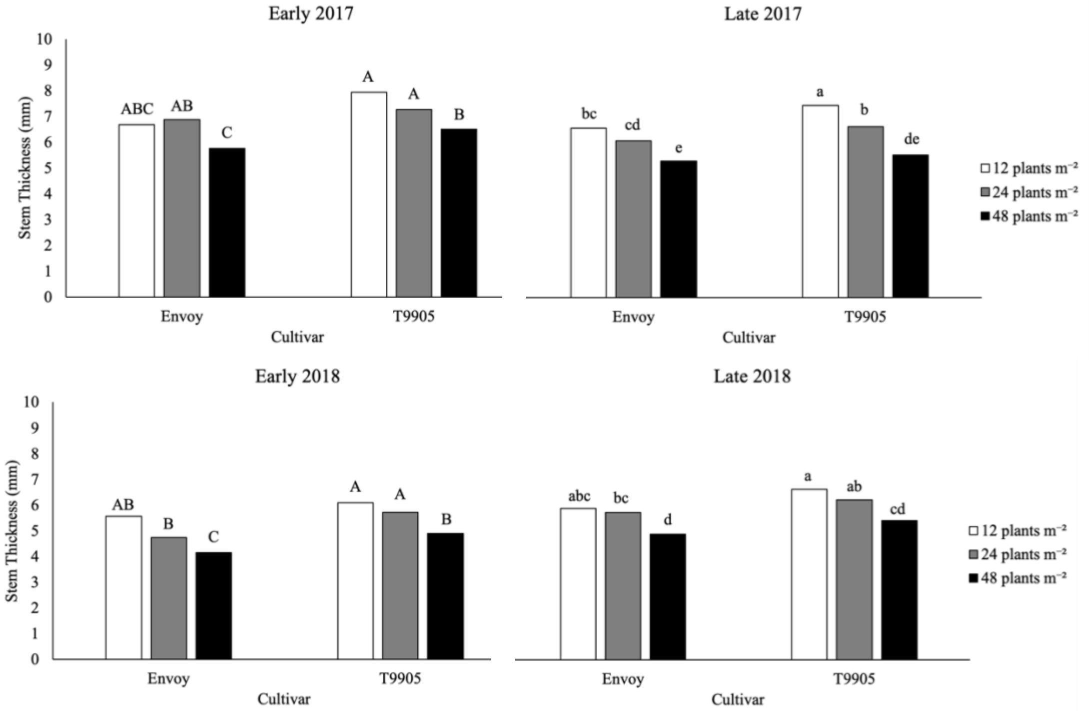

Figure 3.8 The stem thickness (mm) in Envoy and T9905 field bean cultivars across increasing planting densities (12, 24, and 48 plants m$_{-2}$). Experiments were conducted in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

As a result of increasing plant densities, reduced field bean branch numbers were observed in all experiments except Early 2017 (Figure 3.9). Envoy plants in the late-planted 2017 experiment had significantly lower branch numbers at the greatest planting density; this was not observed in the other Envoy treatments or experiments. T9905 plants also had significantly lower branch numbers at the greatest planting density in all but the late-planted 2018 experiment, where no significant difference between the medium and high planting densities occurred.

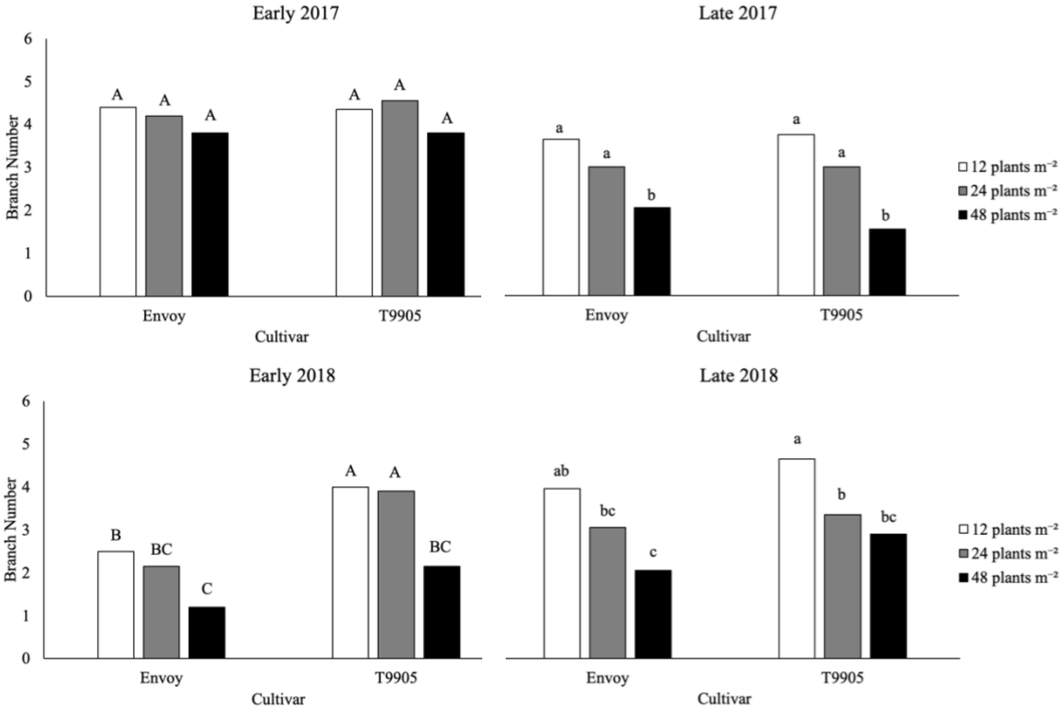

Figure 3.9 The number of branches in Envoy and T9905 field bean cultivars across increasing planting densities (12, 24, and 48 plants m$_{-2}$). Experiments were conducted in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

The response of the first internode length to plant density differed between the two cultivars. In Envoy, increasing bean plant densities caused an elongation in the first internode in all experiments (Figure 3.10). In contrast, the same response in T9905 was only observed in one instance, the early-planted 2017 experiment. In all other experiments, the length of the first internode in T9905 did not respond to changes in plant density. Overall, the Envoy internode length was 10.7% (1.60 cm) and 6% (0.90 cm) lower than T9905 at the low and medium plant densities, respectively.

When differences were observed, length of the first internode was intermediate at the medium plant densities in the early-planted experiments (Figure 3.10). In the late-planted experiments, first internode length in Envoy in the medium density treatment was the same as the low density treatment in 2017, whereas in 2018 it was the same as the high density treatment. First internode length in T9905 showed no response to plant densities in both late-planted experiments and the early-planted 2018 experiment. First internode length in Envoy ranged from 10.7 cm (lowest density early-planted 2017 experiment) to 18.35 cm (highest density early-planted 2018 experiment) which represents an almost a 2-fold difference in first internode length and is indicative of high plasticity in this character. In contrast, in T9905, first internode length ranged from 12.5 cm (lowest density early-planted 2017 experiment) to 17.65 cm (highest density late-planted 2018 experiment) suggesting much lower plasticity in this trait in this cultivar. These differences in plasticity may be reflective of the difference in growth habits between these two varieties.

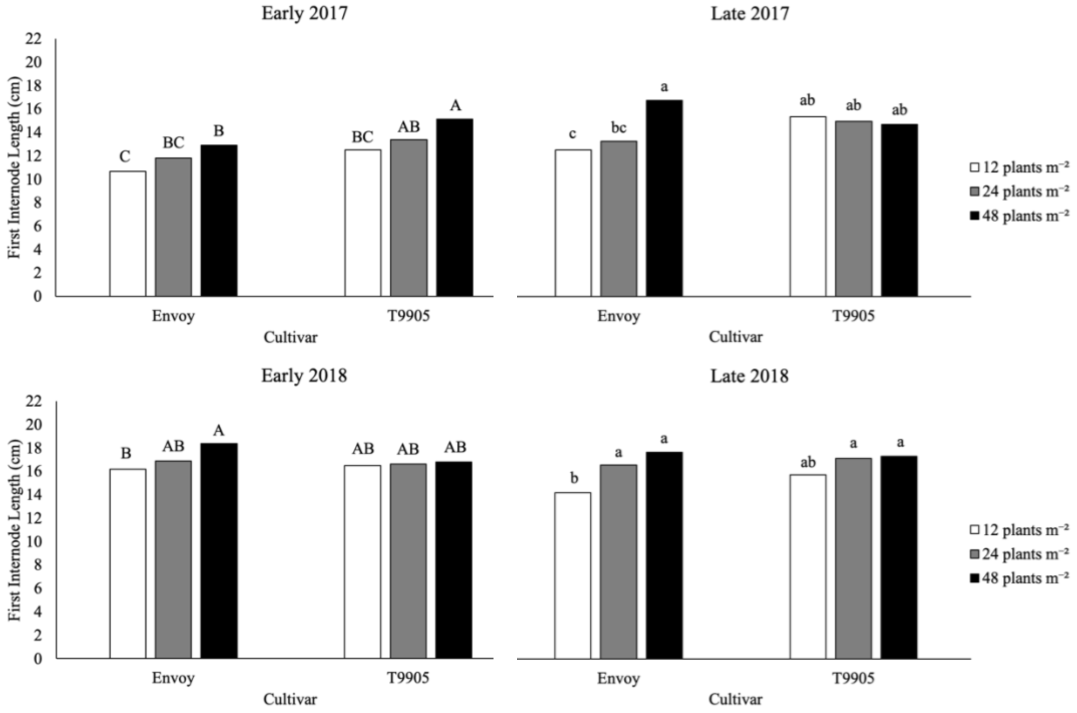

Figure 3.10 The length of the first internode in Envoy and T9905 field bean cultivars across increasing planting densities (12, 24, and 48 plants m-2). Experiments were conducted in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

Pod clearance was different between the two field bean cultivars and among the planting densities (Figure 3.11). In 2017, pod clearance was 1.43 cm higher off the ground in the late-planted experiment than the early-planted experiment, though pod clearance was not different between the cultivars in 2017. However, the pod clearance was greater in 2018 than in 2017, and in 2018, the cultivar difference between pod clearance was 1.13 cm greater in Envoy than in T9905. In Envoy 2018 (9.89 cm above the soil surface), pod clearance was 40.5% greater in 2018 than in 2017 (combined cultivars lowest pod clearance = 5.88 cm), while T9905 (8.75 cm pod clearance in 2018) exhibited a 32.8% increase in pod clearance in 2018. No significant difference was observed between the planting dates in 2018 (9.33 cm pod clearance on average).

Pod clearance increased with increasing plant density in all cultivars and all experiments (Figure 3.11). In the combined analysis, pod clearance was significantly different among each density.

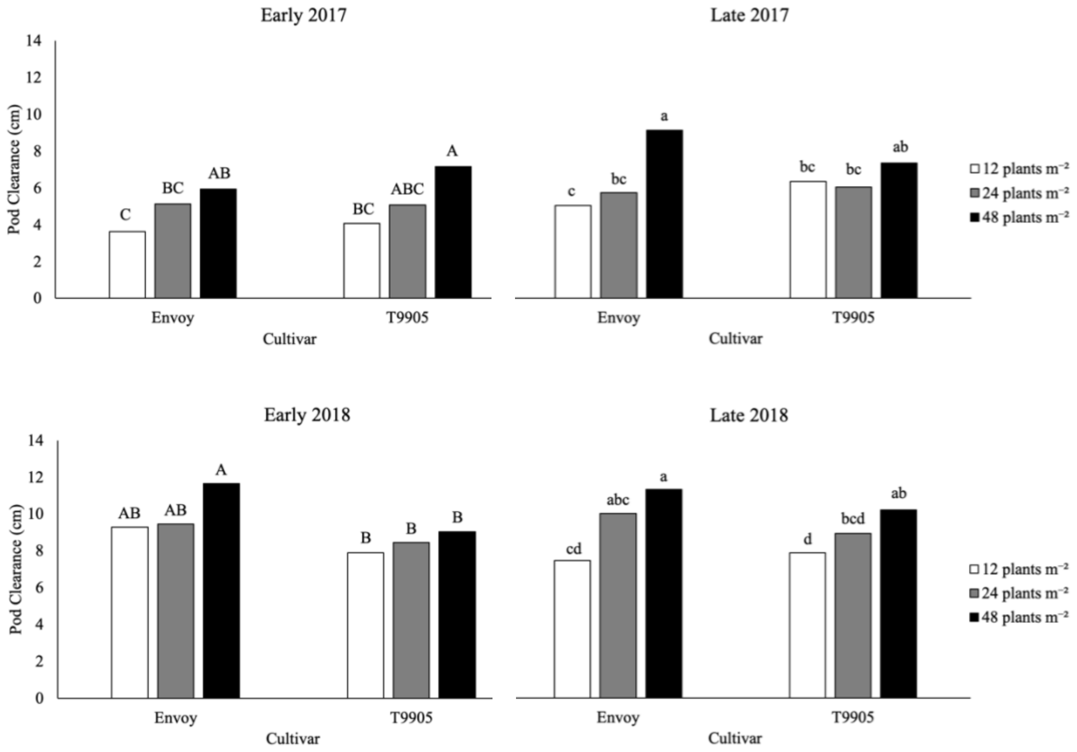

Figure 3.11 The pod clearance of Envoy and T9905 field bean cultivars across increasing planting densities (12, 24, and 48 plants m$_{-2}$). Experiments were conducted in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

Thinner stems, decreased branch numbers, longer first internodes and increased pod clearance suggest that the field bean cultivars were using shade avoidance characteristics to compete for light early during plant development. Increased shade avoidance response often results in taller plants, though a response of plant height at R1-R2 developmental stage to increasing plant densities/spatial arrangement was not observed among cultivars, years or planting dates (Figure 3.12).

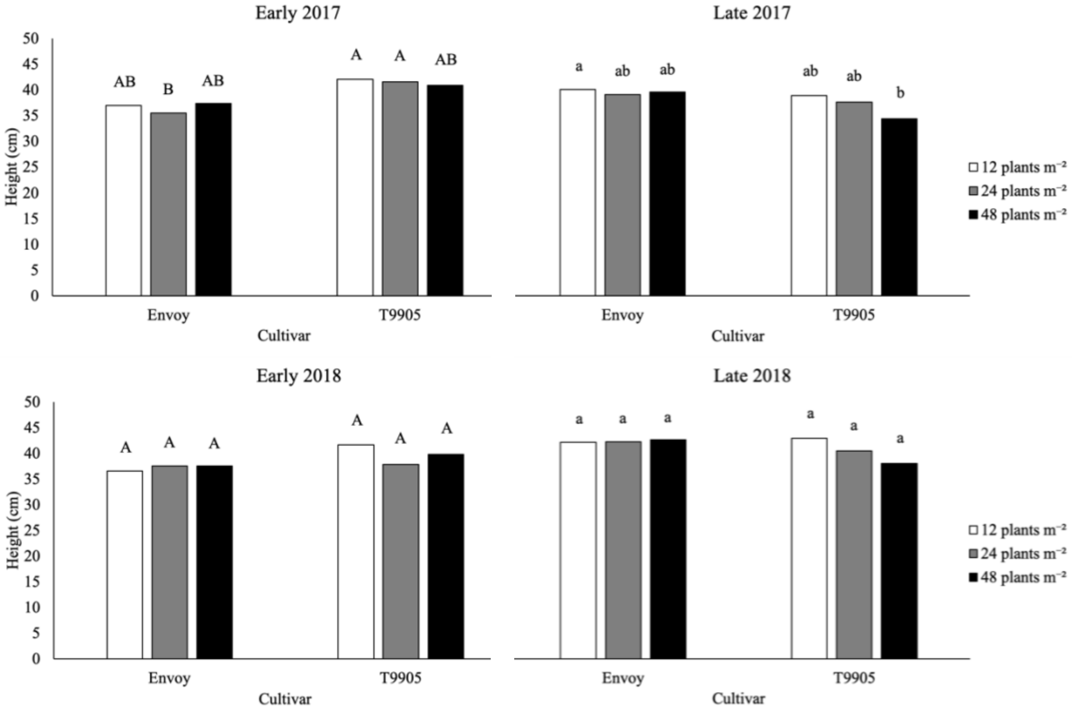

Figure 3.12 The height of the plant from the soil surface to the top of the plant in Envoy and T9905 field bean cultivars across increasing planting densities (12, 24, and 48 plants m$_{-2}$). Experiments were conducted in 2017 (top panels) and 2018 (bottom panels). Fisher's protected LSD mean separations are provided within each experiment (2017 and 2018). Means with different letters are significantly different.

Canopy cover has an important role in shade avoidance characteristics, as a dense canopy can lead to intraspecific competition for light. Rapid canopy closure is beneficial for combatting early weed competition and is manipulated with increasing planting densities. In this experiment, canopy cover increased with increasing plant density in all studies except for early-planted 2017 (Figure 3.13). Canopy cover results from the 2017 early-planted experiment showed a significant interaction between cultivar, planting density, and time of planting. In the late-planted 2017 experiment the lowest planting density had the least amount of canopy cover compared to the 24 plants m$_{-2}$ or 48 plants m$_{-2}$ densities, a result that was not significant in early 2017. Alternatively, in the 2018 early-planted experiment, the canopy cover in the 12 plants m$_{-2}$ and 24 plants m$_{-2}$ planting densities was not significantly different from one another, and canopy cover in the 48 plants m$_{-2}$ was significantly greater than both the 12 plants m$_{-2}$ and 24 plants m$_{-2}$ planting densities. The 2018 late-planted experiment canopy cover at the 48 plants m$_{-2}$ density was significantly greater than at the 24 plants m$_{-2}$ planting densities, followed by the 12 plants m$_{-2}$ density. Cultivar differences were only statistically significant in the late-planted 2017 experiment, with the greater canopy cover observed in T9905 compared to Envoy.

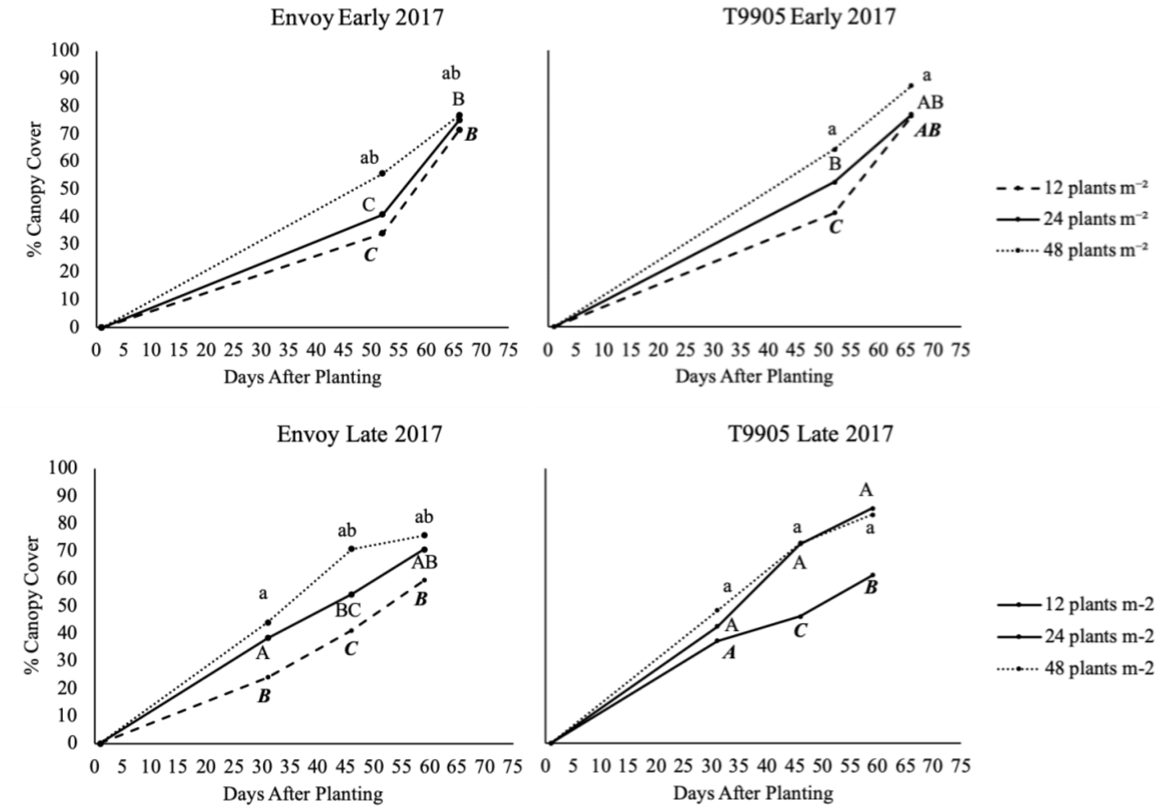

Figure 3.13 Canopy cover in Envoy and T9905 at all times of planting and plant densities in 2017. Data were collected at three different growth stages throughout the season and was analyzed against other planting densities on the same day. Bold and italicized uppercase represent the Fisher's protected LSD means separation for 12 plants m$_{-2}$, uppercase represents 24 plants m$_{-2}$ and lowercase represents 48 plants m$_{-2}$. Within these analyses, means with different letters are significantly different.

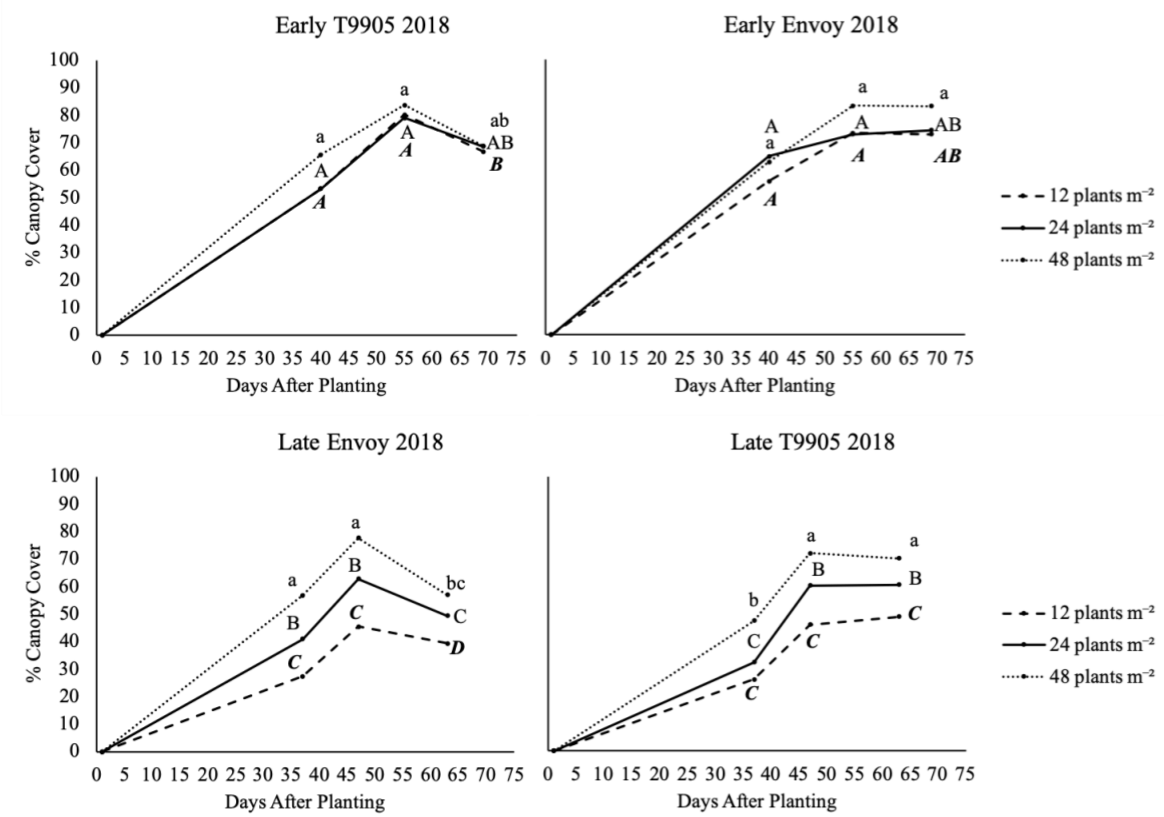

Figure 3.14 Canopy cover in Envoy and T9905 at all times of planting and plant densities in 2018. Data were collected at three different growth stages throughout the season and was analyzed against other planting densities on the same day. Bold and italicized uppercase represent the Fisher's protected LSD means separation for 12 plants m$_{-2}$, uppercase represents 24 plants m$_{-2}$ and lowercase represents 48 plants m$_{-2}$. Within these analyses, means with different letters are significantly different.

3.5 Discussion

In a previous study (Schmidt 2020), yield response of the plant density-yield relationship did not appear to conform to the ‘law of constant final yield’ (LCFY) in navy (Envoy and T9905) and pinto (Monterrey and Windbreaker) field bean. The LCFY stipulates that as density increases, plant yield per unit area increases until a yield plateau is reached and yield becomes independent of plant density (Weiner and Freckleton 2010), yet, the results in navy bean from Schmidt (2020) contradicted this literature. In Schmidt’s research, seed yield in Envoy experienced no change, while T9905 seed yield decreased with increasing plant density. This response was mainly observed in narrow row production (20 cm / 7.5”) in 2015 and 2016. The main focus of the present study was to investigate the causes Schmidt's results (2020) and why bean seed yields did not appear to conform to the LCFY in Schmidt’s work.

Monthly precipitation in 2018 exceeded that of 2017 in five out of the seven months, excluding April and September. In addition, field bean plants in 2018 experienced more pronounced shade avoidance characteristics than in 2017, including decreased stem thickness, decreased number of branches, increased length of the first internode, and increased pod clearance. Previous studies have found that various degrees of shade avoidance such as increased stem length in sunflower and wheat (Casal 1993; Libenson et al. 2002), reduced biomass allocation in maize (Page et al. 2010), reduced branching and biomass allocation in soybean (Green-Tracewicz et al. 2011), and reduced number of spikes per plant in barley (Skinner and Simmons 1993) are linked to yield reductions. The greater shade avoidance occurrence in 2018, in addition to the enhanced seasonal precipitation, likely contributed to the significantly lower yields in 2018 and suggests the lack of conformation to the LCFY.

Differences in sensitivity to shade avoidance response between the two cultivars may have contributed to the greater field bean yield in T9905 compared to Envoy. Certain shade avoidance characteristics, particularly stem thickness, number of branches, and pod clearance, were found to be more pronounced in Envoy than in T9905. First internode length was the only shade avoidance characteristic expressed to a greater degree in T9905 than in Envoy. Overall, the Envoy first internode length was 10.7% (1.60 cm) and 6% (0.90 cm) lower than T9905 at low and medium planting densities, respectively. Few shade avoidance response studies have been conducted in type I field bean, while type II field bean are more similar in architecture to soybeans and thus type II field bean and soybean may be more comparable than type I field bean and soybean (Kelly 2010). Green-Tracewicz et al. (2012) studied soybean and observed internode elongation in weedy or low red to far-red (R:FR) environments. Nienhuis and Singh (1985) found that first internode length of a type I determinate field bean increased with increasing plant density yet remained unchanged for indeterminate type II and III cultivars. Similarly, internode elongation in this study consistently occurred with increased planting density in Envoy (type I), but only in one of the four experiments for T9905 (type II). It is important to note however, that the study by Nienhuis and Singh (1985) was conducted in a very different growing environment (subtropical; Cali, Columbia) than the Canadian Prairies.

Unlike other field bean yield components, such as number of pods per plant or number of seeds per pod (Malik et al. 1993; Woolley et al. 1993), pod clearance is not commonly recorded. Despite this, the influence of spatial arrangement on pod clearance was studied to represent the ability to harvest pods easily. Pod clearance is an important harvestability factor for producers that utilize near-ground operations such as straight cutting. The increase in pod clearance with increasing plant densities was observed more in Envoy relative to T9905 in 2018. The increased internode and pod clearance observations suggests that an increase in overall plant height would be expected in response to increased planting density, which did not reflect results from a study in dry bean that experienced a decrease in plant height with increasing densities (Horn et al. 2000). In contrast, work by Weber et al. (1966) resulted in an increase in plant height with increasing densities in soybean. Field bean plant height at maturity presented here remained unchanged for both Envoy and T9905 navy bean cultivars, irrespective of growth habit. These results agree with those reported by Holmes (2012) who did not observe a height difference in type II small red bean and black bean in response to increasing field bean planting densities. Though no difference in plant height occurred in this study, stem thickness was reduced in response to increasing planting densities. As with the other shade avoidance characteristics, there was a reduction in stem thickness in the second year of this experiment. Additionally, branch number was greatly reduced in 2018, which is in accordance with an experiment by Nienhuis and Singh (1985) that found a decrease in branch numbers with increasing planting densities. Nienhuis and Singh (1985) also found that yield was impacted negatively by the reduced branch numbers and internode elongation shade avoidance responses. It appears that Envoy experienced increased pod clearance, internode length, stem thickness and branch number shade avoidance effects which potentially compromised its yield compared to T9905. Yield reductions and shade avoidance characteristics also occurred in T9905, but effects were always greater in Envoy.

Field bean seed yield appeared to conform to the LCFY in three out of four experiments. Yield data from the early-planted 2018 experiment differed from the LCFY and was similar to what was observed in the study conducted by Schmidt (2020) – Envoy yield did not increase with increasing crop density as expected, but rather was unaffected by all spatial arrangements, and T9905 experienced the greatest seed yield at the lowest planting density followed by a significant decrease in yields with increasing plant density. One explanation for this behaviour may be growing season precipitation. The effects of precipitation on plant growth, biomass accumulation and seed yield are well documented (Heinemann et al. 2002; Bueckert et al. 2015; Huang et al. 2015; Reichert et al. 2015; Kukal and Irmak 2018) thus precipitation may have influenced the differences in yield. To my knowledge, information on the effect of precipitation on dry bean is not available. Precipitation during the growing season in 2018 (303.4 mm) was greater than that observed in 2017 (242.4 mm), especially in June 2018. In contrast, Schmidt's experiments (2020) received 427.5 mm and 496.4 mm of rain during the 2015 and 2016 growing seasons, respectively, suggesting that field bean prefers drier conditions in this region for the yield-density relationship to appear to conform to the LCFY, even though the cumulative precipitation in the 2018 growing season was 31% below the 30-year long-term growing season average for the region. Field bean is a warm-season crop with an ideal growing temperature between 18-24˚C (Helm et al. 1990). While field bean can grow in the black soil zones of the Canadian prairies, they preferably grow on quick-draining soil since their tolerance to excess moisture is low (OMAFRA 2017). The experiments in 2018 consisted of the Rosebank and Elm Creek soil series, which are imperfectly drained and have a slow surface runoff and a high water table during the growing season (Manitoba Agriculture Food and Rural Initiatives 2010) which suggests that the soils may not have drained quickly enough in seasons with higher precipitation such as 2018.

Higher precipitation and soil moisture are conducive to development of plant diseases such as white mould (sclerotinia) and root rots (Goodwin 2005; Singh and Schwartz 2010; Schwartz and Singh 2013). Narrow row spacing encourages a closed plant canopy, thus reducing the ability of the moisture within the canopy to evaporate. Field bean, especially when planted in narrow rows, may be more susceptible to sclerotinia (white mould) and root rot. Sclerotinia was observed in Schmidt's work (2020) and was initially thought to be cause for the unusual decrease in yield over increasing densities; however, it was not a significant covariant in that study. Sclerotinia did not occur in either year of this present study, suggesting the cause of the unexpected yield patterns in Schmidt's work (2020) may have been due to disease below ground. Root rot may have been a factor in the reduced yields but was not examined in either study. Root rot has recently been found in 100% of Manitoban fields (Henriquez et al. 2015; McLaren et al. 2016; Kim et al. 2017, 2019) and on the research farm in nearby plots during the 2018 study. The increased precipitation in 2018 may have caused the soil to retain moisture beneath the field bean canopy.

3.6 Conclusion

The spatial arrangement between field bean plants was very important in this study for yield outcome. The 2017 experiment suggested that 24 and 48 plants m^{-2} experienced greater yield outcomes compared to 12 plants m^{-2}. Cultivar choice also appeared to influence yield, as T9905 had greater yields and lessened shade avoidance responses compared to Envoy. Further research is required on the comparison of other cultivars with similar growth habits. Spatial arrangement also influenced shade avoidance responses that caused plant morphological changes, including reduced stem thickness, greater distances between pods and internodes with the ground, and decreased branch numbers. The results of this experiment suggest that narrow row spacing (approximately 15”) will increase shade avoidance responses, but most importantly improve yields in contrast to wider row spacing. Further research detailing the effect on precipitation levels in field bean at different growth stages, the influence of high root rot incidence on field bean yields, and the influence of root rots on plant morphology would be beneficial to ensure the future of field bean production in Manitoba.

In summary, differences in cultivars were reported in this study, though research in field bean growth habits that were used in this experiment is limited. T9905 experienced reduced shade avoidance characteristics compared to Envoy such as thicker stems and lower pod clearance, as well as reduced yield loss compared to Envoy. In addition, the reasons behind the increase in shade avoidance characteristics and failure to resemble the LCFY in 2018 are unclear, though may be due to precipitation events. The effects of increased precipitation on poorly drained soils can potentially influence the yield response to disease severity; however, research on the effect of common pathogens, such as root rots or white mould, and their influence on shade avoidance characteristics is not yet available. Using the literature provided and the agronomic knowledge of field bean production in Manitoba, the results can be attributed to major seasonal precipitation changes and resulting shade avoidance characteristics that reduced yields since the major difference between the two study years was seasonal precipitation, further influencing disease response, and changes in plant morphology in the form of shade avoidance characteristics due to interference among the bean plants.

4.0 The Density-Yield Relationship in Navy Field Bean under Weed Interference

4.1 Abstract

Increasing planting densities to create a competitive crop canopy has been a useful weed control strategy of Integrated Weed Management (IWM). Since local research on this weed control strategy has seldom been conducted in field bean, this experiment was established to determine the competitive effect of field bean at increasing planting densities against weeds. Envoy and T9905 navy bean cultivars were grown to compare the differences in Type I determinate versus Type II indeterminate growth habits and respective yield response under weed interference. The field bean cultivars were grown over two site-years at the Ian Morrison Research Farm at Carman, Manitoba at densities of 5, 10, 20, 40, and 80, and 160 plants m^{-2} in 20 cm rows to observe the effects of increasing planting density on bean yield and weed populations. The natural weed population was allowed to grow with some mechanical and chemical intervention throughout the season. Both cultivars experienced unacceptably low yields, but T9905 still yielded more than Envoy. Increasing planting density of field bean was not found to reduce weed biomass in 7 out of 8 experiments. Increasing planting density have been shown to reduce weed populations in other crop studies, but without chemical intervention the negative effects of natural weed populations on field bean development and seed yield were found to be unacceptable for a modern producer.

4.2 Introduction

Weeds compete with crops for light and nutrients, ultimately reducing the development and yield of the crop they are interfering with (Afifi and Swanton 2012; Swanton et al. 2015). Various control methods exist, including cultural, biological, mechanical, and chemical weed management methods but implementing multiple methods of control, otherwise known as an Integrated Weed Management (IWM) strategy, reduces the selection pressure for herbicide resistant weed biotypes compared to relying on herbicides for weed control alone (Mohler et al. 2001). Though chemical control is an efficient and popular choice in contemporary production systems, few methods of chemical weed control are registered for field bean use. Implementing an IWM strategy can be used as an addition to chemical weed control, mainly by increasing crop density to compete against weeds without encouraging intraspecific competition. Increasing seeding rate and planting density has been shown to increase yield (Mohler et al. 2001) and suppress weed biomass in some research (Olsen et al. 2005; Evers and Bastiaans 2016), though can also cause self-thinning in the crop and can increase disease incidence.

A Manitoban study by Schmidt (2020) examined the yield response of two navy bean cultivars, Envoy and T9905, in various planting densities and row spacing. The results of the study failed to conform to the ‘law of constant final yield’ (LCFY); a graphical model proposed by Weiner and Freckleton (2010) on the competitive relationship between plant density and plant biomass. Weiner and Freckleton (2010) theorized that plant biomass initially increases at very low densities with no competition. As planting density increases, the plant biomass is proportional to density until competition begins, at which point the slope of the line plateaus as the biomass becomes independent of density. This model has been observed in weed-free work with volunteer canola and soybean (Mierau et al. 2020) and in black bean (Shirtliffe and Johnston 2002) yet was not replicable in Schmidt's navy bean experiment (2020). Manitoba is a key player in Canadian field bean production, contributing 31% of national field bean production. Understanding how to improve IWM strategies to increase field bean seed yield may encourage producers to incorporate field bean in their rotation more frequently.

To further investigate the effects of planting density on field bean seed yield and weed competition, this experiment was conducted at Carman, Manitoba using two navy bean cultivars with different growth habits; Type I determinate Envoy, and Type II indeterminate T9905, and two seeding dates; early and late. The following objectives were created to explore the weed biomass relationship with increasing field bean planting density, and the relationship between field bean seed yield in the presence of weeds and increasing field bean planting densities:

1) Determine the yield response of two navy bean cultivars to increasing planting densities under weed interference
2) Determine the competitive effect of increasing planting density in these two navy bean cultivars under weed interference

4.3 Materials and Methods

4.3.1 Experimental Locations

The experiments were conducted in 2017 and 2018 and were located at the Ian N. Morrison Research Farm, Carman, Manitoba (49° 30' 05.6" N, 98° 01' 43.1" W). The soil series in both 2017 and 2018 were the Elm Creek (EEK) series (Manitoba Agriculture Food and Rural Initiatives 2010). Soil tests were analyzed annually with Agvise laboratories (Table 4.1). All experiments were fertilized with 85.42 kg ha^{-1} (76.09 lb ac^{-1}) granular nitrogen (46-0-0). Local weather data were obtained using the on-farm weather station.

Table 4.1 Agvise soil test results and fertilizer application date for the 2017 and 2018 experiments at Carman, MB.

Year	Experiment	Soil Type	Soil Sampling Date	OM	pH[a]	Fertilizer Application Date
				---%---		
2017	Early	EEK	April 25	2.7	5.6	May 19
2017	Late	EEK	April 25	2.7	5.6	May 19
2018	Early	EEK	April 24	2.6	5.9	May 25
2018	Late	EEK	April 24	2.6	5.9	May 25

[a] pH measured in the 0-6” range

4.3.2 Establishment and Treatments

Four repetitions of ten treatments each (2 cultivars x 5 seeding densities) were established in plots 2.5 m wide by 6 m long using a JT-13DVS seeder (R-Tech industries, Homewood, MB). This made the experiment a two-way factorial randomized complete block design (cultivar x actual planting density) with an early and late seeding date, each with four replicates. Two cultivars were chosen, a Type II indeterminate vining growth habit (T9905), and a Type I determinate bush growth habit (Envoy). The cultivars were seeded in 20 cm rows at densities of 5, 10, 20, 40 and 80 seeds m^{-2} in all experiments except in late 2017, which was seeded at densities of 10, 20, 40, 80 and 160 plants m^{-2} to increase seedling recruitment due to poor seedlot quality observed in the early 2017 experiment. Experiments were fertilized perpendicular to the seeding pattern at an earlier date to avoid plant injury. The early season experiments were seeded on May 26th, 2017 and May 29th, 2018, and the late season experiments were seeded on June 19th, 2017 and June 14th, 2018. All experiments were exposed to the resident weed population which was allowed to recruit. The late-seeded 2018 experiment was supplemented with volunteer canola and barley seed at the time of seeding the beans to ensure sufficient weed interference. Crop emergence and weed counts were recorded once for each experiment (Table 4.2). Weeds were managed as needed using selective in-crop herbicide applications (Table 4.3). When weeds grew taller than field bean, they were mechanically trimmed to the height of the field bean using a lawn trimmer, or controlled selectively using a herbicide wick applicator. Field bean and weed biomass were determined before harvest (Table 4.2), and field bean seed yield and thousand kernel weight were determined after harvest.

Table 4.2 Field bean measurement, date of measurement and bean developmental stage in each experiment in 2017 and 2018.

Measurement	Date	Experiment	Development Stage [a]
		2017	
Crop Emergence	June 22	Early	VE-V3
Crop Emergence	August 8	Late	VE-V3
Weed Counts	August 8	Early & Late	VE-V3
Bean/Weed Biomass	September 26	Early & Late	R8
		2018	
Crop Emergence	July 18	Early	V12-R2
Crop Emergence	July 17	Late	V12-R2
Weed Counts	July 9 / 17	Early & Late	V4-V11
Bean/Weed Biomass	August 17	Early & Late	R7

[a] = Refer to Figure A1 in the appendix for the dry bean development guide

Table 4.3 Formulations and dosage for all chemical applications applied at their respective developmental stages in 2017 and 2018.

Date	Experiment	Formulation [a]	Rate	Development Stage [a]
2017				
June 12	Early	200 g L^{-1} chlorantraniliprole	252.5 mL ha^{-1}	V1-V2
June 12	Late	200 g L^{-1} chlorantraniliprole	252.5 mL ha^{-1}	VE
June 26	Early	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	247 mL ha^{-1}	V2
		Urea Ammonium Nitrate (28-0-0)	500.2 mL ha^{-1}	
July 7	Early	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	741 mL ha^{-1}	V3-V6
		Urea Ammonium Nitrate (28-0-0)	1500.5 mL ha^{-1}	
July 7	Late	20 g L^{-1} imazamox + 429 g L^{-1} bentazon	741 mL ha^{-1}	V1-V2
		Urea Ammonium Nitrate (28-0-0)	1500.5 mL ha^{-1}	
August 28	Early	480 g L^{-1} bentazon	2.28 L ha^{-1}	R8
August 28	Late	480 g L^{-1} bentazon	2.28 L ha^{-1}	R8
2018				
July 14	Early	480 g L^{-1} bentazon	2.28 L ha^{-1}	V4
July 18	Late	480 g L^{-1} bentazon	2.28 L ha^{-1}	V5-V11

[a] = Refer to Figure A1 in the appendix for the dry bean development guide

4.3.3 Data Collection

In 2017, field bean emergence was recorded once between emergence (VE) and the third trifoliate (V3) stage by counting plants alongside a meter stick in three random rows within each plot. Field bean and weed biomass were determined at the R8 stage in 2017, but both field bean and weed biomass was excluded for late Envoy in 2017 due to poor field bean plant stand. In 2018, field bean emergence was recorded during the V12-R2 stage and weed counts at the V4-V11 stage as in 2017. Field bean and weed biomass were determined at the R7 stage in 2018 (Table 4.3) but field bean biomass for both cultivars in early 2018 was omitted due to poor field bean emergence. A plot combine (Kincaid 8-XP single plot combine; Kincaid Equipment Manufacturing, St. Haven, KS, USA) was used to harvest the early experiment on October 6th, 2017 and the late experiment on October 16th, 2017. Due to high levels of weed competition and poor germination, the Envoy cultivar in the late 2017 experiment, and both cultivars in the early-seeded 2018 experiment could not be harvested with a plot combine. The late experiment in 2018 was hand harvested on September 14th, 2018. Harvested field bean seed was stored in labelled cloth bags on a drying bed for future threshing using an Agriculex LBT-2 belt thresher (1-59 Suburban Ave. Guelph, Ontario, Canada N1E 6B4). After threshing, thousand kernel weight (TKW) was obtained. A sample was saved from each plot and dried in an oven at 110°C to determine the moisture-corrected yield analysis with the following equation:

$$\%\ seed\ moisture\ content = \left(\frac{wet\ seed\ weight\ (g) - dry\ seed\ weight\ (g)}{wet\ seed\ weight\ (g)}\right) * 100$$

4.3.4 Statistical Analysis

To determine the relationship between field bean density and yield, the 2017 data were first fit to a non-linear rectangular hyperbola regression model similarly described by Cousens (1985). The rectangular hyperbola is represented by the equation:

$$Y = Id\left(\frac{1 + Id}{A}\right)$$

Where:

Y = Yield (kg ha^{-1})

d = Field bean density (plants m^{-2})

I = Initial slope of the hyperbola at density = 1 (kg ha^{-1} $plant^{-1}$)

A = The asymptote of the hyperbola or the maximum yield attained (kg ha^{-1})

To determine the starting error estimates for the non-linear regression analysis, a two-factor mixed model (PROC MIXED) was run using SAS University Edition (SAS Institute Inc., Cary, MC, USA) software by modelling cultivar and actual planting density against yield in 2017.

Denominator degrees of freedom were computed using the Kenward-Roger method. Main fixed effects included cultivar and plant density and their interactions. Repetitions were the only random effects included in the model. Initial error estimates are required to conduct the nonlinear regression (NLMIXED) and were obtained from the covariance parameter estimates using this mixed model ANOVA (Knezevic et al. 2002). The data were then fit to the rectangular hyperbola using the NLMIXED procedure. To accommodate the range of actual planting densities achieved and conduct a meaningful comparison between cultivars, data were examined as an unabridged (full dataset) and abridged (reduced dataset that spanned equal ranges of emergence for both cultivars) analyses. Initial model parameters were adjusted to fit the data using the “parms” statement in NLMIXED and was adjusted as needed by comparing the input values to the Parameter Estimates table output. In case the data did not conform to a non-linear rectangular hyperbola regression model, a linear and curvilinear approach was used to model the density-yield response. The linear model is represented by the equation:

$$Y = a + bx$$

Where:

Y = The dependent variable (kg ha^{-1})

a = The intercept when x = 0 (kg ha^{-1})

b = The slope of the line $\left(\frac{\text{kg ha}^{-1}}{\text{plants m}^{-2}}\right)$

x = The explanatory variable (plants m^{-2})

Whereas the curvilinear model is represented by the equation:

$$Y = ax^2 + bx + c$$

Where:

Y = The dependent variable (kg ha^{-1})

a = The slope of the quadratic term $\left(\frac{\text{kg ha}^{-1}}{\text{plants m}^{-2}}\right)$

x = The independent variable (plants m^{-2})

b = The slope of the linear term $\left(\frac{\text{kg ha}^{-1}}{\text{plants m}^{-2}}\right)$

c = The intercept of the line (kg ha^{-1})

The mixed model was used to fit curvilinear and linear slopes. For data where linear regression fit best, a mixed model procedure (PROC MIXED) was used to determine the effect of cultivars (intercepts) and actual planting density (slopes) on yield. Denominator degrees of freedom were computed using the Kenward-Roger method. Main fixed effects included cultivar and actual planting density and their interactions and significance between variables (α=0.05) was examined during the analysis. Random variables included replicates. Single degree freedom estimates were used to extract and compare slopes. Where the line was expected to go through zero, the equation was forced through the origin.

The PROC MIXED procedure was run on weed and bean biomass in 2017 and 2018 in both a linear and curvilinear function to determine if biomass was affected by field bean density. Denominator degrees of freedom were computed using the Kenward-Roger method and the

Fishers protected least square means statement included cultivar for both weed and bean biomass. Main fixed effects included cultivar and actual planting density and their interactions. Repetitions were the only random effects included in the model. Single degree freedom estimates were used to extract and compare slopes. PROC CORR was run on field bean biomass in 2017 and 2018 to determine whether field bean biomass correlated with seed yield. A separate correlation analysis was conducted for each cultivar within each experiment.

4.4 Results

4.4.1 Cultivar Response to Weeds Between Seeding Dates and Experimental Years

The yield response to actual plant densities in the presence of weeds was different between the two field bean cultivars in 2017. The data in the abridged analysis was culled at 50 plants m^{-2} to determine if the estimates of the *I* and *A* values differed from the unabridged analysis. No differences were found between unabridged and abridged, and only results from the unabridged analysis are discussed. The effect of the T9905 cultivar on weeds, or competitive response of T9905 to weed interference, was greater than that of Envoy, suggesting that in competitive circumstances, T9905 was capable of producing and retaining greater seed yield than Envoy with fewer plants under weed interference. The T9905 data fit the rectangular hyperbola model in 2017 (Figure **4.1**;

Table **4.4**).

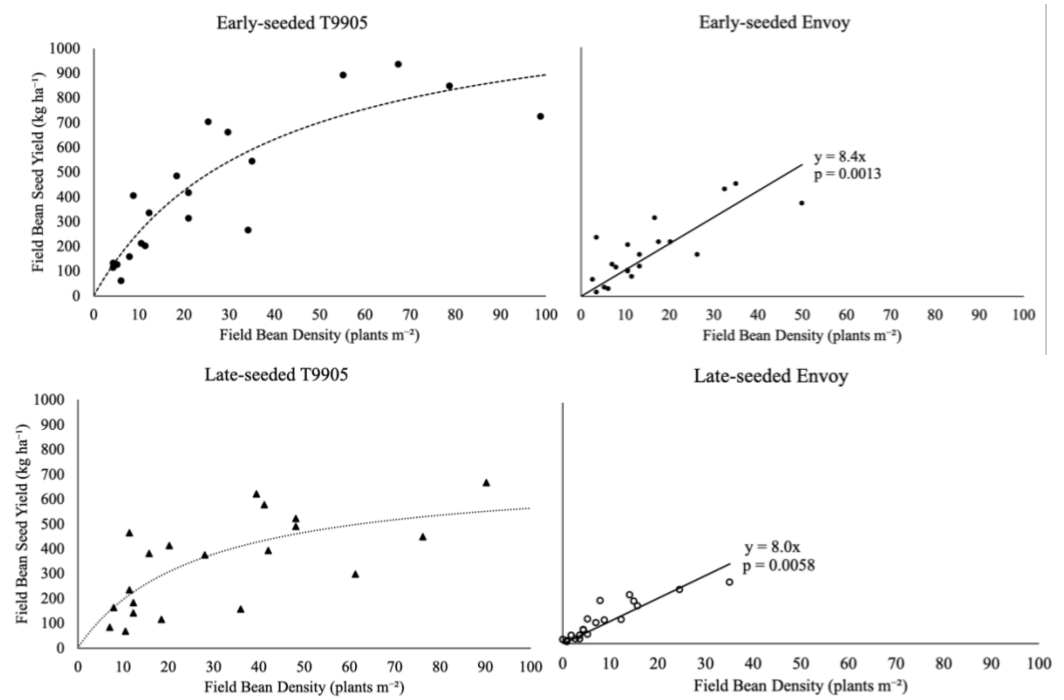

Figure 4.1 The effect of increasing field bean planting densities on T9905 (left panels) and Envoy (right panels) field bean seed yield under weed interference in early-seeded (top panels) and late-seeded (bottom panels) 2017. Regression lines are indicated for significant models. Parameter estimates and approximate standard errors of the linear and non-linear models are indicated in

Table **4.4**.

Table 4.4 Non-linear regression analysis for all experiments (top section) and linear regression analysis for early-seeded Envoy (bottom section) with parameter (*A* and *I*) estimates (+/- standard error) and p-values for parameter estimates in Envoy and T9905 navy field bean seed yields influenced by weed interference in 2017.

Non-linear Regression Analysis				
Experiment	Model Parameter[a]		Pr > [t]	
	A	*I*	*A*	*I*
Envoy early	951.3 (604.3)	16.2 (4.9)	0.2135	0.045
Envoy late	485.6 (410.3)	16.6 (8.7)	0.3218	0.1527
T9905 early	1230.1 (161.4)	32.5 (4.8)	0.0047	0.0067
T9905 late	711.8 (127.2)	26.8 (6.8)	0.0113	0.0292
Linear Regression Analysis for Early- and Late-seeded Envoy				
Experiment	Effect	Estimate	Pr > [t]	
Envoy early	Slope	8.4 (2.4)	0.0013	
Envoy early	Intercept	53.2 (46.7)	0[b]	
Envoy late	Slope	8.0 (2.73)	0.0058	
Envoy late	Intercept	25.2 (33.2)	0[b]	

[a] *A* is the asymptote of the rectangular hyperbola, or the yield as field bean density approaches infinity, and *I* is the slope of increasing yield at a density of one individual field bean plant.

[b] Since the intercept was not significantly different from 0, it was forced though zero.

The asymptote, or *A* values that represent the maximum yield attained, were greater in early-seeded T9905 (1230.1 kg ha^{-1}) compared with late-seeded T9905 (711.8 kg ha^{-1}) by a difference of 518.3 kg ha^{-1} (p = 0.0136;

Table **4.4**). This difference in the *A* value suggests that T9905 may have performed better at an earlier seeding date, though the yield increase gained per individual field bean plant at low densities, or the *I* value, was not significantly greater in early-seeded T9905 (32.5 kg ha^{-1}) compared to late-seeded T9905 (26.8 kg ha^{-1}); a difference of 5.7 kg ha^{-1} (p=0.5008;

Table **4.4**). However, the *I* value for early-seeded T9905 was significantly greater than early-seeded Envoy, a difference of 16.3 kg ha^{-1} (p=0.0205).

Envoy yield in response to increasing plant density under weedy conditions did not fit to a rectangular hyperbola in the early- or late-seeded experiment in 2017 (Figure 4.1;

Table 4.4). Poor germination in Envoy in the 2017 late-seeded experiment resulted in a reduced actual planting density, which may have contributed to an inability to model the yield data using non-linear regression (parameter I: $p = 0.1527$;

Table 4.4). In comparison, T9905 had a greater range of actual plant density (=seedling recruitment; Figure 4.1). The *I* value for early-seeded Envoy was significant, but the level of variation around the *A* value made the asymptote not significant (

Table 4.4), thus the data did not conform to the rectangular hyperbola. The actual density-yield response, however, fit a linear regression model. Neither the *A* nor *I* value of the Envoy cultivar were significant in late-seeded 2017, thus the data did not fit to a curvilinear regression model. The slope was significant, though the intercept was not, and the data were fit to a linear model (

Table 4.4; Figure 4.1).

In 2018, seed yield in response to increasing plant density under weedy conditions did not conform to the rectangular hyperbola in either bean cultivar (Figure 4.2). Only the late-seeded experiment was harvested due to failure of bean establishment and high weed pressure in the early-seeded experiment that resulted in the absence of a bean plant density gradient. In the late-seeded experiment, the yield response in both cultivars was linear (

Table 4.4). Late-seeded T9905 had a greater slope (14.96 kg ha$_{-1}$ plants m$_{-2}$) than Envoy (8.18 kg ha$_{-1}$ plants m$_{-2}$) indicating each additional T9905 plant produced almost twice as much seed yield as each additional Envoy plant. To further examine a potential cause for the yield difference between these bean cultivars, weed biomass was examined.

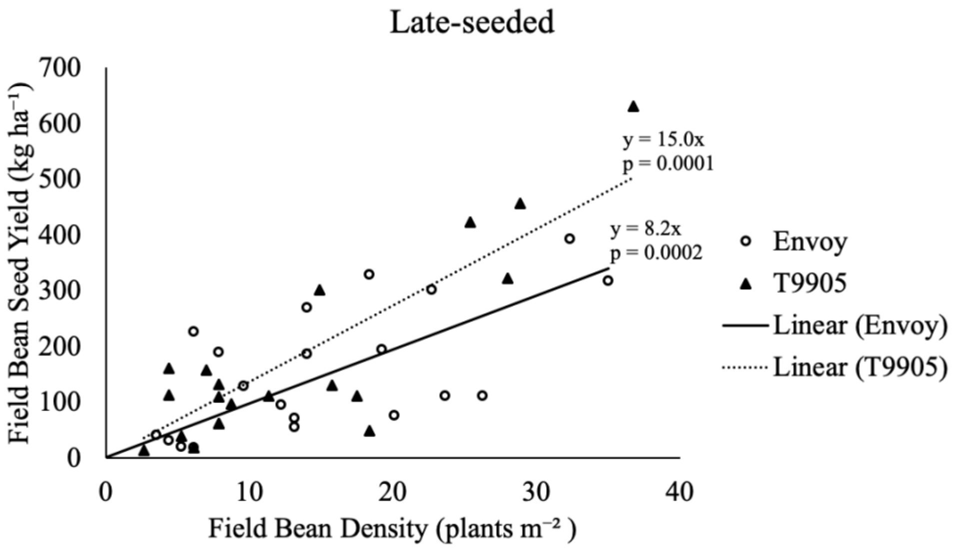

Figure 4.2 The effect of increasing field bean actual planting densities on field bean seed yield under weed interference in 2018. The triangles and broken line represent the T9905 cultivar while circles and solid line represent Envoy. Linear equations and respective p-values are shown beside the respective linear regression lines. Seed yield from early-seeded T9905 and Envoy in 2018 is absent due to failure of bean establishment and high weed pressure.

4.4.2 The Effect of Planting Density on Weed Biomass

The effect of increasing bean plant density on weed biomass, also known as the competitive effect, was minimal among these experiments. In 2017, weed biomass did not fit to either linear or non-linear regression models, indicating that a competitive effect of field bean on weed biomass was not observed in 2017, regardless of seeding date (

Table 4.5).

Table 4.5 The output from the PROC MIXED procedure for weed biomass. The top section represents early-seeded 2017, then late-seeded 2017, then early-seeded 2018 and late-seeded 2018. The Model column describes the cultivars as fit to a linear or quadrative model and their respective significance in the Pr>t column.

Early 2017			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	0.1777	1.5443	0.9091
T9905 Linear	-0.9013	0.7264	0.2237
Envoy Quadratic	-0.00511	0.03172	0.8730
T9905 Quadratic	0.008422	0.007699	0.2821
Late 2017			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	0.1891	0.6661	0.7802
T9905 Linear	.	.	.
Envoy Quadratic	-0.00181	0.007442	0.8109
T9905 Quadratic	.	.	.
Early 2018			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	-5.6829	7.8881	0.4763
T9905 Linear	5.3113	4.9599	0.2924
Envoy Quadratic	0.4821	0.5665	0.4009
T9905 Quadratic	-0.2924	0.2737	0.2935
Late 2018			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	-8.4006	2.0548	0.0003
T9905 Linear	-2.8248	1.7501	0.1172
Envoy Quadratic	0.1669	0.06060	0.0100
T9905 Quadratic	0.04829	0.04704	0.3129

A significant competitive effect, or a decrease in weed biomass with increasing bean plant density, was only noted in the Envoy cultivar in the 2018 late-seeded experiment where a negative quadratic relationship was observed (

Table 4.5). A high weed biomass point in the early-seeded Envoy 2018 and in the early-seeded Envoy 2017 experiments were initially thought to be influential (Figure 4.3) but removing them did not change the interpretation of the results.

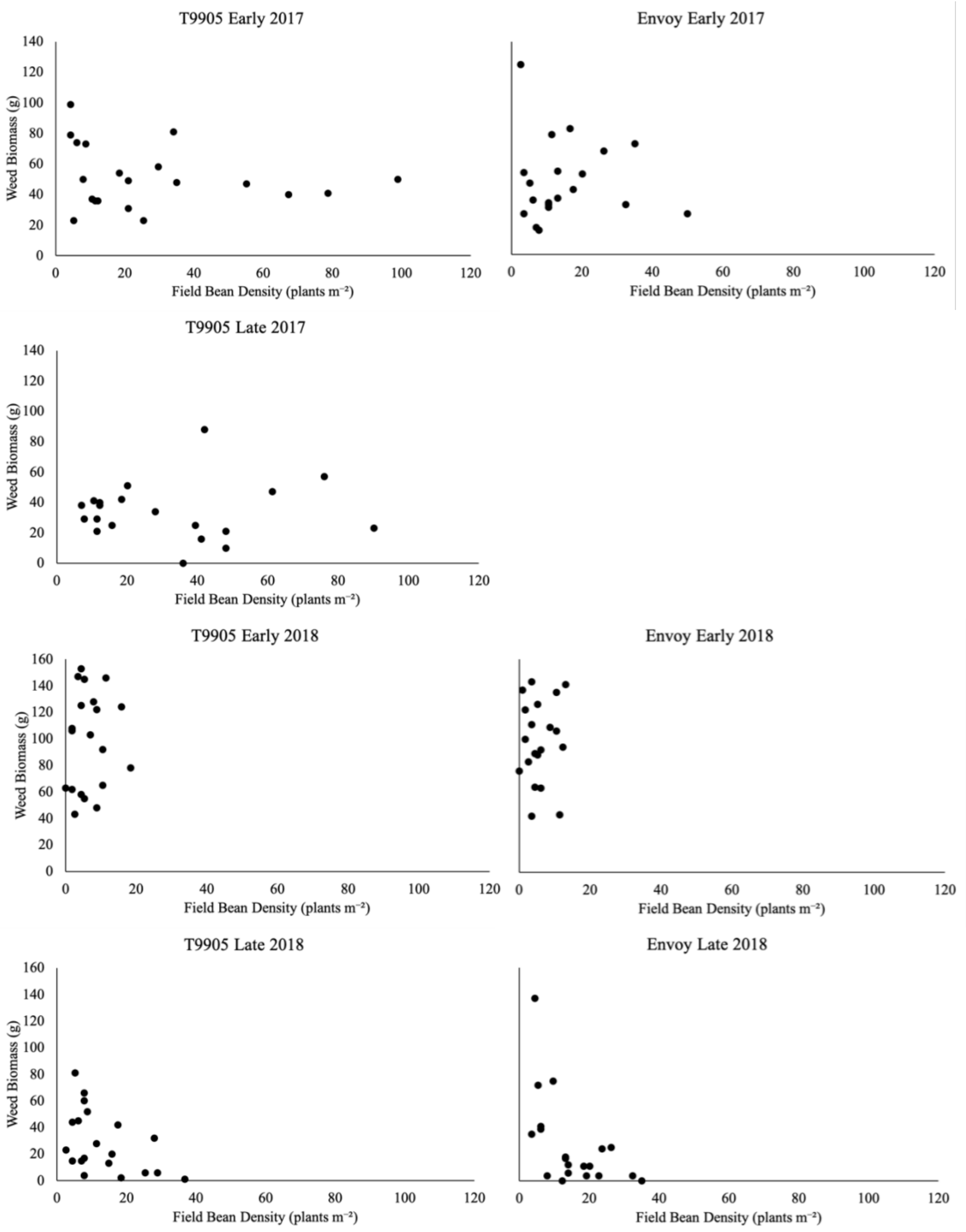

Figure 4.3 The effect of increasing T9905 (left panels) and Envoy (right panels) field bean actual planting densities on weed biomass in 2017 (top four panels) and 2018 (bottom four panels). Analyses were not significantly linear or curvilinear except for late-seeded Envoy in 2018, which experienced a negative quadratic relationship. Weed biomass data from late-seeded Envoy in 2017 was absent due to failure of bean establishment.

Weed biomass was not significantly different between early and late-seeded experiments except for Envoy in the 2018 late-seeded experiment. The lack of a significant effect of actual field bean density on weed biomass in the experiments other than Envoy in the 2018 late-seeded experiment depict an inability for field bean to compete well with weeds in this study. The lack of a competitive effect in T9905 was surprising as it generally produced more yield.

No significant differences in field bean biomass were observed between the two bean cultivars (Figure 4.4). Interestingly, field bean biomass in late 2018 was not related to plant density in most experiments, although a significant quadratic relationship was found in early-seeded T9905 in 2017 (

Table 4.6).

Table 4.6 The output from the PROC MIXED procedure for bean biomass. The top section represents early-seeded 2017, then late-seeded 2017, then early-seeded 2018 and late-seeded 2018. The Model column describes the cultivars as fit to a linear or quadrative model and their respective significance in the Pr>t column.

Early 2017			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	0.01410	1.3349	0.9916
T9905 Linear	1.8859	0.6122	0.0044
Envoy Quadratic	0.02006	0.02728	0.4677
T9905 Quadratic	-0.01400	0.006497	0.0369

Late 2017			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	.	.	.
T9905 Linear	0.1852	0.5105	0.7219
Envoy Quadratic	.	.	.
T9905 Quadratic	-0.00002	0.005770	0.9968

Early 2018			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	.	.	.
T9905 Linear	.	.	.
Envoy Quadratic	.	.	.
T9905 Quadratic	.	.	.

Late 2018			
Model	Estimate	Standard Error	Pr > t
Envoy Linear	1.4150	2.0127	0.4871
T9905 Linear	-1.3017	1.9234	0.5035
Envoy Quadratic	-0.02067	0.05379	0.7033
T9905 Quadratic	0.07266	0.05168	0.1695

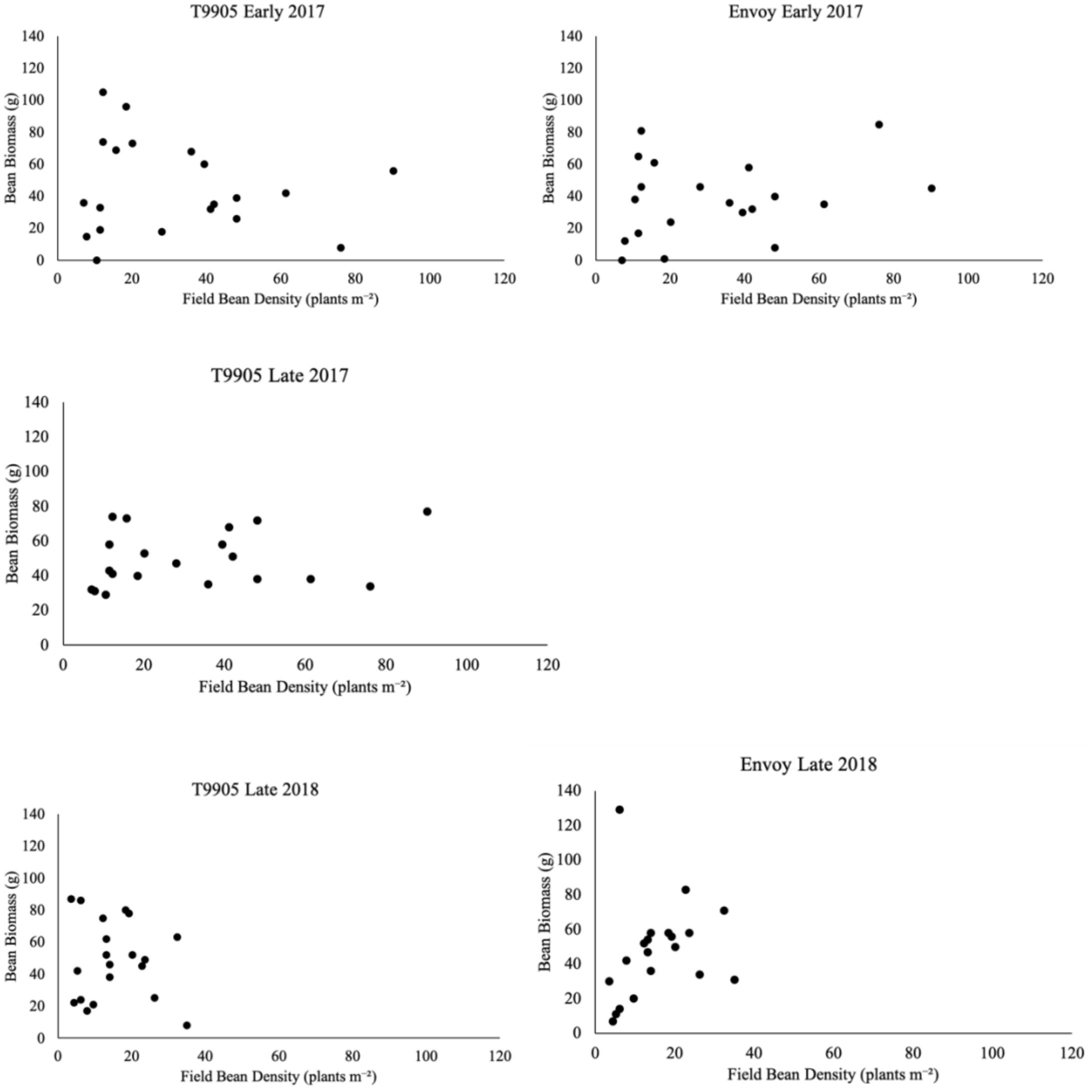

Figure 4.4 The effect of increasing T9905 (left panels) and Envoy (right panels) field bean actual planting densities on field bean biomass in 2017 (top three panels) and 2018 (bottom two panels). Bean biomass from late-seeded Envoy in 2017, early-seeded T9905 in 2018, and early-seeded Envoy in 2018 was absent due to failure of bean establishment and high weed pressure. See table 4.6.

Field bean biomass and seed yield correlated positively in all experiments (Table 4.7). The Pearson R values ranged from 0.54 to 0.84 and at best explaining from 29 to 70% of the total variation, indicating that only part of the variation in yield was due to field bean biomass (Table 4.7). The two cultivars performed very differently under weed interference. Envoy seed yield was weakly correlated with bean biomass with Pearson R values ranging from 0.54 ($p = 0.0136$)

to 0.60 (p = 0.0070), explaining only 29 to 35% of the variation in yield, while T9905 had a somewhat stronger correlation in comparison ranging from 0.61 (p = 0.0045) to 0.84 (p = <0.0001), explaining 36 to 70% of the variation in yield (Table 4.7). Overall, these data confirm that the field bean competition against weeds is limited, though increasing plant densities increased field bean seed yield in most cases.

Table 4.7 The output from the PROC CORR procedure for bean biomass and field bean seed yield within cultivars. The top section represents the 2017 experiments and the bottom column represents the 2018 experiments.

	2017	
Time	Pearson Correlation Coefficient	P value
Envoy early	0.59643	0.0070
Envoy late	.	.
T9905 early	0.83963	<0.0001
T9905 late	0.60757	0.0045
	2018	
Envoy early	.	.
Envoy late	0.54206	0.0136
T9905 early	.	.
T9905 late	0.74194	0.0002

4.5 Discussion

Crop stand density is an important cultural weed management strategy that forms part of an integrated pest management system (Mohler et al. 2001). Increasing crop planting density has successfully suppressed weed biomass in other studies including field pea (Townley-Smith and Wright 1994), soybean (Burnside and Colville 1964; Kust and Smith 1969; Mierau et al. 2020), and white bean (Malik et al. 1993), as well as many non-legume crops (Mohler et al. 2001). An increase in yield with increasing crop density has also been found in most crop species (Mohler et al. 2001). In some cases as outlined by Mohler et al. (2001), an increase in the density of the crop had no effect on yield in wheat (Teich et al. 1993) or pigeon pea (Diaz-Rivera et al. 1985), though these were among very few cases. In our experiment, only Envoy in late 2018 succeeded in reducing weed biomass. In addition, based on visual observation, field bean in this experiment had slow early-season growth and development compared to the rate of the weed population's growth; a factor that potentially gave the field bean crop a competitive disadvantage against the rapidly developing weeds, regardless of the planting density.

The relationship between the crop density and weed biomass in our experiment varied from linear and curvilinear to nonlinear. Crop yield in a non-competitive situation could expect a rectangular hyperbola, as stated by the 'law of constant final yield', though was not the case for some studies. Mierau et al. (2020) conducted experiments in locations across Manitoba and Saskatchewan to examine the effect of increasing soybean density on volunteer canola. The study found that in 6 out of 7 experiments, the effect of seeding rate and planting date caused a curvilinear response on soybean yield, with the remaining experiment being linear due to a reduced range of soybean yield compared to the other site years. In most cases, the 'law of constant final yield' was not achieved in this experiment. The linear relationship in Envoy in our experiment was expected to have occurred due to the lack of sufficient range of the dependent variable, actual planting density, required to describe a nonlinear rectangular hyperbola. Other studies that showed a linear relationship between crop density and yield in a crop species similar to field bean could not be found in the literature.

Due to a lack of replication within growth habit in this experiment, the competitive effect of field bean growth habit on weeds could not be determined but may have been related to the cultivar specific response to weeds. A study comparing four varieties of white bean was conducted in Ontario by Malik et al. (1993) over two years. The navy bean varieties selected for the study consisted of Type I (determinate), II (indeterminate), and III (indeterminate) growth habits, and the indeterminate Type II and III varieties in the study showed reduced weed biomass compared to the determinate varieties. A study by Blackshaw (1991) looked at Type II and III navy bean interactions with hairy nightshade and found that weed biomass was reduced in all three experimental years when field bean was grown at reduced row spacing, and increased plant densities decreased weed biomass in two of the three years. Without herbicidal intervention, field bean seed yield was still considered to be too low to be acceptable in their study.

In our experiment, the indeterminate T9905 cultivar resulted in greater yields than the determinate Envoy cultivar. However, Envoy reduced weed biomass more than T9905, which was observed with the differences in growth habits studied by Blackshaw (1991) and Malik et al. (1993). Though determinate, late-seeded Envoy in 2018 was the only cultivar to cause a reduction in weed biomass with increasing bean plant densities. Nonetheless, T9905 continued to yield greater than Envoy. The responses of weed biomass to determinate and indeterminate field bean growth habits would be an interesting route to explore in future research.

The competitive effects of crops and weeds are highly influenced by environmental factors that control the availability and level of nutrients, water, and temperature (Black et al. 1969; Lindquist et al. 1999). Precipitation differences between years have been known to affect weed competition in pigeon pea (Diaz-Rivera et al. 1985), causing greater weed-crop competition when the precipitation was greater in the early season experiment. In our experiment, the precipitation levels were greater in 2018 than in 2017, potentially explaining why the weeds in early 2018 outcompeted the field bean crop.

4.6 Conclusion

In summary, it is beneficial to implement multiple forms of weed control to reduce weed competition in field bean, especially given registered herbicidal control in field bean is lacking. An alternative method of weed control in field bean is Integrated Weed Management (IWM) by increasing crop density to compete against weeds for nutrients and light. Field bean is generally uncompetitive against weeds, potentially due to its slow early season growth. Cultivar differences were found to increase yield in T9905. Though other studies did show greater weed control with increased planting densities, this was not found in this experiment.

5.0 General Discussion

This M.Sc. thesis aimed to further understand the relationship between spatial arrangement and the law of constant final yield (LCFY) in navy field bean under weed-free conditions and under weed interference. The objectives of the research were to:

1. Determine yield and shade avoidance response in bean plants at different spatial arrangements at narrow row spacing and relate this to the LCFY under weed-free conditions (Chapter 2).
2. Determine if the yield response of two navy bean cultivars appears to conform to the LCFY under weed interference (Chapter 3).

The objectives of this experiment were based on unexpected results in navy bean experiments by Schmidt (2020) Schmidt observed that the LCFY was not observed in Envoy and T9905 navy bean at 20 cm row spacing with increasing planting densities; an outcome which has been observed in other studies with volunteer canola and soybean (Mierau et al. 2020) and in black bean (Shirtliffe and Johnston 2002). This unexpected result was studied in this thesis by further examining T9905 and Envoy navy bean at 20 cm row spacing, though the results of Schmidt (2020) could not be replicated, likely due to very different weather during the two years of this study compared to the two previous years (Schmidt 2020).

5.1 Effect of Planting Density on Shade Avoidance Response in Field Bean

Increasing planting density is an important factor of field bean growth and development and an increase in seed yield in response to density was found in 5 out of 8 weed-free experiments and 5 out of 6 weedy experiments. This was reflected in other studies (Mohler et al. 2001) and benefits the gaps in research surrounding ideal planting densities in field bean today. Many producers continue to seed field bean at wide row spacing that is insufficient at providing adequate interspecific competition, and this research emphasizes that narrow rows and greater planting densities aid in the competitive response of field bean. Increasing planting densities also enhanced shade avoidance responses in nearly all the weed-free experiments, with thinner stems, first internode elongation and greater pod clearance observed in most experiments with both cultivars. In particular, the T9905 cultivar had a better competitive response in the weedy experiments and a greater ability to retain seed yield in weed-free conditions than Envoy under increasing planting densities. This is an important characteristic considering the results from the weedy experiment found planting density to be an unlikely means of competition against weeds; rather it was found to be critical for retaining yield. Shade avoidance responses were not measured in the weedy experiment, though would be advantageous in future experiments to examine whether shade avoidance responses under interspecific interference differ from shade avoidance responses under intraspecific interference.

5.2 Weed Interference in Field Bean

Weeds interfere with plant development and seed yield (Swanton et al. 1993; Mohler et al. 2001; Brady and Weil 2007; Page et al. 2010). In our experiment, the study involving weed interference in field bean resulted in reduced yield compared to the weed-free component, further solidifying this point. Field bean yield loss in the weedy study experienced up to 100% yield loss in some years. Field bean was shown to be a poor competitor in our experiment, as expressed by the rapid yield decline in the weedy experiment. Canopy cover wasn’t measured in the weedy experiment since it was impossible to distinguish the green weed canopy from the green crop canopy, but canopy cover increased with planting densities in the weed-free experiment. Along with the data from the weed-free experiment describing yield to be greatest at 24 and 48 plants m^{-2}, the light interception of a closed canopy from increased planting densities would inevitably help with interspecific plant competition between the crop and weeds as an additional tool to use against weed competition, especially early in the season when the first weed emergence occurs (Howe and Oliver 1987; Rajcan et al. 2004; Green-Tracewicz et al. 2012; Mckenzie-Gopsill et al. 2016). The difficulty of achieving this lies in the growth and development of field bean, which in this experiment, was not fast enough to outgrow the weeds and reduce the light availability for the competing weeds. Both varieties were poor competitors with weeds regardless of the spatial arrangements, and though T9905 produced greater seed yield compared with Envoy regardless of the weedy or weed-free conditions, both cultivars performed poorly under weed interference.

Other studies have examined specific weeds such as Amaranthus species in dry bean (de Carvalho and Christoffoleti 2008) and pitted morning glory and sicklepod in soybean (Howe and Oliver 1987; Pitelli et al. 1998) and found that the competitive intensity and effects of weed species vary greatly depending on the date of the stage of weed interference and the rate of development of the weed species. Examining the weeds and field bean under a more controlled setting would potentially offer greater insight into the specific weed species native to the field bean growing regions of Manitoba that are the most significantly harmful to field bean yield and production. This in turn could be implemented in research to develop a more dependable selection of herbicides registered in field bean.

5.3 Impact on Producers

This research provides beneficial information for field bean producers in Manitoba and neighbouring regions as it offers insight into the benefit and importance of specific production practices that were shown here to improve field bean production, such as increased yields with increasing planting densities, and greater pod clearance from the ground. Certain shade avoidance characteristics, such as increased pod clearance, are beneficial to producers during harvest. Other characteristics such as stem thickness would not affect production for producers but were clear indicators of shade avoidance characteristics for the purpose of this thesis. This research also highlighted some key differences between two popular navy bean cultivars that are commonly selected in Manitoba for field bean production, discovering that T9905 had a greater yield and competitive response compared to Envoy. While more research is required to determine if this was caused by a general difference in growth habits or other genetic difference between the varieties, the results offered insight into cultivar selection. In addition to cultivar selection, field bean producers would find it in their best interest to increase planting density to increase yields. Though planting density did little to control weed biomass accumulation in this study it was beneficial in other studies with snap and white bean (Teasdale and Frank 1983; Malik et al. 1993) and has potential to be explored further with other cultivars or growth types.

5.4 Future Research

Considering that Manitoba is among the leading producers of field bean in the country, limited research has been conducted in field bean in Manitoba. The lack of a reliable registered herbicide in field bean acts as a barrier, which exemplifies the importance of this research – one cannot and should not rely on the effects of herbicides alone to reduce weed biomass and interference in field bean. There is much to learn about the impact of weeds on field bean, especially as they were found in this thesis to be relatively unaffected by increasing planting densities. Further research on cultivar growth habits and their relationships between row spacing, susceptibility to disease caused by agronomic management, and weed biomass would be beneficial to further understand the most ideal production practices for field bean.

The growth habit of a field bean influences both the vertical and horizonal space the bean encroaches, and also influences the length of time it grows after flowering, so the unique growth habit alone has great influence on canopy cover, plant height, and disease potential. Type I and II field bean are the most popular among producers in Manitoba, with many cultivar choices available. Cultivar comparison trials would be beneficial to determine how other cultivars react to shade avoidance conditions and whether the same characteristics occurred, such as the effect of plant height which is a common characteristic in most other research surrounding shade avoidance (Kasperbauer 1987; Rajcan et al. 2004; Liu et al. 2009; Green-Tracewicz et al. 2012; Schmidt 2020), yet not significant in this thesis.

Precipitation levels potentially influenced the growth of field bean and weeds, creating competition between the weeds and the field bean crop, as has been shown in a study involving pigeon pea (Diaz-Rivera et al. 1985). To my knowledge, studies have not been conducted using controlled precipitation on field bean, nor the effect of controlled precipitation on weed interference in field bean and would be an interesting route to explore as it appears to have been influential in this experiment.

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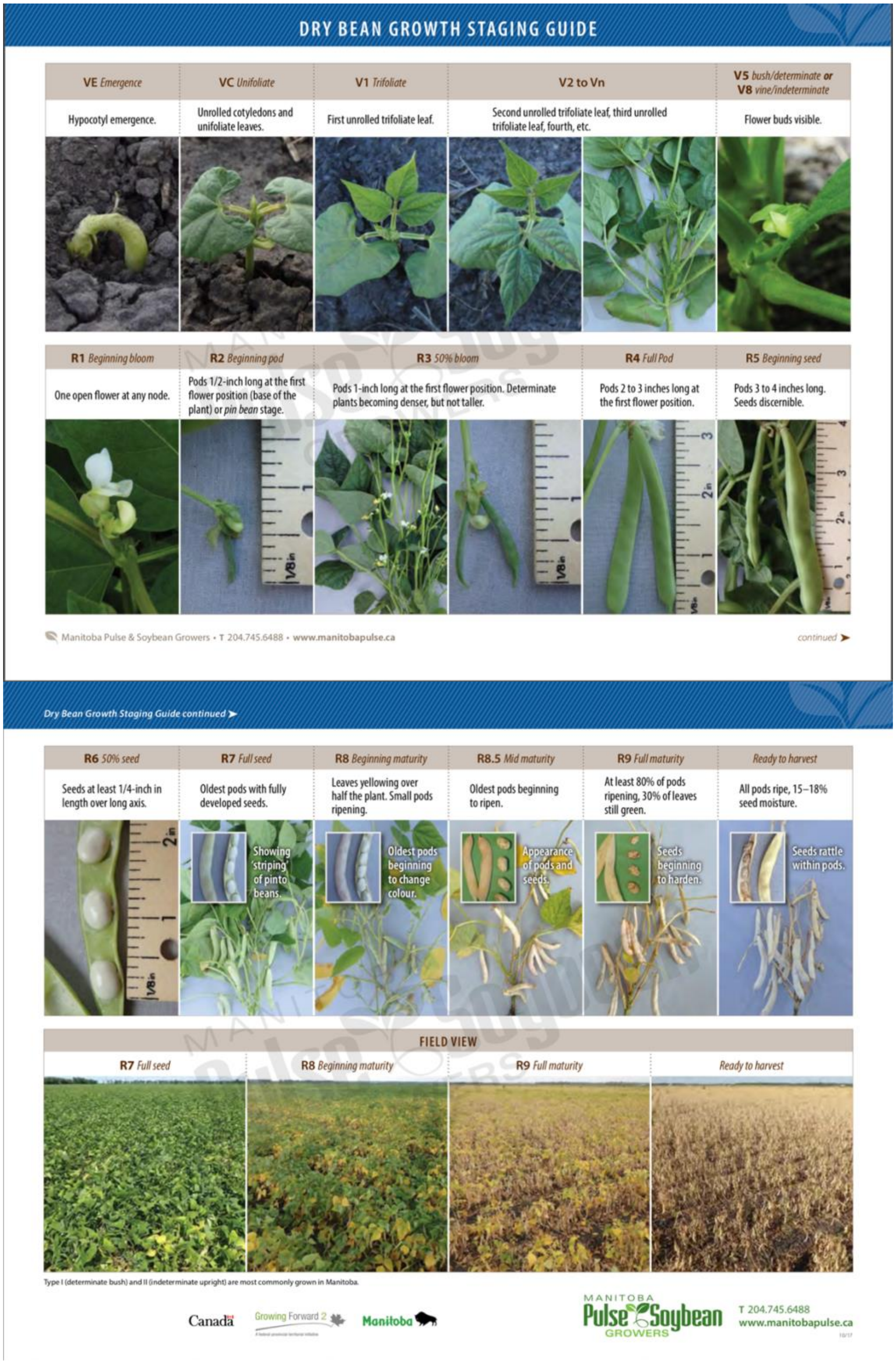
7.0 Appendix



DRY BEAN GROWTH STAGING GUIDE

VE *Emergence*	**VC** *Unifoliate*	**V1** *Trifoliate*	**V2 to Vn**	**V5** *bush/determinate* ***or*** **V8** *vine/indeterminate*
Hypocotyl emergence.	Unrolled cotyledons and unifoliate leaves.	First unrolled trifoliate leaf.	Second unrolled trifoliate leaf, third unrolled trifoliate leaf, fourth, etc.	Flower buds visible.

R1 *Beginning bloom*	**R2** *Beginning pod*	**R3** *50% bloom*	**R4** *Full Pod*	**R5** *Beginning seed*
One open flower at any node.	Pods 1/2-inch long at the first flower position (base of the plant) or *pin bean* stage.	Pods 1-inch long at the first flower position. Determinate plants becoming denser, but not taller.	Pods 2 to 3 inches long at the first flower position.	Pods 3 to 4 inches long. Seeds discernible.

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continued ➤

Dry Bean Growth Staging Guide continued ➤

R6 *50% seed*	**R7** *Full seed*	**R8** *Beginning maturity*	**R8.5** *Mid maturity*	**R9** *Full maturity*	*Ready to harvest*
Seeds at least 1/4-inch in length over long axis.	Oldest pods with fully developed seeds.	Leaves yellowing over half the plant. Small pods ripening.	Oldest pods beginning to ripen.	At least 80% of pods ripening, 30% of leaves still green.	All pods ripe, 15–18% seed moisture.

FIELD VIEW

R7 *Full seed*	**R8** *Beginning maturity*	**R9** *Full maturity*	*Ready to harvest*

Type I (determinate bush) and II (indeterminate upright) are most commonly grown in Manitoba.

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Figure A1. The Manitoba Pulse and Soybean Growers dry bean development guide (Manitoba Pulse & Soybean Growers 2017).