# Plant Spatial Arrangement to Maximize Dry Bean (*Phaseolus vulgaris* L.) Yield in Manitoba

BY

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# ABSTRACT

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Manitoba accounts for a large proportion of dry bean hectarage in Canada, yet current production recommendations have not been validated for this region. The objective of these experiments was to determine the combinations of row spacing and plant densities in pinto and navy bean varieties that maximize seed yield. Field experiments were conducted at Carman and Portage la Prairie, Manitoba in 2015 and 2016. In each market class, two varieties were planted at row widths of 19, 38, 57, and 76 centimeters. Navy bean seeding densities ranged from 20 - 60 plants $m^{-2}$ while pinto bean seeding densities ranged from 10 - 50 plants $m^{-2}$. Planting at narrow row widths of 19 cm significantly increased dry bean seed yield, while increasing plant densities did not influence seed yield consistently in navy and pinto bean. Despite concerns of increased white mould disease pressure with narrow-row plantings, white mould severity was the lowest in beans planted at 19 cm row widths. This may have been due to the increased distance between plants at the same densities within the row in narrow-row compared to wide-row spatial arrangements. White mould severity increased significantly with greater seeding densities and type I growth habits. Further research is needed to explore the plant density-yield relationship in dry bean in Manitoba and the influence root rot diseases may have on this relationship. While narrow-row dry bean production has been proven to result in increased yields, there are other barriers preventing producers from adopting this system. Exploring producer constraints may increase adoption and improve production.

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variable lowest pod height in the pinto bean market class at Carman and Portage la Prairie in 2015 and 2016. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

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# LIST OF ABBREVIATIONS

- C15 = Carman 2015 site-year
- P15 = Portage la Prairie 2015 site-year
- C16 = Carman 2016 site-year
- P16 = Portage la Prairie 2016 site-year
- V = vegetative development stages
- R = reproductive development stages
- SS = sum of squares
- Rep(SY) = replicate within site-year

## 1.0 INTRODUCTION

Manitoba is the second largest producer of dry bean (*Phaseolus vulgaris* L.) in Canada, accounting for approximately 40% of the national hectarage in the last five years with 32,000 – 55,000 hectares harvested annually (Anonymous 2017). The two majority market classes of dry bean grown in Manitoba are pinto and navy bean. Nationally, Manitoba is the leading producer of pinto bean and second in navy bean production. Despite this, plant spatial arrangement recommendations in dry bean have not been validated in this province. Recommendations in Manitoba are based on research conducted in North Dakota, Saskatchewan, and Ontario (Malik et al. 1993; Park 1993; Shirtliffe and Johnston 2002). There is a need to validate these recommendations in modern varieties with divergent growth habits since local research is lacking in this area.

Spatial arrangement combines row spacing and plant stand density and has been shown to be a critical requirement to maximize yield and biomass accumulation through early and effective resource capture (Ball et al. 2000). It also plays a key role in increasing the crop's ability to tolerate biotic and abiotic stresses (Malik et al. 1993). Since Manitoba has a relatively short growing season, the early acquisition of above- and below-ground resources is essential to maximizing plant productivity. Early canopy closure maximizes light interception by the crop and increases the crop's competitive ability against weeds (Kiaer et al. 2013). This is critical for dry bean production since it is a highly uncompetitive crop (Malik et al. 1993). In addition to increasing yield, establishing greater plant stand densities and in narrower rows has been shown to increase crop competitiveness in dry bean (Shirtliffe and Johnston 2002). However, aeration in the canopy is reduced in these dense plant stands, leading to concerns that decreasing row width and increasing density will cause an increased incidence and severity of white mould (*Sclerotinia* *sclerotiorum* (Lib.) de Bary) or other plant pathogens. Economically, white mould is one of the most important diseases of dry bean in western Canada and it thrives under high humidity and low aeration (Saindon et al. 1995). Saindon et al. (1995) reported inconsistent effects of density on white mould disease response and this research will further investigate the effects of spatial arrangement and growth habit on white mould severity. The objective of this research was to validate existing recommendations to determine the plant stand density and row spacing that maximize seed yield in dry bean varieties with differing plant architectures.

# 2.0 LITERATURE REVIEW

## 2.1 Introduction

Dry bean (*Phaseolus vulgaris* L.) is a warm-season herbaceous annual crop in the family Fabaceae and is also commonly known as field bean, common bean, or edible bean (Graham and Ranalli 1997). Dry bean market classes are separated by seed size and colour. They include navy (white pea), pinto, cranberry, black, red kidney, white kidney, great northern, Dutch brown, pink, and small red (Goodwin 2005). The majority of Canadian production consists of pinto, navy, black, and kidney bean market classes with some production of the other coloured market classes (Goodwin 2005). Dry bean were first domesticated more than seven thousand years ago in the upland regions of Mexico and Andean South America and since have expanded world-wide and are currently grown on all continents (Graham and Ranalli 1997; Gepts 1998). Dry bean are produced widely for human consumption, providing a principal source of dietary protein in Latin America and Eastern Africa, in addition to being utilized as a vegetable protein in many countries (Graham and Ranalli 1997; Goodwin 2005).

## 2.2 Dry Bean Plant Morphology and Reproductive Biology

Dry bean is an herbaceous annual plant typically requiring 90-120 days to reach maturity (Graham and Ranalli 1997). Dry bean plant development is divided into two main phases, namely, vegetative development and reproductive development. Vegetative development stages consist primarily of shoot internodes, branching and leaf formation (Fageria and Santos 2008). Reproductive developmental stages consist of flower and pod formation and maturation (Fageria and Santos 2008). Dry bean is polymorphic, displaying large variation among genotypes regarding growth habits, vegetative characters, flower colours, and seed characteristics such as shape, colouration, and size (Fageria and Santos 2008). Dry bean exhibit epigeal emergence where the cotyledons are brought above ground by the elongation of the hypocotyl and, with good quality seed, germination may occur within four to five days under favourable conditions (Graham and Ranalli 1997). After the cotyledons, the first leaves to emerge are unifoliate and subsequent emerging leaves are trifoliate. Root development begins with a tap-root elongating through the soil but, as the plant develops, adventitious roots quickly take over (Graham and Ranalli 1997). Flowers are self-pollinated and borne in axillary and terminal racemes. Time to flowering occurs typically between 28 to 42 days after planting but is heavily dependent on the variety, temperature, and photoperiod (Graham and Ranalli 1997). Fruit is borne in pods and the seeds that give each market class their name occur with a variety of colours and patterns (Goodwin 2005). Dry bean is relatively sensitive to cold temperatures and the risk of a late spring frost is a limitation to dry bean production in western Canada, restricting the planting window to the end of May, once soil temperatures have reached a minimum of 12 °C at the depth of seeding (Anonymous 2015, Mitchell 2016). Fall frosts may also be concerning, but are less damaging once the plants have reached physiological maturity (Fageria and Santos 2008).

Dry bean genotypes are classified into one of four distinct growth habits, types I through IV, based on the plant architecture of that genotype. Type I are an upright bush-type bean exhibiting determinate growth, with the terminal bud ending in a flowering raceme, and no further vegetative growth occurring after the onset of flowering (Fageria and Santos 2008, Singh 1982). Types II – IV exhibit indeterminate growth with the terminal bud providing continued vegetative growth after the plant has entered the reproductive phase (Fageria and Santos 2008, Singh 1982). Type II bean exhibit an upright growth habit with erect stem and branches (Graham and Ranalli 1997). The upright stature of types I and II bean allow them to be adapted for monoculture production systems since they are better suited to disease avoidance, intensive cultivation, and mechanized harvest (Fageria and Santos 2008). Type III and IV beans have weak prostrate stems with varying ability to climb which allows them to be more suited to intercropping than their upright counterparts. Typically, these types are not grown in Canada (Anonymous 2015, Singh 1982).

**2.3 Dry Bean Production Statistics**

Worldwide, dry bean is an important pulse crop with approximately 25 million tonnes produced annually (Anonymous 2016). In 2014, Canada contributed 1.03% to global dry bean production, exporting approximately $328.9 million USD in dry bean (Anonymous 2016). The majority of the Canadian production occurs in the prairie provinces (Bekkering 2014).

Manitoba is the second largest producer of dry bean in Canada, accounting for about 40% of the national hectarage annually. In the last five years (2012 to 2016), this has accounted for 32,000 – 55,000 hectares harvested annually within the province (Anonymous 2017). Market classes grown in Manitoba consist primarily of navy and pinto bean with some production of black, kidney, and cranberry bean (Mitchell 2016). Annually, Manitoba is the leading producer of pinto bean nationally, and the second largest producer of navy bean (StatsCan 2017). Within the province, dry bean is typically grown in the south-central region due to the warmer growing conditions found in this area, and the main contributing rural municipalities to dry bean production are Rhineland, Portage la Prairie, Stanley and Dufferin (Figure 2.1) (Mitchell 2016).

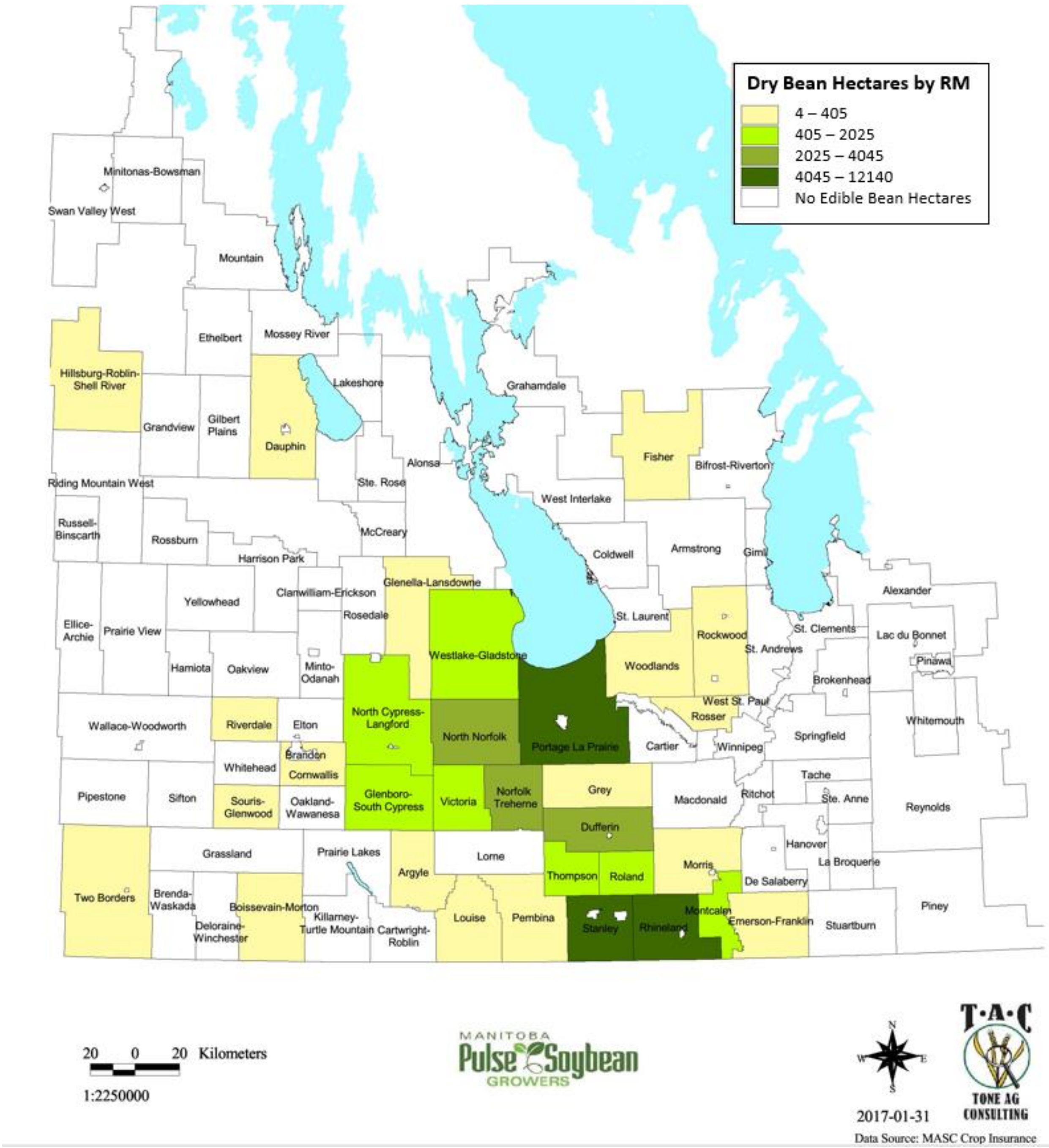



**Figure 2.1.** Dry bean hectares by municipality in Manitoba in 2016 (adopted from Anonymous 2015).

Over the past three years (2014 to 2016), navy bean production decreased in the province while pinto bean acreage has remained constant (Mitchell 2016). The acreage of the most commonly grown bean varieties also has changed in the last three years. In navy bean production, the standard “check” variety, Envoy, with its low-growing bush short-vine growth habit (type I) has decreased in seeded hectarage, while T9905 with its upright short-vine growth type (type II) has increased in hectarage seeded annually by 30%, making it the leading variety of navy bean planted in the province in 2016, when it accounted for 62% of navy bean production (Mitchell 2016). Comparatively, in pinto bean production, the standard “check” variety, Windbreaker (type II), has also decreased in acreage but remains the leading variety planted, accounting for approximately 76% of pinto production in 2016. A new variety, Monterrey (type II) which was introduced in 2015 has been gaining popularity and now accounts for roughly 15% of pinto bean production by area in Manitoba (Mitchell 2016).

### 2.4 Current Dry Bean Spatial Arrangement Recommendations

Since Manitoba accounts for such a large proportion of dry bean production in Canada it is important to invest in research suited to our local climate and soil conditions in order to determine the optimum agronomic methods for dry bean producers in Manitoba. Currently, most of the production recommendations in dry bean are based on data from other regions, specifically North Dakota, Ontario, and Saskatchewan, and have been focused primarily on the navy bean market class (Table 2.1) (Goodwin 2005, Government of Manitoba 2013). Existing recommendations for the province describe traditional wide-row productions methods as well as narrow-row solid-seeded production methods (Government of Manitoba 2013). Traditional production methods of growing dry bean in Manitoba involve the use of specialized row-crop equipment dedicated to row widths of typically 76 – 90 cm, and plant densities of 25 plants $m^{-2}$ (Table 2.1). Recommendations for narrow-row production systems using 19 and 38 cm row widths from Ontario and North Dakota indicate seeding at increased plant densities of 30 and 35 plants m$^{-2}$, respectively, to take advantage of the increased spacing between adjacent plants within the row at more narrow-row widths (Table 2.1) (Government of Manitoba 2013). Planting at narrow-row widths creates a more uniform distribution of plants throughout the field while in comparison, traditional row crop planting methods leave large spaces between rows. Plants are spaced closely together within the wide rows, likely increasing intraspecific competition among the crop plants within the row.

**Table 2.1.** Current recommendations in navy and pinto bean planted at narrow (< 38 cm) and wide (> 57 cm) row widths from Manitoba Agriculture (Anonymous 2015), North Dakota State University (Kandel 2014), Saskatchewan Pulse Growers (Anonymous 2015) and Ontario Ministry of Agriculture, Food and Rural Affairs (Brown 2017).

| Recommendation Source | Market Class | Recommended density (plants m$^{-2}$) |
|---|---|---|
| North Dakota State University | Pinto (wide row) | 17 |
| | Pinto (narrow row) | 25 |
| | Navy (wide row) | 22 |
| | Navy (narrow row) | 35 |
| Manitoba Agriculture | Navy (wide row) | 25 |
| | Navy (narrow row) | 30 – 40 |
| | Pinto (wide row) | 25 |
| | Pinto (narrow row) | 30 – 40 |
| Saskatchewan Pulse Growers | All (wide row) | 25 |
| | All (narrow row) | 45 |
| Ontario Ministry of Agriculture, Food and Rural Affairs | Navy (wide row) | 18 |
| | Navy (narrow row) | 30 |

Recommended seeding density in dry bean crops may be dependent on the growth habit, the yield-density relationship, percent emergence, seed cost and environment (Shirtliffe and Johnston 2002). Between determinate and indeterminate growth types, determinate type I bean genotypes tend to require greater plant densities than their indeterminate counterparts (type II) which tend to be more able to compensate for lower plant densities due to their continued growth during the reproductive phase (Nienhuis and Singh 1985). Breeders have been selecting traits that are more suited to narrow-row production in both type I and type II growth habits, such as characters promoting upright growth, a shorter growing season and increased pod clearance (Shirtliffe and Johnson 2002). These agronomically desirable traits for narrow-row production allow dry bean to be incorporated into a wider array of crop rotations since this enables growers to use existing farm equipment to produce solid-seeded stands. There is a need to invest in local research for production practices for dry bean in Manitoba, specifically plant spatial arrangement, since there has been a shift towards increased narrow-row production in recent years, trending away from traditional wide-row production systems.

**2.5 Plant Spatial Arrangement**

Spatial arrangement combines row spacing and plant stand density and has been shown to be a critical requirement to maximize yield and biomass accumulation through early and effective resource capture (Kiaer et al. 2013). Plant spatial arrangement also plays a key role in a crop's ability to tolerate biotic and abiotic stresses (Malik et al. 1993). More uniform plant spatial arrangements maximize the evenness of plants distributed in a two-dimensional space by creating a uniform grid-like pattern of plants across the field that have been shown to improve crop performance and yield (Griepentrog 2009, Wiener et al. 2001). In other crops, a uniform plant spatial pattern has been shown to increase seed yield by up to 32% in canola (Yang et al. 2014), 48% in maize (Marin and Weiner 2014), and 9.5% in spring wheat (Olsen et al. 2005). The underlying principle of improved crop performance in these spatially uniform stands is that, when crop plants are distributed more evenly throughout the field, resource utilization in each individual plant is maximized and the onset of intra-specific competition among plants is delayed. The degree of uniformity of the plant spatial arrangement displayed is due to a combination of the distance between rows (row spacing) and the distribution of plants within the row, which may be manipulated by altering seeding density while maintaining equidistant spacing of plants within the crop row (Table 2.2). Typically, uniformity is achieved by planting at narrower row widths and greater plant densities to attempt to ensure equidistant spacing within the crop row as well as between crop rows (Olsen et al. 2005, Esmaeilzadeh and Aminpanah 2015). The traditional wide-row cropping system in dry bean production (76 cm rows) creates an uneven distribution of plants throughout the field with large spaces between rows while plants are aggregated within the row resulting in intra-specific competition of light, water, and nutrients much earlier during crop development than if plant spatial arrangement was more evenly distributed across the field. Comparatively, at narrow row widths of 19 cm, more equidistant placement of plants within the row at moderate plant densities of 30 and 40 plants $m^{-2}$ creates a more uniform plant stand with equidistant spacing between and within rows that is not achieved at wider row widths (Table 2.2).

Achieving the ideal dispersion of plants within the row may not be feasible due to seedlings that do not germinate or emerge, creating gaps in the row (Griepentrog et al. 2009). This may be influenced by seeding equipment as well, as some machinery limitations may result in uneven distribution of seeds within the row (Government of Manitoba 2017). Additional considerations need to be taken since many studies in dry bean research are conducted under irrigated conditions which increases the carrying capacity of the field space, allowing for greater productivity and the ability to distribute plants more closely together within the row than may be seen in non-irrigated studies. Conversely under irrigated conditions, closer distribution of plants within the field may increase disease pressure.

**Table 2.2.** Distance (cm) between plants within the row at various plant density and row spacing combinations. Highlighted in bold is the most uniform arrangement.

| | Target plant stand density (plants $m^{-2}$) | | | | | |
|---|---|---|---|---|---|---|
| Row Spacing (cm) | 10 | 20 | 30 | 40 | 50 | 60 |
| 19 | 52.5 | 26.2 | **17.5** | 13.1 | 10.5 | 8.7 |
| 38 | 26.2 | 13.1 | 8.7 | 6.6 | 5.2 | 4.4 |
| 57 | 17.5 | 8.7 | 5.8 | 4.4 | 3.5 | 2.9 |
| 76 | 13.1 | 6.6 | 4.4 | 3.3 | 2.6 | 2.2 |

### 2.6 Row Spacing Effects on Yield

Previous research indicates the potential of type I and II dry bean to experience increased yields by reducing row spacing, despite differences in their plant architectures. Large yield increases have been seen with dry bean planted at increasingly narrow row widths between 19 and 38 cm compared to the traditional row crop production systems of 57 to 76 cm with similar plant densities (Griepentrog et al. 2009, Table 2.3). Grafton et al. (1988) found that by narrowing row widths from 75 cm to 25 cm, indeterminate pinto bean and determinate navy bean yields were increased by 52 and 44%, respectively. Further examining ten navy bean genotypes in that study, Grafton et al. (1988) found a 57% yield increase in seven genotypes grown at 19 cm row widths compared with 76 cm. In Ontario, Park et al. (1993) studied seven different genotypes (three type I bush beans and four type II upright beans) and on average witnessed a yield increase of 69% by planting at narrow rows of 30 cm instead of 80 cm. In a pathology study in Manitoba, Conner et al. (2006) consistently found greater yields in dry bean planted at the narrow row spacing (30 cm). A New Zealand study found a 57% seed yield advantage when decreasing row spacing from 40 cm to 20 cm combined with decreasing the plant spacing within the row from 10 cm to 4.8 cm in navy bean (Goulden 1976). In a study of type II small red bean, Blackshaw et al. (2000) found a 19% seed yield increase in beans planted at 23 cm rather than 69 cm row widths. Similarly, in type II black bean, Holmes and Sprague (2013) found a 19% yield advantage when beans were planted at 38 cm compared to 76 cm row widths.

**Table 2.3.** Summary of the literature comparing row spacing effects on yield in dry bean.

| Source | Narrow row width | Wide row width | Yield increase comparing narrow to wide row width |
|---|---|---|---|
| | -------------- cm | -------------- | % |
| Eckert et al. 2011 | 46 | 76 | 14 |
| Malik et al. 1993 | 23,46 | 69 | 16 |
| Blackshaw et al. 2000 | 23 | 69 | 19 |
| Holmes and Sprague 2013 | 38 | 76 | 19 |
| Grafton et al. 1988 | 25 | 75 | 44-52 |
| Goulden 1976 | 20 | 40 | 57 |
| Grafton et al. 1988 | 19 | 76 | 57 |
| Park et al. 1993 | 30 | 80 | 69 |

In navy bean under weed-free conditions, Malik et al. (1993) found narrow row widths yielded 16% more than the traditional wide row widths of 69 cm. More interestingly, under weedy conditions, the traditional wide row widths performed significantly worse that their narrow row counterparts, producing 40% less seed yield, and planting at the intermediate row width of 46 cm produced 11% less seed yield than at the narrow rows.

Most of these studies compared only two row widths, typically one wide row width of 57 or 76 cm and one narrow row width of either 19 cm, or more commonly, 30-38 cm and to determine the ideal row spacing it may be necessary to examine a wider range of row widths to maximize bean seed yield. Planting at reduced row widths has the potential to increase Manitoban dry bean producer yields.

## 2.7 Plant Density Effects on Yield

Seed is a major input cost of dry bean production, so considering the best target plant density is particularly important for growers. Plant density effects on seed yield are less consistent than row spacing, and the different growth habits of dry bean tend to influence the relationship between seed yield and density (Table 2.4). The yield-density relationship is a generalization of the total seed yield produced by a dry bean plant stand grown at different plant densities (Weiner and Freckleton 2010). The distinction between determinate and indeterminate growth habits may be critical in anticipating a seed yield response to planting density in dry bean. Neinhuis and Singh (1985) evaluated type I, II and III dry bean and noted differences in seed yield were greatest between determinate and indeterminate growth habits (type I vs. type II and III). Type I dry bean is known to respond more positively to increased planting densities, while indeterminate types II and III have been shown to have a consistent yield over a range of planting densities due to their greater ability to compensate for open spaces and fill in gaps in the plant canopy (Westermann and Crothers 1977).

An increase in seed yield with increasing plant densities in type I dry bean has been demonstrated in several studies. Neinhuis and Singh (1985) reported an asymptotic seed yield increase with type I pinto bean grown in Columbia over densities of 5 – 30 plants m$^{-2}$. Crothers and Westermann (1976) also found an asymptotic seed yield response in type I pinto bean grown in Idaho over densities of 11 – 97 plants m$^{-2}$. In Saskatchewan, Shirtliffe and Johnston (2002) found an asymptotic yield-density function provided the best fit in type I black and pinto bean grown at the range of 20 – 100 plants m$^{-2}$ under dryland conditions. Shirtliffe and Johnston (2002) further assessed plant densities economically and found, assuming a bean selling price of \$0.47 kg$^{-1}$, the most economical target plant density in type I pinto bean was 25 plants m$^{-2}$

(Shirtliffe and Johnston 2002). Blackshaw et al. (1999) studied a type I navy bean in Alberta and found a linear seed yield response to density, where increasing plant density from 24 to 48 plants $m^{-2}$ increased yield by an average of 36%. Goulden (1976) recommended that in addition to narrow row production, 70 – 104 plants $m^{-2}$ maximized yield when planted at 20 cm row widths, however plant density had no effect on seed yield when beans were planted at 40 cm row widths. Grafton et al. (1988) evaluated a type I navy bean in North Dakota and found a linear increase in seed yield in response to plants densities of 15 – 37 plants $m^{-2}$. In another North Dakota experiment testing the same density range, Schneiter and Nagle (1980) found no seed yield response in type I dry bean at three out of four site-years and only a small increasing in seed yield (178 kg $ha^{-1}$) at the fourth site-year. The literature tends to agree that type I dry bean responds positively to increasing planting density.

Several studies have shown no yield response to increasing plant densities in type II dry bean, indicating increasing plant density does not always increase bean seed yield. Grafton et al. (1988) determined seed yield was maximized with a plant density of 17 plants $m^{-2}$ in indeterminate pinto bean, irrespective of row width, as they did not observe a yield increase with increasing plant densities. No seed yield response to plant density was also found by Schatz et al. (2000) over a limited range of densities tested (20 –25 plants $m^{-2}$), by Schneiter and Nagle (1980) evaluating 10 – 32 plants $m^{-2}$, nor by Soratto et al. (2017) testing 11 – 17 plants $m^{-2}$ (Table 2.7). One study, conducted by Saindon et al. (1995) to evaluate white mould avoidance characteristics in dry bean, observed a 10 – 20% linear increase in seed yield in response to increased plant density from 20 plants $m^{-2}$ to 60 plants $m^{-2}$ testing four “upright” dry bean genotypes compared to a type III vine-type dry bean. However, Saindon et al. (1995) classified three of the four upright lines as type IIa and the fourth as a type Ia, making no distinction if these genotypes exhibit indeterminate or determinate growth, only describing them as erect plants, with branches producing a narrow crop canopy. It is likely the dry bean genotypes tested in their study were determinate types due to their morphological description and yield response to density, and should be more accurately described as type I growth habits. Malik et al. (1993) reported a significant positive dry bean seed yield response to planting density, evaluating both type I and II navy beans under weedy conditions, but found no response under weed-free conditions. Dry bean planted at lower densities suffered the most by the presence of weeds, suggesting that denser dry bean stands are able to compete more effectively with weeds, preventing yield loss compared to low-density plant stands. Neinhuis and Singh (1985) compared type I, II and III dry bean growth habits, reporting an asymptotic seed yield response in type I pinto bean and a parabolic seed yield response in type II and III pinto bean over a density range of 5 – 30 plants $m^{-2}$ in Columbia. In the literature, Neinhuis and Singh's experiment is one of two studies that evaluated type II dry bean densities lower than 10 plants $m^{-2}$. Reducing planting densities below 22 plants $m^{-2}$ reduced type II dry bean seed yield in their experiment, as did increasing planting densities beyond this optimum (Neinhuis and Singh 1985). Crothers and Westermann (1976) compared two type I and two type II pinto bean cultivars across a wide range of densities (11 – 97 plants $m^{-2}$) in Idaho. In their experiment, type I dry bean exhibited the expected asymptotic seed yield response to plant density, but the type II cultivars, UI-114 and Big Bend, did not respond consistently. Seed yield decreased with increasing planting density in UI-114, where seed yield was greatest at plant densities of 11 plants $m^{-2}$. In Big Bend, a parabolic seed yield response was recorded where plant densities greater and lower than 20 plants $m^{-2}$ resulted in decreased seed yield, similar to Neinhuis and Singh's (1985) experiment. Crothers and Westermann (1976) note that type II seed yields at high plant densities were more erratic due to white mould and severe lodging and that type II pinto bean was able to utilize the larger area per plant at low plant densities compared to type I pinto bean. Two other experiments conducted by Soratto et al. (2017) and Vieira el al. (2010) also found a decrease in type II dry bean seed yield with increasing plant density. Soratto et al. (2017) tested a limited range of plant densities (12 – 17 plants $m^{-2}$) in a type II/III pinto bean (prostrate growth habit with greater branching) in São Paulo, Brazil and found that planting at 12 and 15 plant $m^{-2}$ resulted in greater seed yield than planting at 17 plants $m^{-2}$. Vieira et al. (2010) also reported a reduction in type II/III dry bean seed yield with increasing planting densities, evaluating stand densities of 10 – 28 plants $m^{-2}$ in 2000 and 8 – 29 plants $m^{-2}$ in 2001 in Minas Gerais, Brazil.

Plant density for dry bean cannot be determined conclusively from the existing literature and appears to be heavily influenced by the plant architecture of the cultivar, and environmental and edaphic characteristics of the study sites. Further exploration of the yield-density relationship is necessary for our local environment.

**Table 2.4.** Summary of the literature covering plant density effects on yield in dry bean.

| Source | Location | Market class | Plant type | Row spacing (cm) | Densities tested (plants $m^{-2}$) | Seed yield response |
|---|---|---|---|---|---|---|
| Neinhuis and Singh (1985) | Columbia | pinto | I | 60 | 5 – 30 | asymptotic increase |
| Shirtliffe and Johnston (2002) | Saskatchewan | black | I | 20, 30 | 20 – 100 | asymptotic increase |
| Shirtliffe and Johnston (2002) | Saskatchewan | pinto | I | 20, 30 | 20 – 100 | asymptotic increase (less responsive) |
| Crothers and Westermann (1976) | Idaho | pinto | I | | 11 – 97 | asymptotic increase |
| Blackshaw et al. (1999) | Lethbridge, Alberta | navy | I | 23, 46, 69 | 24, 48 | linear increase (36%) |
| Grafton et al. (1988) | Fargo and Carrington, North Dakota | navy | I | 25, 50, 75, 100 | 15 – 37 | linear increase |
| Goulden (1976) | Christchurch, New Zealand | navy | I | 20, 40 | 35 – 104 | 70 – 104 plants $m^{-2}$ maximized yield at 20 cm row widths, no effect at 40 cm row widths |
| Schneiter and Nagle (1980) | Oakes, Carrington and Fargo, North Dakota | navy | I | 25, 50, 76, 101 | 15 – 37 | no response at three site-years, small increase in seed yield (178 kg $ha^{-1}$) with increasing density at one site-year |
| Malik et al. (1993) | Elora, Ontario | navy (weedy) | I, II | 23, 46, 69 | 25 – 38 | 12 – 16% yield increase (23 – 46 cm row widths) |
| Malik et al. (1993) | Elora, Ontario | navy (weed-free) | I, II | 23, 46, 69 | 25 – 38 | no response |
| Neinhuis and Singh (1985) | Columbia | pinto | II, III | 60 | 5 – 30 | parabolic (maximum at 22 plants $m^{-2}$) |
| Saindon et al. (1995) | Lethbridge, Alberta | navy, black, dark red kidney | I/IIa | 23 | 25 – 60 | linear increase (10 – 20%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Crothers and Westermann (1976) | Idaho | pinto | II | | 11 – 97 | decrease in UI-114 variety and parabolic in Big Bend variety |
| Grafton et al. (1988) | Fargo and Carrington, North Dakota | pinto | II | 25, 50, 75, 100 | 10 – 32 | no response |
| Schatz et al. (2000) | Carrington, North Dakota | navy, black | II | 18, 76 | 22 – 30 | no response |
| Schneiter and Nagle (1980) | Oakes, Carrington and Fargo, North Dakota | pinto | II | 25, 50, 76, 101 | 10 – 32 | no response |
| Soratto et al. (2017) | São Paulo, Brazil | pinto | II | 45 | 11 – 17 | no response |
| Vieira et al. (2010) | Minas Gerais, Brazil | pinto | II/III, III | 50 | 8 – 29 | decrease |
| Soratto et al. (2017) | São Paulo, Brazil | pinto | II/III | 45 | 12 - 17 | decrease; 12 – 15 plants $m^{-2}$ resulted in greater seed yield than 17 plants $m^{-2}$ |

### 2.8 Spatial Arrangement Effects on Canopy Development and Light Capture

Biomass accumulation and plant productivity are maximized by the acquisition and capture of resources above- and below-ground early in the growing season and is essential in Manitoba due to the relatively short growing season. Early canopy closure maximizes light interception (Kiaer et al. 2013). Maximum light interception early in the growing season shades out emerging weed species while increasing solar radiation captured by the crop. Earlier or more complete canopy closure is beneficial since more light is intercepted and utilized by the crop, providing more energy to invest in yield components. Blackshaw et al. (1999) found increased photosynthetically active radiation (PAR) interception by navy bean (type II and III) planted in narrow rows (23 cm) compared to wide rows of 69 cm, which never experienced complete canopy closure. In a similar study, type II small red bean planted in narrow row widths of 23 cm showed earlier canopy closure and increased PAR interception compared with wider row widths (Blackshaw et al. 2000). Further looking at row widths effects on canopy closure, Ziviani et al. (2009) found that ground cover was greater in beans planted in narrow rows of 30 and 40 cm than in 50 and 60 cm rows. Plant densities also play a role in the speed of canopy closure, Vieira et al. (2010) found the increased density stands of 16 plants $m^{-1}$ of row (50 cm) resulted in the quickest canopy closure. Planting at lower densities resulted in delayed canopy closure and sufficiently low densities (5 plants $m^{-1}$ of row) never achieved full closure of the canopy (Ziviani et al. 2009). Canopy closure occurs earliest in beans planted at narrow row widths and greater plant densities and this maximizes light interception which may translate to increased dry bean seed yield.

### 2.9 Pest Management and Spatial Arrangement

**2.9.1 Weed Suppression.** In addition to increasing yield, a dense, uniform plant arrangement increases weed suppression in crops (Esmaeilzadeh and Aminpanah 2015; Olsen et al. 2015) which is important since dry bean are a highly uncompetitive crop (Malik et al. 1993). Uncontrolled weed populations have the potential to reduce yields by more than 70% by competing with the crop for moisture, nutrients, and sunlight (Malik et al. 1993). These yield losses can occur even from relatively low weed pressure (Malik et al. 1993). Along with causing yield loss due to competition, some weeds when present at harvest may stain the bean seed, which may reduce harvest quality. In addition, weeds may contribute to disease pressure that the crop experiences by intensifying the conditions for disease development and by transferring diseases to the crop (Anonymous 2015). Currently recommended weed management practices in dry bean production in Manitoba are to plant into clean fields, and in-crop weed management consists of the application of a herbicide, with the inclusion of inter-row cultivations in beans planted in wider rows (Anonymous 2015, Goodwin 2005). Lack of weed control options is a problem in Manitoba, and an over-reliance on the few in-crop herbicides registered has developed in dry bean production. Of particular concern are broadleaf weeds since they occupy a niche more similar to dry bean than grassy weeds, allowing them to effectively compete for similar nutrients and space, and options for broadleaf weed management in-crop are limited. Additionally, with the popularization of minimum tillage systems, the occurrence of perennial broadleaf weeds is increasing and a need to improve management of these weeds in dry bean crops exists (Goodwin 2005). Maximization of the crops competitive ability may be one method that contributes to lower yield losses from weed pressure and increase the crop's innate advantage over weeds. Earlier canopy closure in the growing season maximizes light interception and increases the crop's competitive ability against weeds by shading the spaces between rows (Kiaer et al. 2013). This reduced weed competition may also then contribute to the increased yields seen with plant stands that have earlier and more complete canopy closure. Earlier canopy closure is possible with decreased row widths since less plant growth is required since the space between rows is reduced. Blackshaw et al. (2000) evaluated spatial arrangement and herbicides and found that the best weed control and highest yield were observed in the plant stands that combined planting in narrow row widths and at increased planting densities. Cultivar choice also plays a significant role in reducing weed biomass. In navy bean, the indeterminate type II short-vine plant architecture was shown to suppress weeds more effectively than their determinate type I bush counterparts (Malik et al. 1993). This is due to the ability of indeterminate growth habits to grow more quickly into the open inter-row space and intercept sunlight before it can reach the weed seedlings below. In the same study, Malik et al. (1993) found beans of both types planted in narrower row widths reduced weed biomass by 15-21% compared with the traditional wide row spacing of 69 cm and they found that increasing planting density had no effect on weed biomass.

Enhancement of a crop's utilization of nutrients and space was shown by Olsen et al. (2005) when they planted spring wheat at several densities and spatial patterns and discovered that the greatest seed yield and best weed suppression was that which combined greater density planting and a uniform crop spatial pattern. The uniformity of the spatial pattern allows for maximization of light capture and nutrient space of each individual plant within the crop. Achieving similar results in dry bean production is a possibility and a more uniform planting pattern occurs naturally when row spacing is reduced. A combination of using an efficacious herbicide and uniform planting pattern may be able to significantly reduce crop losses due to weeds and realize potentially greater seed yields in dry bean (Esmaeilzadeh and Aminpanah 2015). Holmes and Sprague (2013) studied the combined effect of row width and herbicide use in type II black bean in the Canadian prairies. While the effectiveness of herbicides were variable year to year, a consistent reduction of weed biomass occurred with the reduction of row spacing and offered improved management for the control of upright broadleaf weed species (Holmes and Sprague 2013). While weed suppression due to the plant spatial arrangement likely would not be sufficient to replace herbicide applications, it is a major component of an integrated weed management approach in Manitoban cropping systems.

**2.9.2. Disease Pressure.** Concerns of increasing white mould (*Sclerotinia sclerotiorum* (Lib.) de Bary) incidence have been expressed in dry bean crops planted in narrower rows and at greater densities due to reduced aeration and increased humidity below the crop canopy, creating the ideal microclimate for disease to flourish (Saindon et al. 1995). White mould has a widespread occurrence in the prairies, affecting 60-80% of the dry bean acreage annually depending on weather conditions (Goodwin 2005). Established field populations of white mould exhibit high pest pressure on susceptible dry bean crops, attacking all above-ground tissues of the dry bean plant. This is heavily influenced by seasonal growing conditions and the disease history of the field (Anonymous 2015). All dry bean market classes have the potential to increase yields with narrow row spacing as long as prevailing conditions do not favour development of plant diseases. Understanding and mitigating the potential severity of white mould disease presence in dry bean production systems is important to maximize yield potential.

Current disease management practices in Manitoba are based on the application of a fungicide, initially during early bloom and, if conditions for disease development persist, a second application to ensure adequate coverage of floral blossoms (Anonymous 2015, Goodwin 2005). Recommended practices include planting cultivars with upright growth habits that have branches held erect above the ground, thus reducing the amount of leaf area near the soil surface, planting at reduced densities to increase the distance between adjacent plants, and planting at increasing row widths to further separate plants, improve air flow, and slow the spread of the disease (Anonymous 2015). In dry bean production, the optimal time for a fungicide application to limit white mould development is at 100% bloom when there are 2-3 blossoms per plant (Wunsch 2014). Timing of infection is also important. If white mould develops at late bloom, no significant effect on yield is observed, whereas if white mould mycelia develop at early bloom, increased disease presence throughout the canopy will occur, leading to a significant negative impact on bean yield (Wunsch 2014). A crucial component for fungicide efficacy is appropriate coverage with fungicides, and is achieved by timing applications to maximize penetration through the canopy to the soil surface (Schwartz et al. 1978; Wunsch 2014).

The environment below the canopy is heavily influenced by plant architecture (Park 1993, Saindon et al. 1995). Plant architecture and growth habit play a large role in dry bean susceptibility to white mould with vining bean genotypes typically experiencing increased severity when the disease is present compared to cultivars with upright habits since erect canopies experience more air flow and less contact between neighbouring plants (Saindon et al. 1995). In Alberta, Saindon et al. (1995) determined that upright type II genotypes could be grown in 23 cm rows without increasing the risk of white mould under irrigation. Schwartz et al. (1978) determined that the growth habit, indeterminate or determinate, did not exclusively affect the prevalence of white mould, but that a more important factor was the distribution of the leaf area near the ground. Selecting dry bean genotypes with an upright plant architecture has been shown to be a beneficial tool to prevent the rapid spread of white mould throughout the crop canopy.

During a prolonged period of high humidity throughout flowering, the distance between plants within the row (planting density) is the most important factor in determining disease severity (Lee et al. 2005). Lee et al. (2005) used equal seeding densities at 19 and 76 cm row widths and recorded a greater disease severity index, accompanied by a significantly lower yield, in beans planted at 76 cm row widths. This was due to the increased crowding within rows with the wide-row spacing.  Even though additional space between rows for air flow is present, the density within the row contributes to the disease severity and the spread of disease throughout the row.

Reduced densities within-rows decreased the white mould incidence and severity in a study in Brazil in cultivars with an indeterminate vining growth habit (Vieira et al. 2010). Spatial arrangement of plants within rows was more important in white mould management than the distance between rows under high disease pressure conditions (Wunsch 2014). Reducing plant densities may be necessary to effectively manage white mould disease incidence, and should be an important consideration when determining plant spatial arrangement in dry bean production. Additionally, in North Dakota, Wunsch (2014) concluded that, while a greater overall severity of white mould was observed in narrow-row spacing production practices, the yield maximization that occurred with narrow-row production could effectively combat this loss since narrow-row production resulted in significantly greater yields, despite increased disease severity.

**2.9.3 Integrated Pest Management Strategies.** Development of independent integrated pest management strategies for weed management and disease management tends to provide conflicting recommendations with respect to the spatial arrangement of plants within the field. Developing recommendations that provide a synthesis of these two conflicting pest management practices, minimizing their trade-offs, is a crucial component of determining the recommended plant spatial arrangement in dry bean production in Manitoba and is especially difficult since a substantial variation in weed and disease pressures is present among years. Timing of these two management systems differs, with damage from weed interference occurring earlier in the season, between 20 – 42 days after planting during vegetative development, while damage from white mould principally accumulates later during bean reproductive development phases (Anonymous 2015). Disease management is important, but only economically critical if the yearly growing conditions in the field are conducive to white mould development and prevalence. Unfortunately, these conditions are often not readily predictable earlier in the growing season before symptoms are apparent in the crop, at which point it is often too late for management. Weed management is equally important since large yield losses are seen annually as dry bean is such a poor competitor. Effective management of weeds in-crop has a substantial influence on disease prevalence, reducing white mould severity and contributes to disease management (Pynenburg et al. 2011). Improving the competitive ability of dry bean crops, while limiting the conditions for the development of serious white mould outbreaks is important to consider in the development of integrated pest management strategies and plant spatial arrangement recommendations. Planting arrangements will need to produce a plant stand with that can balance effective white mould prevention and minimization with a crop stand that is effective at competing weeds through early canopy closure and light interception. Field experiments are necessary to determine the ideal combination of row spacing and plant stand density, but it may be that the best arrangement is the one that is able to effectively maximize yield, which typically occurs in conjunction with improved weed control, while allowing for adequate aeration below the crop canopy. This is expected to be influenced by the growth habit of the plant, since plant architecture inherently influences the competitive ability and disease susceptibility characteristics of the plant. Yield maximization may occur in intermediate row widths and plant densities due to an effective balance of disease avoidance and weed suppression, or it may be that the yield gained from planting at narrow rows widths is able to outweigh the damage from disease pressure in the years where conditions for disease are met.

### 2.10 Experimental Objectives and Hypotheses

The objective of this research is to validate existing recommendations or determine new recommendations on plant stand density and row spacing for dry bean varieties with differing plant architectures to maximize seed yield. From this research, I hypothesize that dry bean planted at narrow-row widths will yield better than when planted at wide-row widths, regardless of plant architecture. Regarding plant densities, the navy variety Envoy (type I) will respond positively to increasing plant density while T9905 (type II) navy bean and pinto varieties Windbreaker (type II) and Monterrey (type II) will not respond to plant density. Additionally, canopy closure will occur more quickly in beans planted in narrow row widths than in wider rows, and the greater density plant stands should have earlier canopy closure than the lower plant density stands. In environments conducive to white mould development it is expected that, with increasing plant densities, a corresponding increase in white mould severity will occur.

# 3.0 MATERIALS AND METHODS

## 3.1 Experimental Site Characteristics

**3.1.1 Soil composition.** Field experiments were conducted at the Ian N. Morrison Research Farm at Carman, Manitoba, and at the Agriculture and Agri-Food Canada Crop Development Site at Portage la Prairie, Manitoba in 2015 and 2016. The soil at the Carman site in 2015 was a Rignold, Gleyed Black, Chernozemic imperfectly-drained loam soil (Lacustrine, Gleyed black) andin 2016, the soil was an Eigenhof, Orthic Black well-drained clay loam (Lacustrine, Orthic Black) (Ellis and Shafer 1943, Anonymous 2016). The soil at the Portage la Prairie site was a Chenozemic imperfectly-drained loam (Lacustrine) (Ehrlich, Poyser, and Pratt 1957, Anonymous 2016). Soil characteristics and residual soil test information are provided in Table 3.1.

**Table 3.1.** Soil characteristics of experimental sites in 2015 and 2016.

| Site-year | | Sample depth | Soil characteristics | | | | | | | | | Preceding Crop |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | N | S | P | K | Soil subgroup | Texture | Drainage | pH | O.M. | |
| | | cm | --- kg ha$^{-1}$ --- | | --- ppm --- | | | | | | - % - | |
| Carman 2015[a] | | 0-15 | 52.6 | 17.9 | 16 | 294 | GB | CL | Imperfect | 5.5 | 6.0 | Wheat |
| | | 15-30 | - [c] | - [c] | - | - | | | | - [c] | | |
| Portage la Prairie 2015[b] | Navy | 0-15 | 35.8 | 336.0 | 16 | 250 | Black | L | Imperfect | 8.0 | 5.8 | Millet |
| | | 15-30 | 26.9 | 181.4 | - | - | | | | 8.7 | | |
| | Pinto | 0-15 | 31.4 | 20.2 | 13 | 347 | | | | 8.0 | 6.0 | Barley |
| | | 15-30 | 37.0 | 87.4 | - | - | | | | 8.5 | | |
| Carman 2016[a] | | 0-15 | 11.2 | 11.2 | 9 | 350 | OB | CL | Well | 6.6 | 5.5 | Oats |
| | | 15-30 | 12.3 | 6.7 | - | - | | | | 7.1 | | |
| Portage la Prairie 2016[a] | Navy | 0-15 | 14.6 | 11.2 | 21 | 272 | Black | L | Imperfect | 8.0 | 4.7 | Flax |
| | | 15-30 | 97.4 | 188.2 | - | - | | | | 8.4 | | |
| | Pinto | 0-15 | 48.2 | 31.4 | 14 | 357 | | | | 8.0 | 6.0 | Wheat |
| | | 15-30 | 70.6 | 134.4 | - | - | | | | 8.5 | | |

[a] Spring soil test
[b] Fall soil test
[c] Data unavailable since sample not taken

## 3.2 Experimental Design and Plot Management

**3.2.1 Field Preparation.** In the 2015 experiments, the preceding crop at Carman was spring wheat, and at Portage la Prairie, the prior crops were millet in the navy bean trail and barley in the pinto bean experiment. In the 2016 experiments, the preceding crops at Carman were oats and at Portage la Prairie, they were flax in the navy bean experiment, and wheat in the pinto bean experiment.

Field preparation consisted of a fall cultivation with an additional spring glyphosate pre-seeding burn-off application at Carman at a rate of 2 kg a.e. $ha^{-1}$. At Portage la Prairie, an additional spring cultivation pass was needed to prepare a weed-free seedbed. A pre-emergent herbicide application was administered at Carman in 2015, and Portage la Prairie in 2015 and 2016, consisting of s-metolachlor (Dual II Magnum, Syngenta Corporation) at a rate of 130.85 g a.i. $ha^{-1}$ plus sulfentrazone (Authority, Nufarm Agriculture) at a rate of 619.2 g a.i. $ha^{-1}$. Pre-emergent herbicide application at Carman was applied using a tractor-mounted sprayer (R-Tech) calibrated to deliver 111.25 L $ha^{-1}$ at 262 kPa using flat fan nozzles. At Portage la Prairie, pre-emergent herbicide applications were performed with a tractor-mounted sprayer (Summers) with flat fan nozzles, delivering 166.3 L $ha^{-1}$ at 275.8 kPa.

Prior to seeding, granular fertilizer was broadcast based on AgVise recommendations and incorporated perpendicular to the plot direction to ensure adequate soil fertility levels. Soil fertility (N-P-K-S) was determined by soil samples taken at depths of 0 – 15 cm and 15 – 30 cm (Table 3.1). At Carman in 2015, 61.74 kg of actual nitrogen $ha^{-1}$, 16.84 kg of actual phosphorous $ha^{-1}$ and 11.79 kg of actual sulfur $ha^{-1}$ were applied. At Portage la Prairie in 2015, 44.64 kg of actual nitrogen $ha^{-1}$, 35.71 kg of actual phosphorous $ha^{-1}$, 26.79 kg of actual potassium $ha^{-1}$ and 8.93 kg of actual sulfur $ha^{-1}$ were applied. At Carman in 2016, 56.13 kg of actual nitrogen $ha^{-1}$

and 28.07 kg of actual phosphorous $ha^{-1}$ were applied. At Portage la Prairie in 2016, 7.14 kg of actual nitrogen $ha^{-1}$ and 35.71 kg of actual phosphorous $ha^{-1}$ were applied.

**3.2.2 Experimental Design and Treatments.** Plant spatial arrangement was evaluated in the two most commonly grown market classes of dry bean in Manitoba, pinto and navy bean. The experimental design was a three-way factorial randomized complete block design that was laid out using a split-split-plot design. The navy and pinto bean experiments each had four replicates with variety, row spacing, and seeding density as the three factors. The main-plot was variety with two levels, cultivars chosen were either an indeterminate bush short vine (Type I) or determinate upright short vine (Type II) growth habit. Navy bean cultivars used were Envoy (Type I) and T9905 (Type II). Pinto bean cultivars included Windbreaker (Type II) and Monterrey (Type II). Within each variety sub-plots were row spacing, sown at four row widths including 19, 38, 57 and 76 cm. Sub-sub-plots comprised of five seeding densities were randomized within each row spacing sub-plot. Navy bean were seeded to target plant densities of 20, 30, 40, 50, and 60 plants $m^{-2}$ and the larger-seeded pinto bean seeded at target plant densities of 10, 20, 30, 40, and 50 plants $m^{-2}$.

**3.2.3 Seeding.** In 2015, experiments at Carman and Portage la Prairie were seeded on May 29 and on June 4, respectively. In 2016, seeding was slightly delayed due to wet weather conditions. The Carman location was seeded on June 9 and at Portage la Prairie navy bean were seeded on June 14 and pinto bean were seeded on June 15. All plots were seeded using a low-disturbance, double-disc opener drill (R-Tech, model). Seeding depth was targeted to a recommended depth of 3-5 cm (Government of Manitoba 2017), though pre-emergent herbicide restrictions suggested depths greater than 4 cm (Government of Manitoba 2015). Prior to seeding, Envoy navy seed (AGT Canada) was treated with 2.35% fludioxonil, plus 3.52% metalaxyl-M as a liquid seed treatment and 500 g $L^{-1}$ sedaxane formulated as a suspension (Vibrance Maxx, Syngenta). T9905 navy seed (Legumex Walker), Monterrey pinto seed (Legumex Walker) and Windbreaker pinto seed (Legumex Walker) were treated with 40.3% fludioxonil (Maxim, Syngenta), 33.3% mefenoxam (Apron XL, Syngenta), and 9.6% azoxystrobin (Dynasty, Syngenta).

Plots were seeded to a length of 8 m and a width of 2.5 m, resulting in twelve rows in the 19 cm row width, six rows in the 38 cm row width, five rows in the 57 cm row width, and four rows in the 76 m row width treatments per plot. The plot area of each respective row width was multiplied by the seeding density to achieve the number of plants required in each plot, this was then corrected using the percent germination of the seeds to achieve the target densities in each plot. In 2015, the percent germination of the seed was taken from the supplier. In 2016, the percent germination was determined by germinating 100 seeds of each variety in petri dishes (Table 3.2). The thousand-kernel weight (TKW) was used to determine the weight of seed required for each row spacing / seeding density combination and was determined by averaging five counts of 100 seed weights and multiplying to get the average TKW (g) in 2015 (Table 3.2). After seeding, plots were trimmed to a length of 6 m.

**Table 3.2.** Percent germination (%) of navy bean and pinto seed in 2015 and 2016 and the average thousand-kernel weight (g) in 2015.

| | Germination | | Thousand-kernel |
|---|---|---|---|
| Variety | 2015 | 2016 | weight |
| | ---- % ---- | | - g - |
| Envoy | 92 | 82 | 214.0 |
| T9905 | 90 | 98 | 252.4 |
| Windbreaker | 97 | 92 | 452.2 |
| Monterrey | 90 | 96 | 358.0 |

**3.2.4 In-season Pesticide Applications.** For in-season weed control at Portage la Prairie, clethodim (Centurion, Bayer CropScience Inc.) (444 g a.i. $ha^{-1}$) and 1.0% AMIGO surfactant (Bayer CropScience Inc.) were applied in the middle of July in 2015 using a tractor-mounted sprayer (Summers) calibrated to deliver 83.0 L $ha^{-1}$ at 275.8 kPa using flat fan nozzles. Towards the end of June at Carman in both years and at Portage la Prairie in 2016, a tank-mix of bentazon (Basagran Forte, BASF Canada) (1080 g a.i. $ha^{-1}$) imazamox (Solo, BASF Canada) (20.23 g a.i. $ha^{-1}$), and BASF 28% UAN (28-0-0) (2.0 L $ha^{-1}$) was applied for in-crop weed control. At Portage la Prairie, in-season herbicide applications were performed with a tractor-mounted sprayer (Summers) with flat fan nozzles, applying 166.3 L $ha^{-1}$ at 275.8 kPa.

Early August in 2016, a foliar fungicide was applied to control white mould (*Sclerotinia sclerotiorum* (Lib.) de Bary) at anthesis. No fungicides were applied in 2015. At Carman 2016, 70% boscalid (Lance WDG Fungicide, BASF Canada) was applied at a rate of 536.0 g a.i. $ha^{-1}$, and at Portage la Prairie 70% thiophanate-methyl (Senator 70WP, Engage Agro Corporation) was applied at a rate of 1.2 kg a.i. $ha^{-1}$. Senator fungicide application at Portage la Prairie was applied using a tractor-mounted sprayer (Summers) calibrated to deliver 988 L $ha^{-1}$ at 275.8 kPa using flat fan nozzles. Pesticides at Carman were applied using a tractor-mounted (R-Tech) sprayer calibrated to deliver 111.25 L $ha^{-1}$ at 262 kPa using flat fan nozzles.

### 3.3 Data Collection

Monthly temperature and precipitation data in 2015 and 2016, and long-term (1981 - 2010) averages were obtained from nearby Environment Canada weather stations at Carman (49°26' N 98°09' W) and Portage la Prairie CDA (49°57' N 98°16' W).

**3.3.1 Plant Stand Densities.** Early season emergence counts were taken to determine actual plant stand densities. To avoid potential edge effects, no samples were obtained from the edge rows or the front or back half meter of each plot. In 2015, the number of emerged seedlings in two meters of row per plot were counted. This count was expanded in 2016 to three meters of row per plot to improve the accuracy of this response variable. From these counts, plant stand density was determined.

**3.3.2 Above-Ground Resource Capture.** The capacity of above-ground resource capture was evaluated using ground cover image analysis measured throughout the growing season until canopy closure (Lati et al. 2011). Ground cover images were taken in the afternoon with the camera held by hand horizontally above each experimental unit at a height of approximately 1.5 m. In 2015, ground cover images were taken during the vegetative development stages (V3) and at the reproductive development stages (R2 - R3). In 2016, four time points of ground cover images were taken at Carman (VE, V2, V4 - V5, R2), and three time points taken at Portage la Prairie (VE - V1, V4, R1). Only three time points were taken at Portage la Prairie since a hailstorm defoliated much of the experiment at the R1 developmental stage, preventing further canopy closure. Ground cover images were processed using *Assess 2.0* to determine the percentage of ground covered by bean foliage in each image. It is worth noting that the accuracy of late-season ground cover assessment can be influenced by the amount of shading of lower leaves in the canopy (Patrignani and Ochsner 2015). As percent ground cover approaches 100% Assess 2.0 may underestimate canopy cover due to shadows.

**3.3.3 Canopy Height and Harvestability.** The height of the main canopy was recorded on five plants per plot once the crop reached maturity (R4 - R5) to estimate the maximum stature of a typical mature individual. Additionally, the height of the attachment point of the lowest pod was measured to estimate the harvestability of the crop (Perez-Harguindeguy et al. 2013).

**3.3.4 Disease Evaluation.** Disease severity ratings of white mould (*Sclerotinia sclerotiorum*) were taken in all treatments using a 0 - 5 rating scale (0 = none, 1 = confined to one to three small leaves, 2 = one to several running lesions with moderate mycelial growth, 3 = mycelial development or wilt involving up to 25% of foliage, 4 = extensive mycelial growth or wilt covering up to 50% of the foliage, 5 = death due to massive mycelial growth or wilt (Saharan and Mehta 2008)). Ten plants were selected randomly and assessed in each plot at the R5 - R7 developmental stage of the dry bean crop. Ratings were averaged to determine mean severity of white mould in each plot.

**3.3.5 Seed Yield.** Beans were harvested by hand near the end of September in both years, by removing three meters of row in every plot, excluding plot edges. Hand-harvested samples were threshed using a stationary thresher (Bill's Welding, Pulman, WA) then the seed was cleaned, weighed, and corrected to a moisture content of 16.5%. Initial moisture content of the samples was determined by placing samples in an oven for two days at 50 °C and then weighed again. The percent moisture content of the sample was determined. Then the final yield (kg $ha^{-1}$) was then determined, correcting for moisture content.

### 3.4 Statistical Analysis

Statistical analysis was conducted using SAS 9.4 software (SAS Institute, Carey, NC). Prior to analysis, residuals for the following response variables: yield (square-root transformed yield), canopy height, lowest pod height, white mould severity, and percent ground cover were tested for normality using the Shapiro Wilks test in the univariate procedure (PROC UNIVARIATE). Potential outliers were identified based on studentized residuals using Lund's test (Type I error rate = 0.05) and were examined to see if they were influential to the analysis (Lund 1975). Influential values were only removed if there was a clear, additional reason to do so. Yield data were square root transformed for analysis, but data presented are untransformed.

Analysis of variance (ANOVA) was used to test treatment effects and their interactions within dry bean market class using the mixed procedure (PROC MIXED) of SAS 9.4 for the following response variables: yield (square-root transformed yield), canopy height, and lowest pod height. Treatment means were separated based on Fisher's protected LSD ($\alpha = 0.05$) using the pdmix 800 macro (Saxton 1998). Where letter separation was not able to be determined by the pdmix 800 macro due to missing data points, LSDvalzz were used to manually determine significant separations. Variety, row spacing, seeding density, site-year, and their interactions were considered fixed effects while experimental replication nested within site-year, variety by replication(site-year) and variety by row spacing by replication (site-year) were considered random. Homogeneity of variance was corrected using the group statement when necessary. The Type 3 option was used to estimate sum of squares which were used to examine variance components which, in addition to p-values, were used to determine how to proceed with the statistical analysis (Eckert et al. 2011, Gulden et al. 2011). White mould severity was used as a covariate, and when significant, included in the model.

The GLIMMIX procedure was used to test treatment effects and their interactions for the white mould severity and ground cover response variables using the beta distribution. Variety, row spacing, seeding density, site-year, and their interactions were considered fixed effects while experimental replication nested within site-year, variety by replication(site-year) and variety by row spacing by replication (site-year) were considered random. The default link function with the beta distribution was used and the model fit was determined by comparing $\chi^2$ values.

To model the effects of plant densities and row spacing, the regression procedure (PROC REG) of SAS 9.4 was used to determine the linear and quadratic slopes and intercepts of actual plant stand density and row spacing on dry bean seed yield, white mould disease severity and ground cover. The regression procedure was run by variety, site-year and row spacing. Data were combined for this analysis as dictated by the ANOVA below.

An additional analysis ANOVA was conducted within each dry bean market class and within each site-year. This analysis modeled the linear and quadratic slopes of the response variables in relation to actual plant density, a continuous variable, rather than seeding density, which is categorical at each site-year. The effect of other factors (variety and row spacing) and their interactions on the slopes was determined using this approach. Treatment differences were gleamed from the PROC REG results. For yield, slopes and intercepts were determined while for ground cover and white mould severity, the lines were forced through the origin. Random effects included replicate, variety by replicate, and variety by row spacing by replicate.

The correlation procedure (PROC CORR) of SAS 9.4 was used to determine Pearson's correlation coefficient (r) for seeding density and actual plant stand density as a measure of the linear correlation between the two variables. Pearson's R was converted to the coefficient of determination ($R^2$) as a measure of the proportion of the variance in the dependent variable that was explained by the independent variable.

## 4.0 RESULTS

In the navy bean experiment, the response variable yield had several significant interactions with variety and site-year (Table 4.3.1). Since other response variables such as white mould severity, above-ground resource capture and canopy and lowest pod heights help explain yield they also have been presented separated by variety and site-year, irrespective of statistical significance.

### 4.1 Growing Conditions

Monthly temperature and precipitation data in 2015 and 2016, and long-term (1981 - 2010) averages were obtained from nearby weather stations at Carman (49°26' N 98°09' W) and Portage la Prairie CDA (49°57' N 98°16' W) (Table 4.1). On 2016 Aug. 16 a hailstorm passed through the Portage la Prairie site, causing damage to the navy bean experiment and substantial damage to the pinto bean experiment. Damage caused by this weather event likely affected white mould severity, crop canopy height parameters and seed yield at this location (Figure 4.5.7, Table 4.8.2, Table 4.4.3).

**Table 4.1.** Monthly and long-term 30-year average (1981-2010) temperature (°C) and average precipitation (mm) at Carman and Portage la Prairie, Manitoba in 2015 and 2016. Long-term temperature averages were not available from Portage la Prairie CDA Weather Station.

| | Carman | | | Portage la Prairie | | |
|---|---|---|---|---|---|---|
| Month | 30-yr average | 2015 | 2016 | 30-yr average | 2015 | 2016 |
| | | | Temperature (°C) | | | |
| May | 11.6 | 10.7 | 13.6 | - | 11.3 | 14.2 |
| June | 17.2 | 17.5 | 17.1 | - | 18.1 | 17.4 |
| July | 19.4 | 19.9 | 19.4 | - | 20.8 | 19.7 |
| August | 18.5 | 18.3 | 18.4 | - | 18.8 | 19.7 |
| | | | Precipitation (mm) | | | |
| May | 69.6 | 98.8 | 108.1 | 58.4 | 84.9 | 65.1 |
| June | 96.4 | 75.3 | 95.4 | 90 | 52.6 | 87.6 |
| July | 78.6 | 109.3 | 78.7 | 78.4 | 176.7 | 114.1 |
| August | 74.8 | 47.3 | 57.7 | 68.3 | 64.2 | 108.4 |
| Total | 319.4 | 330.7 | 339.9 | 295.1 | 378.4 | 375.2 |

The monthly temperature range fell within normal 30-year averages (1981-2010) in 2015 and 2016 at both Carman and Portage la Prairie (Table 4.1). Total rainfall was above the long-term averages in both years, providing sufficient moisture for plant development and pod filling. Above-average rainfall in late May in 2016 delayed planting into June at both sites, and rainfall in early June further delayed planting at Portage la Prairie.

**4.2 Plant Densities**

In both navy and pinto bean experiments at all site-years, mean actual plant stand densities were similar to the targeted planting densities with the exception of the navy experiment at Portage la Prairie in 2016 (Figure 4.2.1). For clarity, targeted planting densities will be referred to throughout as seeding densities. In navy bean at Portage la Prairie in 2016, the actual plant stand density means were 10 – 13 plants $m^{-2}$ and, surprisingly, did not vary with increasing seeding densities (Figure 4.2.1). This reduced emergence was likely due to wet field conditions that contributed to poor and variable seed placement during seeding. Wet soils also contributed to the seeder malfunctioning (plugged openers) in the 19 cm row width treatments. Since the Portage la Prairie 2016 site-year did not provide the anticipated treatment structure and plant spatial arrangements, it was excluded from further analysis.

Pinto bean at Portage la Prairie in 2016 also experienced reduced emergence but only at the greater seeding densities. Seeding densities targeting 30 – 50 plants $m^{-2}$ resulted in proportionally lower emergence, however, these treatments still resulted in the greatest plant stand densities at this site-year (Figure 4.2.2). Seeding densities and actual emerged plant densities were highly correlated in navy bean, excluding Portage la Prairie in 2016, and at all site-years in pinto bean (Table 4.2.1).

**Table 4.2.1.** Correlation and p-values of actual emerged plant density and seeding densities at the Carman and Portage la Prairie in 2015 and 2016.

| | Carman | | | | Portage la Prairie | | | |
|---|---|---|---|---|---|---|---|---|
| | 2015 | | 2016 | | 2015 | | 2016 | |
| | R | p-value | R | p-value | R | p-value | R | p-value |
| Navy bean | 0.83 | <0.0001 | 0.72 | <0.0001 | 0.76 | <0.0001 | 0.06 | 0.4963 |
| Pinto bean | 0.76 | <0.0001 | 0.72 | <0.0001 | 0.82 | <0.0001 | 0.78 | <0.0001 |

In both navy and pinto bean, the actual emerged plant densities of the greater seeding density treatments tended to be lower than targeted, but still produced the highest mean plant densities (Figures 4.2.1, 4.2.2). At all densities, pinto bean at Portage la Prairie in 2015 achieved greater mean emergence than the seeding densities (Figure 4.2.2). Although emergence tended to be slightly greater than the seeding density, it still followed the expected progression of increasing plant stand densities. Variation across seeding densities remained consistent within sites for navy and pinto bean (Table 4.2.2).

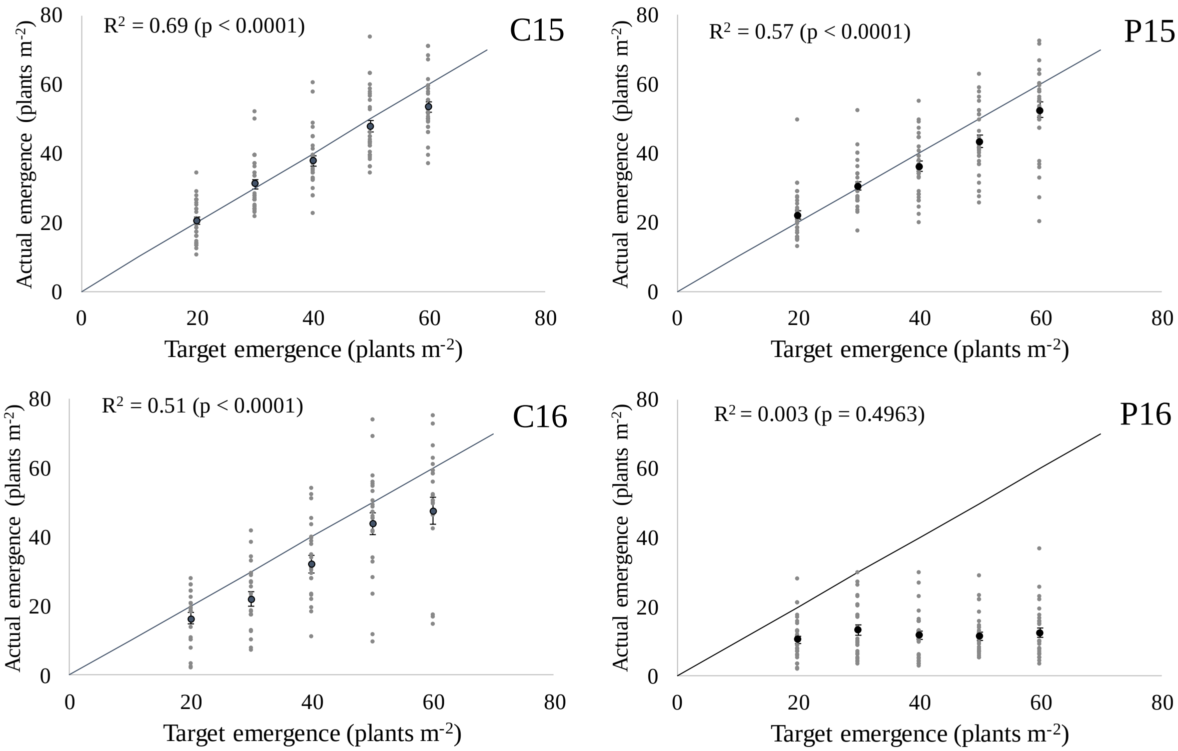



**Figure 4.2.1.** Actual plant emergence (plants $m^{-2}$) at each seeding density, denoted target emergence (plants $m^{-2}$) in navy bean at Carman (C) and Portage la Prairie (P) in 2015 and 2016. The coefficients of determination ($R^2$) and p-values are reported. The solid line indicates where actual emergence equals targeted emergence and the mean actual emergence at each seeding density is reported in black with error bars representing plus/minus one standard error of the mean.

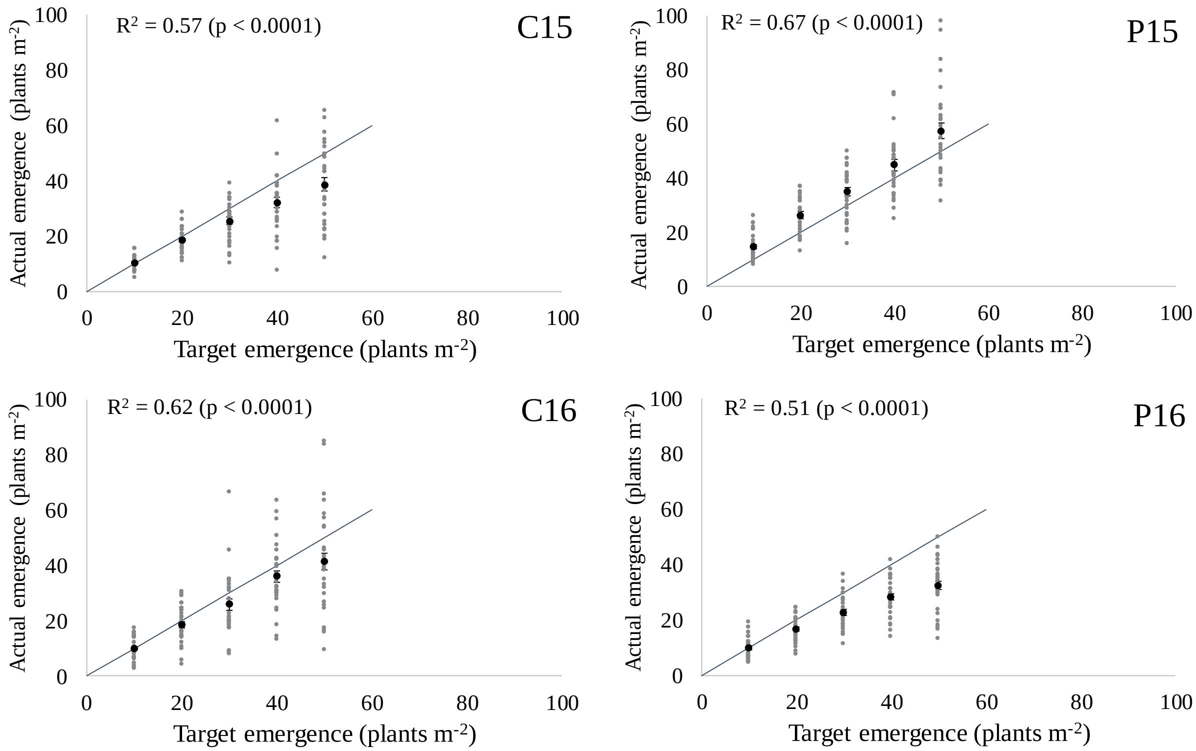



**Figure 4.2.2.** Actual plant emergence (plants $m^{-2}$) at each seeding density, denoted target emergence (plants $m^{-2}$) in pinto bean at Carman (C) and Portage la Prairie (P) in 2015 and 2016. The coefficients of determination ($R^2$) and p-values are reported. The solid line indicates where actual emergence equals targeted emergence and the mean actual emergence at each seeding density is reported in black with error bars representing plus/minus one standard error of the mean.

**Table 4.2.2** Coefficient of variation (%) in navy and pinto bean by seeding density treatment at Carman and Portage la Prairie in 2015 and 2016.

| | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| Seeding density (plants $m^{-2}$) | 2015 | 2016 | 2015 | 2016 |
| | Navy bean | | | |
| | ------------------- % ------------------- | | | |
| 20 | 28.5 | 46.0 | 32.6 | 59.1 |
| 30 | 24.8 | 41.3 | 22.4 | 58.8 |
| 40 | 21.5 | 33.8 | 24.2 | 58.6 |
| 50 | 19.8 | 35.3 | 22.5 | 52.1 |
| 60 | 15.4 | 31.8 | 23.4 | 59.9 |
| | Pinto bean | | | |
| | ------------------- % ------------------- | | | |
| 10 | 25.3 | 39.9 | 32.2 | 40.5 |
| 20 | 23.4 | 34.7 | 25.8 | 27.0 |
| 30 | 27.5 | 43.5 | 25.8 | 26.1 |
| 40 | 32.4 | 32.4 | 26.2 | 24.8 |
| 50 | 36.2 | 42.6 | 28.6 | 27.9 |

## 4.3 Navy Bean Yield

Site-year and row spacing were the primary factors contributing to variation in navy bean seed yield. Together, they accounted for 62.4% of the total variation in navy bean seed yield in these experiments (Table 4.3.1). Overall, Envoy navy bean produced about 8% less seed yield (3 659 kg $ha^{-1}$) than T9905 navy bean (3 963 kg $ha^{-1}$) however, this effect accounted for less than 2% of the total variation in this market class. Several significant interactions among variety, site-year and other fixed effects were observed in the navy bean yield data (Table 4.3.1) and have been separated to distinguish effects (Table 4.3.2). Once separated by variety and site-year, it was apparent that row spacing, and not seeding density, was the main contributor to variation in navy bean seed yield. Variation in row spacing alone contributed between 28.0 - 68.3% to the total sum of squares while the contribution of seeding density was much smaller (2.0 – 16.4% of the total sum of squares) (Table 4.3.3). The contribution of seeding density to navy bean yield was significant only at two site-years and in only one variety in each instance. Additionally, seeding density alone only contributed more than 10% of the total sum of squares at Portage la Prairie in 2015 in the T9905 variety. When the effect of seeding density was significant, the interaction of row spacing*seeding density also was significant, but the interaction effect contributed more to the total sum of squares than the main effect.

At the Portage la Prairie 2016 navy bean experiment, poor and non-uniform bean seedling emergence contributed to a lack of the expected seedling density-gradient treatment structure and as a result, was excluded from subsequent analyses. Excluding this site-year from the analysis caused the variety*row spacing*seeding density and variety*seeding density*site-year interactions to no longer be significant (Table 4.3.1).

**Table 4.3.1.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density, site-year and their interactions and the percentage of the total sum of squares (% SS) in the dependent variable seed yield in a combined analysis in the navy bean market class with and without the Portage la Prairie 2016 site-year. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | All site-years | | Without Portage la Prairie 2016 | |
|---|---|---|---|---|
| Effect | p-value | % SS | p-value | % SS |
| Variety (V) | **0.0003** | 2.14 | **0.0009** | 1.66 |
| Row spacing (RS) | **<.0001** | **27.12** | **<.0001** | **27.18** |
| V * RS | 0.1957 | 0.27 | 0.3697 | 0.17 |
| Seeding density (SD) | **<.0001** | 1.18 | **<.0001** | 1.72 |
| V * SD | 0.4256 | 0.10 | 0.9139 | 0.03 |
| RS * SD | **<.0001** | 1.82 | **<.0001** | 2.03 |
| V * RS * SD | **0.0293** | 0.80 | 0.1809 | 0.58 |
| Site-year (SY) | **<.0001** | **33.94** | **<.0001** | **35.26** |
| V * SY | **0.0102** | 1.65 | **0.0198** | 1.33 |
| RS * SY | **<.0001** | 2.65 | **<.0001** | 3.25 |
| V * RS * SY | **0.0011** | 1.81 | **0.0042** | 1.59 |
| SD * SY | **<.0001** | 1.89 | **0.0032** | 1.13 |
| V * SD * SY | **0.0105** | 0.97 | 0.0852 | 0.73 |
| RS * SD * SY | **0.0004** | 2.66 | **0.0012** | 2.57 |
| V * RS * SD * SY | **<.0001** | 2.79 | **0.0003** | 2.58 |
| Rep(SY) | 0.1174 | 2.13 | 0.1173 | 2.15 |
| V * Rep(SY) | 0.1319 | 1.01 | 0.1238 | 1.03 |
| V * RS * Rep(SY) | **0.0060** | 3.53 | **0.0064** | 3.52 |
| Residual | **<.0001** | **11.54** | **<.0001** | **11.50** |

**Table 4.3.2.** Significance (p-value) of the fixed effects of row spacing, seeding density and their interactions and the percentage of the total sum of squares (% SS) in the dependent variable dry bean yield in each navy bean variety (Envoy and T9905) at each site year (Carman in 2015 and 2016 and Portage la Prairie in 2015). Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Carman | | | | Portage la Prairie | |
|---|---|---|---|---|---|---|
| | 2015 | | 2016 | | 2015 | |
| Effect | p-value | % SS | p-value | % SS | p-value | % SS |
| | ---------------------------Envoy--------------------------- | | | | | |
| Row spacing (RS) | **< .0001** | **62.69** | **0.0018** | **40.89** | **0.0046** | **36.23** |
| Seeding density (SD) | **0.0006** | 6.52 | 0.1421 | 6.17 | 0.0891 | 5.32 |
| RS * SD | **0.0361** | 6.45 | 0.3186 | **12.05** | 0.3712 | 8.38 |
| Rep(SY) | **0.0008** | 9.47 | **0.0268** | **10.04** | 0.2063 | 8.12 |
| V * RS * Rep(SY) | 0.6540 | 1.92 | 0.5339 | 4.29 | **0.0316** | **13.24** |
| Residual | **<.0001** | **12.94** | **<.0001** | **26.56** | **<.0001** | **28.71** |
| | ---------------------------T9905--------------------------- | | | | | |
| Row spacing (RS) | **0.0034** | **42.32** | **0.0046** | **68.27** | **0.0003** | **27.98** |
| Seeding density (SD) | 0.3834 | 2.23 | 0.2192 | 2.00 | **0.0005** | **16.83** |
| RS * SD | 0.3840 | 6.90 | 0.4022 | 4.16 | **0.0516** | **16.22** |
| Rep(SY) | 0.1344 | **10.57** | 0.0971 | **10.04** | 0.6198 | 0.90 |
| V * RS * Rep(SY) | **0.0107** | **13.19** | **0.0111** | 6.49 | 0.7294 | 4.34 |
| Residual | **<.0001** | **24.79** | **<.0001** | 9.04 | **<.0001** | **33.74** |

#### 4.3.1. Interaction Effect of Plant Density and Row Spacing on Navy Bean Seed Yield.

Lower seeding densities of 20 plants $m^{-2}$ resulted in significantly greater navy bean seed yield than the greatest seeding density of 60 plants $m^{-2}$ in Envoy navy bean planted at 19 and 38 cm row widths at Carman in 2015 and in T9905 navy bean planted at 19 and 57 cm row widths at Portage la Prairie in 2015 (Figure 4.3.1). At the other row widths and site-years, relatively little change in seed yield was observed with increasing plant density (Figure 4.3.1). Due to variation between seeding density and actual emergence, variation in the actual plant density is reported as well (Figure 4.3.1). At the two instances where seeding density significantly influenced navy bean yield (Envoy at Carman 2015 and T9905 at Portage la Prairie 2015), actual plant density explained a relatively small amount of the variation in seed yield ($R^2$ ranging from 0.226 to 0.333). In other instances, linear and quadratic models did not provide a good fit, and often explained only a relatively small amount of the variation ($R^2$ ranging from 0.343 to 0.437) (Figure 4.3.1). Overall, in navy bean varieties Envoy and T9905, at row widths greater than 19 cm, little change in seed yield was found with increasing plant density. A negative relationship between plant density and seed yield occurred at the narrow row widths of 19 cm.

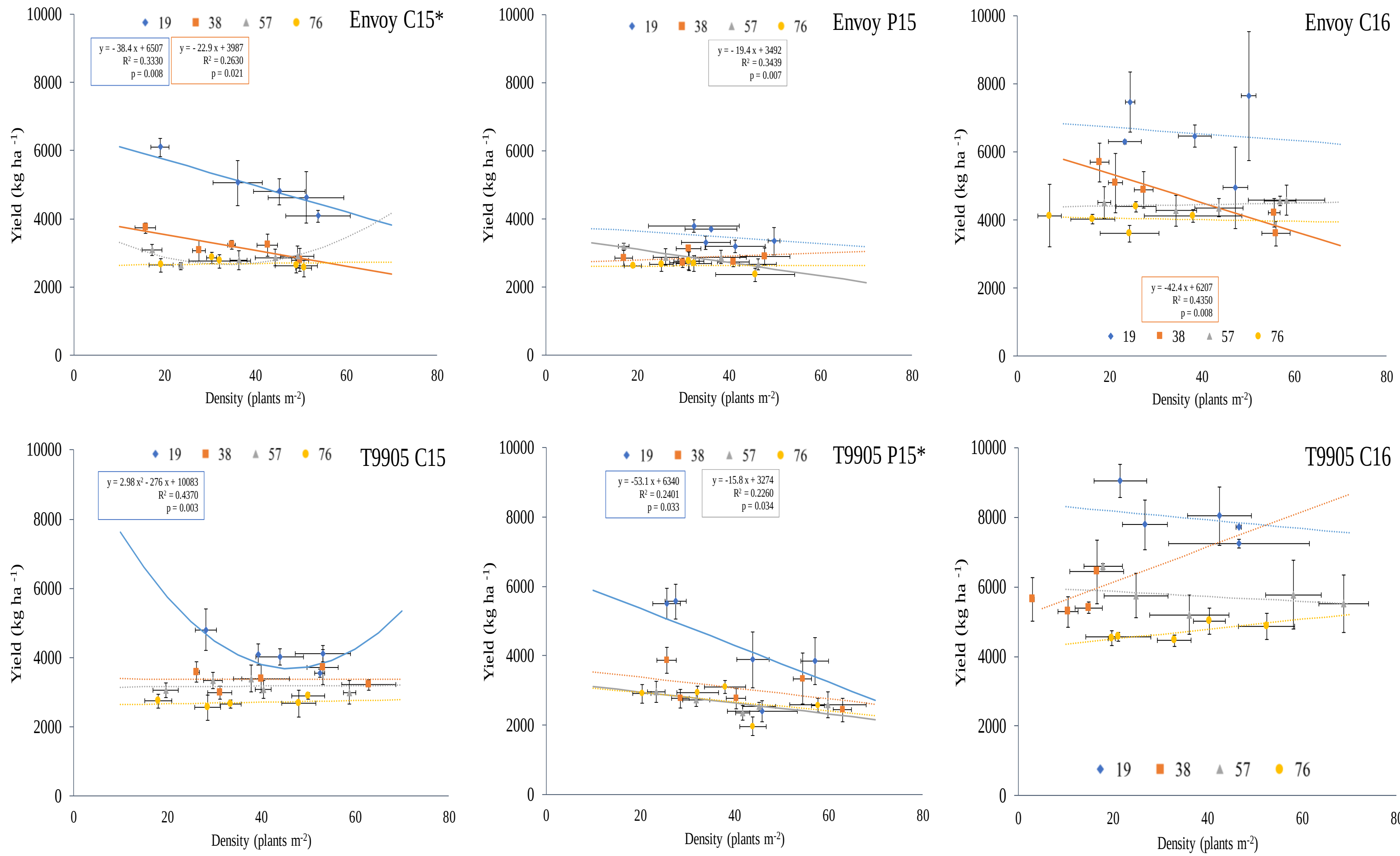


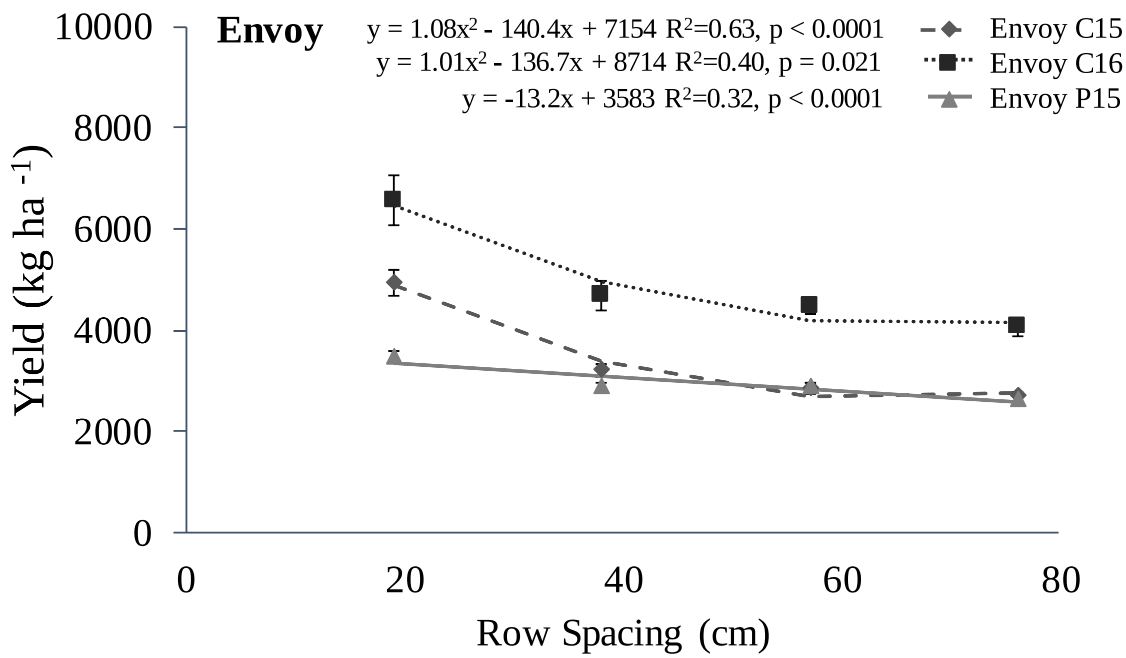

**Figure 4.3.1.** Seed yield (kg ha$^{-1}$) of Envoy and T9905 navy bean varieties at four row widths across plant densities at Carman (C) in 2015 and 2016 and Portage la Prairie (P) in 2015. Data points reported are the mean seed yield at each mean actual plant density with respective plus/minus one standard error from each mean. Equations of the line are reported only when significant ($p < 0.05$). *Site-years where the interaction of seeding density and row spacing were significant.

**4.3.2. Main Effect of Row Spacing on Navy Bean Seed Yield.** Navy bean planted at the narrow row spacing of 19 cm consistently produced the greatest seed yield at all site-years and in both varieties, on average improving seed yield by 71.9% when compared with the widest row spacing of 76 cm (Table 4.3.3, Figure 4.3.2). Seed yield of navy bean planted at 19 cm row widths were significantly greater than those planted at the next narrowest row spacing of 38 cm. No difference in navy bean seed yield was observed between the two widest row widths (57 and 76 cm). Linear and quadratic regression models using row spacing to explain the variation in seed yield resulted in moderate coefficients of determination ($R^2$ ranging from 0.32 - 0.69) (Figure 4.3.2).

Among site years, navy bean seed yield was greatest at the Carman 2016 site-year. This was likely due to differences in precipitation among sites, with Carman in 2016 receiving more early-season precipitation, and overall precipitation, than the 2015 experiments. This may also be attributed to differences in management at the site, since 2016 experiments received a fungicide application to control white mould, while 2015 experiments did not.

**Table 4.3.3**. Seed yield (kg $ha^{-1}$) of Envoy and T9905 navy bean at four row widths at Carman in 2015 and 2016, and Portage la Prairie in 2015. Within each column and variety, means followed by different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie |
|---|---|---|---|
| Row width (cm) | 2015 | 2016 | 2015 |
| **Envoy** | ------------------------------kg $ha^{-1}$------------------------------ | | |
| 19 | 4 849 a | 6 564 a | 3 464 a |
| 38 | 3 207 b | 4 696 b | 2 866 b |
| 57 | 2 843 c | 4 459 b | 2 875 b |
| 76 | 2 682 c | 4 053 b | 2 620 b |
| **T9905** | | | |
| 19 | 4 078 a | 7 967 a | 4 340 a |
| 38 | 3 379 b | 5 688 b | 3 035 b |
| 57 | 3 173 bc | 5 706 b | 2 633 b |
| 76 | 2 704 c | 4 685 b | 2 695 b |



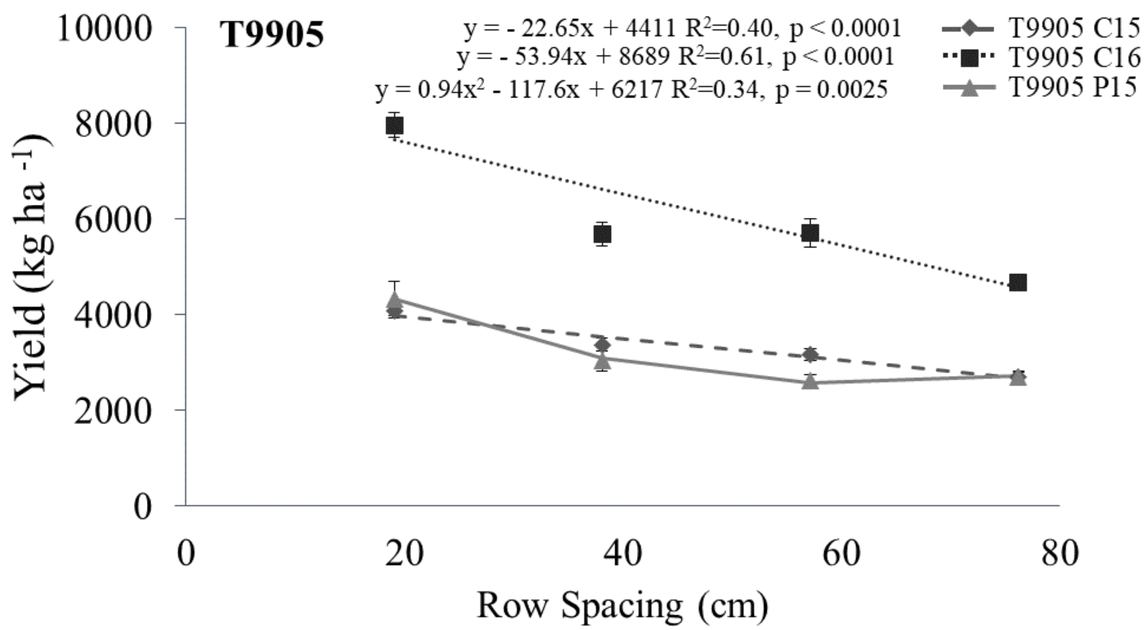




**Figure 4.3.2.** Regression of navy bean seed yield (kg ha$^{-1}$) and row spacing in Envoy (top) and T9905 (bottom) at Carman 2015 and 2016 (C15, C16), and Portage la Prairie 2015 (P15). Data points reported are the mean yields at each row spacing at each site-year with respective plus/minus one standard error of the mean. Linear regression equations, coefficients of determination and p-values are reported.

**4.3.3 Effect of Variety and Row Spacing on the Seed Yield-Actual Plant Density Relationship in Navy Bean.** An interaction effect between variety and row spacing in the density-dependence of navy bean seed yield was observed at Carman in 2015 only (Table 4.3.4). At this site-year, regression analysis showed that Envoy navy bean seed yield had a negative relationship with plant density when planted at 19, 38 and 57 cm row widths while T9905 navy bean seed yield only responded to plant density when planted at 19 cm row widths, where a negative quadratic relationship occurred (Table 4.3.5). At the remaining site-years, yield-density slopes were not affected by navy bean variety or row spacing despite some significant regression lines (Table 4.3.5)

**Table 4.3.4.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing seed yield in navy bean as influenced by actual plant density at three site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie |
|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 |
| | | -------------------- p-value | | ------------------ |
| Variety (V) | linear | 0.5856 | 0.5691 | 0.3130 |
| | quadratic | 0.7568 | 0.6686 | 0.5270 |
| Row spacing (RS) | linear | **0.0006** | 0.4399 | 0.6381 |
| | quadratic | **0.0040** | 0.4916 | 0.8033 |
| V*RS | linear | **0.0299** | 0.5124 | 0.8950 |
| | quadratic | **0.0253** | 0.3377 | 0.9786 |

**Table. 4.3.5.** Linear and quadratic regression slopes and p-values of regressions of dependent variable seed yield as influenced by actual dry bean plant densities in two varieties of navy bean planted at four different row spacings at three site years. The slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Envoy | 19 | **-38.44** | **0.0077** | | | 16 – 74 |
| | | | 38 | **-22.88** | **0.0208** | | | 11 – 55 |
| | | | 57 | -78.22 | 0.0585 | **1.16** | **0.0486** | 12 – 57 |
| | | | 76 | | | | | 13 – 60 |
| | | T9905 | 19 | **-275.97** | **0.0034** | **2.98** | **0.0046** | 24 – 63 |
| | | | 38 | | | | | 22 – 71 |
| | | | 57 | | | | | 13 – 61 |
| | | | 76 | | | | | 14 – 58 |
| | 2016 | Envoy | 19 | | | | | 18 – 53 |
| | | | 38 | **-42.38** | **0.0075** | | | 14 – 60 |
| | | | 57 | | | | | 16 – 74 |
| | | | 76 | | | | | 2 – 51 |
| | | T9905 | 19 | | | | | 11 – 67 |
| | | | 38 | | | | | 3 – 24 |
| | | | 57 | | | | | 11 – 75 |
| | | | 76 | | | | | 7 – 63 |
| Portage la Prairie | 2015 | Envoy | 19 | | | | | 16 – 55 |
| | | | 38 | | | | | 13 – 56 |
| | | | 57 | **-19.39** | **0.0066** | | | 15 – 58 |
| | | | 76 | | | | | 15 – 58 |
| | | T9905 | 19 | **-53.08** | **0.0332** | | | 18 – 63 |
| | | | 38 | | | | | 20 – 67 |
| | | | 57 | **-15.84** | **0.0341** | | | 18 – 73 |
| | | | 76 | | | | | 15 - 60 |

## 4.4 Pinto Bean Yield

Similar to navy bean, site-year and row spacing were the principal factors contributing to variation in pinto bean seed yield. Together, they accounted for 67.2 % of the total variation in pinto bean seed yield in these experiments (Table 4.4.1). Variety was the next most important factor contributing 3.4 % to total variation in pinto bean seed yield. The variation attributed to the variety effect was about 20-times lower than site-year or row spacing. This was followed by a cluster of five effects that contributed between 0.97 and 1.55% to the total variation. Seeding density, and its interactions with row spacing and site-year were the only significant effects in this cluster. All other effects contributed < 0.80% to the total variation and none of these effects were significant. Within site-years, row spacing had the most consistent effect on pinto bean seed yield and significantly affected yield at every site-year (Table 4.4.2). Row spacing was followed by seeding density (Table 4.4.2) and although the effect of density was significant at three out of four sites, it contributed to less than 10% of the total variation observed in bean seed yield (Table 4.4.2).

**Table 4.4.1.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density, site-year and their interactions and the percentage of the total sum of squares (% SS) in the dependent variable seed yield in a combined analysis in the pinto bean market class. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| Effect | All Site-Years | |
|---|---|---|
| | p-value | % SS |
| Variety (V) | **0.0008** | 3.41 |
| Row spacing (RS) | **<.0001** | **21.08** |
| V * RS | 0.0903 | 0.50 |
| Seeding density (SD) | **<.0001** | 1.03 |
| V * SD | 0.6475 | 0.09 |
| RS * SD | **0.0018** | 0.97 |
| V * RS * SD | 0.4754 | 0.37 |
| Site-year (SY) | **<.0001** | **46.16** |
| V * SY | 0.9682 | 0.04 |
| RS * SY | 0.6217 | 0.50 |
| V * RS * SY | 0.3070 | 0.80 |
| SD * SY | **0.0003** | 1.19 |
| V * SD * SY | 0.1271 | 0.52 |
| RS * SD * SY | 0.0766 | 1.55 |
| V * RS * SD * SY | 0.4378 | 1.19 |
| Rep(SY) | 0.4334 | 2.27 |
| V * Rep(SY) | **0.0093** | 2.05 |
| V * RS * Rep(SY) | **<.0001** | 4.84 |
| Residual | **<.0001** | **11.42** |

**Table 4.4.2.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density and their interactions and the percentage of the total sum of squares (% SS) in the dependent variable seed yield in the pinto bean market class at Carman and Portage la Prairie in 2015 and 2016. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Carman | | | | Portage la Prairie | | | |
|---|---|---|---|---|---|---|---|---|
| Effect | 2015 | | 2016 | | 2015 | | 2016 | |
| | p-value | % SS | p-value | % SS | p-value | % SS | p-value | % SS |
| Variety (V) | **0.0484** | 7.93 | 0.1699 | 3.88 | 0.1373 | 5.08 | 0.0725 | **14.57** |
| Row spacing (RS) | **<.0001** | **41.70** | **<.0001** | **38.85** | **<.0001** | **35.32** | **<.0001** | **47.74** |
| V * RS | 0.6703 | 0.22 | 0.1428 | 4.57 | 0.8221 | 0.71 | **0.0159** | 2.36 |
| Seeding density (SD) | **<.0001** | 9.96 | **0.0063** | 3.58 | **0.0068** | 3.77 | 0.2396 | 1.00 |
| V * SD | 0.053 | 1.78 | 0.8767 | 0.26 | 0.0802 | 2.14 | 0.5481 | 0.64 |
| RS * SD | **<.0001** | **13.56** | 0.5155 | 2.74 | 0.277 | 3.66 | 0.5906 | 2.00 |
| V * RS * SD | 0.721 | 1.69 | 0.2861 | 3.79 | 0.7575 | 2.08 | 0.3632 | 2.55 |
| Rep(SY) | 0.8216 | 0.74 | 0.3834 | 4.36 | 0.2818 | 8.73 | 0.8280 | 1.70 |
| V * Rep(SY) | **0.0064** | 2.41 | 0.2615 | 3.00 | 0.1977 | 4.14 | **0.0003** | 5.75 |
| V * RS * Rep(SY) | 0.7502 | 2.54 | **0.0005** | **12.46** | **0.0003** | **12.63** | 0.5732 | 3.18 |
| Residual | **<.0001** | **17.48** | **<.0001** | **22.51** | **<.0001** | **21.74** | **<.0001** | **18.51** |

**4.4.1. Main Effect of Site-Year on Pinto Bean Seed Yield.** Site-year was the most important variable in explaining differences among pinto bean yields, contributing to 46.2% of the total sum of squares (Table 4.4.1). While the interaction of seeding density and site-year was significant, it only contributed 1.2% to the total sum of squares; planting at lower seeding densities resulted in greater seed yield at all site-years except at Portage la Prairie in 2016 where there was no effect of seeding density on yield (Table 4.4.1). Pinto bean seed yield was greatest at Carman in 2016 (5 576 kg ha$^{-1}$), followed by Carman in 2015 (3 532 kg ha$^{-1}$) and Portage la Prairie in 2015 (3 310 kg ha$^{-1}$) (Table 4.4.3). The lowest pinto bean seed yields occurred at Portage la Prairie in 2016 (2 072 kg ha$^{-1}$) due to the August hail storm that caused substantial defoliation and pod damage during reproductive development (Table 4.4.3).

Differences in seed yield among Carman in 2016 and the two sites in 2015 were likely due to the differences in disease management among site-years in addition to inherent edaphic and environmental characteristics among sites. In 2016, foliar fungicides were used to control white mould, while no fungicide application occurred in 2015.

**Table 4.4.3.** Pinto bean seed yield (kg $ha^{-1}$) at Carman and Portage la Prairie in 2015 and 2016. Means followed by different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| | 2015 | 2016 | 2015 | 2016 |
| | ------------------------- | kg $ha^{-1}$ | -------------------------- | |
| Yield | 3 532 b | 5 576 a | 3 310 b | 2 072 c |

**4.4.2. Interaction Effect of Plant Density and Row Spacing on Pinto Bean Seed Yield.** Seed yield of pinto bean at the narrow row width of 19 cm had a negative relationship with plant density across site-years and produced the only significant linear regression model ($p = 0.0367$, Figure 4.4.1). Pinto bean seed yield in the other three row spacing treatments (38, 57, and 76 cm) was not affected by plant density (Figure 4.4.1). Though the interaction effect of seeding density and row spacing was significant ($p = 0.0018$) it contributed relatively little to the total variance partitioning overall (0.97% of the total sum of squares). At Carman in 2015, the interaction effect of seeding density and row spacing contributed 13.6% to the total sum of squares and seed yield had a negative relationship with plant density at both narrow row widths of 19 and 38 cm and no relationship with density at wide row widths of 57 and 76 cm (Figure 4.4.2).

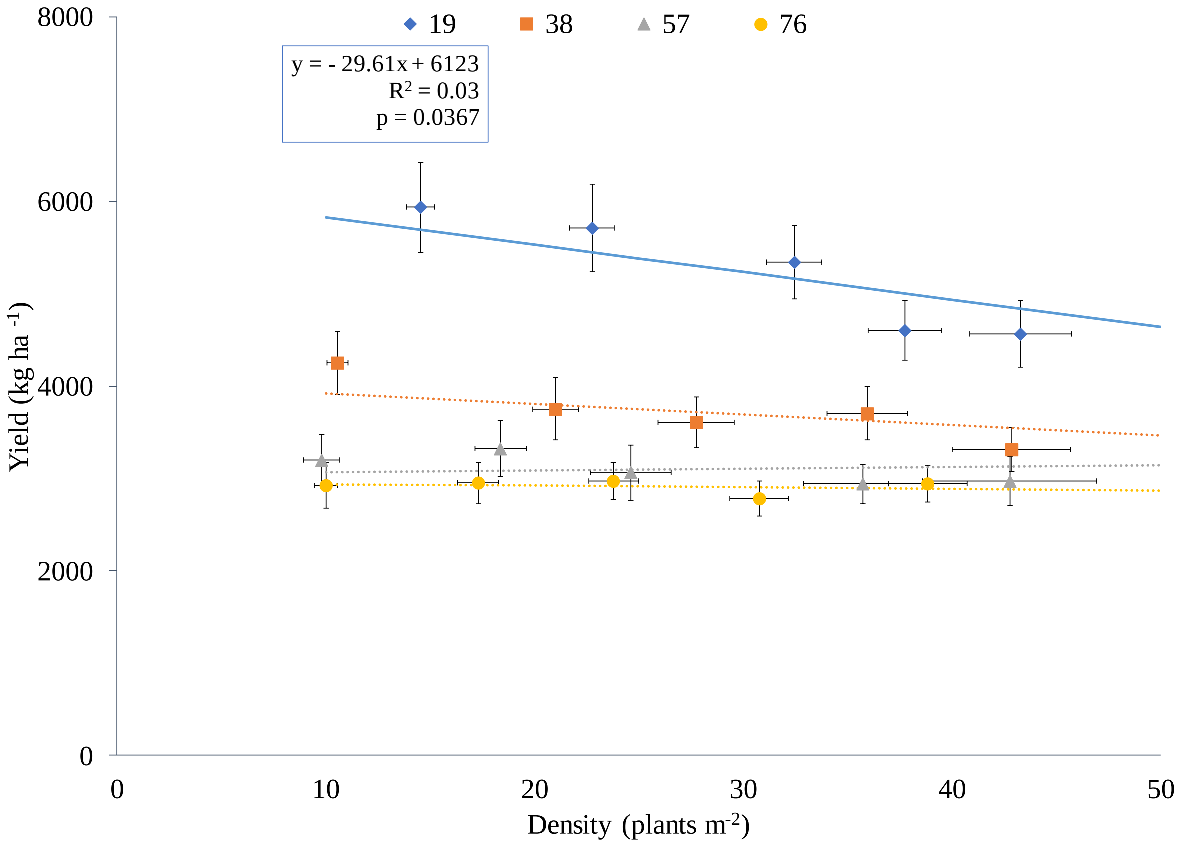



**Figure 4.4.1.** Seed yield (kg $ha^{-1}$) of the pinto bean market class at each row spacing (cm) and plant density (plants $m^{-2}$). The mean yield and plant density at each row spacing are plotted separately with plus/minus one standard error of the mean. The linear model of each row width has been plotted, though only the regression of the 19 cm model was significant and is reported ($p$ = 0.037, $R^2$=0.03). Solid regression lines indicate significant regression models and dotted lines are non-significant.

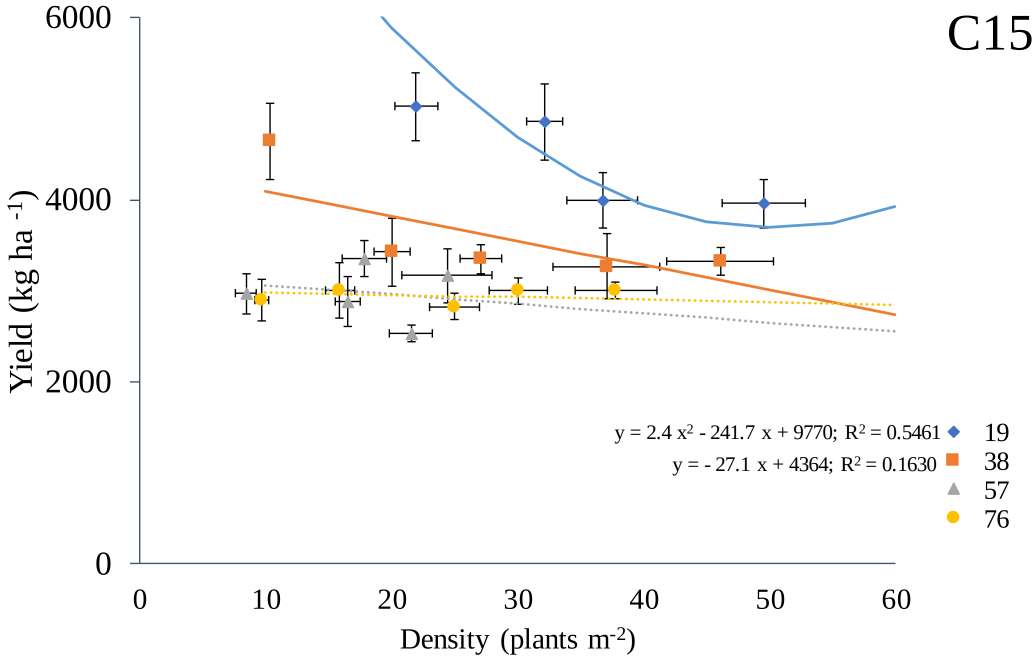



**Figure 4.4.2.** Seed yield (kg ha$^{-1}$) of the pinto bean market class at each row spacing (cm) and plant density (plants m$^{-2}$) at Carman in 2015 (C15). The mean yield and plant density at each row spacing are plotted separately with plus/minus one standard error of the mean. Solid regression lines indicate significant ($p<0.05$) regression models where the equation of the line has been reported and dotted lines are non-significant.

**4.4.3. Main Effect of Row Spacing on Pinto Bean Seed Yield.** Row spacing was the second most important explanatory variable in pinto bean seed yield following site-year, contributing 21.2% of the total variation (Table 4.4.1). Within each site-year, row spacing contributed 35.3 – 47.7% to the total variation (Table 4.4.2). Narrow row widths of 19 cm consistently resulted in greater pinto bean yield than other row widths, improving seed yield by 78.7% when compared with the widest row width of 76 cm (Table 4.4.4). Beans at row widths of 38 cm produced significantly greater seed yields than at the wider row widths of 57 and 76 cm, resulting in a 24.2% increase in bean seed yield (Table 4.4.4). Pinto bean seed yields at wider row widths of 57 and 76 cm were not significantly different.

**Table 4.4.4.** Mean pinto bean seed yield (kg ha$^{-1}$) at four row widths at Carman and Portage la Prairie in 2015 and 2016 and in a combined analysis. Means followed by different letters within each column are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | | All site-years |
|---|---|---|---|---|---|
| Row spacing (cm) | 2015 | 2016 | 2015 | 2016 | combined |
| | ---------------------------- | --------kg ha$^{-1}$ | ---------------------------- | ---------------------------- | ---kg ha$^{-1}$--- |
| 19 | 4 877 a | 7 786 a | 4 784 a | 3 043 a | 4 985 a |
| 38 | 3 541 b | 5 543 b | 3 312 b | 2 198 b | 3 552 b |
| 57 | 2 947 c | 4 915 bc | 2 669 c | 1 641 c | 2 931 c |
| 76 | 2 925 c | 4 342 c | 2 679 c | 1 560 c | 2 789 c |

**4.4.2. Main Effect of Variety on Pinto Bean Seed Yield.** On average, Windbreaker pinto beans yielded 664 kg ha$^{-1}$ greater than Monterrey pinto beans (Table 4.4.5). No interactions among variety or any other effects were observed, indicating that the variety effect was consistent throughout these experiments.

**Table 4.4.5.** Seed yield (kg ha$^{-1}$) of pinto bean varieties at Carman and Portage la Prairie in 2015 and 2016 and in a combined analysis. Means followed by different letters within each column are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | | All site-years |
|---|---|---|---|---|---|
| Variety | 2015 | 2016 | 2015 | 2016 | combined |
| | ---------------------------- | --------kg ha$^{-1}$ | ---------------------------- | ---------------------------- | ---kg ha$^{-1}$--- |
| Windbreaker | 3 856 a | 5 948 a | 3 615 a | 2 402 a | 3 855 a |
| Monterrey | 3 222 b | 5 216 b | 3 018 b | 1 766 b | 3 191 b |

**4.4.4. Main Effect of Plant Density on Pinto Bean Seed Yield.** Seeding densities affected pinto bean seed yield at three of four site-years, although the contribution of this relatively large range in seeding densities to the total sum of squares was surprisingly small (1.1 – 8.6%, Table 4.4.2) in pinto bean as well. No differences in seed yield due to changes in seeding densities were observed at Portage la Prairie in 2016, possibly masked by the reduced yields due to hail damage. At site-years where seeding densities significantly affected seed yield, seed yield decreased with increasing seeding densities (Table 4.4.6). Across site-years, planting pinto bean at seeding densities of 10 plants m$^{-2}$, on average, resulted in an increase in seed yield of 567 kg ha$^{-1}$ compared with seeding at 50 plants m$^{-2}$. Greatest seed yields were seen at seeding densities of 10 and 20 plants m$^{-2}$, and lowest seed yields occurred at 40 and 50 plants m$^{-2}$. The greatest seeding densities of 40 and 50 plants m$^{-2}$ resulted in statistically similar seed yields at all site-years.

**Table 4.4.6.** Pinto bean seed yield (kg ha$^{-1}$) at five seeding densities at Carman and Portage la Prairie in 2015 and 2016 and in a combined analysis. Means followed by different letters within each column are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| Seeding densities | Carman | | Portage la Prairie | | All site-years |
|---|---|---|---|---|---|
| (plants m$^{-2}$) | 2015 | 2016 | 2015 | 2016 | combined |
| | ------------------------------kg ha$^{-1}$------------------------------ | | | | ---kg ha$^{-1}$--- |
| 10 | 4 204 a | 5 902 ab | 3 693 a | 2 034 | 3 830 a |
| 20 | 3 486 bc | 6 087 a | 3 547 ab | 1 934 | 3 618 ab |
| 30 | 3 534 b | 5 663 ab | 3 256 abc | 2 112 | 3 532 bc |
| 40 | 3 306 bc | 5 001 c | 3 169 bc | 2 199 | 3 347 cd |
| 50 | 3 171 c | 5 263 bc | 2 914 c | 2 084 | 3 263 d |

**4.4.5. Effect of Variety and Row Spacing on the Seed Yield-Actual Plant Density Relationship in Pinto Bean.** With the exception of row spacing at one site year, variety or row spacing had no effect on the plant density-yield relationship in pinto bean. At Carman 2015, however, row spacing affected the slopes of the density-yield relationship (Table 4.4.7). At this site year, seed yield of Monterrey pinto bean planted at 19 cm row widths had a negative linear relationship with plant density. Regression analysis of the simple effects showed that at Carman in 2015, Windbreaker pinto bean planted at 19 and 38 cm row widths had a negative linear relationship with density, indicating that maximum seed yields were obtained at lower planting densities. (Table 4.4.8), however, ANOVA did not deem these slopes different from other row spacings in this variety.

**Table 4.4.7.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing seed yield in pinto bean as influenced by actual plant density at four site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie | |
|---|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 | 2016 |
| | | ----------------------- p-values | ----------------------- | | |
| Variety (V) | linear | 0.7238 | 0.5864 | 0.3040 | 0.7087 |
| | quadratic | 0.6056 | 0.4503 | 0.5353 | 0.7155 |
| Row spacing (RS) | linear | **0.0070** | 0.6265 | 0.7055 | 0.2360 |
| | quadratic | 0.2521 | 0.3481 | 0.8449 | 0.1160 |
| V*RS | linear | 0.3472 | 0.5362 | 0.8912 | 0.9492 |
| | quadratic | 0.5293 | 0.7089 | 0.9483 | 0.8989 |

**Table. 4.4.8**. Linear and quadratic regression slopes and p-values of regressions of dependent variable seed yield as influenced by actual dry bean plant densities in two varieties of pinto bean planted at four different row spacings at four site years. The slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Monterrey | 19 | **-88.11** | **0.0003** | | | 13 – 63 |
| | | | 38 | | | | | 9 – 66 |
| | | | 57 | | | | | 7 – 39 |
| | | | 76 | | | | | 9 – 49 |
| | | Windbreaker | 19 | **-54.11** | **0.0255** | | | 8 – 58 |
| | | | 38 | **-39.02** | **0.0479** | | | 11 – 54 |
| | | | 57 | | | | | 5 – 34 |
| | | | 76 | | | | | 8 – 45 |
| | 2016 | Monterrey | 19 | | | | | 9 – 47 |
| | | | 38 | **171.13** | **0.0456** | **-2.12** | **0.0425** | 3 – 85 |
| | | | 57 | | | | | 6 – 66 |
| | | | 76 | | | | | 7 – 63 |
| | | Windbreaker | 19 | | | | | 9 – 42 |
| | | | 38 | **-76.92** | **0.0031** | | | 9 – 59 |
| | | | 57 | | | | | 4 – 84 |
| | | | 76 | | | | | 3 – 46 |
| Portage la Prairie | 2015 | Monterrey | 19 | | | | | 16 – 71 |
| | | | 38 | | | | | 11 – 67 |
| | | | 57 | | | | | 14 – 98 |
| | | | 76 | | | | | 10 – 53 |
| | | Windbreaker | 19 | | | | | 13 – 66 |
| | | | 38 | | | | | 11 – 51 |
| | | | 57 | | | | | 9 – 84 |
| | | | 76 | | | | | 8 – 62 |
| | 2016 | Monterrey | 19 | | | | | 7 – 44 |
| | | | 38 | | | | | 5 – 37 |
| | | | 57 | | | | | 6 – 50 |
| | | | 76 | **25.72** | **0.0049** | | | 6 – 40 |
| | | Windbreaker | 19 | | | | | 12 – 42 |
| | | | 38 | | | | | 7 – 46 |
| | | | 57 | **22.39** | **0.0403** | | | 5 – 34 |
| | | | 76 | | | | | 5 - 43 |

## 4.5 White Mould Severity

**4.5.0 Environmental Factors.** Environmental conditions at anthesis of dry bean are important as white mould initiates infection through colonizing floral blossoms. In Manitoba, dry bean typically flower in July, thus temperature and rainfall during this month can play a large role in disease development. In these experiments, navy and pinto bean began flowering in mid-July in 2015 and plants did not begin to flower until Augustin 2016. White mould thrives under maximum daily temperatures below 28°C. Both years in July at Carman and Portage la Prairie, average daily temperatures were between 19 - 21°C (Table 4.1). While daily maximum temperatures rose above 28°C at both sites periodically in July, the crop canopy would have provided a buffer from that air temperature, maintaining a cooler microclimate below the canopy even on these warmer days. During flowering, sustained leaf wetness below the canopy is also required for disease development. In 2015, total July rainfall was above the 30-year average while the dry bean crop was flowering at both sites (Table 4.1). Rainfall was greater in 2015 than in 2016, likely contributing to the increased disease severity experienced at the sites in 2015 (Table 4.1). In 2016, August rainfall in 2016 was below normal at Carman and above normal at Portage la Prairie, however, the majority of precipitation at Portage la Prairie occurred in the latter half of the month. Despite this rainfall pattern, sufficient precipitation occurred at all site-years for noticeable white mould disease development.

Differences in white mould severity among sites may be attributed to different environmental factors, as well as different fungicide application regimes. In 2015, Carman and Portage la Prairie sites received above-average July rainfall, combined with no fungicide application. This resulted in greater severity of white mould at those site-years than at the sites in 2016.

### 4.5.1 Navy Bean White Mould Severity

The severity of white mould in the navy bean market class was largely associated with variety, followed by spatial arrangement. Navy bean data was separated by site-year due to differences in disease pressure and management practices among sites. Row spacing and seeding density both played a role in influencing white mould severity, each significant at two out of three site-years. Their interaction, however, was only significant at Carman in 2015 where white mould severity in navy bean had a positive relationship with plant density only when planted at 19 cm row widths. Varieties responded differently to row spacing, as indicated by a significant interaction effect at Carman in 2016 and Portage la Prairie in 2015 (Table 4.5.1). White mould severity results were further separated by variety in the navy bean market class for more direct comparison with yield results. Once separated by variety, row spacing no longer influenced white mould severity at Carman in 2016. At Portage la Prairie in 2015, T9905 navy bean planted at 19 cm and 76 cm row widths resulted in significantly lower white mould severity than when planted at the intermediate row widths. Seeding density influenced disease severity in Envoy navy bean at every site-year, and at two out of three site-years in T9905 navy bean. The interaction of row spacing and seeding density was significant at Carman in 2015 in both varieties (Table 4.5.2). In both Envoy and T9905 navy bean, white mould severity had a positive relationship with seeding density when planted at row widths of 19, 38, and 57 cm, but not when planted at 76 cm row widths.

**Table 4.5.1.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable white mould severity in the navy bean market class at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | Portage la Prairie |
|---|---|---|---|
| Fixed effect | 2015 | 2016 | 2015 |
| | ---------------------------- p-values | ---------------------------- | ---------------------------- |
| Variety (V) | **0.0117** | **<.0001** | **0.0365** |
| Row spacing (RS) | **0.0001** | 0.3471 | **0.0275** |
| V * RS | 0.0778 | **0.0368** | **0.0314** |
| Seeding density (SD) | **<.0001** | 0.1486 | **<.0001** |
| V * SD | 0.7622 | 0.9314 | 0.1257 |
| RS * SD | **<.0001** | 0.8558 | 0.1001 |
| V * RS * SD | 0.3553 | 0.9428 | 0.6549 |

**Table 4.5.2.** Significance (p-value) of the fixed effects of row spacing, seeding density and their interactions in the dependent variable white mould severity in the navy bean varieties Envoy (top) and T9905 (bottom) at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | Portage la Prairie |
|---|---|---|---|
| Fixed effect | 2015 | 2016 | 2015 |
| | --------------------------Envoy | --------------------------- | |
| Row spacing (RS) | **0.0016** | 0.3160 | 0.7386 |
| Seeding density (SD) | **<.0001** | **<.0001** | **<.0001** |
| RS * SD | **<.0001** | 0.5158 | 0.3690 |
| | ----------------------------T9905 | --------------------------- | |
| Row spacing (RS) | 0.0984 | 0.1096 | **0.0175** |
| Seeding density (SD) | **0.0002** | 0.3989 | **<.0001** |
| RS * SD | **0.0001** | 0.8382 | 0.2119 |

**4.5.1.1. Interaction Effect of Row Spacing and Variety on White Mould Severity in Navy Bean.** White mould in each variety responded differently to row spacing, as indicated by the significant interaction effect at Carman in 2016 and Portage la Prairie in 2015. At Portage la Prairie in 2015, T9905 navy bean seeded at the narrowest and widest row widths (19 and 76 cm) resulted in significantly lower white mould severity ratings than when seeded at intermediate row widths of 38 and 57 cm, while row spacing did not influence white mould severity in Envoy navy beans at that site-year (Figure 4.5.1). At Carman in 2015, the narrowest row width of 19 cm resulted in the lowest white mould severity in Envoy navy beans, while row spacing did not influence white mould severity in T9905 navy beans at that site-year (Figure 4.5.1). At Carman in 2016, once separated by variety, row spacing no longer had an effect on white mould severity (Table 4.5.2). Envoy navy bean white mould severity was significantly greater than T9905 navy bean at Carman in 2016, scoring, on average, 2 points greater in white mould severity than T9905 indicating that the average Envoy navy bean plant had one to several running lesions with moderate mycelial growth while the average T9905 navy bean plant had only one to three small infected leaves at that site-year (Figure 4.5.1). White mould severity was consistently greater in Envoy navy bean than T9905 navy bean.

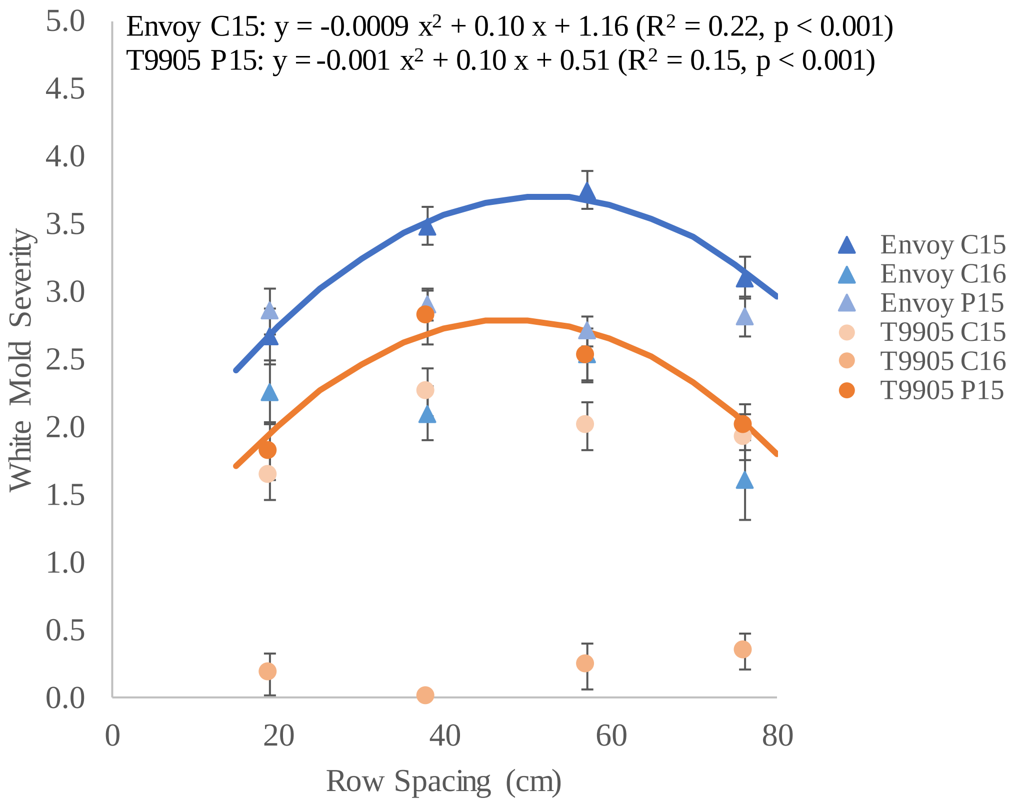
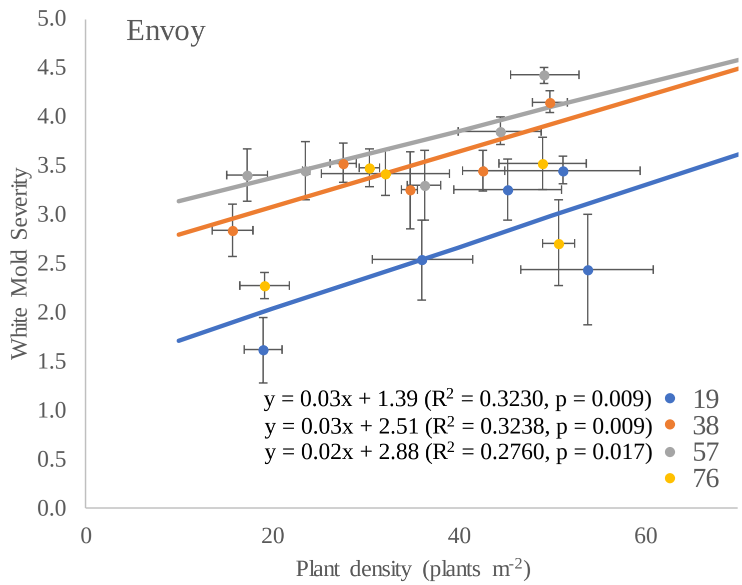



**Figure 4.5.1.** Mean white mould severity in Envoy and T9905 navy bean seeded at four row widths at Carman in 2015 (C15) and 2016 (C16) and Portage la Prairie in 2015 (P15). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.5.1.2. Interaction Effect of Plant Density and Row Spacing on White Mould Severity in Navy Bean.** Plant density had a positive linear relationship with white mould severity in navy beans planted at row widths of 19, 38 and 57 cm where significant at Carman in 2015 in both Envoy and T9905 navy bean (Figure 4.5.2). There was no relationship between plant density and white mould severity in beans planted at the widest row width of 76 cm.



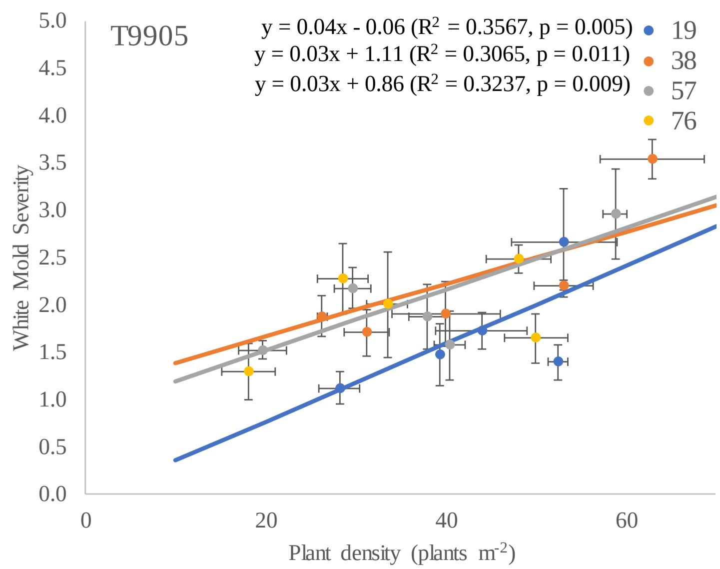




**Figure 4.5.2.** White mould severity ratings at four row widths and five seeding densities in Envoy and T9905 navy bean at Carman in 2015. Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.5.1.3. Main Effect of Plant Density on White Mould Severity in Navy Bean.** Increasing plant density significantly increased the severity of white mould (Figure 4.5.3). The positive relationship between plant density and white mould severity was seen in Envoy navy bean at every site-year and in T9905 navy bean at two of three site-years. At Carman in 2016, where the effect of seeding density was not significant in T9905 bean, very low disease severity levels were recorded with mean ratings below one in every seeding density treatment, indicating little to no mycelial development or wilt (Figure 4.5.3). The linear models for white mould severity in relation to plant density were significant ($p < 0.01$) and showed an increase in white mould severity with increasing plant density, although they explain only a relatively small portion of the variation in white mould severity ($R^2$ ranging from 0.09 to 0.15; Figure 4.5.3). In 2015, navy bean linear models appeared to have similar slopes in both varieties, indicating a consistent increase in the disease severity of white mould with increasing plant density that year.

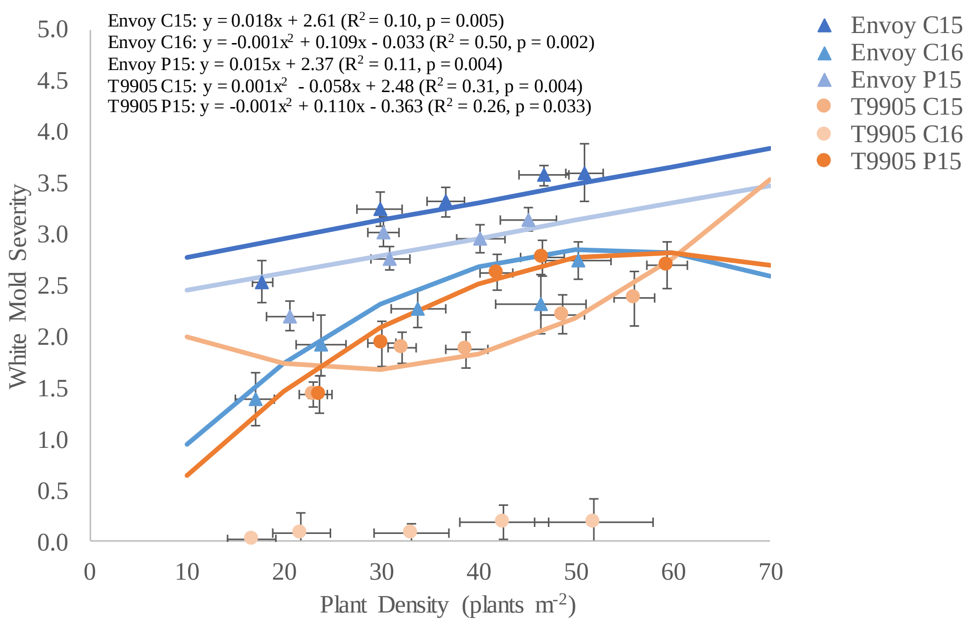



**Figure 4.5.3**. White mould severity with increasing plant density in Envoy and T9905 navy bean at Carman in 2015 (C15) and 2016 (C16) and Portage la Prairie in 2015 (P15). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.5.1.4. Effect of Variety and Row Spacing on the White Mould Severity-Actual Plant Density Relationship in Navy Bean.** Variety affected the plant density-white mould severity relationship at Carman in 2015 and 2016 (Table 4.5.3), where regression analysis showed that white mould severity had a positive relationship with plant density in Envoy and T9905 navy bean (Table 4.5.4). This relationship was an asymptotic increase in Envoy navy bean in 2016 and a positive linear relationship in Envoy navy bean at Carman in 2015 and T9905 navy bean at Carman in 2016, indicating that white mould severity was greater when planted at increased densities (Table 4.5.4). In T9905 navy beans at Carman in 2015, the relationship between white mould severity and plant density was a positive parabola, with the minimum severity occurring at the 30 plants $m^{-2}$ seeding density, indicating that white mould severity was greatest in T9905 navy bean planted at densities greater or lower than 30 plants $m^{-2}$. (Table 4.5.4).

Row spacing affected the plant density-white mould severity relationship in 2015 at Carman and Portage la Prairie (Table 4.5.3). Regression analysis indicated that white mould severity had a positive relationship with planting density in navy beans planted at every row width in 2015 at Carman, except in T9905 navy bean planted at the 38 cm row width, which had a positive parabolic relationship where a minimum occurred at 50 plants $m^{-2}$, meaning that white mould severity increased at densities below and above 50 plants $m^{-2}$ (Table 4.5.4). In 2015 at Portage la Prairie, white mould severity had a positive relationship with density in T9905 navy bean planted at 19 – 57 cm row widths and in Envoy navy bean when planted at 19 cm row widths, meaning that as density increased the severity of white mould increased in those treatments (Table 4.5.4).

**Table 4.5.3.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing white mould in navy bean as influenced by actual plant density at three site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie |
|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 |
| | | --------------- p-values | ---------------- | |
| Variety (V) | linear | **0.0239** | **0.0444** | 0.3766 |
| | quadratic | **0.0328** | 0.6047 | 0.6841 |
| Row spacing (RS) | linear | **0.0411** | 0.6924 | **0.0371** |
| | quadratic | **0.0239** | 0.7067 | **0.0186** |
| V*RS | linear | 0.4807 | 0.825 | 0.9254 |
| | quadratic | 0.4927 | 0.6678 | 0.9688 |

**Table. 4.5.4.** Linear and quadratic regression slopes and p-values of regressions of dependent variable white mould severity as influenced by actual dry bean plant densities in two varieties of navy bean planted at four different row spacings at three site years. The slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Envoy | | **0.02** | **0.0051** | | | 11 – 74 |
| | | | 19 | **0.03** | **0.0089** | | | 16 – 74 |
| | | | 38 | **0.03** | **0.0088** | | | 11 – 55 |
| | | | 57 | **0.02** | **0.0174** | | | 12 – 57 |
| | | | 76 | | | | | 13 – 60 |
| | | T9905 | | **-0.06** | **0.0524** | **0.001** | **0.004** | 13 – 71 |
| | | | 19 | **0.04** | **0.0054** | | | 24 – 63 |
| | | | 38 | | | **0.001** | **0.0466** | 22 – 71 |
| | | | 57 | **0.03** | **0.0089** | | | 13 – 61 |
| | | | 76 | | | | | 14 – 58 |
| | 2016 | Envoy | | **0.11** | **< 0.001** | **-0.001** | **0.002** | 2 – 74 |
| | | | 19 | **0.04** | **0.0214** | | | 18 – 53 |
| | | | 38 | **0.03** | **0.0193** | | | 14 – 60 |
| | | | 57 | **0.03** | **0.0333** | | | 16 – 74 |
| | | | 76 | **0.06** | **0.0020** | | | 2 – 51 |
| | | T9905 | | **0.02** | **< 0.001** | | | 3 – 75 |
| | | | 19 | | | | | 11 – 67 |
| | | | 38 | | | **0.001** | **0.0365** | 3 – 24 |
| | | | 57 | | | | | 11 – 75 |
| | | | 76 | | | | | 7 – 63 |
| Portage la Prairie | 2015 | Envoy | | **0.02** | **0.0017** | | | 13 – 58 |
| | | | 19 | **0.23** | **0.0252** | **0.002** | **0.0332** | 16 – 55 |
| | | | 38 | | | | | 13 – 56 |
| | | | 57 | | | | | 15 – 58 |
| | | | 76 | | | | | 15 – 58 |
| | | T9905 | | **0.11** | **0.0046** | **-0.001** | **0.0327** | 15 – 73 |
| | | | 19 | **0.27** | **0.0127** | **0.003** | **0.0162** | 18 – 63 |
| | | | 38 | **0.03** | **0.0080** | | | 20 – 67 |
| | | | 57 | **0.04** | **0.0009** | | | 18 – 73 |
| | | | 76 | | | | | 15 - 60 |

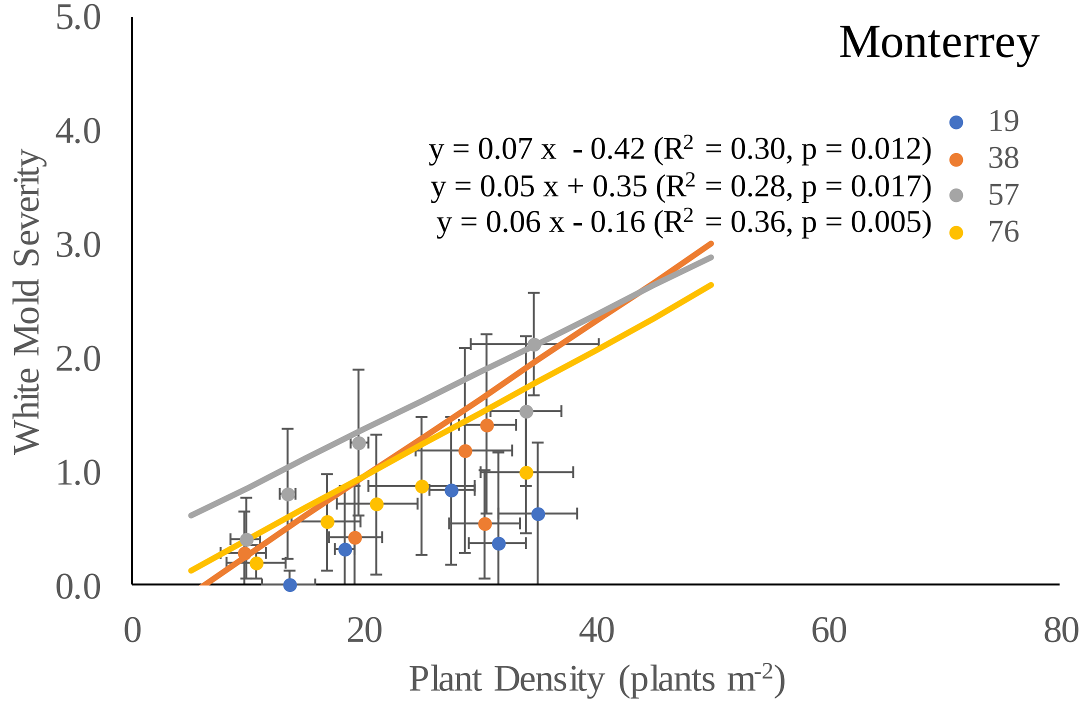
### 4.5.2 Pinto Bean White Mould Severity

Seeding density was the most consistent significant fixed effect influencing white mould severity of pinto bean as it was highly significant at every site-year (Table 4.5.5). Row spacing was significant at three out of the four site-years in the pinto bean market class (Table 4.5.5). The interaction of seeding density and row spacing was significant at Portage la Prairie in 2015 and 2016. At Portage la Prairie in 2015, a positive linear relationship between plant density and white mould severity occurred in pinto beans planted at 19, 38 and 57 cm row widths and a parabolic quadratic relationship in pinto beans planted at 76 cm row widths. At Portage la Prairie in 2016, the interaction of variety, row spacing and seeding density was significant, where a positive linear relationship occurred between white mould severity and plant density in Monterrey and Windbreaker pinto bean planted at 38 and 76 cm row widths. Monterrey pinto bean planted at 57 cm row widths also had a positive linear relationship between plant density and white mould severity, but in Windbreaker pinto bean planted at 57 cm row widths the relationship was quadratic. Pinto bean data were separated by site-year due to differences in disease pressure and management practices among sites.

**Table 4.5.5.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable white mould severity in the pinto bean market class at Carman and Portage la Prairie in 2015 and 2016. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| Fixed effect | 2015 | 2016 | 2015 | 2016 |
| | ------------------------------------ p-values | ---------------------------------- | | |
| Variety (V) | 0.6211 | 0.8044 | 0.8371 | **0.0070** |
| Row spacing (RS) | 0.1115 | **0.0489** | **0.0309** | **0.0285** |
| V * RS | 0.7771 | 0.1399 | 0.4757 | 0.0641 |
| Seeding density (SD) | **<.0001** | **<.0001** | **<.0001** | **<.0001** |
| V * SD | 0.2831 | 0.7419 | **0.0007** | **0.0023** |
| RS * SD | 0.9047 | 0.8949 | **0.0042** | **0.0238** |
| V * RS * SD | 0.7197 | 0.7583 | 0.8723 | **0.0164** |

**4.5.2.1. Interaction Effect of Variety, Row Spacing and Plant Density on White Mould Severity in Pinto Bean.** At Portage la Prairie in 2016, the interaction of variety, row spacing and seeding density was significant, where a positive linear relationship occurred between white mould severity and plant density in Monterrey and Windbreaker pinto bean planted at 38 and 76 cm row widths (Figure 4.5.4). Monterrey pinto bean planted at 57 cm row widths also had a positive linear relationship between plant density and white mould severity, but in Windbreaker pinto bean planted at 57 cm row widths the relationship was quadratic (Figure 4.5.4). In both Monterrey and Windbreaker pinto bean at Portage la Prairie in 2016, there was no relationship between plant density and white mould severity in beans planted at 19 cm row widths.



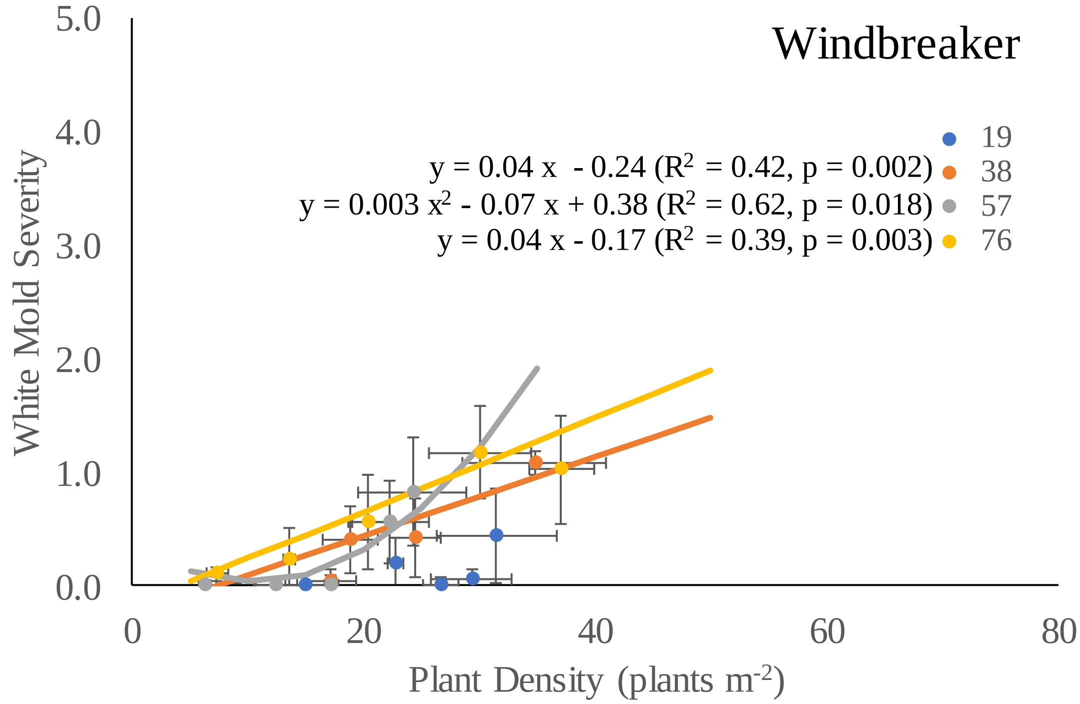




**Figure 4.5.4.** White mould severity with increasing plant density in Monterrey and Windbreaker pinto bean planted at four row widths (19, 38, 57, 76 cm) at Portage la Prairie in 2016. Plus/minus one standard error of the mean are reported and regression models are reported only when significant ($p < 0.05$).

**4.5.2.2. Interaction Effect of Row Spacing and Plant Density on White Mould Severity in Pinto Bean.** At Portage la Prairie in 2015, a positive linear relationship between plant density and white mould severity occurred in pinto beans planted at 19, 38 and 57 cm row widths (Figure 4.5.5). A parabolic quadratic relationship between plant density and white mould severity occurred in pinto beans planted at 76 cm row widths (Figure 4.5.5).

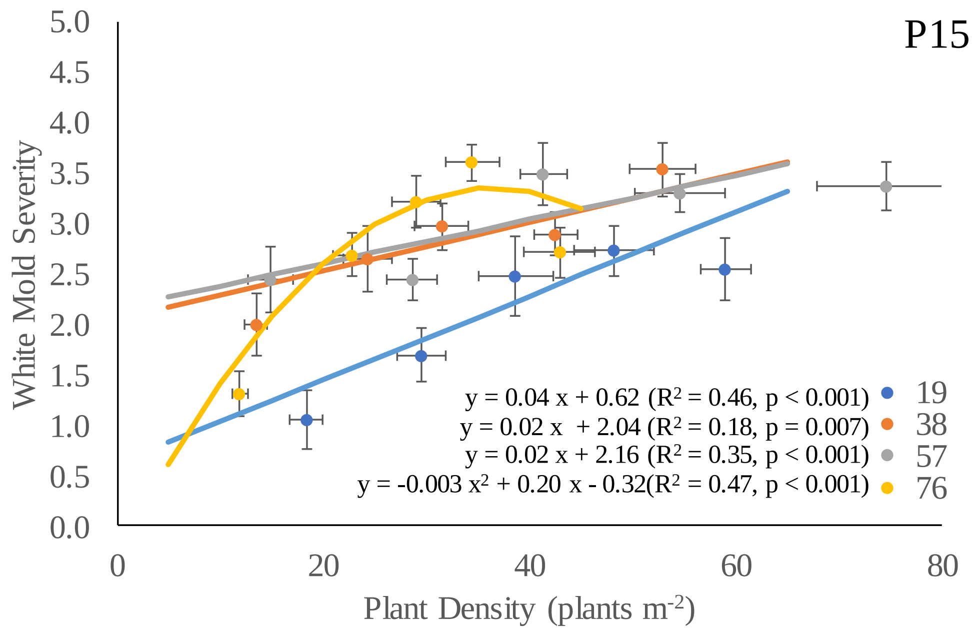



**Figure 4.5.5.** White mould severity with increasing plant density in pinto bean planted at four row widths (19, 38, 57, 76 cm) at Portage la Prairie in 2015 (P15). Plus/minus one standard error of the mean and significant linear models ($p < 0.01$) are reported.

**4.5.2.3 Interaction Effect of Variety and Plant Density on White Mould Severity in Pinto Bean.** White mould severity had a positive linear relationship with plant density in both Monterrey and Windbreaker pinto bean, when significant at Portage la Prairie in 2015 (Figure 4.5.6). At low seeding densities targeting 10 plants m$^{-2}$, Monterrey had greater white mould severity than Windbreaker, but at greater seeding densities above 30 plants m$^{-2}$, both varieties had similar levels of white mould severity, averaging a white mould severity score of 3.0

indicating the average plants had mycelial development or wilt involving up to 25% of foliage (Figure 4.5.6).

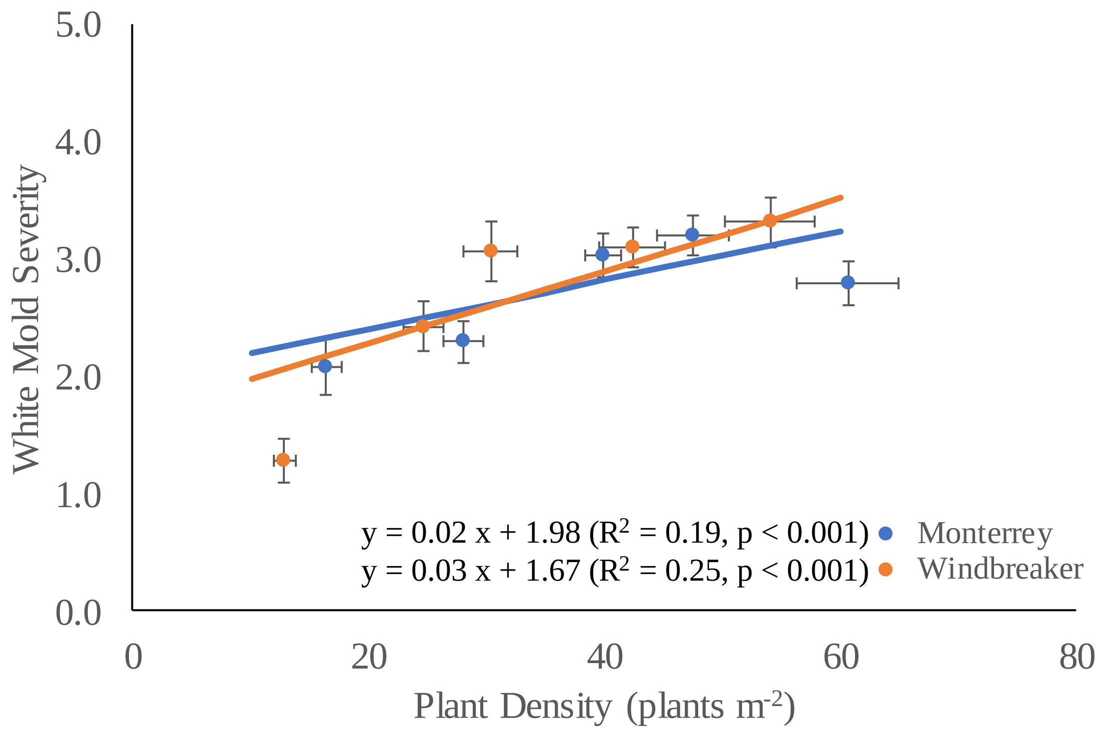



**Figure 4.5.6.** White mould severity with increasing plant density in Monterrey and Windbreaker pinto bean at Portage la Prairie in 2015. Plus/minus one standard error of the mean and significant linear models ($p < 0.01$) are reported.

**4.5.2.4. Main Effect of Plant Density on White Mould Severity in Pinto Bean.** White mould severity had a positive relationship with plant density in pinto bean at every site-year ($p < 0.05$, Figure 4.5.7). This relationship was quadratic at Carman in 2015 and 2016 and at Portage la Prairie in 2015; at Portage la Prairie in 2016, the relationship was linear.

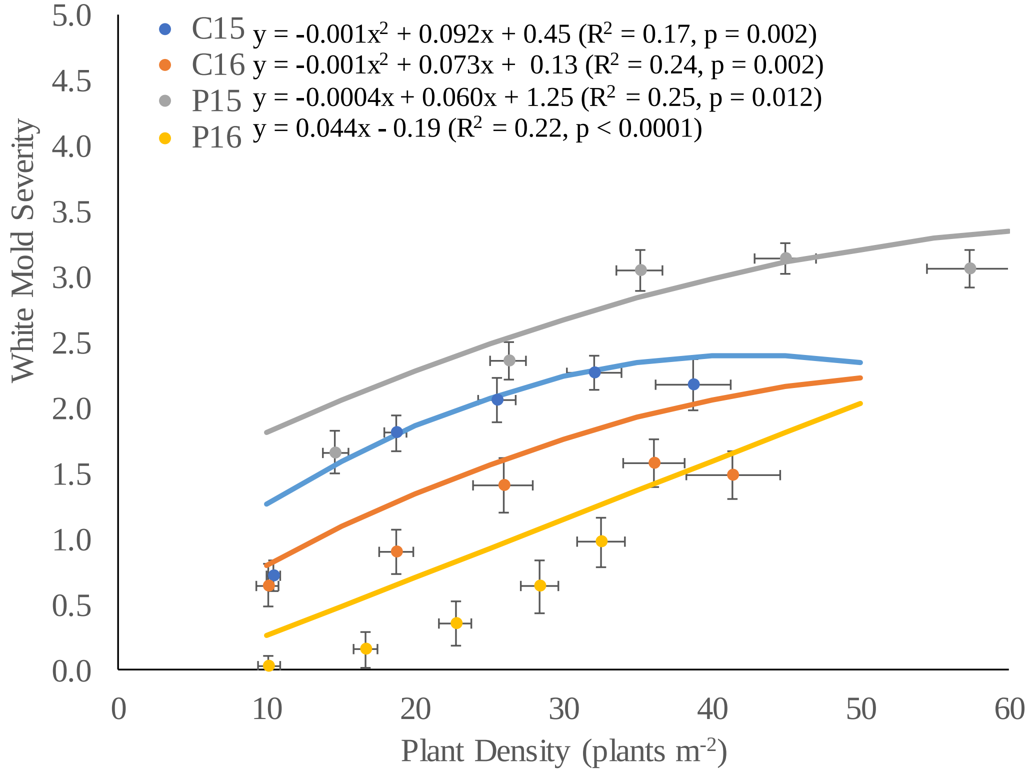



**Figure 4.5.7**. White mould severity as influenced by increasing plant density in pinto bean at Carman (C) and Portage la Prairie (P) in 2015 and 2016. Plus/minus one standard error of the mean and significant linear models ($p < 0.05$) are reported.

**4.5.2.5. Main Effect of Row Spacing on White Mould Severity in Pinto bean.** Pinto bean grown at the narrow row spacing of 19 cm consistently had lower severity of white mould than at the widest row spacing of 76 cm (Figure 4.5.8). Otherwise, the effect of row width varied with each site-year. At Carman in 2015, pinto bean planted at all row widths had similar white mould severity ratings and, at Carman in 2016, planting pinto bean at 19 and 57 cm row widths resulted in lower white mould severity than planting at the wide row width of 76 cm, however, dry bean planted at the 38 and 76 cm row widths performed no differently.

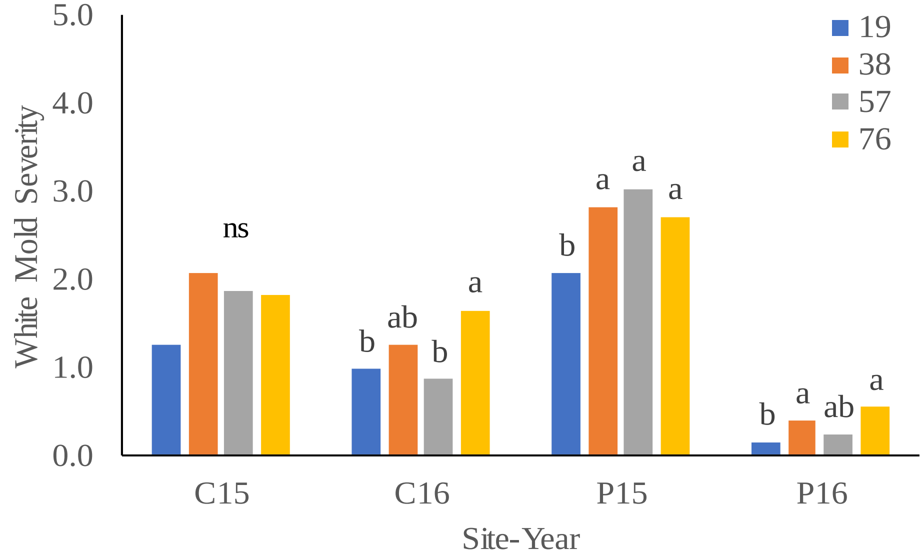



**Figure 4.5.8.** Mean white mould severity at four row widths in the pinto bean market class at four site-years, Carman (C) and Portage la Prairie (P) in 2015 and 2016. Within site-year, bars followed by different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

**4.5.2.6. Effect of Variety and Row Spacing on the White Mould Severity-Actual Plant Density Relationship in Pinto Bean.** An interaction effect between variety and row spacing in the density-dependence of pinto bean white mould severity was observed at Portage la Prairie in 2016 only (Table 4.5.6). At this site-year, regression analysis showed that white mould severity in Monterrey and Windbreaker pinto bean had a positive relationship with density except when planted at 19 cm row widths, indicating that at row widths equal to or greater than 38 cm white mould severity increased with greater plant densities (Table 4.5.7). Varieties differed in this response when planted at 57 cm, where the positive relationship with density was linear for Monterrey and quadratic for Windbreaker.

Row spacing affected the plant density-white mould severity relationship in pinto bean at Portage la Prairie in 2015. Regression analysis indicated that, at Portage la Prairie in 2015, white mould severity in pinto bean had a positive relationship with density, except in Monterrey pinto bean planted at 38 and 57 cm intermediate row widths (Table 4.5.7).

**Table 4.5.6**. P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing white mould in pinto bean as influenced by actual plant density at four site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie | |
|---|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 | 2016 |
| | | p-values | | | |
| Variety (V) | linear | 0.3149 | 0.7086 | 0.0987 | 0.5843 |
| | quadratic | 0.1784 | 0.9091 | 0.3015 | 0.5535 |
| Row spacing (RS) | linear | 0.2773 | 0.9155 | **0.0003** | 0.5400 |
| | quadratic | 0.2491 | 0.9511 | **0.0003** | 0.4340 |
| V * RS | linear | 0.1864 | 0.1353 | 0.3518 | 0.0573 |
| | quadratic | 0.1906 | 0.1089 | 0.2825 | **0.0243** |

**Table. 4.5.7.** Linear and quadratic regression slopes and p-values of regressions of dependent variable white mould severity as influenced by actual dry bean plant densities in two varieties of pinto bean planted at four different row spacings at four site years. The slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Monterrey | 19 | | | | | 13 – 63 |
| | | | 38 | **0.02** | **0.0218** | | | 9 – 66 |
| | | | 57 | **0.29** | **0.0001** | **-0.006** | **0.0007** | 7 – 39 |
| | | | 76 | **0.04** | **0.0092** | | | 9 – 49 |
| | | Windbreaker | 19 | | | | | 8 – 58 |
| | | | 38 | **0.06** | **0.0109** | | | 11 – 54 |
| | | | 57 | **0.08** | **0.0010** | | | 5 – 34 |
| | | | 76 | **0.05** | **0.0416** | | | 8 – 45 |
| | 2016 | Monterrey | 19 | **0.04** | **0.0477** | | | 9 – 47 |
| | | | 38 | **0.04** | **0.0003** | | | 3 – 85 |
| | | | 57 | **0.14** | **0.0443** | **0.002** | **0.0372** | 6 – 66 |
| | | | 76 | **0.02** | **0.0342** | | | 7 – 63 |
| | | Windbreaker | 19 | **0.06** | **0.0013** | | | 9 – 42 |
| | | | 38 | **0.04** | **0.0056** | | | 9 – 59 |
| | | | 57 | **0.03** | **0.0215** | | | 4 – 84 |
| | | | 76 | **0.18** | **0.0073** | **0.003** | **0.0427** | 3 – 46 |
| Portage la Prairie | 2015 | Monterrey | 19 | **0.03** | **0.0056** | | | 16 – 71 |
| | | | 38 | | | | | 11 – 67 |
| | | | 57 | | | | | 14 – 98 |
| | | | 76 | **0.27** | **0.0005** | **0.004** | **0.0012** | 10 – 53 |
| | | Windbreaker | 19 | **0.05** | **0.0008** | | | 13 – 66 |
| | | | 38 | **0.04** | **0.0213** | | | 11 – 51 |
| | | | 57 | **0.03** | **0.0004** | | | 9 – 84 |
| | | | 76 | **0.19** | **0.0002** | **0.002** | **0.0010** | 8 – 62 |
| | 2016 | Monterrey | 19 | | | | | 7 – 44 |
| | | | 38 | **0.07** | **0.0124** | | | 5 – 37 |
| | | | 57 | **0.05** | **0.0166** | | | 6 – 50 |
| | | | 76 | **0.06** | **0.0052** | | | 6 – 40 |
| | | Windbreaker | 19 | | | | | 12 – 42 |
| | | | 38 | **0.03** | **0.0020** | | | 7 – 46 |
| | | | 57 | | | **0.003** | **0.0185** | 5 – 34 |
| | | | 76 | **0.04** | **0.0031** | | | 5 - 43 |

### 4.6 Above-Ground Resource Capture

Ground cover image analysis was used to asses light interception as a measure of above-ground resource capture. Ground cover results have been separated by site-year due to the differences in timing of each image capturing session. The timing of image capture has been reported as the plant development stage at time of capture. While images were captured at more than two bean developmental stages at some site-years, image capture at the V3-V5 vegetative development stages and the R1-R2 reproductive development stages was common to all site-years.

It is worth noting that at the later image capturing sessions during reproductive development, shading of lower leaves in the canopy would have influenced the accuracy of the ground cover assessment. As percent ground cover approached 100% Assess 2.0 underestimated ground cover due to shadows and failed to detect the presence of leaves lower in the canopy (Figure 4.6.1). Where row closure was not achieved (Figure 4.6.2), percent ground cover was often below 90%. Due to this, percent ground cover ratings greater than 90% will be assumed to have achieved full canopy closure.


**Figure 4.6.1.** Full canopy closure image captured at R1 at Portage la Prairie in 2015 (left) and the percent ground cover assessment from Assess 2.0 (right).


**Figure 4.6.2.** Incomplete canopy closure image captured at R1 at Portage la Prairie in 2015 (left) and the percent ground cover assessment from Assess 2.0 (right).

### 4.6.1 Navy Bean Above-Ground Resource Capture

Seeding density was the most consistent driver of ground cover in navy bean as it was significant at every site-year during vegetative and reproductive development (Table 4.6.1). This was followed by the effect of row spacing and the interaction of variety by row spacing on ground cover (Table 4.6.1). Navy bean ground cover data was further separated by variety, for comparison with yield data. Once separated by variety, the interaction effect of row spacing by seeding density was apparent, as it was significant during vegetative development at two site-years and during reproductive development at three site-years (Table 4.6.2). The combination of planting navy bean at greater seeding densities and narrower row widths resulted in greater ground cover.

**Table 4.6.1.** Significance (p-value) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable ground cover in the navy bean market class during the V3-V5 and R1-R2 plant development stages at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | | | Portage la Prairie | |
|---|---|---|---|---|---|---|
| | 2015 | | 2016 | | 2015 | |
| Fixed effects | V3 | R1 | V4/V5 | R2 | V3 | R1 |
| | p-values | | | | | |
| Variety (V) | 0.5456 | **0.0269** | 0.1406 | 0.0969 | 0.5596 | 0.3862 |
| Row spacing (RS) | **<.0001** | **0.0281** | 0.0564 | **0.0215** | **<.0001** | 0.2162 |
| V * RS | 0.5071 | **0.0479** | **0.0416** | **0.0064** | **0.0207** | 0.9316 |
| Seeding density (SD) | **<.0001** | **<.0001** | **0.0507** | **<.0001** | **<.0001** | **0.0327** |
| V * SD | 0.9332 | 0.1302 | 0.2462 | 0.2594 | 0.1616 | 0.5625 |
| RS * SD | **0.0089** | 0.5310 | 0.5063 | 0.0627 | **0.0189** | 0.6114 |
| V * RS * SD | 0.4179 | **0.0087** | 0.4171 | **0.0007** | 0.7582 | 0.0710 |

**Table 4.6.2.** Significance (p-value) of the fixed effects of row spacing, seeding density and their interactions in the dependent variable ground cover in Envoy and T9905 navy bean varieties during the V3-V5 and R1 – R2 plant development stages at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | | | Portage la Prairie | |
|---|---|---|---|---|---|---|
| | 2015 | | 2016 | | 2015 | |
| Fixed effects | V3 | R1 | V4 – V5 | R2 | V3 | R1 |
| | Envoy | | | | | |
| Row spacing (RS) | **0.0181** | 0.9543 | **<.0001** | 0.6169 | **0.0008** | 0.2077 |
| Seeding density (SD) | **<.0001** | **<.0001** | **<.0001** | **0.0011** | **<.0001** | 0.6017 |
| RS * SD | 0.4036 | **0.007** | **0.0287** | **0.0055** | 0.0608 | 0.6388 |
| | T9905 | | | | | |
| Row spacing (RS) | **0.002** | **0.0085** | 0.0618 | **0.0054** | **0.0029** | 0.7796 |
| Seeding density (SD) | **<.0001** | **0.0476** | **0.0178** | **0.0016** | **<.0001** | **0.0258** |
| RS * SD | **0.0043** | 0.7073 | 0.1588 | **0.0016** | 0.481 | **0.0014** |

**4.6.1.1. Interaction Effect of Plant Density and Row Spacing on Ground Cover in Navy Bean.** The combination of narrow row widths and increased plant densities resulted in significantly greater ground cover than low densities at wide row widths during vegetative development (Figure 4.6.3). The interaction of row spacing and seeding densities was significant at one site in each variety during vegetative development - in T9905 navy bean at Carman in 2015 and Envoy navy bean at Carman in 2016 (Table 4.6.2). Once navy bean reached reproductive development stages the interaction effect of row spacing and seeding density was inconsistent among site-years (Table 4.6.2). This interaction was significant at two site-years in each variety during R1-R2 development stages. In Envoy navy bean, a significant interaction occurred at Carman in both 2015 and 2016 and in T9905 navy bean at Carman in 2016 and Portage la Prairie in 2015 (Table 4.6.2). In Envoy navy bean at Carman in 2015, planting at narrow row widths of 19 cm and low seeding densities of 20 plants $m^{-2}$ resulted in significantly lower ground cover compared with other treatments, achieving 10 – 14% less ground cover than bean planted at a seeding density targeting 20 plants $m^{-2}$ at 38 – 76 cm row widths (Figure 4.6.3). This treatment combination was the only one to not achieve canopy closure (greater than 90%) by the R1 developmental stage at that site-year. At Carman in 2016, Envoy navy bean planted targeting 20 and 50 plants $m^{-2}$ at 76 cm row widths also did not achieve canopy closure. This response was anticipated at the wide row widths at low seeding densities, but not at the greater seeding density of 50 plants $m^{-2}$. The low ground cover at this greater seeding density is likely due to variable seed placement within the row, creating a combination of dense patches of foliage and patches of bare soil. At Carman in 2016, T9905 navy bean planted at 38 cm row widths had 63-89% ground cover at the R2 developmental stage while all other treatment combinations achieved more than 89% ground cover (Figure 4.6.3). The limited ground cover achieved at the 38 cm row width can be attributed to skips in the plots where poor seed placement led to bare patches of soil. While there was a significant interaction effect in T9905 navy bean planted at Portage la Prairie in 2015 where beans planted at low seeding densities and 38 cm row widths had less ground cover than other treatments, all treatment combinations achieved greater than 90% ground cover by the time they had reached the R1 development stage (Figure 4.6.3).

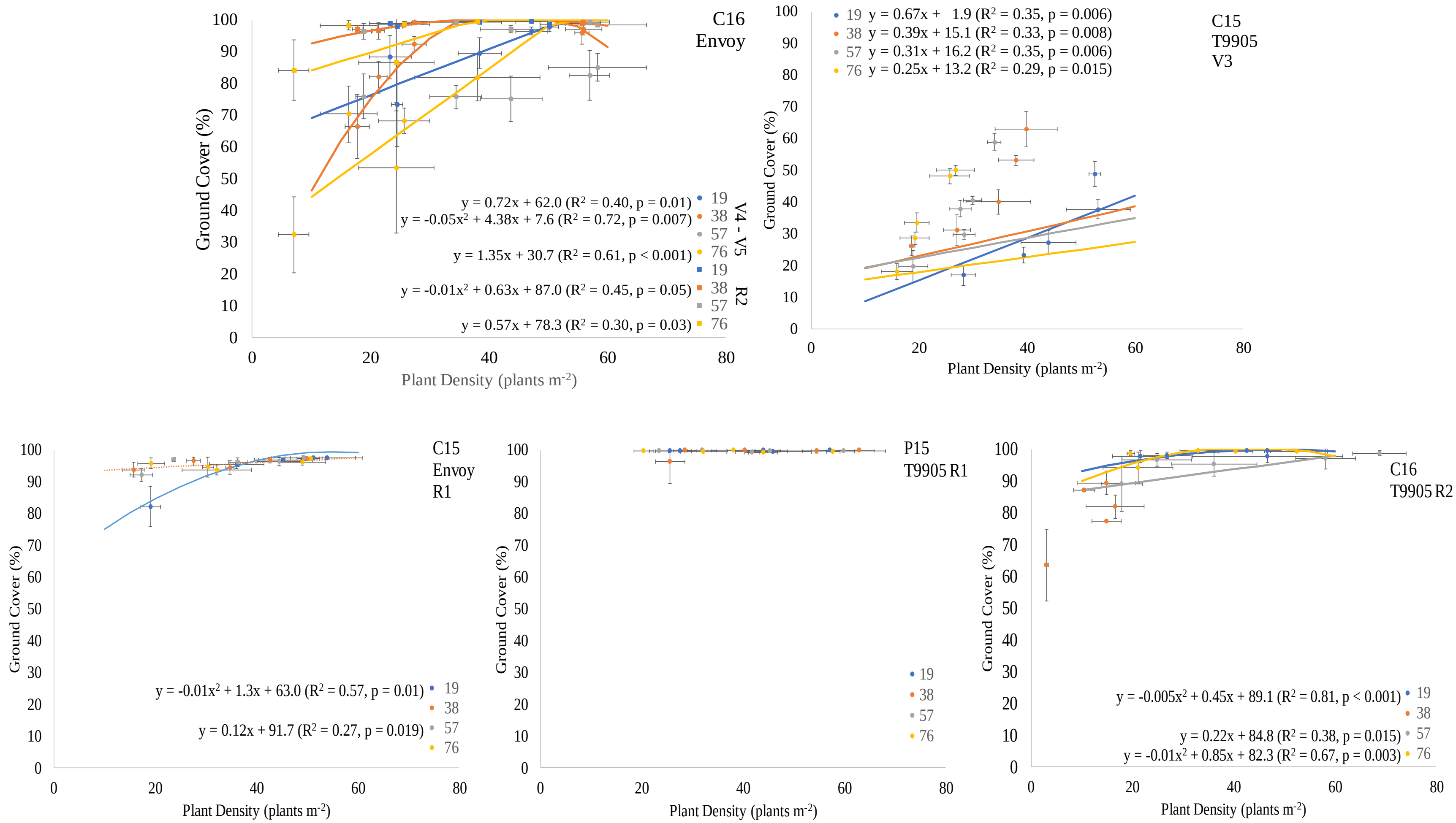
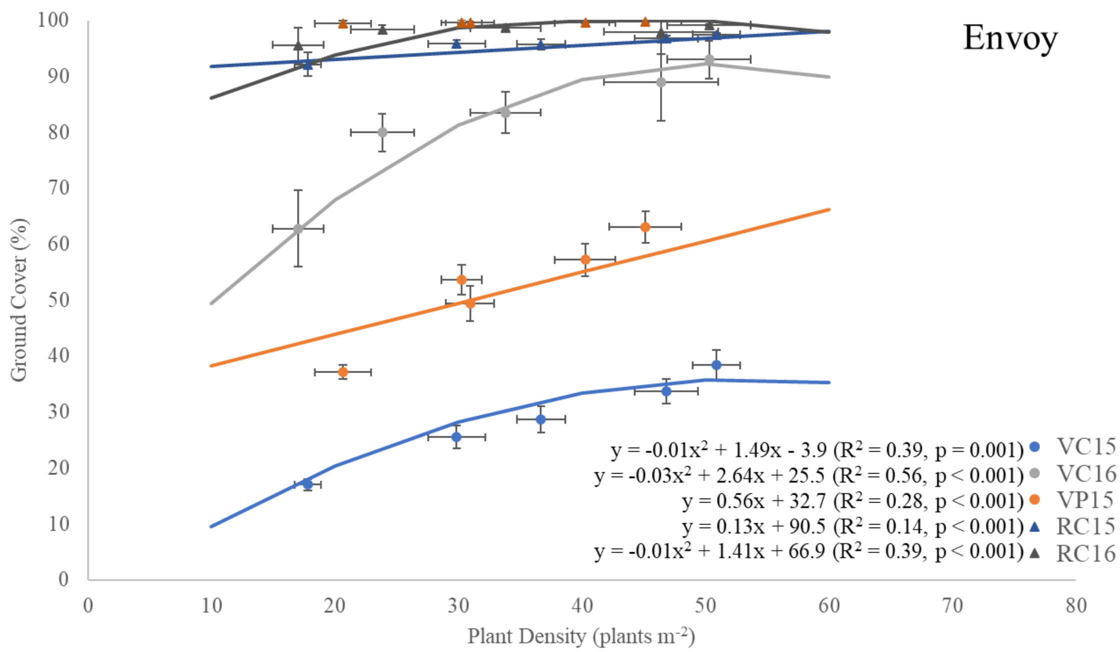


**Figure 4.6.3.** Percent ground cover in Envoy and T9905 navy bean during vegetative (V3 – V5) and reproductive (R1 – R2) development for the interaction of seeding density and row spacing at site-years where the interaction was significant based on the ANOVA results in Table 4.6.2 (Carman in 2016 = C16, Carman in 2015 = C15 and Portage la Prairie in 2015 = P15). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.1.2 Main Effect of Plant Density on Ground Cover in Navy Bean.** Increasing seeding densities increased early-season ground cover during vegetative development at every site-year and in both navy bean varieties (Figure 4.6.4). Overall, navy bean planted at lower seeding densities (10 – 20 plants $m^{-2}$) had significantly lower ground cover during vegetative development stages compared with beans planted at greater seeding densities (30 – 60 plants $m^{-2}$) (Figure 4.6.4). Navy bean planted at seeding densities of 30 and 40 plants $m^{-2}$ covered the same proportion of the soil surface during vegetative development but tended to have lower ground cover than beans planted targeting 50 and 60 plants $m^{-2}$. This effect persisted into the reproductive development stages in T9905 navy bean at all site-years and Envoy navy bean at two out of three site-years. Low seeding densities maintained lower ground cover than beans planted at greater seeding densities throughout the experiments. However, by the time Envoy and T9905 navy bean reached R1 – R2, ground cover was greater than 90%, indicating that effective canopy closure was achieved at all seeding density treatments once reproductive development stages had been reached. Though planting at increased seeding densities achieved increased ground cover and increased early-season light capture, this did not translate into increased navy bean seed yield in these experiments. Navy bean grown at lower seeding densities of 20 plants $m^{-2}$ achieved significantly greater seed yield than increased seeding densities, despite having the lowest percent ground cover (Table 4.3.1).



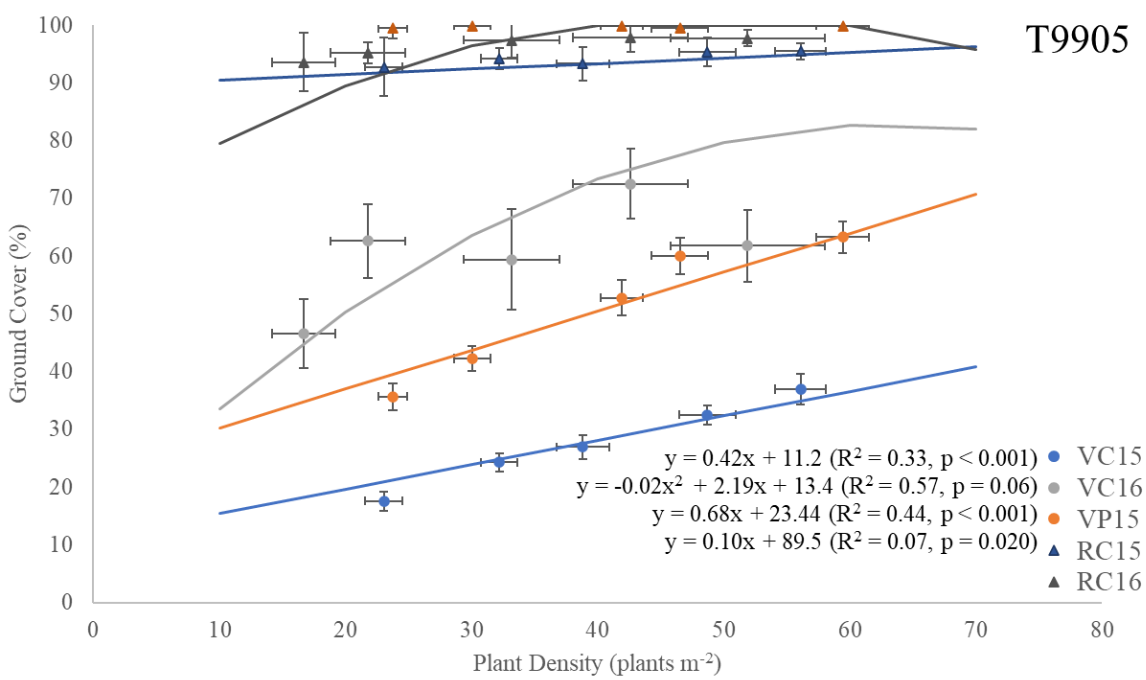




**Figure 4.6.4.** Percent ground cover in Envoy and T9905 navy bean during vegetative (V = V3 – V5) and reproductive (R = R1 – R2) development at five seeding densities at Carman in 2015 (C15) and 2016 (C16) Portage la Prairie in 2015 (P15). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.1.3 Main Effect of Row Spacing on Ground Cover in Navy Bean.** Increasing the distance between rows decreased ground cover during vegetative development at every site-year in Envoy navy bean, and at the 2015 sites in T9905 navy bean (Table 4.6.2). Planting at wide row widths of 76 cm decreased early-season ground cover in both navy bean varieties while beans planted at 19 cm row widths consistently achieved the highest ground cover during vegetative development (Figure 4.6.5). Increased navy bean seed yield with planting in narrower row widths could be due, in part, to the increased early-season ground cover achieving increased light capture during vegetative development. T9905 navy bean planted at 19 to 57 cm row widths had similar early-season ground cover at all site-years (Figure 4.6.5). Envoy navy bean planted at 38 cm row widths yielded greater than wide-row treatments of 76 cm at two site-years, and had greater ground cover than the wide-row treatment of 57 cm at only one site-year. Envoy navy bean planted at all row widths achieved complete ground closure by the time they reached reproductive development, and no treatment effects were apparent (Figure 4.6.5). On the other hand, ground cover in T9905 navy bean at Carman in 2015 and 2016 was influenced by row spacing during late-season reproductive development. At Carman in 2015, T9905 bean planted in 76 cm row widths did not exhibit complete canopy closure at the R1 developmental stage. In 2016, T9905 navy bean planted at 38 cm row widths did not achieve complete canopy closure, though this was likely due to poor and variable seed placement at planting, causing clumped plant distribution throughout the 38 cm row treatment plots due to skips in the row where the seeder did not distribute seed for portions of the row due to plugged openers.

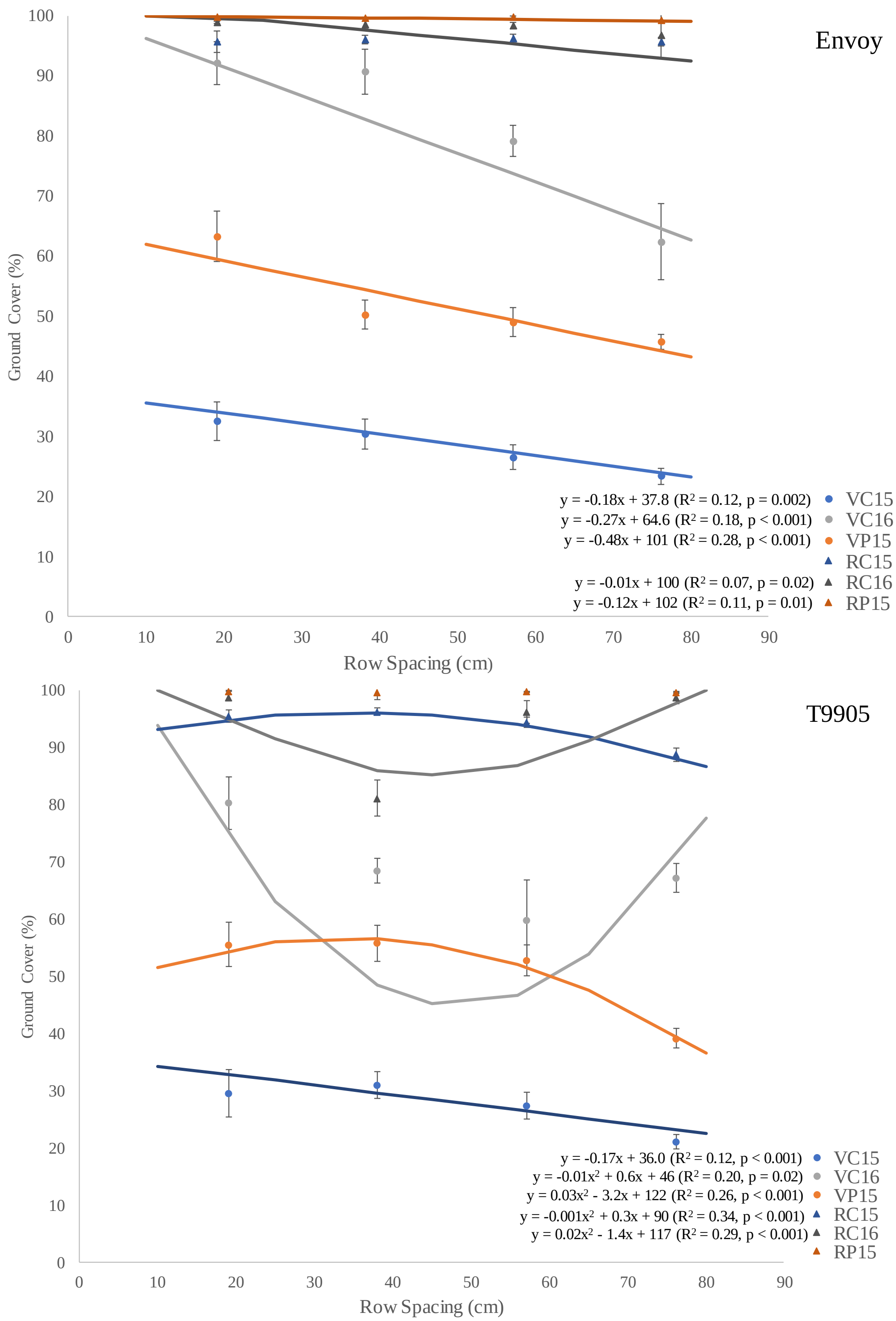



**Figure 4.6.5.** Percent ground cover in Envoy and T9905 navy bean during vegetative (V = V3 – V5) and reproductive (R = R1 – R2) development at four row spacings at Carman in 2015 (C15) and 2016 (C16) Portage la Prairie in 2015 (P15). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.1.4 Main Effect of Variety on Ground Cover in Navy Bean.** Despite having contrasting growth types, type I Envoy navy bean and type II T9905 navy bean behaved similarly throughout the growing season with regards to light capture. Variety only had a significant effect at one out of three site-years, and only during the R1 reproductive development stage (Table 4.6.1). At Carman in 2015, Envoy navy bean had 1.6% greater ground cover than T9905 navy bean, though both varieties had achieved greater than 94% ground cover and complete canopy closure.

**4.6.1.5. Effect of Variety and Row Spacing on the Ground Cover-Actual Plant Density Relationship in Navy Bean.** During vegetative development, yield-density slopes were not affected by navy bean variety or row spacing despite some significant regression lines (Table 4.6.3). Within each treatment combination, regression analysis showed that, during vegetative development, ground cover had a positive relationship with density, though there were no differences in slopes among treatments according to ANOVA (Table 4.6.4).

During reproductive development, row spacing affected the plant density-ground cover relationship in navy bean at Carman in 2015 (Table 4.6.5). Regression analysis indicated that, at Carman in 2015, ground cover of Envoy navy bean planted at 19 and 57 cm row widths and T9905 navy bean planted in 76 cm rows had a positive relationship with density, whereas density increased, the percent of ground cover increased (Table 4.6.5).

**Table 4.6.3.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing ground cover during vegetative development in navy bean as influenced by actual plant density at three site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie |
|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 |
| | | -------------------- p-values | | ----------------- |
| Variety (V) | linear | 0.3042 | 0.6531 | 0.5972 |
| | quadratic | 0.2808 | 0.7336 | 0.9715 |
| Row spacing (RS) | linear | 0.1436 | 0.1440 | 0.0760 |
| | quadratic | 0.2270 | 0.1656 | 0.1543 |
| V*RS | linear | 0.7023 | 0.1253 | 0.7745 |
| | quadratic | 0.5612 | 0.3972 | 0.6501 |

**Table 4.6.4.** Linear and quadratic regression slopes and p-values of regressions of dependent variable ground cover as influenced by actual plant densities during vegetative development in two varieties of navy bean planted at four different row spacings at three site-years. Slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Envoy | 19 | **2.49** | **0.0044** | **-0.025** | **0.0107** | 16 – 74 |
| | | | 38 | **0.65** | **0.0002** | | | 11 – 55 |
| | | | 57 | **1.74** | **0.0109** | **-0.019** | **0.0448** | 12 – 57 |
| | | | 76 | **0.27** | **0.0042** | | | 13 – 60 |
| | | T9905 | 19 | **0.67** | **0.0059** | | | 24 – 63 |
| | | | 38 | **0.39** | **0.0078** | | | 22 – 71 |
| | | | 57 | **0.31** | **0.0057** | | | 13 – 61 |
| | | | 76 | **0.23** | **0.0149** | | | 14 – 58 |
| | 2016 | Envoy | 19 | **0.72** | **0.0117** | | | 18 – 53 |
| | | | 38 | **4.38** | **0.0030** | **-0.050** | **0.0074** | 14 – 60 |
| | | | 57 | | | | | 16 – 74 |
| | | | 76 | **1.35** | **0.0006** | | | 2 – 51 |
| | | T9905 | 19 | **3.28** | **0.0030** | **-0.034** | **0.0124** | 11 – 67 |
| | | | 38 | | | | | 3 – 24 |
| | | | 57 | **0.92** | **0.0011** | | | 11 – 75 |
| | | | 76 | **1.32** | **0.0010** | **-0.012** | **0.0198** | 7 – 63 |
| Portage la Prairie | 2015 | Envoy | 19 | | | | | 16 – 55 |
| | | | 38 | **0.67** | **0.0001** | | | 13 – 56 |
| | | | 57 | **0.45** | **0.0240** | | | 15 – 58 |
| | | | 76 | **0.22** | **0.0308** | | | 15 – 58 |
| | | T9905 | 19 | **0.86** | **0.0004** | | | 18 – 63 |
| | | | 38 | **0.68** | **0.0003** | | | 20 – 67 |
| | | | 57 | **0.62** | **0.0002** | | | 18 – 73 |
| | | | 76 | **0.39** | **0.0004** | | | 15 - 60 |

**Table 4.6.5.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing ground cover during reproductive development in navy bean as influenced by actual plant density at three site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie |
|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 |
| | | ------------------- p-values | ------------- | |
| Variety (V) | linear | 0.9342 | 0.3760 | 0.6597 |
| | quadratic | 0.8874 | 0.3606 | 0.6100 |
| Row spacing (RS) | linear | **0.0102** | 0.0772 | 0.9728 |
| | quadratic | **0.0116** | 0.0548 | 0.9858 |
| V*RS | linear | 0.4422 | 0.0556 | 0.9149 |
| | quadratic | 0.6615 | 0.1161 | 0.9701 |

**Table 4.6.6.** Linear and quadratic regression slopes and p-values of regressions of dependent variable ground cover as influenced by actual plant densities during reproductive development in two varieties of navy bean planted at four different row spacings at three site-years. Slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Envoy | 19 | **1.33** | **0.0023** | **-0.012** | **0.0106** | 16 – 74 |
| | | | 38 | | | | | 11 – 55 |
| | | | 57 | **0.12** | **0.0189** | | | 12 – 57 |
| | | | 76 | | | | | 13 – 60 |
| | | T9905 | 19 | | | | | 24 – 63 |
| | | | 38 | | | | | 22 – 71 |
| | | | 57 | | | | | 13 – 61 |
| | | | 76 | | | | | 14 – 58 |
| | 2016 | Envoy | 19 | | | | | 18 – 53 |
| | | | 38 | **0.63** | **0.0334** | **-0.007** | **0.0504** | 14 – 60 |
| | | | 57 | | | | | 16 – 74 |
| | | | 76 | **0.57** | **0.0334** | | | 2 – 51 |
| | | T9905 | 19 | **0.44** | **0.0002** | **-0.005** | **0.0012** | 11 – 67 |
| | | | 38 | | | | | 3 – 24 |
| | | | 57 | **0.22** | **0.0150** | | | 11 – 75 |
| | | | 76 | **0.85** | **0.0010** | **-0.010** | **0.0034** | 7 – 63 |
| Portage la Prairie | 2015 | Envoy | 19 | | | | | 16 – 55 |
| | | | 38 | | | | | 13 – 56 |
| | | | 57 | | | | | 15 – 58 |
| | | | 76 | | | | | 15 – 58 |
| | | T9905 | 19 | | | | | 18 – 63 |
| | | | 38 | | | | | 20 – 67 |
| | | | 57 | | | | | 18 – 73 |
| | | | 76 | | | | | 15 - 60 |

### 4.6.2 Pinto Bean Above-Ground Resource Capture

Early-season resource capture was influenced similarly by seeding density and row spacing in pinto bean as both effects were significant at every site-year during vegetative development (V3-V5) (Table 4.6.7). This continued into reproductive development as seeding density was significant at each site-year and row spacing was significant at two of four site-years during reproductive development (Table 4.6.7). The interaction of row spacing and seeding density was significant at Carman in 2015 during both vegetative and reproductive development and at Portage la Prairie in 2015, where pinto bean planted at lower seeding densities caused similar percent ground cover, regardless of row width, but pinto bean planted at greater seeding densities resulted in greater ground cover if planted at row widths less than or equal to 57 cm (Table 4.6.7, Figure 4.6.6). At Carman in 2016, there was a significant interaction among variety, row spacing and seeding density in pinto bean ground cover during reproductive development though, once standard errors of the mean are taken into consideration, each treatment achieved greater than 90% ground cover, indicating the canopy had achieved full canopy closure (Table 4.6.7, Figure 4.6.6). At other site-years, ground cover was not different between the pinto bean varieties.

**Table 4.6.7.** Significance (p-value) of fixed effects variety, row spacing, seeding density and their interactions in the dependent variable ground cover in the pinto bean market classes during the V3-V5 and R1 – R2 plant development stages at four site-years. Values indicated in bold were p-values significant at the 5% level of significance.

| | Carman | | | | Portage la Prairie | | | |
|---|---|---|---|---|---|---|---|---|
| | 2015 | | 2016 | | 2015 | | 2016 | |
| Fixed effects | V3 | R1 | V4/V5 | R2 | V3 | R1 | V4 | R1 |
| | ------------------------------------------- p-values ------------------------------------ | | | | | | | |
| Variety (V) | 0.1413 | 0.8555 | 0.748 | 0.6492 | 0.3703 | 0.4185 | 0.7633 | 0.8552 |
| Row spacing (RS) | **<.0001** | **0.0458** | **0.0089** | **0.0531** | **<.0001** | 0.4539 | **0.0524** | 0.0652 |
| V * RS | 0.6245 | 0.1521 | 0.1605 | 0.2357 | 0.6559 | 0.1803 | 0.4755 | **0.0036** |
| Seeding density (SD) | **<.0001** | **<.0001** | **<.0001** | **<.0001** | **<.0001** | **<.0001** | **<.0001** | **<.0001** |
| V * SD | 0.6984 | 0.232 | 0.3191 | 0.9325 | 0.3501 | 0.3803 | 0.5944 | 0.1383 |
| RS * SD | **0.0385** | **0.0092** | 0.2361 | **0.0001** | **0.0321** | 0.0928 | 0.4673 | 0.8974 |
| V * RS * SD | 0.2340 | 0.4697 | 0.6417 | **0.0334** | 0.8492 | 0.3749 | 0.6073 | 0.2834 |

**4.6.2.1 Interaction Effect of Variety, Row Spacing and Plant Density on Ground Cover in Pinto Bean.** At Carman in 2016 during reproductive development, a significant interaction effect of variety, row spacing and seeding density was observed, where ground cover in Windbreaker pinto beans planted at 19 and 76 cm row widths responded to plant density, but Monterrey pinto bean planted at the same row widths did not change with plant density. However, this effect was of little agronomic significance as every treatment achieved full canopy closure at that site-year (Figure 4.6.6).

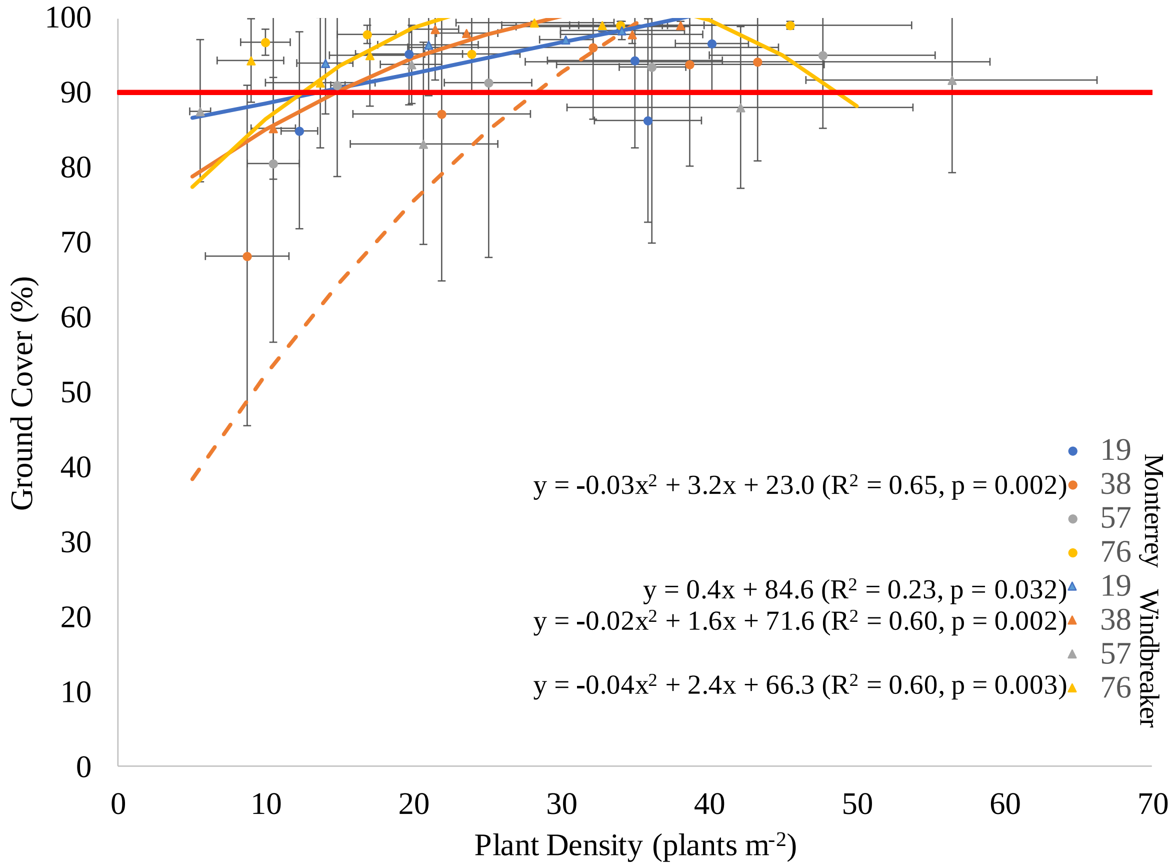



**Figure 4.6.6.** Percent ground cover in Monterrey and Windbreaker pinto bean during reproductive (R2) development for the interaction effect of variety, seeding density and row spacing at Carman in 2016. The red line indicates 90% canopy closure where "complete" canopy closure has been achieved. Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.2.2 Interaction Effect of Row Spacing and Plant Density on Ground Cover in Pinto Bean.** Similar to navy bean, pinto bean planted at narrow row spacings and greater seeding densities had greater early-season ground cover than those at low seeding densities and wide row widths (Figure 4.6.7). During vegetative development this interaction effect was significant in 2015 at Carman and Portage la Prairie (Table 4.6.7). This reduced ground cover persisted at Carman in 2015 where beans planted at low seeding densities of 10 plants m$^{-2}$ did not achieve full canopy closure at any row width by reproductive development. Beans planted at wider row spacings of 57 and 76 cm with lower seeding densities of 10 – 20 and 10 – 30 plants $m^{-2}$, respectively, also did not achieve row closure (Figure 4.6.7). Pinto bean grown at Carman in 2015 were also the one site-year where the interaction of row spacing and seeding density had a significant effect on seed yield (Table 4.4.2). The greatest yielding treatment combination was pinto bean planted at 19 cm row widths and seeding density of 10 plants $m^{-2}$, which is surprising since those beans had 5 – 30% less foliage cover during vegetative development and 14 – 16% less ground cover during reproductive development than other seeding densities planted at 19 cm row widths (Figure 4.4.1, Figure 4.6.7). More complete ground cover did not translate into greater bean seed yield in these experiments (Figure 4.4.1).

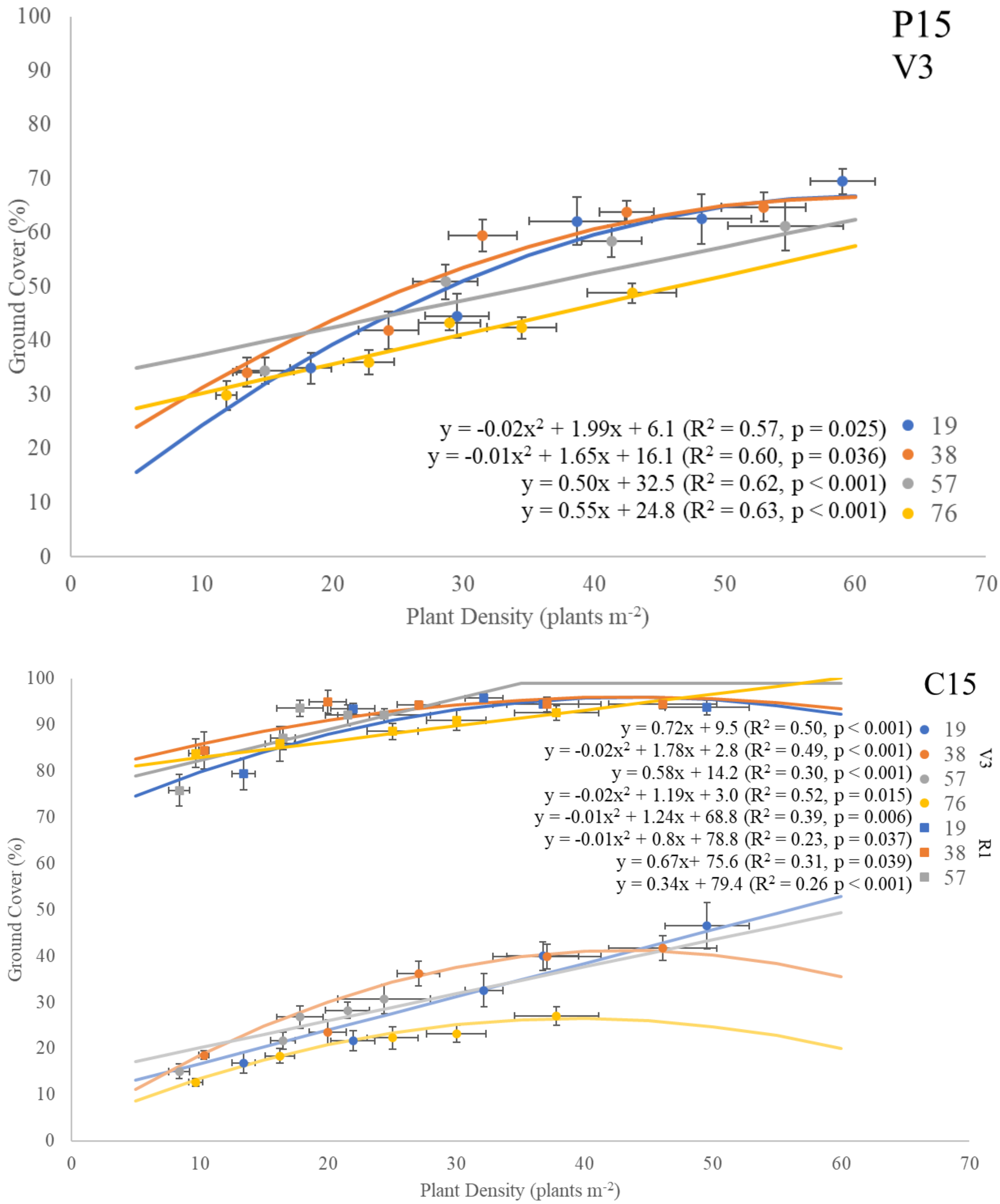



**Figure 4.6.7.** Percent ground cover in pinto bean during vegetative (V3 – V5) and reproductive (R1 – R2) development for the interaction of seeding density and row spacing at significant site-years (Portage la Prairie in 2015 (P15) and Carman in 2015 (C15)). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.2.3 Interaction Effect of Variety and Row Spacing on Ground Cover in Pinto Bean.**

Monterrey pinto bean had greater ground cover than Windbreaker pinto bean when grown at 57 cm row widths at Portage la Prairie in 2016 during reproductive development (Figure 4.6.8). When grown at 38 or 76 cm row widths, however, the opposite occurred at Portage la Prairie in 2016, where Windbreaker pinto bean produced more ground cover than Monterrey pinto bean during the R2 reproductive development stage.

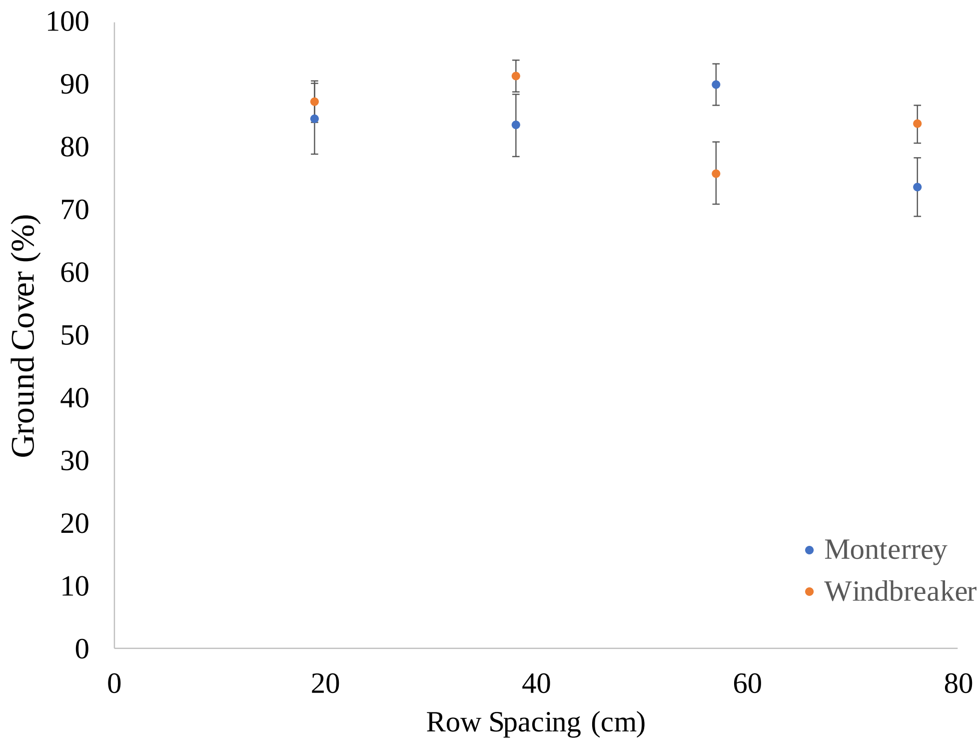



**Figure 4.6.8.** Percent ground cover in Monterrey and Windbreaker pinto bean during reproductive (R2) development for the interaction of variety and row spacing at Portage la Prairie in 2016. Error bars represent plus/minus one standard error of the mean. Neither linear nor quadratic regression models were significant ($p < 0.05$).

**4.6.2.4 Main Effect of Plant Density on Ground Cover in Pinto Bean.** Increasing seeding density increased percent ground cover of pinto bean at every site-year during vegetative and reproductive development (Table 4.6.7, Figure 4.6.9). By the time pinto bean reached reproductive development, pinto bean planted at seeding densities of 10 plants m$^{-2}$ did not achieve complete row closure at three of four site-years, while other seeding densities had achieved greater than 90% ground cover (Figure 4.6.9). At Portage la Prairie in 2016, only pinto bean planted targeting 40 – 50 plants m$^{-2}$ achieved row closure by reproductive development (Figure 4.6.9). Though increasing seeding density increased bean foliage cover and light capture, this did not translate into greater seed yields in pinto bean planted at increased seeding densities (Table 4.4.6). However, beans planted at greater seeding densities also experienced greater white mould severities, likely exacerbated by the greater amount of foliage cover, creating a cool, shaded understory for white mould development (Figure 4.5.7).

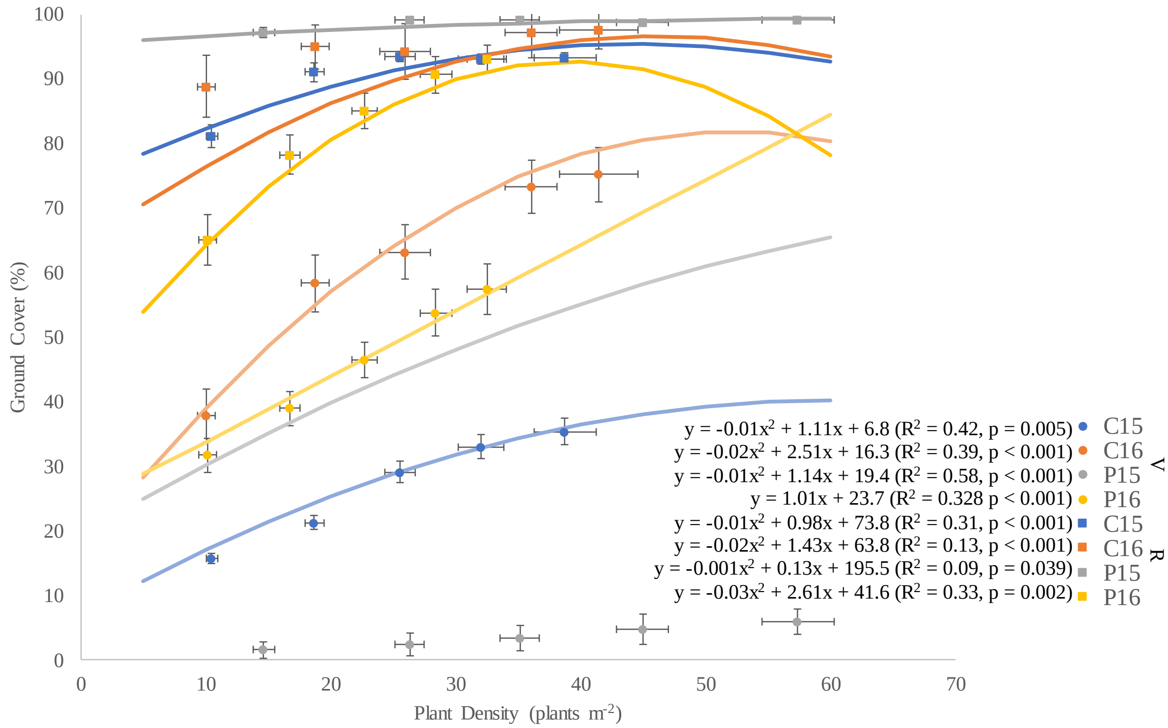



**Figure 4.6.9.** Percent ground cover in pinto bean during vegetative (V = V3 – V5) and reproductive (R = R1 – R2) development at five seeding densities at Carman in 2015 (C15) and 2016 (C16) and Portage la Prairie in 2015 (P15) and 2016 (P16). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.2.5 Main Effect of Row Spacing on Ground Cover.** Decreasing the distance between rows tended to increase the percent ground cover in pinto bean (Figure 4.6.10). Planting at wide row widths of 76 cm reduced ground cover during vegetative development at three out of four site-years (Figure 4.6.10). Pinto bean planted on 19 – 57 cm row widths performed similarly at two out of three significant site-years. At the third significant site-year, at Carman in 2015, pinto bean planted at 19 – 38 cm row widths had the greatest early-season ground cover, followed by 57 cm row widths. At one site-year, at Carman in 2015, wide row spacing significantly reduced late-season ground cover. There, pinto bean planted at 57 and 76 cm row widths did not achieve ground closure by the R1 developmental stage (Figure 4.6.10). Row spacing also had a significant effect at Carman in 2016, where 57 cm row widths had significantly less ground cover than 76 cm row widths, though both had achieved greater than 90% ground cover (Figure 4.6.10).

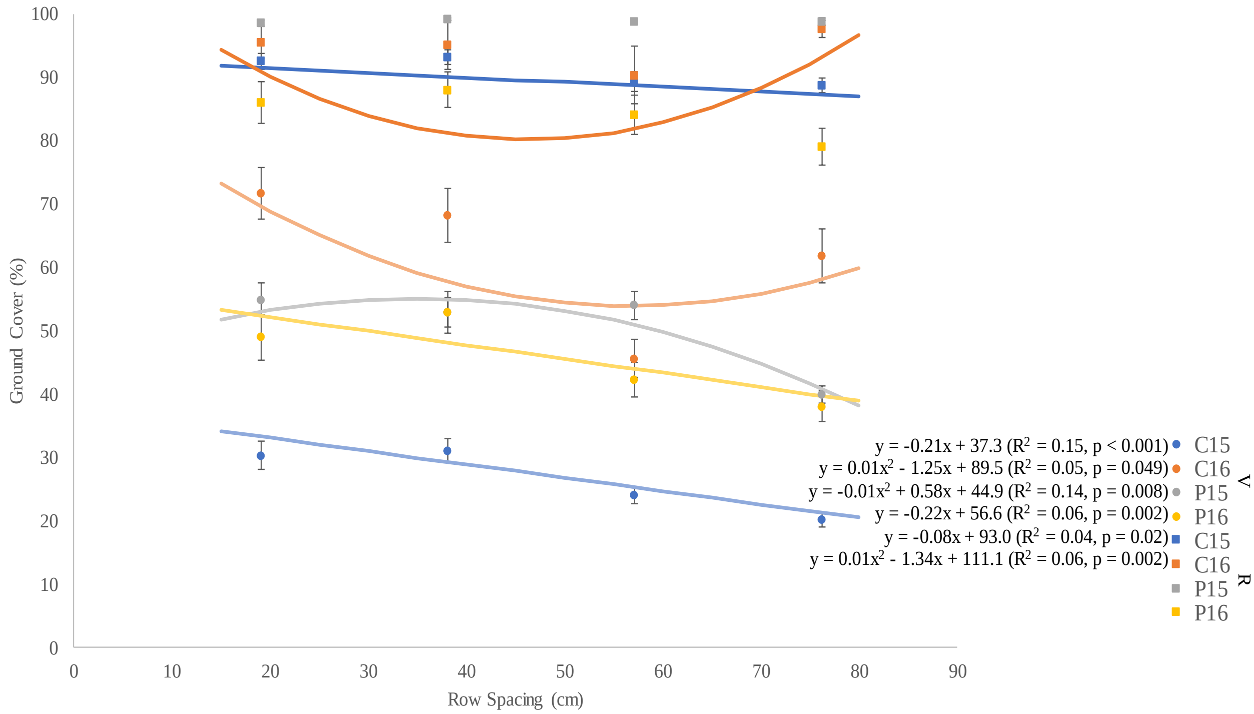



**Figure 4.6.10.** Percent ground cover in pinto bean during vegetative (V = V3 – V5) and reproductive (R = R1 – R2) development at four row widths at Carman in 2015 (C15) and 2016 (C16) Portage la Prairie in 2015 (P15) and 2016 (P16). Error bars represent plus/minus one standard error of the mean. Linear and quadratic regression models are reported only when significant ($p < 0.05$).

**4.6.2.6. Effect of Variety and Row Spacing on the Ground Cover-Actual Plant Density Relationship in Pinto Bean.** Variety affected the plant density-ground cover relationship in pinto bean during vegetative development at Portage la Prairie in 2016, where regression analysis showed that Monterrey and Windbreaker pinto bean ground cover had a positive relationship with density (Table 4.6.8, Table 4.6.9). Row spacing affected the plant density-ground cover relationship in pinto bean during vegetative and reproductive development at Carman in 2016, where regression analysis showed that at select row widths ground cover had a positive relationship with density (Table 4.6.10, Table 4.6.11).

**Table 4.6.8.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing ground cover in pinto bean during vegetative development as influenced by actual plant density at four site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie | |
|---|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 | 2016 |
| | | ----------------------- p-values | | ----------------------- | |
| Variety (V) | linear | 0.7493 | 0.0965 | 0.5564 | **0.0038** |
| | quadratic | 0.9427 | 0.1345 | 0.5754 | **0.0020** |
| Row spacing (RS) | linear | 0.5080 | **0.0018** | 0.2894 | 0.8111 |
| | quadratic | 0.4239 | **0.0033** | 0.4321 | 0.4502 |
| V*RS | linear | 0.4465 | 0.2461 | 0.6473 | 0.7418 |
| | quadratic | 0.3960 | 0.1519 | 0.7188 | 0.7549 |

**Table 4.6.9.** Linear and quadratic regression slopes and p-values of regressions of dependent variable ground cover as influenced by actual plant densities during vegetative development in two varieties of pinto bean planted at four different row spacings at four site-years. Slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Monterrey | 19 | **0.76** | **<0.0001** | | | 13 – 63 |
| | | | 38 | **1.45** | **0.0016** | **-0.015** | **0.0109** | 9 – 66 |
| | | | 57 | | | | | 7 – 39 |
| | | | 76 | **0.33** | **0.0001** | | | 9 – 49 |
| | | Windbreaker | 19 | **0.76** | **0.0009** | | | 8 – 58 |
| | | | 38 | **2.21** | **0.0049** | **-0.028** | **0.0277** | 11 – 54 |
| | | | 57 | **0.82** | **0.0001** | | | 5 – 34 |
| | | | 76 | **1.47** | **0.0034** | **-0.018** | **0.0529** | 8 – 45 |
| | 2016 | Monterrey | 19 | **1.35** | **0.0034** | | | 9 – 47 |
| | | | 38 | **2.97** | **<0.0001** | **-0.025** | **0.0012** | 3 – 85 |
| | | | 57 | | | | | 6 – 66 |
| | | | 76 | **0.68** | **0.0010** | | | 7 – 63 |
| | | Windbreaker | 19 | **1.58** | **0.0009** | | | 9 – 42 |
| | | | 38 | **3.04** | **0.0017** | **-0.033** | **0.0187** | 9 – 59 |
| | | | 57 | **0.76** | **0.0005** | | | 4 – 84 |
| | | | 76 | **4.61** | **0.0001** | **-0.066** | **0.0024** | 3 – 46 |
| Portage la Prairie | 2015 | Monterrey | 19 | **0.55** | **0.0116** | | | 16 – 71 |
| | | | 38 | **0.60** | **0.0003** | | | 11 – 67 |
| | | | 57 | **1.15** | **0.0046** | **-0.006** | **0.0534** | 14 – 98 |
| | | | 76 | **0.52** | **<0.0001** | | | 10 – 53 |
| | | Windbreaker | 19 | **0.78** | **0.0002** | | | 13 – 66 |
| | | | 38 | **0.88** | **0.0001** | | | 11 – 51 |
| | | | 57 | **0.56** | **<0.0001** | | | 9 – 84 |
| | | | 76 | **0.57** | **0.0001** | | | 8 – 62 |
| | 2016 | Monterrey | 19 | **1.59** | **0.0079** | | | 7 – 44 |
| | | | 38 | **1.56** | **0.0006** | | | 5 – 37 |
| | | | 57 | **0.65** | **0.0221** | | | 6 – 50 |
| | | | 76 | **1.07** | **0.0009** | | | 6 – 40 |
| | | Windbreaker | 19 | | | | | 12 – 42 |
| | | | 38 | **1.28** | **0.00043** | | | 7 – 46 |
| | | | 57 | | | | | 5 – 34 |
| | | | 76 | | | | | 5 - 43 |

**Table 4.6.10.** P-values for the effects of variety, row spacing and variety by row spacing on linear and quadratic slopes describing ground cover in pinto bean during reproductive development as influenced by actual plant density at four site-years. The slopes were modeled and compared using PROC MIXED.

| | | Carman | | Portage la Prairie | |
|---|---|---|---|---|---|
| Fixed Effect | | 2015 | 2016 | 2015 | 2016 |
| | | ---------------------- p-values | | ---------------------- | |
| Variety (V) | linear | 0.7498 | 0.2730 | 0.9967 | 0.2340 |
| | quadratic | 0.5738 | 0.1583 | 0.8421 | 0.1544 |
| Row spacing (RS) | linear | 0.1210 | **0.0062** | 0.1963 | 0.4242 |
| | quadratic | 0.2177 | **0.0038** | 0.2833 | 0.1657 |
| V*RS | linear | 0.1780 | 0.6581 | 0.1220 | 0.4181 |
| | quadratic | 0.3491 | 0.7847 | 0.2155 | 0.3664 |

**Table 4.6.11.** Linear and quadratic regression slopes and p-values of regressions of dependent variable ground cover as influenced by actual plant densities during reproductive development in two varieties of pinto bean planted at four different row spacings at four site-years. Slopes were generated using PROC REG. Linear and quadratic slopes are reported only when significant.

| Site | Year | Variety | Row spacing | Linear slope | Linear slope p-value | Quadratic slope | Quadratic slope p-value | Density range (plants $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Carman | 2015 | Monterrey | 19 | **1.81** | **0.0001** | **-0.021** | **0.0004** | 13 – 63 |
| | | | 38 | | | | | 9 – 66 |
| | | | 57 | **0.81** | **0.0051** | | | 7 – 39 |
| | | | 76 | **0.39** | **0.0016** | | | 9 – 49 |
| | | Windbreaker | 19 | | | | | 8 – 58 |
| | | | 38 | **1.57** | **0.0204** | **-0.021** | **0.0533** | 11 – 54 |
| | | | 57 | **0.64** | **0.0020** | | | 5 – 34 |
| | | | 76 | **0.41** | **0.0173** | | | 8 – 45 |
| | 2016 | Monterrey | 19 | | | | | 9 – 47 |
| | | | 38 | **3.22** | **0.0002** | **-0.030** | **0.0021** | 3 – 85 |
| | | | 57 | | | | | 6 – 66 |
| | | | 76 | | | | | 7 – 63 |
| | | Windbreaker | 19 | **0.40** | **0.0318** | | | 9 – 42 |
| | | | 38 | **1.55** | **0.0003** | **-0.020** | **0.0018** | 9 – 59 |
| | | | 57 | | | | | 4 – 84 |
| | | | 76 | **2.41** | **0.0005** | **-0.039** | **0.0030** | 3 – 46 |
| Portage la Prairie | 2015 | Monterrey | 19 | | | | | 16 – 71 |
| | | | 38 | | | | | 11 – 67 |
| | | | 57 | **0.30** | **0.0114** | **-0.002** | **0.0270** | 14 – 98 |
| | | | 76 | **0.14** | **0.0502** | | | 10 – 53 |
| | | Windbreaker | 19 | | | | | 13 – 66 |
| | | | 38 | | | | | 11 – 51 |
| | | | 57 | | | | | 9 – 84 |
| | | | 76 | | | | | 8 – 62 |
| | 2016 | Monterrey | 19 | **1.34** | **0.0284** | | | 7 – 44 |
| | | | 38 | **1.35** | **0.0052** | | | 5 – 37 |
| | | | 57 | **0.62** | **0.0239** | | | 6 – 50 |
| | | | 76 | **1.54** | **0.0001** | | | 6 – 40 |
| | | Windbreaker | 19 | **1.17** | **0.0029** | | | 12 – 42 |
| | | | 38 | **2.17** | **0.0041** | **-0.029** | **0.0355** | 7 – 46 |
| | | | 57 | | | | | 5 – 34 |
| | | | 76 | **0.82** | **0.0002** | | | 5 - 43 |

## 4.7 Navy Bean Canopy and Lowest Pod Heights

**4.7.1 Navy Bean Canopy Heights.** T9905 navy bean was consistently taller than Envoy navy bean, although canopy height differences between varieties varied among site-years (Table 4.7.1, 4.7.2). Variety and its interaction with site-year was the most influential contributor to canopy height differences in navy bean, contributing 41.9% and 13.4% of the total variation, respectively (Table 4.7.1). The difference in height between T9905 and Envoy navy bean ranged from 1.9 – 11 cm. On average, the type II T9905 variety was 7.5 cm taller than the type I Envoy variety (Table 4.7.2). Although T9905 navy bean had a taller canopy, ground cover of these canopies was not different between varieties (Table 4.6.1). However, the taller canopy may have contributed to the lower white mould severity ratings found in T9905 navy bean (Figure 4.5.1).

**Table 4.7.1.** Significance (p-value) and the percentage of the total sum of squares (% SS) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable canopy height in the navy bean market class at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Canopy height | |
|---|---|---|
| Effect | p-value | % SS |
| Variety (V) | **<.0001** | **41.87** |
| Row spacing (RS) | 0.2029 | 0.68 |
| V * RS | 0.5492 | 0.25 |
| Seeding density (SD) | **0.0327** | 0.93 |
| V * SD | 0.3034 | 0.41 |
| RS * SD | 0.8095 | 0.67 |
| V * RS * SD | **0.0238** | 2.05 |
| Site-year (SY) | 0.9019 | 0.05 |
| V * SY | **0.0001** | **13.38** |
| RS * SY | 0.2799 | 0.92 |
| V * RS * SY | 0.6701 | 0.51 |
| SD * SY | **0.0362** | 1.43 |
| V * SD * SY | 0.6768 | 0.50 |
| RS * SD * SY | **0.0068** | 3.97 |
| V * RS * SD * SY | 0.6246 | 1.71 |
| Rep(SY) | 0.4607 | 2.05 |
| V * Rep(SY) | 0.0857 | 1.91 |
| V * RS * Rep(SY) | **0.0238** | 5.96 |
| Residual | **<.0001** | **20.77** |

**Table 4.7.2.** Mean canopy height (cm) in Envoy and T9905 navy bean varieties at Carman in 2015 and 2016 and Portage la Prairie in 2015. Within each column, means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| | 2015 | 2016 | 2015 | Overall |
| Variety | ---------------------------- | cm | ---------------------------- | |
| Envoy | 36.1 b | 37.1 b | 40.9 | 38.0 b |
| T9905 | 47.0 a | 46.1 a | 42.8 | 45.2 a |

Seeding density had a limited influence on canopy height of navy bean, contributing less than 2% of the total sum of squares. (Table 4.7.1). Navy bean planted at lower seeding densities were slightly taller than those grown at greater seeding densities (Figure 4.7.1). This is surprising since it would be expected that bean grown at greater seeding densities, with increased canopy cover, would result in taller plants as a shade-avoidance response. Navy bean grown at increased seeding densities did have greater canopy coverage, but this did not result in a taller canopy. However, the difference in canopy height among seeding density treatments was small (< 2 cm) in this experiment and of little biological significance. There was an interaction in the response of canopy height to variety, row spacing and seeding density ($p = 0.0238$, % SS = 2.05), where the canopy height of Envoy navy beans decreased with increasing seeding density when planted at every row width, but the canopy height of T9905 navy beans only decreased with increasing seeding density when planted at 57 cm row widths; however, this effect was small and of little biological significance (Figure 4.7.1).

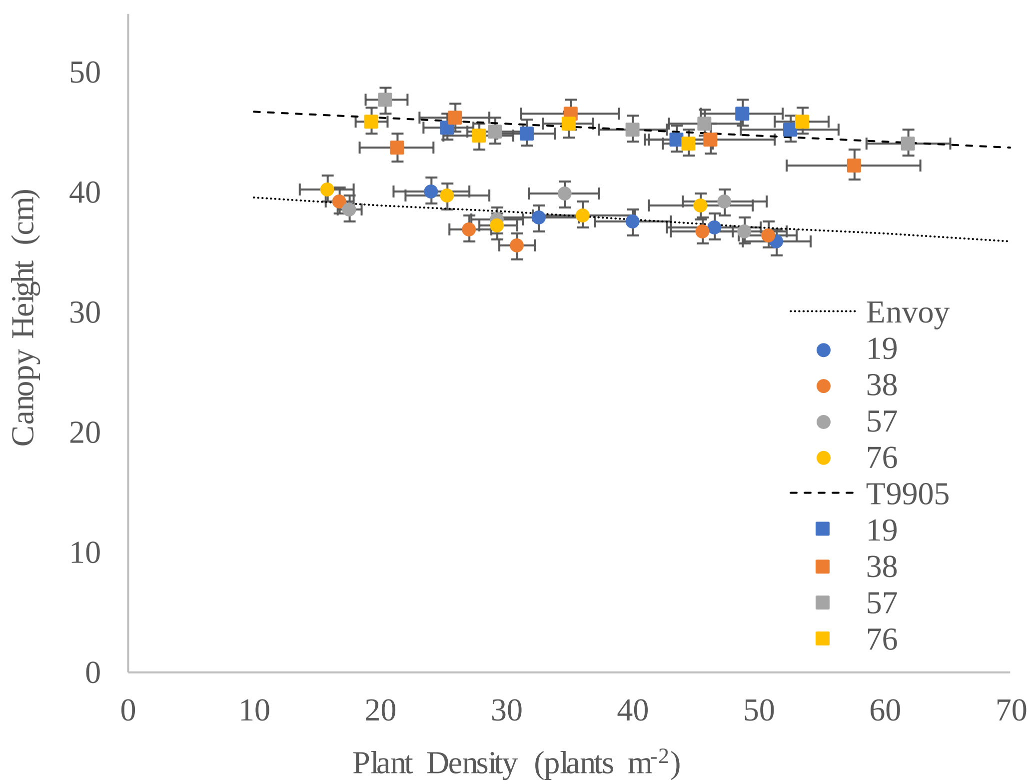



**Figure 4.7.1.** Mean canopy height (cm) in Envoy and T9905 navy bean varieties planted at four row widths (19 – 76 cm) and five seeding densities (20 – 60 plants m$^{-2}$). Error bars represent plus/minus one standard error of the mean.

**4.7.2 Navy Bean Lowest Pod Heights.** Variety, site-year, and their interaction contributed the most to differences in lowest pod heights (LPH), contributing 15.6%, 32.4% and 10.7%, respectively to the total sum of squares (Table 4.7.3). Similar to the canopy height results, LPHs were also higher in the T9905 variety than in Envoy navy bean. The difference in LPH between T9905 and Envoy navy bean ranged from 0.9 – 5.4 cm, depending on the site-year (Table 4.7.4). On average, LPH were 2.9 cm higher in T9905 navy bean than Envoy navy bean (Table 4.7.4). Increased LPH facilitates mechanical harvest of dry bean and therefore is a desirable characteristic.

**Table 4.7.3.** Significance (p-value) and the percentage of the total sum of squares (% SS) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable lowest pod height in the navy bean market class at Carman in 2015 and 2016 and Portage la Prairie in 2015. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Lowest pod height | |
|---|---|---|
| Effect | p-value | % SS |
| Variety (V) | **<.0001** | **15.64** |
| Row spacing (RS) | 0.8202 | 0.07 |
| V * RS | 0.1299 | 0.60 |
| Seeding density (SD) | 0.2154 | 0.55 |
| V * SD | 0.9553 | 0.06 |
| RS * SD | 0.9989 | 0.21 |
| V * RS * SD | **0.0003** | 3.55 |
| Site-year (SY) | **0.0001** | **32.38** |
| V * SY | 0.2071 | **10.65** |
| RS * SY | 0.6493 | 0.43 |
| V * RS * SY | 0.5618 | 0.46 |
| SD * SY | 0.1477 | 1.18 |
| V * SD * SY | 0.4681 | 0.70 |
| RS * SD * SY | 0.135 | 2.97 |
| V * RS * SD * SY | 0.9292 | 1.30 |
| Rep(SY) | **0.0439** | 1.47 |
| V * Rep(SY) | 0.7819 | 0.41 |
| V * RS * Rep(SY) | 0.6314 | 4.05 |
| Residual | **<.0001** | **23.33** |

**Table 4.7.4.** Mean lowest pod height (cm) in Envoy and T9905 navy bean varieties at Carman in 2015 and 2016 and Portage la Prairie in 2015. Within each column, means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| Variety | 2015 | 2016 | 2015 | Overall |
| | ----------------------------- | cm | ----------------------------- | |
| Envoy | 10.3 b | 8.6 b | 12.8 b | 10.6 b |
| T9905 | 15.7 a | 9.4 a | 14.0 a | 13.5 a |
| Overall | 13.0 a | 9.0 b | 13.4 a | |

Variety, row spacing and seeding density interacted to have an effect on LPH, contributing to 3.6% of the total sum of squares (Table 4.7.3). In T9905 navy bean, lowest pod height of beans planted at 19 to 57 cm row spacing increased with increasing seeding densities, while LPH decreased with increasing seeding densities in T9905 navy bean planted at 76 cm row widths. The opposite relationship was found in Envoy navy bean. Envoy navy bean planted at 19 to 57 cm row widths had slightly lower LPH with increasing seeding densities, while Envoy navy bean planted at 76 cm row widths had higher LPH with seeding densities (Figure 4.7.2). Though we anticipate higher LPH with increased seeding densities and narrower row widths due to increased shade avoidance by bean plants encouraging a taller first internode, it does not seem that spatial arrangement may be a consistent management tool to manipulate LPH in navy bean.

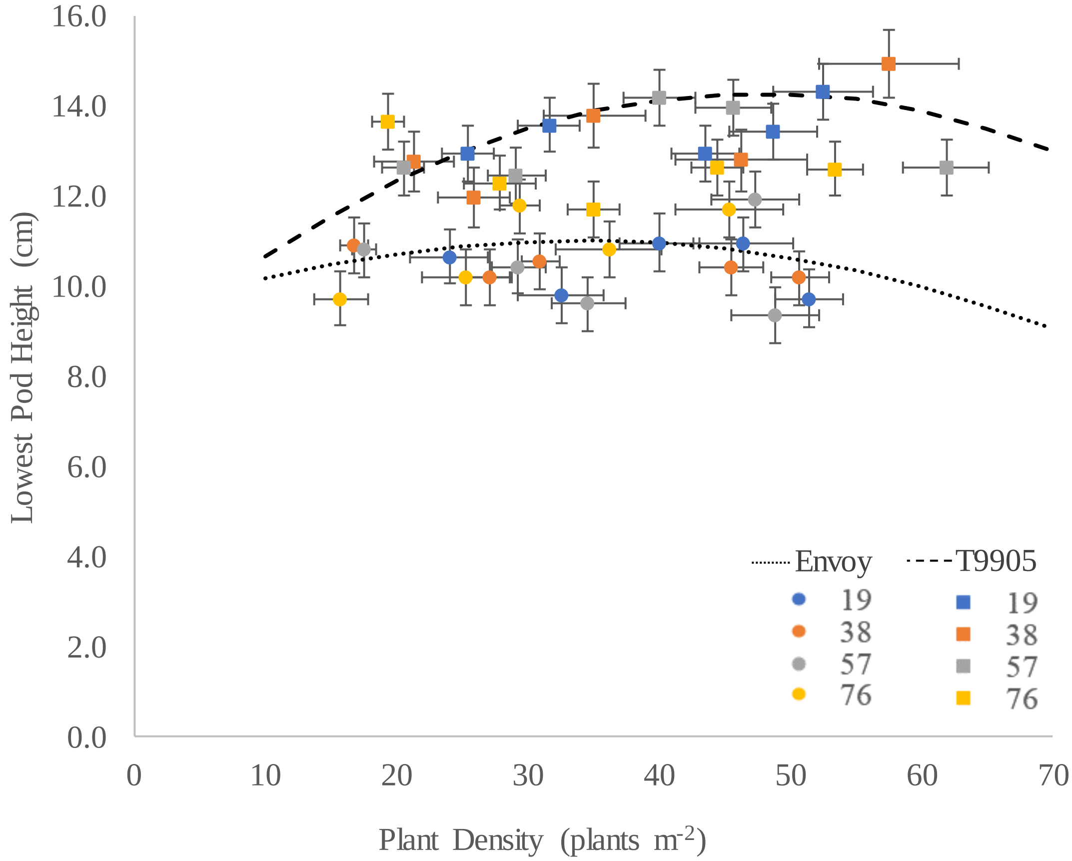



**Figure 4.7.2.** Mean lowest pod heights (cm) in Envoy and T9905 navy bean planted at four row widths (19 – 76 cm) and five seeding densities (20 – 60 plants $m^{-2}$). Error bars represent plus/minus one standard error of the mean.

Taken together, the type II T9905 variety of navy bean had a clear advantage over the Envoy variety in these experiments. T9905 navy bean had greater seed yield, lower white mould disease severity and higher lowest pod heights (Table 4.7.5).

**Table 4.7.5.** Comparison of type I Envoy and type II T9905 navy bean response variables seed yield, white mould severity, canopy height and lowest pod height evaluated in this experiment. Means reported are across other treatments and site-years. Values in bold indicate a significant, agronomically-desirable advantage.

| Response Variable | Envoy | T9905 |
|---|---|---|
| Growth type | Type I | Type II |
| Seed Yield | 3659 kg ha$^{-1}$ | **3963 kg ha$^{-1}$** |
| White mould severity | 2.74 | **1.45** |
| Canopy height | 38.0 cm | **45.2 cm** |
| Lowest pod height | 10.6 cm | **13.5 cm** |

### 4.8 Pinto Bean Canopy and Lowest Pod Heights

**4.8.1 Pinto Bean Canopy Heights.** Differences in pinto bean canopy height were driven largely by variety and site-year, contributing to 23.0% and 42.1%, respectively to the total sum of squares (Table 4.8.1). Canopy heights of the Monterrey pinto bean variety were, on average, 7.9 cm taller than that of Windbreaker pinto bean (Table 4.8.2). In 2015, pinto bean were taller than pinto bean grown in 2016. Particularly short canopy heights were recorded at Portage la Prairie in 2016 due to hail damage from a storm in August which reduced leaf area and canopy height.

**Table 4.8.1.** Significance (p-value) and the percentage of the total sum of squares (% SS) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable canopy height in the pinto bean market class at Carman and Portage la Prairie in 2015 and 2016. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Canopy height | |
|---|---|---|
| Effect | p-value | % SS |
| Variety (V) | **<.0001** | **22.96** |
| Row spacing (RS) | 0.4204 | 0.24 |
| V * RS | **0.0155** | 0.91 |
| Seeding density (SD) | **<.0001** | 1.41 |
| V * SD | **0.0243** | 0.38 |
| RS * SD | 0.4247 | 0.41 |
| V * RS * SD | 0.7846 | 0.26 |
| Site-year (SY) | **<.0001** | **42.12** |
| V * SY | 0.4725 | 0.87 |
| RS * SY | 0.0664 | 1.46 |
| V * RS * SY | 0.6061 | 0.63 |
| SD * SY | **0.0292** | 0.76 |
| V * SD * SY | 0.4193 | 0.41 |
| RS * SD * SY | 0.3727 | 1.28 |
| V * RS * SD * SY | 0.3786 | 1.27 |
| Rep(SY) | 0.9054 | 1.95 |
| V * Rep(SY) | **<.0001** | 4.26 |
| V * RS * Rep(SY) | **<.0001** | 5.89 |
| Residual | **<.0001** | **12.51** |

**Table 4.8.2.** Mean canopy height (cm) of Monterrey and Windbreaker pinto bean varieties at Carman and Portage la Prairie in 2015 and 2016. Within each column, means followed by different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | | |
|---|---|---|---|---|---|
| Variety | 2015 | 2016 | 2015 | 2016 | Overall |
| | ----------------------------- cm ----------------------------- | | | | |
| Monterrey | 49.6 a | 41.3 a | 46.9 a | 37.2 a | 43.8 a |
| Windbreaker | 41.1 b | 34.4 b | 41.4 b | 27.3 b | 36.0 b |
| Overall | 45.4 A | 37.8 B | 44.2 A | 32.2 C | |

Pinto bean planted at seeding densities greater than 30 plants m$^{-2}$ were shorter than beans planted at lower seeding densities of 10 – 20 plants m$^{-2}$ (Table 4.8.3). Across site-years and varieties, this meant pinto bean planted at seeding densities of 10 plants m$^{-2}$ were 2.5 cm taller than bean planted targeting 50 plants m$^{-2}$. Windbreaker pinto bean canopy height had a negative relationship with seeding density, while Monterrey pinto bean canopy height did not change with increasing seeding density (Table 4.8.3). In pinto bean canopy height, however, the seeding density effect contributed a small amount (1.4%) to the partitioning of variance (Table 4.8.1).

**Table 4.8.3.** Mean canopy height (cm) of pinto bean grown at five seeding densities at Carman and Portage la Prairie in 2015 and 2016. Within site-year, varieties and overall, means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | | Seeding density (plants m$^{-2}$) | | | | |
|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 |
| Site | Year | cm | | | | |
| Carman | 2015 | 45.7 ab | 45.8 ab | 44.9 ab | 45.7 ab | 44.7 ab |
| | 2016 | 40.8 cd | 38.9 d | 36.7 e | 35.7 e | 37.0 e |
| Portage | 2015 | 46.0 a | 45.0 ab | 44.7 ab | 43.2 bc | 42.1 c |
| | 2016 | 33.2 f | 32.6 fg | 32.5 fg | 31.1 g | 31.6 fg |
| Variety | | | | | | |
| Monterrey | | 44.5 | 44.3 | 43.6 | 43.5 | 43.2 |
| Windbreaker | | 38.3 a | 36.9 b | 35.8 bc | 34.5 cd | 34.4 d |
| Overall | | 41.4 A | 40.6 AB | 39.7 BC | 38.9 C | 38.9 C |

**4.8.2 Pinto Bean Lowest Pod Heights.** Site-year effects were the largest contributor to differences in lowest pod heights (LPH) among the pinto bean varieties (Tables 4.8.4, 4.8.5). Pinto bean at Carman in 2016 had mean LPH 3.1 – 4.5 cm shorter than at other site-years, likely due to environmental conditions at that site-year. Carman in 2016 received the greatest amount of precipitation of all sites in May and June, limiting early internode growth and elongation.

Variety was the second largest contributor to differences in LPH, though the effect of variety contributed only 6.6% of the total variation in LPH (Table 4.8.4). Mean LPH were 1.74 cm higher in Monterrey than in Windbreaker pinto bean (Table 4.8.4). Monterrey is a variety that has been selected for improved pod clearance for suitability to direct harvest systems, though in these experiments Monterrey LPH were only 1 – 2.7 cm taller than Windbreaker LPH. Additionally, Monterrey pinto bean did not yield as well as Windbreaker pinto bean.

**Table 4.8.4.** Significance (p-value) and the percentage of the total sum of squares (% SS) of the fixed effects of variety, row spacing, seeding density and their interactions in the dependent variable lowest pod height in the pinto bean market class at Carman and Portage la Prairie in 2015 and 2016. Values indicated in bold were p-values significant at the 5% level of significance or where the % SS contributed to more than 10% of the total sum of squares.

| | Lowest pod height | |
|---|---|---|
| Effect | p-value | % SS |
| Variety (V) | **<.0001** | 6.63 |
| Row spacing (RS) | **0.0215** | 1.11 |
| V * RS | 0.4900 | 0.30 |
| Seeding density (SD) | 0.1151 | 0.52 |
| V * SD | 0.0716 | 0.58 |
| RS * SD | 0.5208 | 0.82 |
| V * RS * SD | 0.8717 | 0.49 |
| Site-year (SY) | **0.0001** | **32.10** |
| V * SY | **0.0148** | 2.48 |
| RS * SY | 0.7644 | 0.61 |
| V * RS * SY | 0.5330 | 0.89 |
| SD * SY | **<.0001** | 3.31 |
| V * SD * SY | 0.1218 | 1.30 |
| RS * SD * SY | 0.1964 | 3.21 |
| V * RS * SD * SY | 0.3978 | 2.78 |
| Rep(SY) | **0.0154** | 7.00 |
| V * Rep(SY) | 0.1656 | 1.87 |
| V * RS * Rep(SY) | **0.0076** | 7.54 |
| Residual | **<.0001** | **26.46** |

**Table 4.8.5.** Lowest pod height (cm) in Monterrey and Windbreaker pinto bean varieties at Carman and Portage la Prairie in 2015 and 2016. Within each column, means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Carman | | Portage la Prairie | | |
|---|---|---|---|---|---|
| Variety | 2015 | 2016 | 2015 | 2016 | Overall |
| | ------------------------------ | cm | ------------------------------ | | |
| Monterrey | 15.1 a | 9.3 a | 13.3 a | 13.3 a | 12.7 a |
| Windbreaker | 12.3 b | 9.0 a | 12.3 b | 11.1 b | 11.2 b |
| Overall | 13.7 A | 9.2 C | 12.8 AB | 12.2 B | |

The effect of seeding density varied with site-year in pinto bean and contributed only 3.3% to the total sum of squares (Table 4.8.4). At Carman in 2015, pinto bean planted at greater seeding densities had higher lowest pod heights while there was no response to seeding density at Carman nor Portage in 2016 (Table 4.8.6). The opposite occurred at Portage la Prairie in 2015, where pinto beans planted at the lowest seeding densities had increased lowest pod heights, however, this was a less than one-centimetre difference (Table 4.8.6). Increased target seeding densities resulted in greater canopy cover in this study, but did not result in higher LPH nor greater yields.

**Table 4.8.6.** Lowest pod height (cm) of pinto beans planted at five seeding densities at Carman and Portage la Prairie in 2015 and 2016. Means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| Seeding density | Carman | | Portage la Prairie | |
|---|---|---|---|---|
| (plants $m^{-2}$) | 2015 | 2016 | 2015 | 2016 |
| | ------------------------------------- | cm | ------------------------------------- | |
| 10 | 12.4 d | 9.9 e | 13.2 abcd | 12.1 d |
| 20 | 12.7 d | 8.7 f | 13.2 bcd | 12.2 cd |
| 30 | 14.7 ab | 9.1 ef | 13.1 cd | 12.5 cd |
| 40 | 14.8 a | 8.9 ef | 12.2 d | 12.2 d |
| 50 | 13.9 abc | 9.2 ef | 12.5 cd | 12.0 d |

Row spacing, while significant, was found to have a small influence on the lowest pod heights of pinto bean, contributing only 1.1% to the total sum of squares (Table 4.8.4). Pinto bean planted at 19 cm row widths had slightly higher lowest pod heights than when seeded at the wider 57 – 76 cm row widths (Table 4.8.7).

**Table 4.8.7.** Lowest pod height (cm) of pinto bean planted at four row spacings at Carman and Portage la Prairie in 2015 and 2016. Means with different letters are significantly different according to Tukey-Kramer LSD at the 0.05 level of significance.

| | Row spacing (cm) | | | |
|---|---|---|---|---|
| | 19 | 38 | 57 | 76 |
| | ----------------------------- cm ----------------------------- | | | |
| Lowest pod height | 12.4 a | 12.1 ab | 11.6 c | 11.8 bc |

# 5.0 DISCUSSION

## 5.1 Plant Spatial Arrangement

### 5.1.1 Row Spacing

Navy and pinto bean planted at narrow row widths of 19 cm consistently produced the greatest seed yield in these experiments, confirming findings from previous research that has found increased seed yield with planting at more narrow row widths (Blackshaw et al. 2000, Goulden 1976, Grafton et al. 1988, Greipentrog et al. 2009, Holmes and Sprague 2013, Malik et al. 1993, Park et al. 1993). Increased ground cover and earlier row closure achieved in narrow-row treatments resulted in increased total canopy light interception and potentially also more efficient below-ground resource capture earlier in the season. Improved distribution of plants within the row in narrow row widths may have increased the evenness of resource acquisition in each individual bean plant. This research indicates that navy and pinto bean producers in Manitoba have the opportunity to increase yields substantially by planting dry bean at narrower row widths. While narrow-row dry bean production has been proven to result in increased yields, there are other barriers preventing producers from adopting this system. Exploring producer constraints may increase adoption and improve production further.

More dense, uniform planting arrangements have been shown to increase weed suppression since earlier canopy closure and maximized canopy cover has been effective at shading out late-emerging weeds, successfully reducing weed biomass (Grafton et al. 1988, Malik et al. 1993). We did not measure weed biomass in these experiments, however, in addition to failing to maximize light interception in this experiment, planting at wide row widths left open field space that was utilized by late-emerging weeds (Figure 5.1., bottom right).


**Figure 5.1.** Ground cover images of pinto bean at V4 planted at four row widths, at a seeding density of 30 plants $m^{-2}$.

Planting dry bean at wide row widths has been shown to reduce disease pressure due to the large inter-row spaces that allow for sufficient airflow between rows (Saharan and Mehta 2008), however, that was not the case in these experiments. When planting at row widths of 76 cm, interplant spaces within the row are reduced at equal plant densities (Figure 5.2). Once white mould has infected bean plants growing in wide rows, increased plant to plant contact may facilitate quick dispersal of the disease within the crop row. This was demonstrated previously by Lee et al. (2005) wherein they compared beans planted at row widths of 19 and 76 cm at equal seeding densities and recorded greater disease severity in the wide-row treatment due to increased crowding within the crop row. Wunsch (2014), Vieira et al. (2010) and the present experiments indicate that optimizing plant density, rather than row width, is more important for white mould management under conditions adequate for disease development. The more uniform spatial distribution of bean plants throughout the field at narrow row spacings allows for increased plant densities before plant-plant contact is sufficient for efficient white mould transfer.

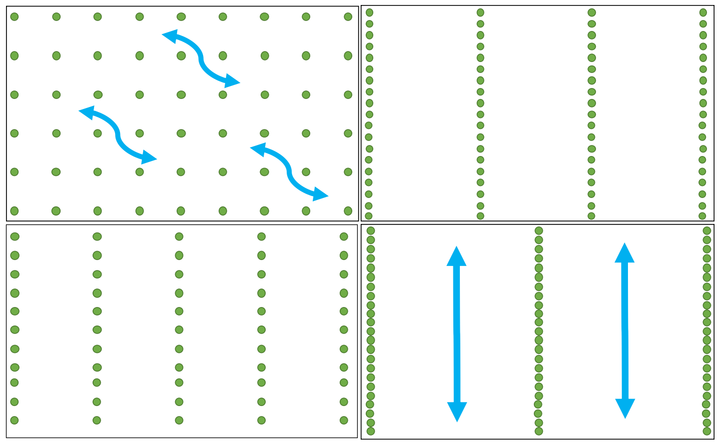


**Figure 5.2.** Illustration of 30 plants m$^{-2}$ at four row widths, 19 cm (top left), 38 cm (bottom left), 57 cm (top right), and 76 cm (bottom right). Blue arrows represent speculative dominative air flow.

### 5.1.2 Plant Density

Dry bean yield did not conform to the rectangular hyperbola that describes the law of constant final yield in all cases in these experiments. A plant density-yield plateau was observed in some of the plant density-seed yield relationships and as such these would have conformed to the law of constant final yield. Increasing seed yield with increasing plant density has been well documented in type I dry bean (Blackshaw et al. 1999, Grafton et al. 1988, Saindon et al. 1995, Shirtliffe and Johnston 2002) and a lack of seed yield response to plant density has been well documented in type II dry bean over a wide range of row widths (18 – 100 cm) and densities (10 – 97 plants m$^{-2}$) (Grafton et al. 1988, Malik et al. 1993, Neinhuis and Singh 1985, Saindon et al.1995, Schatz et al. 2000, Schneiter and Nagle 1980, Soratto et al. 2017, Westermann and Crothers 1977). Decreasing seed yield with increased plant densities is uncommon in the literature, though it has occurred in some studies (Crothers and Westermann 1976, Soratto et al. 2017, Vieira et al. 2010). While the research previously described supports the results found in our experiments in type II dry bean, it does not explain why the type I Envoy navy variety did not have a positive seed yield response to increasing plant densities. Crothers and Westerman (1976) tested a wide range of plant densities (10 – 97 plants m$^{-2}$) and attributed the negative relationship between seed yield and density to the observation that the yield of beans planted at greater plant densities were more erratic due to white mould and severe lodging in those treatments. They also note that type II pinto bean was able to utilize the larger area per plant at low plant densities compared to type I pinto bean due to their ability to compensate for open spaces and fill in gaps in the plant canopy (Crothers and Westerman 1976). While lodging was not observed in our experiments, white mould was prevalent at every site-year. Plant density was the largest driver influencing white mould severity, but white mould did not significantly influence the relationship of yield and density in these experiments.

Increased intraspecific competition may have occurred in beans planted at increased densities and narrower row widths, causing the negative response in seed yield in those treatments. Nienhuis and Singh (1985) found that in type II pinto beans planted at densities above 22 plants m$^{-2}$, intraspecific competition was sufficient to reduce crop yield. Goulden (1976) also found that increasing plant densities at 20 cm row widths subjected bean plants to sufficient intraspecific competitive stress for within-row spacing to negatively affect yield, however varying the spacing within-row at 40 cm row widths caused little effect on yield. Since the distance between rows in narrow-row widths is already reduced, further reducing plant spacing within the row may result in greater intraspecific competitive stress than at other row widths as plants are more crowded. On the other hand, other studies conducted under similar environments to Manitoba in type I and

II dry bean do not report a negative relationship between seed yield and density, indicating that the results found in these experiments were likely due to factors other than intraspecific competition limiting resources.

One shortcoming of these experiments was that the spacing of seeds within the row was not uniform. While the distance between rows, the row widths, were consistently attained as desired, the spacing of plants within the row was variable with some portions of the row being clumped and other being sparsely populated by plants. Uneven plant spacing can limit crop performance, as intraspecific competition within the crop will start earlier where plants are clumped together and different seeding implements will result in variable levels of uniformity of seed spacings within the row, most commonly due to their seed metering technologies and the method of seed delivery to the furrow (Griepentrog et al. 2009). Investigating the yield-density relationship further with more accurate plant placement may more precisely determine recommendations of plant density in dry bean in Manitoba.

Root disease complexes (*Fusarium* spp., *Rhizoctonia solani*, *Pythium* spp.) were not evaluated in these experiments, but these may have influenced the results. Fungicide seed treatments used in these experiments would have protected seedlings for two to three weeks after planting, but root diseases are able to infect plants throughout the growing season (Gossen et al. 2016). Annually during mid-July, select dry bean crops are surveyed across Manitoba to determine the incidence and severity of root diseases. Fusarium root rot (*Fusarium spp*.) was consistently detected in all fields surveyed in 2015 and 2016 (McLaren et al. 2015, McLaren et al. 2016). Based on the prevalence of Fusarium root rot in Manitoba, it is likely that Fusarium root rot was present in these experiments and may have affected bean seed yield. Mean severity of Fusarium root rot increased across the province from 2015 to 2016, the mean severity ratings were recorded as 3.8

in 2015 and 5.5 in 2016 on a 0-9 scale (McLaren et al. 2015, McLaren et al. 2016). It is generally believed that yield loss will occur with a root rot severity rating greater than four (McLaren et al. 2018). Root diseases, if present in these experiments, could have caused significant yield loss. Favourable conditions for root rot include moist-wet soil and any conditions that cause plant stress and reduced growth (Gossen et al. 2016). Overcrowding within rows may induce additional stress, leading to greater root rot severity. Naseri and Marefat (2011) evaluated the influence of several agronomic practices on Fusarium root rot and found that plant density significantly affected disease incidence, severity and index. In their assessment, dense plant stands resulted in severely diseased bean plants during reproductive development stages, citing the additional stress of intra-specific competition and dense moist canopies as drivers encouraging Fusarium root rot development (Naseri and Marefat 2011). Some sources even rate plant density as a high-risk factor favouring root rot development in dry bean (Harveson 2011, Schwartz 2011). Harveson (2011) recommended maintaining 5 to 8 centimeters between plants within the row to avoid increasing root rot severity. Out of the twenty row-spacing-by-plant-density treatment combinations examined in these experiments, under ideal seed singulation (equidistant spacing between each seed in the row), adjacent in-row plant spacing was below 5 centimeters per plant in eight treatment combinations. Treatments that combined greater plant densities and narrower row widths resulted in greater canopy cover during vegetative development in these experiments, achieving a denser plant canopy. It is possible that the denser canopy treatments that combined narrow row widths with greater plant densities may have experienced greater incidence and severity of Fusarium root rot, potentially causing the negative relationship found between density and seed yield in those treatments. Unfortunately, root disease incidence or severity were not evaluated in these studies.

This research suggests that current plant density recommendations from North Dakota (17 – 25 plants $m^{-2}$ in pinto bean and 22 – 35 plants $m^{-2}$ in navy bean) are sufficient since dry bean seed yield did not respond to increased densities in these experiments. Decreasing plant densities further below these recommendations may have negative repercussions not evaluated in this study, such as increased weed pressure and weed management concerns. In these experiments, planting densities below 40 plants $m^{-2}$ in navy beans and 30 plants $m^{-2}$ in pinto beans minimized white mould severity. Increasing plant densities beyond the current recommendations increased white mould severity, even when a fungicide was applied later in the season. Further research is necessary to investigate the yield-density relationship in dry bean and the different responses of determinate and indeterminate growth habits.

## 5.2 Plant Architecture and Varietal Differences

The two navy bean varieties in these experiments differed in plant architecture, with contrasting type I and type II growth habits. These differences were associated with significant interactions with all other treatment factors. T9905 navy bean had a clear advantage over Envoy navy bean, producing greater seed yield, lower disease severity, taller canopies and pod height clearance (Table 4.7.5). There were no differences in canopy cover between these two varieties. Previous research (Fageria and Santos 2008, Singh 1982) has supported an advantage of type II over type I dry bean, reporting improved disease tolerance, better resource utilization, and increased pod heights allowing for the adoption of direct harvest operations which require less specialized equipment and less time and labour (Goodwin 2005). In these experiments, T9905 navy bean did have improved disease tolerance, seed yield and higher lowest pod heights compared to Envoy navy bean, but the two navy bean varieties were similar in above-ground resource utilization (i.e. ground cover). Though there were no differences between navy varieties in percent canopy coverage, T9905 navy bean had a taller canopy, possibly contributing to the reduced white mould disease severity ratings, though canopy height alone is likely not enough to provide a snapshot of the difference in plant architecture between varieties. T9905 navy bean canopy heights were 7.6 cm taller than Envoy navy bean and Monterrey pinto bean canopy heights were 7.9 cm taller than Windbreaker pinto bean. Similar standing canopy height differences were seen between navy and pinto varieties, yet differences in white mould severity between varieties only occurred between the navy bean varieties. This suggests that differences in white mould severity between growth types is likely due to the differences in branch orientation. Branches in beans with type II growth habits are more vertical in orientation (i.e. more phototropic) which leads to increased density of foliage away from the soil surface (Schwartz et al. 1978). The low-growing, bush-type stature of type I Envoy navy bean concentrates foliage and branches near the soil surface which restricts air movement in the lower canopy. This restricted air flow may have contributed to creating a suitable microclimate for white mould development (Saindon et al. 1995). Conversely, the reduced white mould severity in T9905 navy bean may be attributed to their upright type II growth habit, where branches were held erect above the ground, allowing more air movement below the crop canopy. Producers would be advised to select varieties with type II upright growth habits to maximize yield, disease avoidance, and improved harvestability.

# 6.0 GENERAL DISCUSSION AND CONCLUSIONS

While plant spatial arrangements may be used to increase yields in Manitoba dry bean production it must also be able to be incorporated into successful weed and disease management systems. Spatial arrangement plays an important role to help produce sustainable, resilient management practices for cropping systems in the Canadian prairies.

Planting dry beans at narrow row widths of 19 cm increased seed yield by 71.9 and 78.7% in navy and pinto beans, respectively, when compared with 76 cm row widths. Navy and pinto beans planted at narrower row widths resulted in increased canopy cover during vegetative and reproductive development. Despite concerns of increased white mould disease pressure with narrow-row plantings, white mould severity was the lowest in beans planted at 19 cm rows. This may be due to the increased distance between plants within the row in narrow row spatial arrangements.

Planting at increased seeding densities resulted in an inconsistent effect on navy bean seed yield in these experiments. Where significant, increased seeding densities resulted in decreased seed yield. This was also the case in pinto beans where increasing seeding densities resulted in decreased seed yield. Planting navy and pinto beans at 19 cm row widths resulted in a negative relationship between seed yield and plant density. In these experiments, beans planted at greater seeding densities resulted greater ground cover, earlier in the growing season, however, this did not translate to increased yield. Planting at greater seeding densities consistently increased the severity of white mould disease infection.

Further research is needed to further explore the plant density-yield relationship in dry beans in Manitoba and the influence root diseases may have on this relationship. Measuring root rot incidence and severity among a range of plant spatial arrangements would provide insight on the influence plant density has on root diseases and if it may increase the severity of the disease, limiting yield. Smaller-seeded and larger-seeded market classes of dry beans should be evaluated to determine differences in response to plant density and disease. While narrow-row dry bean production has been proven to result in increased yields, there are other barriers preventing producers from adopting this system. One such barrier is that air delivery systems that are typically used to achieve narrower row widths during seeding are known to cause damage to bean seed coats, especially when loaded with an augered metering system. As seed is a major cost in dry bean production, research is necessary to quantify this damage so producers can more accurately determine seeding densities. Another barrier is harvest loss, further equipment improvements and research are necessary to quantify and minimize direct harvest losses. Exploring producer constraints may increase adoption and improve production.

## 7.0 REFERENCES

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