EVALUATION OF SOYBEAN (*GLYCINE MAX*) PLANTING DATES AND PLANT DENSITIES IN NORTHERN GROWING REGIONS OF THE NORTHERN GREAT PLAINS

BY

CASSANDRA FAYE TKACHUK

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

MASTER OF SCIENCE

Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

ACKNOWLEDGEMENTS

To my advisor Yvonne: Thank you for opening the door to research, allowing me to realize my potential. This program has been a positive experience for me because of your kind and patient guidance. In future endeavours, I hope to nurture confidence in others, as you have done for me.

To my committee members, Dr. Rob Gulden, Dr. Francis Zvomuya, and Dr. Michael Ostlie: The support I have received from each of you has helped me extend beyond what I believed I was capable of. I am grateful to be connected with such a strong network of researchers.

A tremendous thank you to Eric Wallace and Iris Vaisman for your support and dedication in the field to ensure that my experiments were successful from start to finish. To the numerous Farming Systems lab members: Laryssa, Masayo, Megan, Richard, Simone, Nia, Zhen, Jesse, Nasir, and Braeden. Also to the research collaborators: Scott at Melita, and Mark, Dena, Janet, and Anfu at Morden. The extensive amount of data collection for this project would not have been possible without your help.

To my former office-mates, Gagan Sidhu and Greg Bartley, and fellow graduate students in both plant and soil science: Thank you for making this a truly fun experience. I feel so lucky to come away from grad school with lasting friendships.

To Mom, Vicki and Jeremy, Christine and Isaac: Thank you for being such a strong support system. Mom, thank you for your love, strength, and unquestioning understanding of everything I do in this life. Vicki, thank you for always blazing a trail for me to follow. Your help along the way is appreciated more than you will ever know.

To Don: Thank you for sharing this experience with me. Your support, encouragement, and understanding know no bounds.

DEDICATION

This thesis is dedicated to the memory of my father, Rick Tkachuk, and grandmother, Mary Tkachuk. Grandma, thank you for showing me the value of an unending quest for knowledge. Dad, thank you for instilling the love of agriculture and belief in higher education. It is the fierce qualities I inherited from both of you that have helped me accomplish this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Tkachuk, Cassandra F. M.Sc., The University of Manitoba, January 2017. Evaluation of soybean planting dates and plant densities in northern growing regions of the Northern Great Plains. Major Professor: Yvonne Lawley.

Soybean (*Glycine max* L. Merr.) planting date and plant density are agronomic decisions made simultaneously at the beginning of the growing season that can be used to maximize yield and economic return. Research on these basic soybean agronomic decisions must be conducted to support the expansion of soybean production in northern growing regions of the Northern Great Plains (NGP). The objectives of this study were to evaluate the effects of planting dates based on soil temperature on soybean emergence, maturity, and yield for short and long season varieties in Manitoba, and to determine optimum soybean plant density for early to very late planting dates in northern growing regions of the NGP. In the first experiment, calendar date had a greater influence than soil temperature at planting on soybean yield. Soybean yield declined with later planting rather than increasing soil temperature at planting. The earliest planting dates resulted in the greatest soybean yields. In the second experiment, soybean yield-density relationships were responsive to planting date. Yield-density relationships formed early/mid (May 4 to 26) and late/very late (June 2 to 23) planting date groups for combined site years. Early/mid planting dates resulted in greater maximum yields. According to the yield-density model, true yield maximization did not occur for any planting dates and site years within the range of plant densities tested in this field study. Soybean economic optimum seed densities (EOSDs) were much lower than predicted plant densities that maximized yield. Soybean EOSDs were identified as 492,000 and 314,000 seeds ha^{-1} by marginal cost analysis for early/mid and late/very late planting, respectfully. These values were sensitive to changes in soybean grain price and seed cost. Thus, growers need to adjust EOSDs for changes in price and cost. A combined analysis of soybean yields from both experiments using similar target plant densities determined that a significant negative linear relationship existed between soybean yield and planting date. The greatest soybean yields resulted from early planting and declined by 16 kg ha^{-1} for each one-day delay in planting from Apr 27 to June 16. However, yield responses varied among site years. The overall recommendation from this study would be to plant soybeans during the month of May at a profit-maximizing seed density, accounting for fluctuating grain price and seed cost.

1.0 INTRODUCTION

Soybean (*Glycine max* L. Merr.) production has increased dramatically over the past decade in northern growing regions of the Northern Great Plains (NGP) and continues to increase (StatCan, 2016; USDA, 2016). Due to this expansion in production, research on basic soybean agronomic decisions must be conducted to support growers in northern regions. Among these agronomic decisions are soybean planting dates and plant density, which can both be managed to maximize yield and economic return. Short growing seasons are characteristic of northern growing regions of the NGP, which limits the window of planting. The risks of late spring frost and early fall frost are high for northern growing regions. Thus, the time of soybean planting is critical to ensure the highest possible yield potential.

Site-specific research on soybean planting dates and plant density is important due to regional differences. Extensive soybean production research has been conducted in Ontario and across the United States; however, growing conditions are quite different for the northern part of the Northern Great Plains, particularly for Manitoba and Western Canada. Soybean response to planting date and plant density varies with environmental conditions (Tanner and Hume, 1978; Pedersen, 2003; De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009), as influenced by location and year, and varieties due to the range of maturity groups grown in different regions (Wiggans, 1939; Elmore, 1990; Grau et al., 1994; Popp et al., 2006; De Bruin and Pedersen, 2008a; Cox et al., 2010). Plant density is also influenced by planting date itself (De Bruin and Pedersen, 2008a).

Separate recommendations for soybean planting date and plant density currently exist. However, optimum soybean plant density can depend on the date of planting

(Heatherly and Elmore, 2004). For example, it is recommended to increase soybean seed density by 20% if planted before or after the optimum planting date in the Midwestern United States (May 10 to 20) due to cold soil and shorter plants, respectively (Heatherly and Elmore, 2004). In Manitoba, it is currently recommended to increase soybean seed density with later planting. However, the extent to which seed density should be increased is unclear. Joint recommendations on soybean planting date and plant density must be strengthened in Manitoba.

The focus of this research was to assess the suitability of current planting date and plant density recommendations for maximized soybean yield and profit in northern growing regions of the NGP. The main objectives of this study were to:

1) Evaluate the effects of planting dates based on soil temperature on soybean emergence, maturity, and yield for short and long season soybean varieties in Manitoba (Chapter 3).
2) Determine the optimum soybean seed density for early, mid, and late planting dates in northern growing regions of the NGP (Chapter 4).

It was hypothesized that soybean planting date and plant density recommendations would differ from current recommendations due to regional and varietal differences. It was also hypothesized that optimum soybean plant densities would be influenced by planting date.

2.0 LITERATURE REVIEW

2.1 Soybean Production in the Northern Great Plains

The domestication of soybeans (*Glycine max* L. Merr.) took place in China from 1766 to 1125 BCE (Johnson et al., 2008). Soybeans were first cultivated in the United States in 1765, in Canada in 1855 and Manitoba in 1898 (Johnson et al., 2008; Shurtleff and Aoyagi, 2010). Soybeans are grown to produce soy flour, protein and oil, which are commonly used in several commercially prepared foods such as margarine, beverages, cheeses, and meat alternatives (AAFC, 2015). As soybeans contain high levels of vitamins, minerals, carbohydrates, unsaturated fats, and protein, soy foods are desirable around the world (AAFC, 2015). The primary markets for soybeans grown in Canada are soybean meal and oil (COPA, 2015). Soybean grain is largely exported from Canada to several countries including the Netherlands, China, the United States and Japan (Stat Can, 2016). In 2015, 3.48 million tonnes of soybeans were exported from Canada generating 1.96 billion dollars (Stat Can, 2016).

Several factors have contributed to the expansion of soybean production in the NGP. These factors include the development of glyphosate resistant varieties, higher-yielding, earlier-maturing varieties (Brown and Blackburn, 1987), and high demand for soybeans worldwide causing an increase in commercial soybean grain price. Soybeans are a warm season crop (Hay and Porter, 2006) and climate restrictions in Canada previously limited production to only southern Ontario until the 1970s (Stat Can, 2009).

Seeded soybean area has dramatically increased in Manitoba over the past decade. In 2005, only 38,400 hectares of soybeans were seeded in Manitoba (Stat Can, 2016). In 2010, seeded soybean area in Manitoba increased to 206,400 hectares, and more than doubled by 2014 and 2015 with 509,900 and 558,500 seeded soybean hectares, respectively (Stat Can, 2016). Soybean area has also increased in North Dakota over the past decade, reported at 1,295,000 hectares seeded in 2005, 1,522,000 million hectares in 2010, increasing to 2,408,000 and 2,335,000 hectares in 2014 and 2015, respectively (USDA, 2016).

Extensive soybean research has been conducted in Ontario and the Midwestern and southern United States; however, as soybean production is relatively new in the northernmost growing regions of the NGP, regional research is limited and several production practices remain in question. Among these production practices in question are soybean planting date and plant density. Planting date and plant density are important agronomic decisions in all soybean production systems that can be used to maximize yield and increase economic return. The response of soybeans to planting date and plant density vary across geographic regions, environmental conditions, and maturity groups (De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009); therefore, continued research on these topics is necessary for new northern production areas. This literature review will discuss the effects of soybean planting dates, air and soil temperatures, and plant density on soybean emergence, growth and development, yield, and seed quality. Economic return in response to plant density will also be examined.

2.2 Soybean Planting Dates

2.2.1 Growing Season Length in the Northern Great Plains

Northern growing areas of the NGP pose a risk to soybean production due to shorter growing seasons. Soybeans require long, warm growing seasons to achieve high yields (Bootsma and Brown, 1995); however, fewer frost-free days, and an increased risk of late spring and early fall frosts are typical of northern growing regions (Table 2.1). Thus, the time of soybean planting is critical to ensure the highest possible yield potential. Research suggests that climatic temperature characteristics, such as night time lows, may be more of a determinant for identifying suitable soybean production areas rather than the length of the frost-free growing season (Raper and Kramer, 1987). As soybean plants are sensitive to photoperiod, the length of the growing season also depends on a complex relationship between photoperiod and temperature (Raper and Kramer, 1987). Photoperiod is defined as the day length encountered by crops at any given stage (Edey, 1977). Photoperiods can affect the phenological development of soybeans (Raper and Kramer, 1987). Soybeans sensitivity to day length, through a photoreceptor called phytochrome (Raven et al., 2005), affects flowering induction (Hicks, 1978). Short days are responsible for floral initiation in soybeans, thus soybeans are considered to be “short day plants” (Hicks, 1978).

Table 2.1. Range of frost-free days, date of last spring frost, and date of first fall frost for Manitoba and North Dakota growing seasons (Nadler, 2007; NDSU, 2015).

Location	Frost-free days	Last spring frost	First fall frost
	-----------------------------probability of -0.0°C†-----------------------------		
Manitoba	60-145	May 5-Jul 13	Jul 24-Oct 1
North Dakota	112-170	May 2-Jun 6	Aug 21-Oct 2
	-----------------------------probability of -2.2°C†-----------------------------		
Manitoba	71-165	Apr 25-Jun 23	Aug 13-Oct 11
North Dakota	130-188	Apr 23-May 26	Sep 10-Oct 6

† Ranges encompass probability levels of 10 to 50% for all regions within each province and state.

2.2.2 Soybean Classification

Soybeans are classified according to maturity groups (MG) in Canada and the United States. Maturity groups indicate the growing season length that a variety is suited to and are assigned to each soybean variety by plant breeding companies. Maturity groups range from 000 to VIII, spanning from northern regions including Canada to the southeastern United States, respectively (Tanner and Hume, 1978). There is an approximate difference of 10 to 15 days between successive maturity groups, depending on year and location (Tanner and Hume, 1978). Primarily 000 to 00 soybean varieties are grown in Manitoba (Podolsky, 2015), whereas a range of 00 to I are grown in North Dakota (Kandel and Akyüz, 2012). Soybean yields will be reduced if varieties are grown that are not adapted to the region. In contrast, if later-than-adapted soybean varieties are grown, the crop may not reach maturity nor set seed, resulting in reduced yield and poor seed quality (Tanner and Hume, 1978).

Soybean maturity may also be classified according to thermal time units such as corn heat units (CHU), also known as crop heat units, and growing degree-days (GDD). Classification according to GDD involves the concept of a physiological baseline, or minimum, temperature at which plant development starts to take place (Nadler, 2007). An acceptable baseline temperature for soybeans is 10°C (Raper and Kramer, 1987; Miller et al., 2002). Prior to establishment of the MG classification system for soybeans in Manitoba, soybeans were classified by CHU. Corn heat units are based upon the relationship between temperature and corn (*Zea mays* L.) hybrid suitability to different regions (Smith et al., 1982). One desirable characteristic of CHU compared to GDD classification is that daytime and night time temperatures are accounted for separately by using daily maximum and daily minimum temperatures (Nadler, 2007).

Growing degree-day data is useful to standardize information across years, sites, and calendar dates. For example, the number of GDD required for soybeans to reach a specific development stage can benefit our understanding of the effect of planting date on soybean development. Conley and Gaska (2008) determined that soybeans require 130 GDD to reach 50% emergence, and 155 GDD to reach 90% emergence. North Dakota State University trials from 2007-2011 determined that soybeans require a range of 1679 to 1992 accumulated GDD with a base temperature of 10°C to reach full maturity for MG 00 to I, respectively (Kandel and Akyüz, 2012). Growing degree-day information can be compared to any site year, location or calendar date.

Different types of soybean growth habits are suited to different regions due to the length of the growing season required for maturity. The majority of soybean varieties grown in northern regions have an indeterminate, rather than a determinate growth habit (Beuerlein, 1988). Indeterminate growth habits are defined by continued main stem elongation for several weeks after flowering has begun, whereas main stem elongation ceases at the onset of reproductive growth for determinate growth habits (Bernard, 1972).

2.2.3 Current Soybean Planting Recommendations in the Northern Great Plains

Soybean planting date recommendations vary among geographic regions and may be based on calendar date or soil temperature. In Manitoba, it is recommended to plant soybeans prior to the end of May, or when soil temperature at the desired seeding depth is 10°C or higher with warm weather forecasted following soybean seeding (MASC, 2016;

MPSG, 2016a). Crop insurance data from 1989 to 2008 for Manitoba has shown that soybeans consistently yield the greatest when seeded during the second and third weeks in May (MASC, 2016). Soybean crops in Manitoba can also maintain 100% yield potential until the end of May, after which yield potential may drop dramatically (MASC, 2016). In North Dakota it is generally recommended to plant soybeans during the first half of May, or when soil temperatures are consistently 10°C or higher (NDSU, 2014). The earliest date soybeans can be planted under crop insurance coverage in North Dakota is May 1 (Endres, 2016).

The risk of a yield penalty exists for both early and late planting of soybeans in northern growing regions. As soybeans are a long season crop, late planting should be avoided due to the risk of early fall frosts, loss of yield potential, and imminent crop insurance deadlines, for the last planting date soybeans will be covered under insurance. However, early planting of soybeans is associated with a risk of late spring frost, delayed emergence and worn off seed treatment. Loss of seed treatment from the seed over time can leave plants susceptible to early season insect predators and seedling diseases. Currently, the incidence of soybean seedling disease is relatively low in Manitoba compared to other regions, such as North Dakota, where soybeans have been grown for a longer period of time (USDA, 2016). However, soybean seedling disease incidence is expected to increase due to the northward movement of pathogens through the Red River Valley watershed between Manitoba and North Dakota. Repeated annual production of soybeans on farm land over time may also increase disease inoculum in the soil. Therefore, it is expected that delayed emergence will become more of a concern in the future for northern growing regions.

Growers must consider a combination of several factors to determine when to plant soybeans in northern growing regions of the NGP. Research conducted in the Midwestern United States suggests that soybean planting date decisions should be based mainly on calendar date and seedbed conditions (Pedersen, 2006). However, soybean growers in Manitoba are currently advised to assess the combination of calendar date, soil temperature, weather forecast following seeding, and personal risk (Figure 2.1). Personal risk includes the geographic location of the farm, tolerance of crops to spring or fall frost, number of soybean acres compared to other crop acres to be seeded, and the timeline for growers to complete seeding and harvest practices (Figure 2.1).

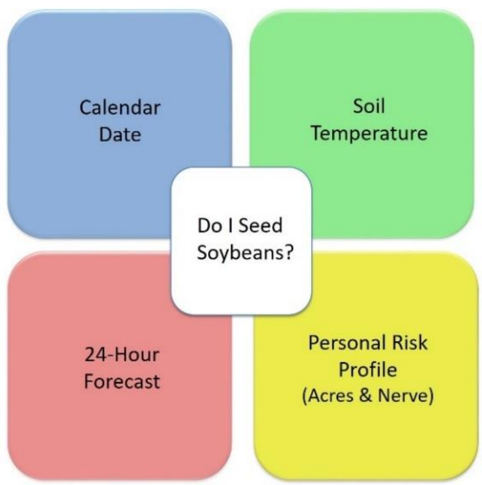

Figure 2.1. The four quadrants of the time of soybean seeding compromise (Buss, 2015).

2.3 Soybean Response to Planting Date

Planting date is a critical management decision that affects soybean emergence (Andric et al., 2007), growth characteristics (Bastidas et al., 2008), yield (Egli and Cornelius, 2009; Zhang et al., 2010), and seed quality (Rahman et al., 2005). Environmental conditions influence how soybeans respond to planting date (Tanner and

Hume, 1978; Egli and Cornelius, 2009). The three most important environmental factors influencing soybean response to planting date are air temperature, photoperiod, and moisture distribution over time (Tanner and Hume, 1978). Locations, years (Pedersen, 2003), and varieties (Elmore, 1990; Grau et al., 1994) also influence soybean response to planting date, in which variety responses depend on maturity group and growth habit (Wilcox and Frankenberger, 1987). Beuerlein (1988) reported that soybean varieties with indeterminate growth habits responded more dramatically to planting date compared to varieties with a determinate growth habit. In contrast, soybean varieties grown in northern areas of the United States have also been characterized as less sensitive to photoperiod (Tanner and Hume, 1978). Thus, it is important to examine all facets of soybean production including emergence, growth and development, yield, and seed quality to clearly understand how soybeans respond to planting date.

2.3.1 Soybean Emergence

Emergence is considered to be “the most important phenological stage that determines the success or failure of crop production,” (Forcella, 1993). It influences plant stand establishment (Edje and Burris, 1971; Stewart et al., 1990), growth and yield (Hobbs and Obendorf, 1972). Both early and late planting of soybeans have the potential to reduce percentage soybean emergence; however, results are inconsistent in the literature. A four-year study by Oplinger and Philbrook (1992) determined that earlier soybean planting (May 15) reduced soybean seedling emergence compared to later planting (May 31 to June 13) for MG I to II soybean varieties in Wisconsin. Lee et al. (2008) found that April planting resulted in 60% of total seedling emergence in the field compared to an average of 70% for May, June, and July planting in Kentucky. In contrast, De Bruin and Pedersen (2008a) observed that early planting in late April did not have a negative effect on plant establishment in a study that examined four planting dates at six locations in Indiana. However, other studies have found that late planting reduced soybean plant stands due to poor seedbed conditions such as dry soil during the imbibition period (Helms et al., 1996), and heavy rains followed by soil crusting (Johnson and Wax, 1979). Grabe and Metzer (1969) also found that reduced stands were caused by the interaction of late planting and greater seeding depth.

The time of soybean emergence is also influenced by planting date. Underlying this relationship, the air or soil temperature associated with the time of soybean planting affects the time of soybean emergence (Andales et al., 2000). In the Midwestern United States, it has been reported that mid-May planting dates result in soybean emergence after two to three weeks, whereas soybeans planted in early June emerge after three to five days (Tanner and Hume, 1978). However, Egli (1993) indicated that variation in time of soybean emergence has little influence on yield.

2.3.2 Soybean Growth and Development

Planting date can affect both early and late season soybean growth. Heatherly and Elmore, (2004) reported that planting date affects plant size prior to flower initiation. Earlier soybean planting has been found to produce more nodes per plant (Wilcox and Frankenberger, 1987; Bastidas et al., 2008), and reduce internode length (Bastidas et al., 2008) compared to later soybean planting. Pedersen and Lauer (2004b) determined that soybeans seeded in early May were 35 cm taller than soybeans seeded in late May at 64 days after emergence (R3/R4). However, plants reached equal heights by the R6 stage of development in this study, eliminating any late-season differences in soybean plant height (Pedersen and Lauer, 2004a). Other early-season growth characteristics such as leaf area and canopy closure may be reduced by delayed soybean planting (Tanner and Hume, 1978).

Late-season effects of planting date also occur for soybean growth and development characteristics after floral induction. Early soybean planting can result in more pods and seeds per plant (Pedersen and Lauer, 2004b), total dry matter (Pedersen and Lauer, 2004a), and main stem nodes per plant at maturity compared to late planting (Egli et al., 1985; Pedersen and Lauer, 2004a). In contrast, late planting has been reported to increase floral abortion rate (Heitholt et al., 1986), reduce soybean seed mass (Elmore, 1990) and reduce the number of pods per plant (Anderson and Vasilas, 1985; Elmore, 1990). A study by Pedersen and Lauer (2004) determined that while earlier planting produced more seeds and pods per plant, later planting resulted in more seeds per pod. Anderson and Vasilas (1985) also found that late planting increased total soybean seed weight.

Soybean development, including the onset and duration of vegetative and reproductive growth stages, is largely influenced by planting date. However, soybean development response to planting date varies in the literature. Studies have found that delayed planting can result in reduced reproductive growth duration (Board and Hall, 1984; Egli and Cornelius, 2009). However, a study by Chen and Wiatrak (2010) determined that later planting shortened the vegetative growth phase more than the reproductive, especially for later maturity groups (V through VIII). In that study, late planting (mid-June) was also found to reduce pod-set duration of soybean plants (Chen and Wiatrak, 2010). Finally, Bastidas et al. (2008) determined that node development was five days behind for soybeans planted in late May compared to early May. Other studies found that early soybean planting resulted in earlier initiation of the R5 stage, extending the period from R5 to R6 (Wilcox and Frankenberger, 1987; Bastidas et al., 2008), during which seed-fill takes place. In contrast, a study by Egli et al. (1987) discovered that planting date did not have an effect on the seed-filling period.

The influence of planting date on soybean development is closely linked with response to photoperiod. Short photoperiods can limit the length of the vegetative growth period and induce premature flowering, which in turn reduces yield (Hicks, 1978; Board, 2002). Both photoperiod and the length of the growing season decrease with later planting (Tanner and Hume, 1978). A study by (Board and Hall, 1984) conducted in the southeastern United States examining the effects of non-optimal planting dates on premature soybean flowering and yield reduction, determined that day length of early-planted soybeans (early April) was short enough to induce premature flowering. However, photoperiods of late-planted soybeans (mid-June) were not short enough to cause premature flowering (Board and Hall, 1984). Delayed flowering genotypes in this study (MG V to VIII) had potential to avoid yield losses caused by premature flowering (Board and Hall, 1984).

2.3.3 Soybean Yield

Planting date can dramatically impact soybean yield (Ryder and Beuerlein, 1979; Beaver and Johnson, 1981). Soybean planting date studies conducted across the

Midwestern United States share the predominant conclusion that mid-May planting dates generally achieve maximum soybean yields, and that yields decline with late May, early June, and mid-June planting (Beaver and Johnson, 1981; Anderson and Vasilas, 1985; Wilcox and Frankenberger, 1987; Beuerlein, 1988; Elmore, 1990; Lueschen et al., 1992; Oplinger and Philbrook, 1992; Whigham et al., 2000; Pedersen and Lauer, 2004a; b; De Bruin and Pedersen, 2008a). However, it is important to examine results of these studies in greater detail, as soybean yield response to planting date varies among locations and may differ yet for northernmost growing regions of the NGP.

Results of soybean yield response to early planting are inconsistent in the literature. A study by Pedersen (2003) in Wisconsin reported that early May planting of MG II varieties achieved high yields, results varied among locations and years. De Bruin and Pedersen (2008a) determined that early planting of MG II soybean varieties from late April to early May consistently yielded greater than planting from late May to early June in Indiana. Wilcox and Frankenberger (1987) found that indeterminate soybean varieties planted in early May had a yield advantage compared to planting dates ranging from late May to mid-June in Indiana. Robinson et al. (2009) observed the greatest yields from soybeans seeded April 10 to May 9 in Indiana, whereas late March and early June seeding dates produced lower yields. Kane and Grabau (1992) determined that early planted MG II varieties in Kentucky resulted in greater yields compared to maturity groups greater than II. A study by Kane et al. (1997a) examining soybean varieties ranging from MG 00 to IV in the southeastern United States found no yield advantage to early planting of earlier maturing varieties under adequate moisture conditions.

Interest in planting soybeans earlier than current seeding dates has increased, particularly in the Midwestern United States. It is reported that two thirds of growers in Indiana currently plant soybeans one to three weeks earlier than a decade ago due to positive yield responses (Robinson et al., 2009). A survey conducted by Conley and Santini (2007) also reported that farmers believe earlier soybean planting results in greater yields. Due to the increase of soybean acres in northern growing regions, it is suspected that this trend may shift northward as producers become more experienced with soybean production. Rowntree et al. (2013) indicated continual genetic improvement of soybean varieties over the past few decades has likely supported the shift to earlier soybean planting.

Late planting of soybeans has been widely documented to cause yield reductions. A meta-analysis of nine planting date studies by Egli and Cornelius (2009) determined that soybean yield declines rapidly when planting is delayed beyond May 27, regardless of maturity group in the southeastern United States. De Bruin and Pedersen (2008a) reported that June planting of soybeans consistently yielded the lowest. Finally, Bastidas et al. (2008) found that yield steadily declined beyond early May planting, with June planting resulting in the lowest soybean yields. It is important to note that much of the literature on late soybean planting originates from the southern United States where double-cropping and irrigation are common due to the long growing season (Kane et al., 1997a). Double-cropping involves late planting of soybeans, as the soybean crop is planted following a small grain or other soybean crop within one season. However, these results may still provide useful background information for soybean yield response to late planting.

The interaction between soybean yield loss and planting date is commonly the cause of moisture stress. Kane et al. (1997a) reported a significant relationship between total rainfall and yield in the southern United States, where the relationship was more pronounced for earlier planting in late April, and decreased with later planting. It was further determined in this study that rainfall during the vegetative stage was the most critical for early and late June plantings, pod-set rainfall for mid-May planting, and seed-fill rainfall for late April planting (Kane et al., 1997a). In general, the R5 to R6 stages of soybean development have been identified as the most susceptible to drought stress (Foroud et al., 1993), during which seed-filling takes place (Board, 2002). Drought stress during the R5 to R6 stages caused by late planting has been reported to reduce pod number and yield (Foroud et al., 1993). Finally, Chen and Wiatrak (2010) reported that precipitation during pod set was the main determinant for yields of all MG.

Soybean yield loss resulting from late planting is often linked with specific yield components that are highly influenced by planting date. Yield loss from late soybean planting may be attributed to the reduction in total biomass, pod number per plant, plant height, branch number (Bhatia et al., 1999), seed number and mass (Egli, 1975; Parker et al., 1981; Egli et al., 1987; Bhatia et al., 1999), soil moisture as the season progresses (Tanner and Hume, 1978), insolation, or solar radiation that reaches the earth’s surface, received during the reproductive growth phase (Egli and Bruening, 1992), and time from planting to flowering and maturity (Bhatia et al., 1999). However, Egli et al. (1987) found that soybean yield was reduced regardless of moisture limitation when soybeans were planted in early July under irrigation.

2.3.4 Soybean Seed Quality

Soybean seed quality factors such as oil and protein content are influenced by planting date (Hu and Wiatrak, 2012). Environmental conditions, variety, and maturity group also influence oil and protein content in soybean seed, but it is argued that the environment has the greatest influence of the three factors (Yaklich et al., 2002; Bastidas et al., 2008). Both temperature and moisture stress during the reproductive stage have been shown to alter soybean seed composition (Dornbos and Mullen, 1992; Gibson and Mullen, 1996).

Soybean oil and protein levels are inversely related to each other in response to planting date; however, this is not always the case. A study by Kane et al. (1997b) in the southeastern United States determined that delayed soybean planting in early to late June increased protein content and reduced oil content compared to late April and mid-May planting dates for MG 00 to IV. This study also found a strong correlation between higher oil content and high air temperatures during seed-fill that are associated with early planting. In contrast, a study by Tremblay et al. (2006) in Quebec examining early to late maturing soybean varieties, found that delayed planting (first half of June) reduced oil content but had no effect on protein content. Bastidas et al. (2008) also reported an inconsistent effect of delayed planting on seed protein. Finally, Helms et al. (1996) determined that overall quality of soybean seed was reduced with delayed planting.

2.4 Soybean Response to Low Temperature

Arguably, the most important factor influencing plant response to the environment is temperature (Edey, 1977). Temperature can cause plant stress on soybean emergence, growth and yield. Temperature stress also involves both air and soil temperature (Burris, 1976; Powell, 1988; Hay and Porter, 2006), high and low temperature levels (Raper and Kramer, 1987), and day to night temperature fluctuations (Seddigh and Jolliff, 1984; Skrudlik and Kościelniak, 1996; Gibson and Mullen, 1996). Plant stress is defined by Raper and Kramer (1987) as "any condition that reduces yield below the maximum attainable level" in situations where perturbations from normal conditions at environmental, whole plant, cellular, and subcellular levels occur. The level of stress from environmental factors, including temperature, is reliant on the crop stage of development, variety, and interaction with other stress factors such as solar radiation and water stress (Littlejohns and Tanner, 1976; Raper and Kramer, 1987). A study by Holmberg (1973) defined base, sufficient and optimum air temperature ranges for soybean crops (Table 2.2). The base temperature was defined as the minimum air temperature that would allow formation of soybean reproductive organs and flowers (Holmberg, 1973).

Table 2.2. Base, sufficient, and optimum air temperature requirements of soybean plants (adapted from Holmberg, 1973).

Stage of development		Base	Sufficient	Optimum
		-----------------------	°C	----------------------
Germination	VE	6-7	12-14	20-22
Emergence	VE – VC	8-10	15-18	20-22
Formation of reproductive organs	V5 – V(n)†	16-17	18-19	21-23
Flowering	R1 – R2	17-18	19-20	22-25
Seed formation	R2 – R5	13-14	18-19	21-23
Ripening	R6 – R8	8-9	14-16	19-20

† V(n) represents vegetative development stages with any number beginning with 6 as n (Fehr and Caviness, 1977).

Freezing temperatures are considered "the most widespread hazard to crop production in Canada" (Brown and Blackburn, 1987). Freezing is defined as, "subfreezing temperature conditions that cause crop damage," interchangeably referred to as a killing frost (Brown and Blackburn, 1987). A killing frost occurs when temperatures reach -2.2°C or lower, which can result in plant death (Bootsma and Brown, 1995). Frost on the other hand can be defined as, "the condition that exists when air temperatures drop to 0°C or lower, which may or may not result in damage to crops" (Brown and Blackburn, 1987). The risk of frost or freezing damage to soybeans is increased in the spring by early planting, and in the fall by late planting (Halvorson et al., 1995).

Soybeans and field peas (*Pisum sativum* L.) are considered to be moderately tolerant to frost, compared with navy and pinto beans (*Phaseolus vulgaris* L.), the least tolerant, and forage legumes which are the most tolerant (Badaruddin and Meyer, 2001; Meyer and Badaruddin, 2001). Meyer and Badaruddin (2001) determined that the LT_{50} temperature, at which 50% of seedlings are killed by freezing, is -4.5°C for soybean seedlings (Meyer and Badaruddin, 2001). In contrast, Hume and Jackson (1981a) found the LT_{50} level to be -3°C for soybean seedlings; however, soybean plants were exposed to a longer freezing period in this study. Thus, duration of freezing temperatures influences the LT_{50} level (Badaruddin and Meyer, 2001).

2.4.1 Soybean Imbibition and Emergence

Soybean is one of many plant species sensitive to chilling injury (Obendorf and Hobbs, 1970; Bramlage et al., 1978; Nykiforuk and Johnson-Flanagan, 1998). Field pea was also classified as sensitive, dry bean as medium sensitive, and corn as low-sensitive

(Markowski, 1988a; b). For sensitive species, chilling temperatures may range from 0 to 10°C (Markowski, 1988b). Chilling injury to soybean seeds can directly inhibit germination, reduce seedling survival (Markowski, 1988b), delay emergence (Simon et al., 1976; Bramlage et al., 1978; Raper and Kramer, 1987; Nykiforuk and Johnson-Flanagan, 1998), inhibit photosynthesis, and indirectly interfere with water absorption (Taylor and Rowley, 1971).

Cold temperatures imposed during imbibition, the process of water uptake by the seed after planting, can cause injury by chilling stress in soybean seeds (Obendorf and Hobbs, 1970; Bramlage et al., 1978; Helms et al., 1996; Nykiforuk and Johnson-Flanagan, 1998; Wuebker et al., 2001). Imbibition is one of the most highly susceptible phases of soybean development to temperature stress (Markowski, 1988a). During the first minutes of imbibition, also known as the period of membrane reorganization, seed embryos leak solutes (Parrish and Leopold, 1977; Bramlage et al., 1978). Low temperatures imposed at this time can cause prolonged, rapid solute leakage from seed embryos (Bramlage et al., 1978). Prolonged leakage of solutes from seed embryos demonstrates a delay in seed membrane reorganization, which is an alteration of the physical state of membrane phospholipids (Bramlage et al., 1978; Knypl and Janas, 1979). Delayed membrane reorganization indicates damage to the imbibing seed embryo (Simon et al., 1976; Bramlage et al., 1978). Embryo damage involves depletion of soluble food reserve tissues and stimulated growth of pathogenic microorganisms (Schulz and Bateman, 1968).

The level of chilling injury depends on the severity and duration of exposure to low temperatures (Bramlage et al., 1978; Raper and Kramer, 1987). Bramlage et al.

(1978) found that chilling injury can occur during the first minutes of imbibition; however, this effect occurred for seeds without seed coats. Seeds with intact seed coats can withstand 90 minutes at 2°C before chilling injury occurs (Bramlage et al., 1978). The intact seed coat delays water penetration and reduces solute leakage (Larson, 1968). Markowski (1988b) reported that germination was inhibited completely when soybeans were exposed to 2°C for seven days. Also, if chilling temperatures persist throughout early development, they can harm older seedlings (Markowski, 1988b).

Emergence involves two developmental processes: germination and early seedling growth (Nykiforuk and Johnson-Flanagan, 1998), which are both influenced by soil temperature. Germination occurs after imbibition and ends with protrusion of the radicle from the seed coat, whereas early seedling growth begins once stored reserves are mobilized for cellular division (Finkelstein and Crouch, 1984; Nykiforuk and Johnson-Flanagan, 1998). Soybeans germinate between air temperatures of 6 and 40°C (Holmberg, 1973; Whigham and Minor, 1978; Mederski, 1983; Nykiforuk and Johnson-Flanagan, 1998); however, the optimum temperature range for soybean germination is 20 to 22°C (Holmberg, 1973). One study reported soybean germination at air temperatures of 2 to 4°C (Inouye, 1979). Although the most rapid germination occurs at 30°C, this temperature does not occur at the time of germination in the temperate regions where soybeans are grown (Whigham et al., 2000). Delayed soybean germination in response to cold soil has been attributed to slowed rates of enzyme-mediated processes that take place during respiration and hydrolysis of seed food reserves, or slow translocation rates of metabolites (Raper and Kramer, 1987). Early seedling growth, or emergence, occurs at air temperatures ranging from 8 to 30°C (Holmberg, 1973). The optimal temperature range for emergence is 10 to 22°C and the most rapid emergence occurs at 25 to 30°C (Mederski, 1983).

Soybean seedlings are sensitive to freezing due to epigeal emergence (Tanner and Hume, 1978; Miller et al., 2002). Epigeal emergence causes the apical growing point and the axillary buds in the cotyledon node to move above the soil surface after emergence (Tanner and Hume, 1978). One symptom of frost damage to soybean plants is leaf chlorosis (Meyer and Badaruddin, 2001). Exposure of soybean seedlings to spring freezing temperatures can result in soybean plant mortality and thus plant stand loss (Brown and Blackburn, 1987; Badaruddin and Meyer, 2001). Soybeans are susceptible to damage at all stages of growth and flowering when temperatures drop below 0°C (Brown and Blackburn, 1987). Hume and Jackson (1981a) found that soybeans are more susceptible to freezing at -3.8°C in the unifoliate stage compared to the cotyledon stage. Hicks (1978) further reported that the third trifoliate stage was more tolerant to freezing than the unifoliate stage.

Soybean seedlings damaged by frost or freezing can continue growth if the growing point remains active. Regrowth involves initiation of new leaves within two weeks following frost damage (Badaruddin and Meyer, 2001). If the shoot tip of a bean plant is removed, lateral buds begin to grow due to the shift away from apical dominance (Raven et al., 2005). Growth of lateral buds leads to the development of two main stems in soybean plants.

Low air and soil temperatures associated with early planting influence soybean emergence (Hatfield and Egli, 1974; Andales et al., 2000); however, results are inconsistent in the literature. When moisture is not limiting, temperature is the most influential factor on time to soybean emergence (Falk, 1981). Exposure of young soybean seedlings to cold, wet soil can delay germination and emergence (Andales et al., 2000), reduce plant stands and increase susceptibility to late spring frost (Meyer and Badaruddin, 2001). However, Obendorf and Hobbs (1970) determined that seed survival, dry matter accumulation, and plant height were all reduced when low moisture soybean seeds were exposed to a low air temperature of 5°C. Fehr et al. (1973) found that soil temperature did not consistently influence percentage soybean emergence of different varieties. Finally, Grabe and Metzer (1969) determined that inconsistent soybean emergence may be partially explained by planting depth, variety, and soil temperature during the germination period.

2.4.2 Soybean Growth and Development

Cold air and soil temperature exposure to soybean seedlings can affect soybean growth and yield. When discussing air and soil temperature, it is important to note that soil temperatures lag somewhat behind air temperature (Brady and Weil, 2008), and surface soil temperatures are cooler in the spring and warmer in the fall. Skrudlik and Kościelniak (1996) determined that low air temperature exposure during the seedling stage lengthened the vegetative growth period, decreased the rate of increase for leaf area and dry weight, increased the number of axillary buds produced, and delayed flowering by as much as 13 days. Markowski (1988b) found that low air temperature exposure altered dry matter and seedling height of soybeans. Plant weight was more inhibited by air temperatures of 10 to 15°C compared to plant height (Markowski, 1988b). Symptoms of plants subjected to low root temperatures throughout their lifespan include lower photosynthetic rates (Duke et al., 1979), nodulation, and N_2 fixation (Mague and Burris, 1972), and inhibited water absorption (Musser et al., 1983). Musser et al. (1983) also determined that shoot chilling could have a greater effect on soybean growth than root chilling.

Anthesis, or flowering, is another particularly sensitive soybean development stage to cold temperature stress (Goto and Yamamoto, 1972). Cold stress during flowering may result in symptoms such as non-opening of flowers (Erickson, 1975; Thomas and Raper, 1978; Thomas et al., 1981), small seedless pods at the top of the plant, deformed pods along the stem (Hume and Jackson, 1981b; Thomas et al., 1981; Musser et al., 1983), poor pod set (Saito et al., 1970) causing lack of pollen development (Ohnishi et al., 2010). All listed symptoms of cold stress during flowering can reduce soybean yield. Nectar secretion of unopened soybean flowers ceases at a daily mean temperature of less than 21°C, reducing pollination by honey bees (Erickson, 1975). Reduced pollination has negative implications on yield (Erickson, 1975). Ohnishi et al. (2010) determined that insufficient pollination reduced pod set due to low temperature stress during both early and late stages of flowering. They found that pollination was reduced due to abnormally shaped pollen grains. A study by Saito et al. (1970) discovered that low temperature exposure before and after flowering resulted in fewer pods and lower seed yield per plant. Finally, Hume and Jackson (1981b) reported that cold-tolerant soybean varieties could produce pods at day/night temperatures of 15/9°C; however, less cold-tolerant varieties ceased to produce pods at temperatures that low. Plant compensation mechanisms within the pod are essential to maintain yield potential in the field (Gass et al., 1996). Maturity may also be delayed when plants must compensate for loss of reproductive structures (Gass et al., 1996). Delayed maturity, especially in areas with short growing seasons, increases the risk of fall frost and yield loss.

Legume seedlings are more susceptible to freezing during vegetative stages compared to later development stages (Calder et al., 1965); however, all development stages of soybean are susceptible to injury at temperatures of 0°C or lower (Brown and Blackburn, 1987). Frost exposure early in the growing season has been linked to reduced pod development (Raper and Kramer, 1987). A study by Judd et al. (1982) tested the effects of freezing temperatures from -2 to -12°C for up to 32 hours on detached soybean pods at the green, yellow, and brown pod stages (equivalent to R6, R7, and R8, respectively). They determined that only extremely low temperatures below 0°C for an extended period of time, -7°C for 8 hours, reduced seed vigor and germination at the yellow pod stage. Soybean plants at the green pod stage, prior to the onset of physiological maturity, experienced seed injury at -2°C (Judd et al., 1982). They concluded that as seed moisture declines, seeds become more tolerant to freezing temperatures (Judd et al., 1982). Halvorson et al. (1995) further reported that fall freezing at the R6 stage or later has no effect on soybean seed quality.

2.4.3 Soybean Yield

Soybean yields are influenced by both low and high temperatures, and day to night temperature fluctuations throughout vegetative and reproductive development. Low yields of early planted soybeans can be attributed to low air temperatures during vegetative growth and high temperatures during seed filling (Kane et al., 1997a). Hot, dry weather during July and August while soybean seed formation is taking place can negatively affect soybean yield and interfere with physiological processes (Raper and Kramer, 1987). Schou et al. (1978) determined that the period from flowering to physiological maturity is more influential on yield than emergence to flowering. Soybean yield increases have been observed from exposure to day/night air temperatures near 26/20°C compared to temperatures of 18/12°C, whereas yield and pod number decreased from exposure to temperatures above 26/20°C (Sionit et al., 1978; Thomas and Raper, 1978). Egli and Wardlaw (1980) observed an increase in seed growth rate (SGR) from plants exposed to day/night temperatures of 18/13°C to 27/22°C during flowering to pod set. However, SGR was reduced by 36% when soybean plants were exposed to day/night temperatures of 33/28°C, regardless of temperatures experienced following these stages (Egli and Wardlaw, 1980). Gibson and Mullen (1996) determined that high daytime temperatures had a greater effect on yield components than moderate to high nighttime temperatures. High daytime temperatures imposed on soybeans during the flowering and pod set stages decreased seed formation and reduced photosynthetic rates (Gibson and Mullen, 1996).

2.4.4 Soybean Seed Quality

Temperature can influence soybean seed quality components. Wilcox and Cavins (1992) reported that temperatures 20 to 40 days prior to maturity have the greatest effect on seed composition, including oil and fatty acid. Piper and Boote (1999) indicated that mean temperature, rather than minimum or maximum temperature, has the strongest correlation with oil and protein concentrations. Khan et al. (2011) found that a temperature increase from 23 to 30°C during the R6 to R7 stages of development resulted in higher soybean oil and protein content. The same temperature increase from 23 to 30°C during the R5 to R6 stage, however, decreased soybean oil and protein content. Spears et al. (1997) reported that high temperatures of 33/28°C or higher during the seed development phase reduced seed quality.

2.5 Soybean Plant Density

Plant density is a management tool that soybean growers can manipulate to increase yield and economic return. Plant density is the number of live plants per unit of area. Plant establishment may vary with location, environmental conditions, soil conditions, seeding equipment, seeding depth, and planting date. In order to reach a specific number of live plants per unit of area, growers first set a target plant density and calculate the appropriate seed density to reach that target. Target plant density is the intended plant density goal set by growers prior to seeding, and actual plant density, described interchangeably with plant density, is the number of live plants per unit of area achieved in the field after seeding. Seed density, or seeding rate, is the number of seeds per unit of area sown into the soil. Seed density calculations are adjusted to factor in potential losses such as lack of germination or seedling mortality.

Soybean seed density calculations should include germination of the given seed lot, seed weight, economic return, and assumed percentage seed or seedling mortality under weed-free conditions. Seedling mortality is defined as the percentage of seeds that will germinate but will not produce a plant (MAFRD, 2016a). Endres and Kandel (2014) reported that 10 to 20% soybean mortality can typically occur between planting and emergence. A seedling mortality level of 10% mortality is considered to be normal in North Dakota. Economic return factors include the expected commodity price, cost of seed, and expected yield (Mohr et al., 2014; MPSG, 2016). It is also recommended to adjust seed densities upward for later planting, narrow row spacing, or for no-till soil (NDSU, 2014).

2.5.1 Current Plant Establishment Recommendations in the Northern Great Plains

Recommended target plant densities vary slightly among regions. In Manitoba, the recommended target plant density of soybeans is 395,000 plants ha^{-1} (Mohr et al., 2014). In North Dakota, the recommended target plant density is 371,000 plants ha^{-1} (NDSU, 2014). To determine the number of seeds per unit area required to reach these target densities, seed density should be calculated as previously discussed.

Soybeans are sown using two different types of seeding equipment in northern regions of the NGP: air drills and planters. Recommended seed densities are higher for air drills compared to planters. Erratic seed metering and placement with air drills lowers seedling emergence uniformity, especially if soils are dry or compacted (Epler and Staggenborg, 2008). In Manitoba, the average expected seed survival is 71% for air seeders and 81% for planters (MPSG, 2016a). The current recommended soybean seed density for Manitoba ranges from 470,000 to 519,000 seeds ha^{-1}, and 420,000 to 445,000 seeds ha^{-1} for air drills and planters, respectively (MPSG, 2016a).

Seeding depth is another management factor that influences soybean plant establishment (Fehr et al., 1973). Soybeans should be sown at a depth of 1.9 to 3.8 cm, depending on soil type (MAFRD, 2016b). Shallower seeding depths are recommended for loam or clay soils for ease of soybean emergence, whereas deeper seeding depths are recommended for sandy soils to ensure seed contact with soil moisture (MAFRD, 2016b). However, deep seeding increases the risk of poor emergence, and seed or seedling disease (MAFRD, 2016b).

2.6 Soybean Response to Plant Density

Plant density influences soybean yield and seed quality, and can initiate compensatory growth in soybean plants throughout development. The response of soybeans to plant density is influenced by planting date (De Bruin and Pedersen, 2008a), environmental conditions (Wiggans, 1939; Andrade and Abbate, 2005; De Bruin and Pedersen, 2008a), and variety (Wiggans, 1939; Popp et al., 2006; De Bruin and Pedersen, 2008a; Cox et al., 2010). The influence of variety may be caused by differences in plant architecture, such as upright versus bush-type plants.

2.6.1 Compensatory Growth and Shade Avoidance of Soybeans

Signals induced by adjacent plants during the early stages of plant development allow soybean plants to initiate a compensatory or shade avoidance response (Aphalo and Ballaré, 1995; Andrade and Abbate, 2005). These signals are often stress-related and occur due to changes in the plant’s environment. They allow plants to adjust their physiology to avoid resource limitation on growth and reproduction (Aphalo and Ballaré, 1995). For example, signals received by the soybean plant indicating a threat of reduced light in the crop canopy due to high plant densities will initiate a shade avoidance response (Aphalo and Ballaré, 1995). As plants sense changes in the light climate, chloroplast physiology acclimates, modifying the response of photosynthetic rate to changes in light (Chow et al., 1990). This process may then induce architectural changes in the plant that prevent shading by adjacent plants.

Soybean plants have a high capacity for vegetative plasticity, which is the ability to compensate in growth due to spaces between neighbouring plants or less productive plants (Egli, 1993; Carpenter and Board, 1997; Andrade and Abbate, 2005). One form of compensatory growth of soybean plants is via the addition of branches. Carpenter and Board (1997) determined that branch dry matter per plant and the number of branch nodes increased at reduced plant densities. In contrast, Hay and Porter (2006) found that high plant densities reduced the number of branches produced by soybean plants. They determined that adjacent plants either prevented a large proportion of branches from developing beyond the bud stage, or caused premature death (Hay and Porter, 2006). The benefit of additional branches is increased potential for plants to generate more leaf area, and thus intercept more solar radiation and increase photosynthetic capacity (Hay and Porter, 2006).

The growth response of soybean plants to low and high plant densities extends beyond branching. Seed densities as low as 148,000 seeds ha^{-1} have been reported to produce plants with a combination of more branches, reduced height, and pods closer to the soil surface (Beuerlein, 1988). Beaver and Johnson (1981) found that lowest pod heights were reduced by seed densities of 350,000 compared to 650,000 seeds ha^{-1}. In contrast, other studies found that higher seed densities resulted in fewer branches, taller plants (Weber et al., 1966; Beuerlein, 1988), fewer pods and seeds per plant (Weber et al., 1966), and raised height of the lowest pod (Beuerlein, 1988). Aphalo and Ballaré 1995) determined that the shade avoidance response of soybeans to adjacent plants under high plant densities is an increased rate of internode elongation and alteration in the pattern of dry matter allocation. Thus, a reduced rate of internode elongation under low plant densities results in lower pod heights and shorter plants (Aphalo and Ballaré, 1995).

Higher seed densities and narrower row spacing of indeterminate soybean varieties are often explored to increase productivity (Beuerlein, 1988). Indeterminate soybean varieties have greater main stem elongation compared to determinate varieties, which improves the ability of plants to intercept sunlight earlier in the growing season (Beuerlein, 1988). Main stem elongation of indeterminate soybean varieties continues past flowering, whereas stem elongation and leaf production ceases at flowering for determinate varieties (Bernard, 1972). However, greater main stem elongation associated with indeterminate soybean varieties increases the risk of lodging at seed densities as high as 618,000 seeds ha^{-1} (Beuerlein, 1988). Lodging then increases the risk of reduced soybean yield (Weber et al., 1966; Cooper, 1971).

2.6.2 Soybean Yield

Soybean canopy closure and spatial distribution of plants are important prerequisites for maximum seed yield (Weber et al., 1966; Tanner and Hume, 1978). Two concepts surround the relationship between row spacing, plant density, and yield: 1) a sufficient amount of leaf area provides maximum insolation interception to maximize yield (Weber et al., 1966; Tanner and Hume, 1978), and 2) equidistant plant spacing minimizes interplant competition and maximizes yield (Wiggans, 1939; Johnson, 1987).

A study by Egli (1988) reported that under low plant densities where there was no intraspecific competition, yield increased in direct proportion with increases in plant density. However, the presence of intraspecific competition interfered with the directly proportional relationship, causing the rate of yield increase to decline.

The relationship between plant density and yield can be described by two relationships: 1) an asymptotic relationship where yield increases to a maximum level and remains constant with further increases in plant density, and 2) a parabolic relationship where yield increases to a maximum level then declines with further increases plant density (Willey and Heath, 1969). Yield reduction in the parabolic relationship is due to increased intraspecific competition (Mohler, 2001), whereas the asymptotic relationship does not account for competition among plants. Asymptotic relationships best describe the relationship between plant density and biomass production, whereas parabolic relationships are more appropriate for the relationship between plant density and crop yields (Mohler, 2001).

Representation of the relationship between soybean yield and plant density influences interpretation of results and determination of an “optimum” plant density. Optimum plant density is defined by maximized yield, which occurs at the beginning of the plateau phase in asymptotic relationships, and at the peak of a parabolic relationship. The plateau phase often begins at a lower plant density than a parabolic peak (Willey and Heath, 1969). Some studies have described the soybean yield-density relationship as parabolic (Epler and Staggenborg, 2008; Mohr et al., 2014), whereas others have described the relationship as asymptotic (Epler and Staggenborg, 2008; Lee et al., 2008).

A wide range of plant densities and seed densities are capable of producing maximum soybean yield. Results from studies examining the response of soybean yield to plant and seed density are summarized in Table 2.3. Maximum yield was reached at plant densities ranging from 108,000 to 618,000 plants ha^{-1}, and seed densities ranging from 346,000 to 618,000 seeds ha^{-1} across sites in the United States and Canada (Table 2.3). Lee et al. (2008) specified optimum plant density ranges of 108,000 to 232,000 plants ha^{-1} and 232,000 to 282,000 plants ha^{-1} for May and June planting, respectively. Southern areas of the United States often attained maximum yield at lower plant densities or seed densities; however, this trend is inconsistent. Finally, environmental conditions, among many other factors examined in these studies such as planting date and variety, also influenced soybean yield response to plant density. As few studies identifying optimum soybean plant densities have been conducted in Canada and other northern soybean growing regions, continued site-specific research on this topic is important.

Table 2.3. Summary of soybean plant and seed densities that maximized soybean yield under weed-free conditions from studies conducted in the United States and Canada.

Location	Range tested	Maximum yield	Maturity group	Reference
Kentucky	43,000 to 560,000 seeds ha^{-1}	108,000 to 232,000 plants ha^{-1} (May planting) 238,000 to 282,000 plants ha^{-1} (June planting)	II to IV	(Lee et al., 2008)
Iowa	185,000 to 556,000 seeds ha^{-1}	194,000 to 290,800 plants ha^{-1} †	II	(De Bruin and Pedersen, 2008a)
Kansas	148,000 to 544,000 seeds ha^{-1}	198,000 to 346,000 plants ha^{-1}	III	(Epler and Staggenborg, 2008)
Nebraska	111,000 to 815,000 seeds ha^{-1}	346,000 seeds ha^{-1}	II and III	(Elmore, 1998)
Iowa	64,000 to 516,000 plants ha^{-1}	387,000 plants ha^{-1}	III	(Weber et al., 1966)
Manitoba	200,000 to 500,000 seeds ha^{-1}	395,000 plants ha^{-1}	00	(Mohr et al., 2014)
Iowa	185,000 to 556,000 seeds ha^{-1}	462,200 plants ha^{-1} †	II	(De Bruin and Pedersen, 2008b)
Ohio	371,000 to 741,000 seeds ha^{-1}	494,000 to 618,000 seeds ha^{-1}	III	(Beuerlein, 1988)
Wisconsin	124,000 to 741,000 seeds ha^{-1}	618,000 seeds ha^{-1}	I to II	(Oplinger and Philbrook, 1992)

† Represents 95% of maximum yield achieved.

Specific yield components linked to soybean plant density response can influence yield; however, results are inconsistent in the literature. Carpenter and Board (1997) determined that greater soybean branch dry matter per plant, associated with more pods per reproductive branch, was highly correlated with improved yield. A study by Egli (1988) found that yield increased with increasing plant density due to increased seed production. Weber et al. (1966) reported the rate of soybean seed dry weight accumulation to increase with increasing plant density; however, it had no effect on yield. Wells (1991) found that reduced canopy photosynthesis was correlated with reduced soybean yield. Finally, Weber et al. (1966) also determined that leaf area index (LAI) and plant dry weight accumulation in response to plant density were poor predictors of yield.

2.6.3 Soybean Seed Quality

Soybean seed quality components such as oil and protein content are influenced by plant density. Mohr et al. (2014) found inconsistent trends in oil and protein content among sites in Manitoba, where percentage oil content decreased with increasing seed density at some sites, and increased at others. Protein content increased with increasing seed density in 7 out of 19 site years, and decreased in one site year (Mohr et al., 2014). Overall responses in oil and protein were slight and inconsistent in the study by Mohr et al. (2014), concurrent with a previous study by Weber et al. (1966) that found protein and oil content was affected only slightly by soybean plant spacing and density.

2.7 Economic Optimum Soybean Plant Density

Economic optimum plant density is based on the trade-off between crop yield maximization and seed cost minimization (Mohler, 2001; De Bruin and Pedersen, 2008a). Economic optimum plant density is defined by maximized profit (French et al., 1994). Plant density recommendations for soybeans are often based on maximized yield and minimized weed competition (Mohler, 2001). However, incorporating seed cost and commodity price would provide a better indication of profitability (Wahab et al., 1986; Saindon et al., 1995; Jettner et al., 1999; De Bruin and Pedersen, 2008a).

2.7.1 Determining Economic Optimum Plant Density for Soybeans

Microeconomic theory can be used to calculate the economic optimum plant density for soybeans (French et al., 1994). Marginal cost analysis involves calculation of marginal cost (MC) of seed and marginal revenue (MR) of grain from the yield-density relationship. Marginal cost and marginal revenue are defined as the change in cost and revenue, respectively, for one plant per unit of area over a range of plant densities (Baumol and Blinder, 2015). The slope, or first derivative, of the yield-density relationship is determined to calculate MC and MR. Economic optimum plant density occurs where marginal revenue is equal to marginal cost, representing maximum profit (French et al., 1994; Baumol and Blinder, 2015). Marginal cost analysis may also be represented as the total cost (TC) of seed and total revenue (TR) of grain over a range of plant densities (Shirtliffe and Johnston, 2002; Baumol and Blinder, 2015). In this relationship, economic optimum plant density occurs at the peak in the curve, or point of greatest difference between TC and TR, where profit is maximized. Economic optimum plant density of soybean calculated using this method is not available in the literature; however, this method has been employed by other studies to calculate economic optimum plant densities for crops such as lupin (*Lupinus angustifolius* L.) (French et al., 1994), faba bean (*Vicia faba* L.) (Loss et al., 1998), desi chickpea (*Cicer arietinum* L.) (Jettner et al., 1999), and dry bean (*Phaseolus vulgaris* L.) (Shirtliffe and Johnston, 2002).

Alternative methods have been used to calculate economic optimum plant density for soybeans. A study by Lee et al. (2008) in Kentucky used a partial economic return analysis to calculate economic optimum plant population (EOPP). In their study, EOPP was defined as, "the population that produced 95% of the predicted partial economic return at the highest observed plant population." Partial economic return was calculated as the product of commodity price and seed yield, minus the sum of seed cost and hauling. Based on an asymptotic yield-density relationship, soybean EOPPs ranged from 76,000 to 241,000 plants ha^{-1}, 7 and 33% lower than plant densities that maximized yield. A study by De Bruin and Pedersen (2008a) used a partial budget analysis to examine economic return of four soybean seed densities ranging from 185,000 to 556,000 seeds ha^{-1}. Partial budget analysis in this study incorporated grain revenue and seed cost. Economic soybean plant density was reported at 171,000 plants ha^{-1}. Although the economic plant density in this study was not capable of producing maximum yield, economic return of this reduced plant density was offset by lower seed cost.

2.8 Need for Continued Soybean Planting Date and Plant Density Research

Soybean growers in the northernmost growing regions of the NGP are relatively inexperienced with soybean production compared to the United States, where soybeans have been grown for almost 100 years longer than in Canada (Johnson et al., 2008; Shurtleff and Aoyagi, 2010). Soybean production also continues to expand dramatically over time (StatCan, 2016; USDA, 2016), driving the need for site-specific research to support some of the most basic soybean management practices. Among these management practices are soybean planting date and plant density.

Information on the effects of planting date on soybean yield in northern growing regions of the NGP is limited. Several studies conducted across the United States have determined that mid-May planting dates result in the greatest soybean yields, whereas late May, early June, and mid-June planting dates produce significantly lower soybean yields (Beaver and Johnson, 1981; Anderson and Vasilas, 1985; Wilcox and Frankenberger, 1987; Beuerlein, 1988; Elmore, 1990; Lueschen et al., 1992; Oplinger and Philbrook, 1992; Whigham et al., 2000; Pedersen and Lauer, 2004a; b; De Bruin and Pedersen, 2008a). However, soybean yield response to planting date varies among locations, years (Pedersen, 2003), and varieties (Elmore, 1990; Grau et al., 1994). Northern growing regions experience fewer frost-free days and an increased risk of later spring and earlier fall frosts, where shorter season, indeterminate soybean varieties are grown. Thus, it is important to test the effects of planting date on soybean growth, development, and yield for varieties and locations in northern growing regions.

Low air and soil temperatures are associated with earlier planting dates. Previous studies have focused on the effects of air temperature on soybean growth and development; however, information on the influence of soil temperature and its effects on late season factors, such as soybean maturity and yield, is limited. The biological base air temperature ranges for soybean germination and emergence are 6 to 7°C and 8 to 10°C, respectively (Holmberg, 1973). The optimum air temperature range for soybean germination and emergence is 20 to 22°C (Holmberg, 1973). However, base and optimum soil temperature ranges have yet to be determined. Chilling injury during soybean imbibition can occur at air temperatures ranging from 0 to 10°C (Bramlage et al., 1978; Markowski, 1988b). Symptoms of chilling injury include inhibited soybean germination, reduced seedling survival (Markowski, 1988b), and delayed emergence (Simon et al., 1976; Bramlage et al., 1978; Raper and Kramer, 1987; Nykiforuk and Johnson-Flanagan, 1998). However, the effects of chilling injury on field-grown soybeans and the influence of low soil temperature exposure at the time of planting on late season factors is also unknown.

Research on the interaction between soybean planting date and plant density is needed for northern growing regions of the NGP. Optimum soybean plant densities have been identified across the United States and in Manitoba; however, few studies have examined the effect of planting date on soybean plant density. A study by Lee et al. (2008) in Kentucky identified optimum plant density ranges that maximized soybean yield for May and June planting dates. Heatherly and Elmore (2004) reported that soybean seed densities should be increased by 20% if planted before or after the optimum planting date (May 10 to 20) due to cold soil and shorter plants, respectively. However, optimum soybean plant densities would likely differ for northern regions and this recommendation was based on research conducted across the United States. Optimum soybean plant densities need to be identified for different planting windows in northern growing regions to help guide new soybean growers with planting decisions.

Economic return should also be a focus of soybean planting date and plant density recommendations in northern growing regions of the NGP to maximize profit. Previous studies across the NGP have identified economic optimum soybean plant or seed densities that maximize yield (De Bruin and Pedersen, 2008a; Lee et al., 2008). Incorporation of seed cost, commercial grain price, and seedling mortality into soybean seed density calculations would determine the profitability of soybean plant density (Wahab et al., 1986; Saindon et al., 1995; Jettner et al., 1999; De Bruin and Pedersen, 2008a). Thus, economic optimum soybean plant or seed densities should also be determined for different planting windows so soybean growers can maximize profit, rather than maximize yield alone.

3.0 THE EFFECTS OF PLANTING DATES BASED ON SOIL TEMPERATURE ON SOYBEAN (*GLYCINE MAX*) EMERGENCE, MATURITY, AND YIELD IN MANITOBA

3.1 Abstract

Soybean producers in Manitoba are faced with the decision of when to plant soybeans (*Glycine max* L. Merr.). It is currently recommended to plant soybeans when the soil temperature at seed depth is at least 10°C on the day of planting. However, current information on the effects of soil temperature at planting is limited. The objectives of this study were to determine if soil temperature at planting was an important factor for soybean yield, seedling emergence, and days to maturity (DTM), and to identify the soil temperature that produced maximum soybean yield. Short (DK 23-10RY) and long season (DK 25-10RY) soybean varieties were seeded on six planting dates determined by target soil temperatures of 6, 8, 10, 12, 14, and 16°C at 10:00 AM at seed depth. The experiment was located at Carman and Melita in 2014 and 2015, and at Morden in 2015. No differences between short and long season soybean varieties were found for yield and emergence. A significant quadratic relationship between soil temperature and yield was found for only one in three site years. Yields at Carman in 2015 increased with increasing soil temperature and reached a maximum at 9°C. Beyond 9°C, yield declined with further increases in soil temperature, the opposite of what was expected. A significant negative linear relationship between soybean yield and Julian planting date at Carman in 2015 confirmed that yield responded to planting date rather than soil temperature. Yield declined by 14 and 22 kg ha^{-1} for short and long season soybean varieties, respectively, for each one-day delay in planting. Days to 50% emergence clustered into cool (6 to

12°C) and warm (14 to 22°C) soil temperature groups for three combined site years. It took more days to reach 50% emergence under cool soil temperatures (24 to 35 days) compared to the warm temperature group (4 to 16 days). This analysis suggested that 14°C or higher was mid for rapid soybean emergence. Variety differences occurred for days to maturity. Negative linear models were significant for each site year, where DTM declined with later planting rather than soil warming. Low temperatures tested in this study had no negative effect on soybean yield and DTM. However, this finding should be tested with additional site years to strengthen planting date recommendations for Manitoba. Results of this study suggest that other planting considerations such as calendar date, weather forecast following seeding, tolerance to loss from spring or fall frost, and timeline to complete seeding and harvest may be more important than soil temperature.

3.2 Introduction

Limited information is available to soybean (*Glycine max* L. Merr.) producers in Manitoba to help guide the decision of when to plant soybeans. Short growing seasons are characteristic of Manitoba, including fewer frost-free days, and an increased risk of late spring and early fall frost events. Thus, the timing of soybean planting is critical to ensure maximum yield potential. Earlier season soybean varieties have been developed for Manitoba growing seasons, supporting the expansion of soybeans into new growing areas, as soybeans are a long season crop. However, growers are interested in longer season soybean varieties, which produce greater yields. Due to the continued expansion of soybean production and variety development, time of planting recommendations need to be validated in Manitoba.

Decisions on the timing of soybean planting are currently based on a combination of soil temperature and calendar date criteria. The earliest recommended time to plant soybeans in Manitoba is when the soil temperature at seed depth is at least 10°C on the day of planting (MASC, 2016; MPSG, 2016a). It is also recommended to plant soybeans no later than the end of May due to crop insurance deadlines (MASC, 2016) and the decline in yield potential (Bastidas et al., 2008; De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009). Recommendations that define the beginning of this planting window focus largely on soil temperature. However, growers experience uncertainty about the beginning of this soybean planting period, as it is not clearly defined. Planting recommendations in the Midwestern United States have shifted away from soil temperatures. Pedersen (2003) determined that calendar date and seedbed conditions are the most important determinants for soybean planting. Thus, it is possible that continued investigation of the time of soybean planting in Manitoba may result in similar conclusions as the Midwest.

Soybean growers in Manitoba are also generally advised to consider a combination of factors, including calendar date, the weather forecast following seeding, tolerance to loss from spring or fall frost, and timeline to complete seeding and harvest, in conjunction with soil temperature when determining soybean planting dates. Recommendations of when to plant soybeans in Manitoba require validation because it is unclear which of these factors has the greatest influence on soybean yield in the province.

Information on the effects of soil temperature on field-grown soybeans is limited. Most studies that have examined the effect of soil temperature on soybeans have focused on early-season variables such as germination, emergence (Edje and Burris, 1971; Powell, 1988; Hay and Porter, 2006) and vegetative growth (Brown and Blackburn, 1987), rather than late season factors such as physiological maturity or yield. Schou et al. (1978) reported that the late season period from flowering to physiological maturity is more influential on yield compared to the early season period from emergence to flowering. Thus, it is important to determine whether or not early season factors, such as soil temperature at planting, influence yield of field grown soybeans in Manitoba.

Soybeans are one of many species sensitive to chilling injury during imbibition (Obendorf and Hobbs, 1970; Bramlage et al., 1978; Nykiforuk and Johnson-Flanagan, 1998). Research documenting chilling sensitivity of soybeans has been conducted in growth chambers or greenhouses. Air temperatures ranging from 0 to 10°C have been reported to cause chilling injury in soybeans (Markowski, 1988b), which can result in delayed emergence (Simon et al., 1976; Bramlage et al., 1978; Raper and Kramer, 1987; Nykiforuk and Johnson-Flanagan, 1998) and reduced plant stands (Markowski, 1988b). However, it is not well understood if low soil temperatures imposed during germination and emergence reduce soybean yield.

The first objective of this study was to determine if soil temperature at planting was an influential factor on early season response variables such as soybean emergence and plant stand establishment, or late season response variables such as days to maturity and yield. It was hypothesized in this experiment that soil temperature at planting would be an influential factor for soybean yield, and that yield would increase with increasing soil temperature until a maximum yield was reached. It was also designed to determine if the optimum soil temperature of 10°C produces the greatest soybean yield. It was hypothesized that a soil temperature of approximately 10°C at planting would result in maximum soybean yield. It was also hypothesized that the "optimal" soil temperature would likely occur on an intermediate, more "ideal" calendar date in the planting period in spring. Soil temperature at planting was also hypothesized to influence early-season variables such as emergence and plant establishment. Cold soil temperatures were expected to injure germinating seedlings or delay emergence, and higher soil temperatures were expected to cause more rapid emergence (Cutforth et al., 1985; Raper and Kramer, 1987).

3.3 Materials and Methods

3.3.1 Site Description

The field experiments were initiated in 2014 and 2015 at the University of Manitoba Ian N. Morrison Research Station in Carman, Manitoba (49.501459, -98.028689) and the Westman Agricultural Diversification Organization (WADO) in Melita, Manitoba (49.244274, -101.016278), with the addition of a third site in 2015 at the Agriculture and Agri-Food Canada (AAFC) Morden Research and Development Centre in Morden, Manitoba (49.189637, -98.089131). These locations encompassed differing agricultural regions of Manitoba. The soil at Carman was an Orthic Black Chernozem of the Denham series (year 1) and Rignold series (year 2) with a fine sandy loam texture, a pH of 5.5, and 3.1% organic matter. The soil at Melita was an Orthic Black Chernozem of the Newstead series with a loam to fine sandy loam texture, a pH of

7.5, and 2.9% organic matter. The soil at Morden was an Orthic Black Chernozem of the Eigenhof Series with moderately fine clay loam texture, a pH of 7.7 and 6.0% organic matter. The previous crop was spring wheat at Carman, and winter wheat at Melita in 2014. The previous crop was chemical fallow at Melita, and spring wheat at Carman and Morden in 2015.

3.3.2 Weather

Climatic conditions were variable among site years (Figure 3.1). Climatic data were obtained from Agriculture and Agri-Food Canada and Manitoba Agriculture weather monitoring stations at Carman, Melita, and Morden. Carman and Melita experienced a cool spring in 2014, resulting in delayed seeding. However, all sites experienced a warm, early spring in 2015, which allowed for earlier planting.

3.3.3 Experimental Design

The experimental design at each site was a randomized complete block with four replications. Plots measured 2 m × 8 m (Carman), 1.7 m × 8 m (Melita), and 4 m × 5 m (Morden). Treatments consisted of two soybean varieties: 1) Dekalb 23-10RY (short season variety, MG 00.1) and 2) Dekalb 25-10RY (long season variety, MG 00.8), and six seeding dates targeting soil temperatures of 6, 8, 10, 12, 14, and 16°C.

Similar to air temperature, soil temperature fluctuates in a diurnal pattern on a daily basis (Brady and Weil, 2008). Therefore, an operational definition of soil temperature was created to achieve a range of soil temperature treatments from which to test our hypotheses. Target soil temperature was defined as the soil temperature at a 5 cm depth at 10:00 am for two consecutive days, where seeding took place on the second day. Soil sensors attached to a cellular data logger (EM50G, Decagon Devices Inc., Pullman, WA) at each site allowed real-time monitoring of soil temperatures to accurately determine each planting date.

Actual soil temperatures and corresponding calendar dates of target soil temperatures are summarized in Table 3.1. Individual soil temperatures on the day of planting were not used in this study, as temperatures frequently deviated from targets based on weather patterns. Thus, days prior to planting were included in the definition of soil temperature in this study. Actual soil temperature was calculated as the three-day average soil temperatures at 10:00 AM two days before planting, one day before planting, and the day of planting. The three-day average actual soil temperature was used in data analysis and interpretation of results. Actual soil temperature is simply referred to as “soil temperature” or “soil temperature at planting” for the remainder of this chapter.

Calendar dates varied slightly among site years and formed natural groups of early, mid and late planting dates. Low soil temperatures corresponded with “early” planting dates from late April to early May, intermediate soil temperatures corresponded with “mid” planting dates in late May, and high soil temperatures corresponded with “late” planting dates from the end of May to early June (Table 3.1; Figure 3.2). For all site years, weather patterns causing cool temperatures occurred in mid-May. This shifted mid planting dates from mid to late May.

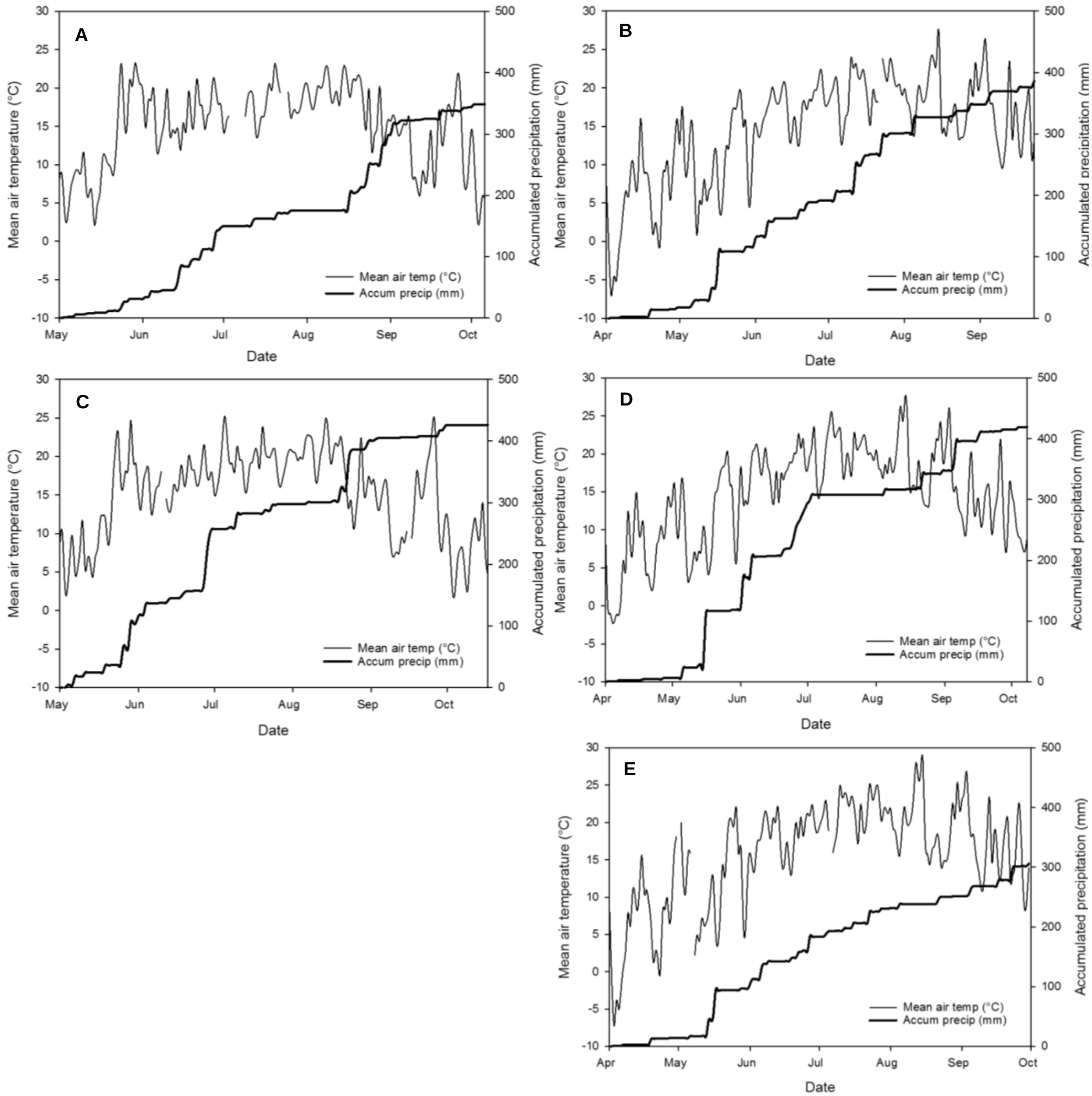

Figure 3.1. Mean daily air temperature and accumulated precipitation for the growing seasons at **(A)** Carman, MB in 2014, **(B)** Carman, MB in 2015, **(C)** Melita, MB in 2014, **(D)** Melita, MB in 2015, and **(E)** Morden, MB in 2015.

Table 3.1. Summary of actual soil temperatures and planting dates for each corresponding target soil temperature.

Location	Year	Target soil temperature (°C)	Actual soil temperature (°C at 10:00 AM)				Planting date
			Day of Planting	One Day Before Planting	Two Days Before Planting	Three-Day Average	
Carman	2014	6	6.0	-	-	6.0	May 05
		8	8.6	-	-	8.6	May 09
		10	10.6	6.9	7.8	8.4	May 23
		12	12.3	14.5	14.1	13.6	May 26
		14	15.5	14.8	12.3	14.2	May 28
		16	19.0	16.1	15.5	16.9	May 30
	2015	6	8.2	6.6	5.3	6.7	Apr 27
		8	10.3	8.7	5.9	8.3	Apr 30
		10	11.2	10.3	10.3	10.6	May 02
		12	14.7	14.1	12.7	13.8	May 25
		14	15.0	15.1	14.7	14.9	May 27
		16	16.7	18.1	16.5	17.1	Jun 10
Melita	2014	6	5.2	-	-	5.2	May 12
		8	8.1	-	-	8.1	May 20
		10	11.1	8.0	9.5	9.5	May 22
		12	17.3	16.2	13.9	15.8	May 25
		14	15.7	15.2	17.3	16.1	May 27
		16	16.4	15.4	15.2	15.7	Jun 10
	2015	6	4.9	6.6	7.1	6.2	Apr 28
		8	10.0	7.7	9.5	9.1	May 02
		10	18.3	16.9	12.3	15.8	May 22
		12	22.0	21.7	20.6	21.4	May 25
		14	22.1	22.0	21.7	21.9	May 26†
		16	10.6	15.7	16.6	14.3	May 29
Morden	2015	6	6.5	8.5	6.4	7.1	Apr 28
		8	9.9	8.3	6.5	8.2	Apr 30
		10	10.5	11.5	11.3	11.1	May 04
		12	12.7	11.2	10.5	11.5	May 06
		14	16.4	17.6	15.8	16.6	May 27
		16	20.4	19.6	17.7	19.2‡	Jun 12

† Treatment seeded one day early.

‡ Seeding date delayed by four days due to breakdown of seeding equipment.

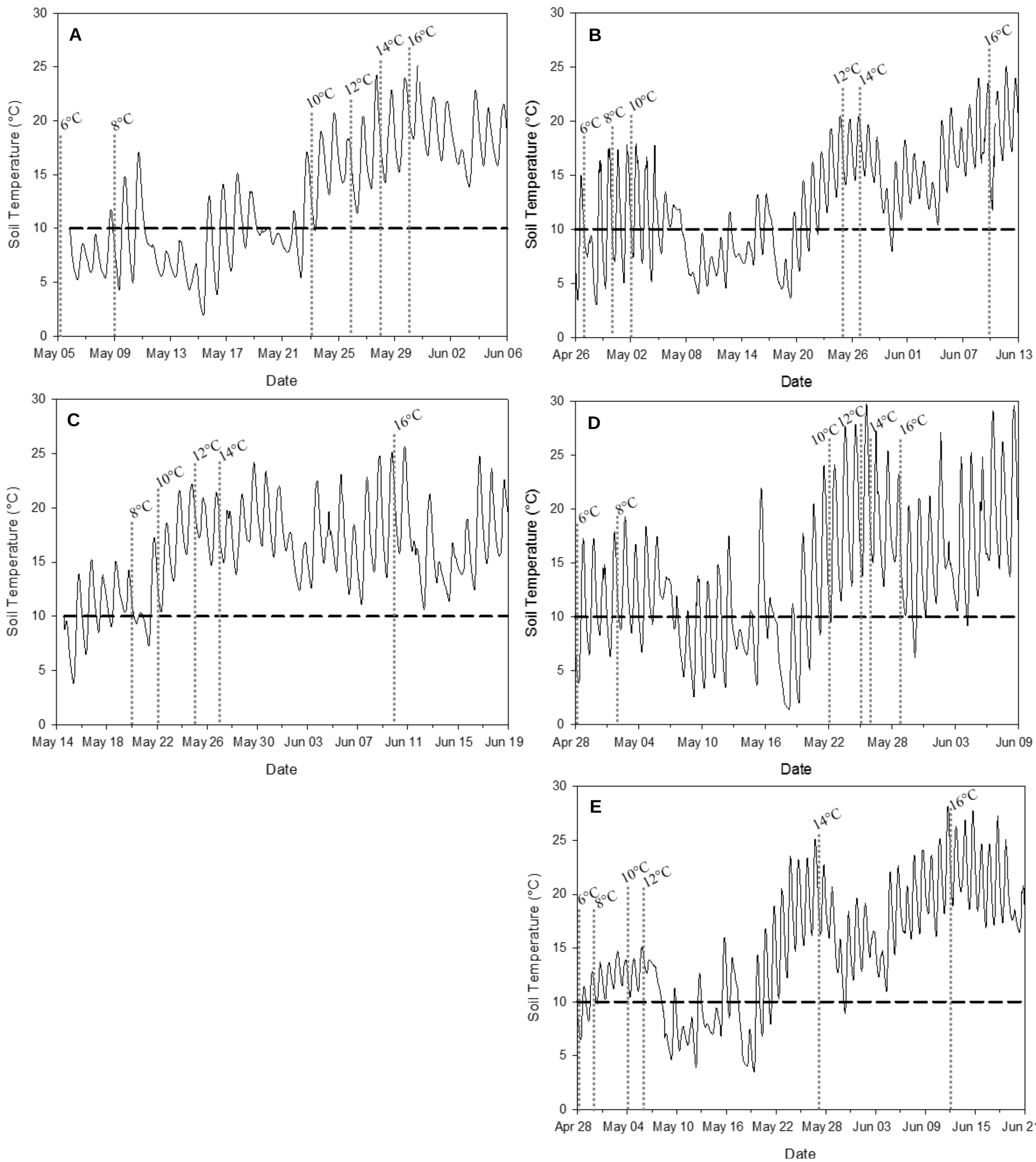

Figure 3.2. Hourly soil temperature at a 5 cm depth from the start of seeding to the end of emergence at **(A)** Carman, MB from May 5 to June 6, 2014, **(B)** Carman, MB from April 26 to June 13, 2015, **(C)** Melita, MB from May 14 to June 19, 2014, **(D)** Melita, MB from April 28 to June 9, 2015, and **(E)** Morden, MB from April 28 to June 21, 2015. The dashed horizontal line represents the average recommended soil temperature for planting at 10°C.

A comparison between target and actual soil temperatures at planting is shown in Figure 3.3 to depict the range of soil temperatures tested in this study and represent how close actual temperatures were to target soil temperatures. The majority of actual soil temperatures at planting were very close to the intended targets (Figure 3.3). However, four temperature treatments at Melita in 2015 did not match intended target soil temperatures. Actual soil temperatures were much greater for 10 to 14°C target soil temperatures, and much lower than the intended target of 16°C. The variation in actual soil temperatures must be considered when analyzing results from Melita in 2015.

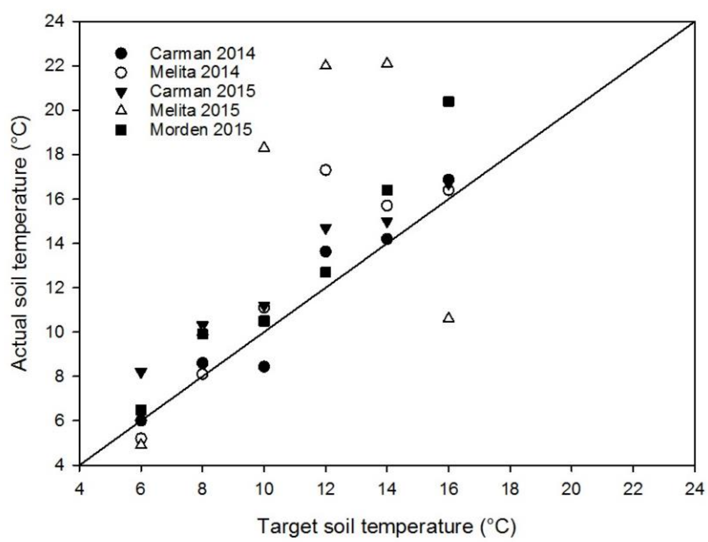

Figure 3.3. The comparison between target and actual soil temperatures at Carman and Melita, MB in 2014 and 2015, and at Morden, MB in 2015.

3.3.4 Crop Management

One tillage operation was conducted at all sites prior to seeding the first treatment. Tillage operations were performed by a cultivator with tine harrows and packing wheels at Carman, a rototiller (John Deere 681) at Melita, and a field cultivator (Case International) at Morden. Soybeans were seeded at the target plant density of 444,790 plants ha^{-1} adjusted for seed lot germination and 20% mortality. Soybeans were inoculated with *Bradyrhizobium japonicum* liquid inoculant (Optimize®, Monsanto Canada Inc.) at a rate of 1.8 mL kg seed^{-1} and granular inoculant (Cell Tech®, Monsanto Canada Inc.) at a rate of 2.4 kg ha^{-1} placed with the seed to ensure nodulation. In 2014, soybean seed was treated with fludioxonil and metalaxyl-M fungicide (ApronMaxx® RTA®, Syngenta Canada Inc.) at a rate of 3.25 mL kg seed^{-1}. In 2015, soybean seed was treated with penflufen, prothioconazole and metalaxyl fungicide (Evergol Energy®, Bayer CropScience Inc.) at a rate of 0.65 mL kg^{-1} of seed. Seeding operations were performed with a disk drill cone seeder with 35.6 cm row spacing at Carman, a cone seeder with dual knife openers and 24.1 cm row spacing at Melita, and a double disc zero-till drill with 25.0 cm row spacing at Morden. Sowing depth of soybeans ranged from 2.5 to 3.8 cm, depending on soil conditions.

At Carman in 2014, a tank mix of saflufenacil (Heat®, BASF Canada Inc.) at a rate of 25.7 g a.i. ha^{-1}, glyphosate (Roundup Transorb®, Monsanto Canada Inc.) at a rate of 1.65 L ha^{-1} (540 g a.e./L) and surfactant (Merge®, BASF Canada Inc.) at a rate of 0.494 L ha^{-1} was applied for pre-emergent weed control. Two post-emergent applications of glyphosate (Roundup WeatherMax®, Monsanto Canada Inc.) took place at rates of 0.988 and 0.815 L ha^{-1} (540 g a.e./L) respectively, with surfactant (Agral 90®, Syngenta Canada Inc.) at a rate of 0.346 L ha^{-1}. At Melita in 2014, a tank mix of saflufenacil at a rate of 24.7 g ha^{-1} (342 g a.i./L), carfentrazone (Aim EC®, FMC Corporation) at a rate of 37.1 mL ha^{-1} (240 g a.i./L), glyphosate (Credit 45®, Nufarm Agriculture Inc.) at a rate of 2.47 L ha^{-1} (450 g a.e./L), and surfactant (Merge®) at a rate of 0.5% v/v was applied for pre-emergent weed control. Two post-emergent applications of glyphosate (Roundup

Transorb®) were applied at a rate of 0.815 L ha^{-1} prior to flowering. At Carman in 2015, one post-emergent application of glyphosate (271 g a.e./L) and fomesafen (67 g a.e./L) (Flexstar GT®, Syngenta Canada Inc.) took place at a rate of 2.08 L ha^{-1} with surfactant/solvent (Turbocharge®, Syngenta Canada Inc.). At Melita in 2015, one post-emergent application of glyphosate (Roundup Transorb®) was applied at a rate of 0.815 L ha^{-1} (540 g a.e./L). At Morden in 2015, one post-emergent application of glyphosate (Roundup Transorb®) took place at a rate of 1.98 L ha^{-1} (540 g a.e./L).

3.3.5 Data Collection

3.3.5.1 Soil Temperature and Volumetric Soil Moisture Content

Prior to the first seeding date, soil temperature and moisture sensors (5TM, Decagon Devices Inc.) were installed at a 5-cm depth with hourly readings recorded on (cellular) data loggers (EM50 or EM50G, Decagon Devices Inc.). One data logger and soil sensor pair was installed within one plot of each rep, with the exception of two soil sensors attached to the cellular data logger in case of failure. Sensors and data loggers were initially installed in plots designated for the last seeded treatment, removed prior to seeding the last treatment, and reinstalled in a guard row following seeding.

3.3.5.2 Plant Density and Emergence

In 2014, plots were monitored every Monday, Wednesday, and Friday for the first signs of emergence. Emerging plants were counted on both sides of a marked 1-m of row length in each plot at two, three, four and five weeks after planting. In 2015, a more detailed method of measuring emergence was conducted with plant density counts and plant growth stages recorded every Monday, Wednesday and Friday from planting until the V4 stage of development. Due to the high variability of plant densities measured in 2014, plant stand counts were increased in 2015 from two adjacent rows of a 1-m length, to two adjacent rows of a marked 3-m length in each plot.

3.3.5.3 Frost Damage

Frost damage was assessed visually and conducted in affected plots on June 10 (Carman) and June 17 (Morden). The number of frost-damaged plants were counted in adjacent rows of the marked 3-metre length in each plot used for emergence counts. This number was converted to a percentage frost rating using the total number of emerged plants for that given date.

3.3.5.4 Plant Height

In 2014, plant height measurements took place at the R8 stage. The distance from the soil to the top node of the plant was measured for three random plants per plot. In 2015, plant height measurements were conducted at the V4 stage and R8 stage of development. At the V4 stage, three random plants per plot were measured from the soil to the highest point on the plant. The method used for plant height measurement at the R8 stage was repeated in 2015.

3.3.5.5 Main Stem Branching

At the R5 stage of development, five plants were randomly selected from each plot for main stem branch counts. All branches extending from the main stem were considered, including immature or dead branches. Lateral branches were not considered in these counts. Main stem branching values were averaged for each plot.

3.3.5.6 Biomass

At the R5 stage of development, two 1-metre row lengths of soybean plants were cut at the soil surface and removed from each plot. Biomass sample sizes were 1-metre x 2 rows at Carman and Morden. At Melita in 2014, biomass sample sizes were 1-metre x 1 row at the front and back of each plot, and 2-metres x 1 row at the front and back of each plot in 2015. Plants were placed in large paper bags and oven dried at 60°C for at least 48 hours. Dried biomass samples were weighed.

3.3.5.7 Lowest Pod Height

At the R8 stage of development, the distance from the soil surface to the node of the lowest pod was measured for three random plants per plot. Lowest pod height values were averaged for each plot.

3.3.5.8 Days to Maturity

Soybean maturity ratings began once plants started to turn yellow. Ratings were conducted every Monday, Wednesday and Friday, forward and back-dated for missed days. One average maturity rating was recorded each day for each plot as a percent yellow or brown pod (MPSG, 2016b). Ratings began with the yellow pod phase and continued until approximately 75% yellow pod, then shifted to the brown pod phase. Plots with only green plants were not given a rating, unless a frost was forecasted.

Ratings were conducted at approximately 2:00 pm on assigned days and plots were viewed from the same angle each day for consistency. Ratings continued until all plots had reached physiological maturity defined as 95% brown pod. The calendar date of physiological maturity was recorded for each plot, and the Julian dates of physiological maturity and first emergence were used to calculate days to maturity.

3.3.5.9 Yield

Harvest lengths of each plot were recorded prior to harvest. Plots at Carman and Morden were harvested gradually as individual treatments reached physiological maturity for harvest. All plots at Melita were harvested together once all treatments were at physiological maturity for harvest. Plots were harvested with a plot combine. Following harvest of all plots, samples were cleaned using a seed cleaner (Clipper, A.T. Ferrell Company Inc.).

In 2014, grain moisture was determined gravimetrically. Fresh weights of grain subsamples were recorded, subsamples were oven dried at 60°C for at least 48 hours, and dry weights were recorded following oven-drying. In 2015, grain moisture was tested using an electronic moisture analyzer (GAC® 2500-AGRI, DICKEY-john). Weights of total grain samples from each plot were weighed the same day as moisture testing. Sample weights, moisture content, and harvested area were factored into yield calculations for each plot.

3.3.6 Statistical Analysis

3.3.6.1 Analysis of Variance

Analysis of variance (ANOVA) was used to compare treatment means of all response variables as a preliminary statistical analysis tool using the mixed procedure (PROC MIXED) of SAS 9.4 (SAS Institute Inc., Cary, NC). It was used to assess the significance of fixed effects and interactions prior to regression analysis.

3.3.6.2 Linear and Polynomial Regression

The regression procedure (PROC REG) of SAS 9.4 was used for further statistical analysis to examine the relationships between all response variables and actual soil temperature at planting. Linear and quadratic models were tested for all relationships between response variables and actual soil temperature. Data points on linear and polynomial regression graphs represented individual plots.

3.3.6.3 Non-Linear Regression

Sigmoidal growth functions were tested on soybean emergence, or plant density response, to days after planting (DAP) and growing degree-days (GDD) from 2015 site using the non-linear regression procedure (PROC NLIN) of SAS 9.4 (Torres and Frutos, 1989; Archontoulis and Miguez, 2015). The relationship between emergence and time follows a sigmoidal pattern, in which the rate of growth increases as time increases from low values, reaches a maximum at the point of inflection, then decreases toward zero at an upper asymptote, resembling an S-shape (Birch, 1999). Three sigmoidal models were tested on soybean emergence response over time:

Logistic:	$E = M / (1 + \exp(-kt + b))$	[1]
Mitscherlich:	$E = M (1 - \exp(-k (t - z)))$	[2]
Gompertz:	$E = M (\exp(-\exp(-kt + b)))$	[3]

where E is cumulative emergence in thousand plants ha^{-1}, M is the asymptotic maximum as plant density in thousand plants ha^{-1} at 100% emergence, t is time in days after planting or growing degree days, and k, b, and z are function parameters where k is used to determine rate, b has no biological significance, but positions the curve in relation to time, and z represents time at the point of inflection (Brown and Mayer, 1988; Torres and Frutos, 1990). The lag, or time at the point of inflection, is given by b/k (Torres and Frutos, 1990).

Statistical criteria were used to compare the goodness of fit between models. Model convergence for each site year and treatment was considered first. Convergence occurred when parameters were successfully identified through iterative processing of values for each parameter in SAS 9.4 (Brown and Mayer, 1988). All sigmoidal models successfully converged for all treatments and sites. The Akaike Information Criterion (AIC) (Akaike, 1974) was the primary statistical criterion used to compare the goodness of fit for each model. Similar AIC values were found for all models (Appendix A, Table 7.4), thus additional decision-making criteria were examined such as the root mean squared error (RMSE), overall model simplicity, and biological relevance (Katanda, 2014).

Logistic model parameters were assessed to determine differences between treatments. In order to test for statistical differences in model parameters, the logistic model was first fitted to each variety and soil temperature treatment. Significant differences in variety and soil temperature treatments between emergence curves were assessed using 95% confidence intervals to compare model parameters (M, k, b) from non-linear regression analysis. Overlap between 95% confidence intervals indicated no significant difference. Parameters derived from the logistic model included the point of inflection and plant density at 100% emergence. These parameters were determined for each replicate and tested for significant differences using analysis of variance.

The emergence response of each soil temperature treatment was examined as the relationship between soybean planting density and DAP as a unit of time. Data points on sigmoidal response graphs represented individual plant density counts conducted every Monday, Wednesday, and Friday until the V4 stage in 2015. As a next step in the analysis, DAP values were converted to GDD, calculated as the number of GDD accumulated from each planting date until the date of each plant density measurement. Statistical differences between model parameters (M, k, b) for DAP and GDD emergence models for each soil temperature treatment were compared using 95% confidence intervals.

3.4 Results and Discussion

3.4.1 Soybean Yield Response to Soil Temperature

Soybean yields at individual site years were examined to determine if a relationship existed between soybean yield and soil temperature at planting. Yield data was available from three out of five site years. Soybean yield data was not combined in this study due to a significant interaction between site year and soil temperature

(Appendix A, Table 7.1). Regression relationships between soil temperature at planting and soybean yield were examined for the individual site years of Carman 2014 and 2015, and Melita 2015 (Figure 3.4). No significant interactions occurred between variety and soil temperature for soybean yield in each individual site year (Appendix A, Table 7.2). Yield results were therefore averaged across both varieties. A significant relationship between soil temperature and soybean yield was found only at Carman in 2015 (Figure 3.4B). Thus, soil temperature at planting influenced yield at only one in three site years. No significant relationships between yield and soil temperature were found at Carman in 2014 and Melita in 2015.

At Carman in 2015, a significant quadratic relationship between yield and soil temperature at planting occurred (Figure 3.4B). The quadratic model depicts a parabolic relationship that explains 67% of the yield variation in response to soil temperature. The soil temperature that resulted in maximum soybean yield, or the peak in the parabolic curve, was 9°C at 10:00 AM at a 5 cm depth (Figure 3.4B). Beyond 9°C, yield declined with further increases in soil temperature. This "optimum" soil temperature is very similar to our hypothesized soil temperature of 10°C. Holmberg (1973) identified optimum air temperature ranges for specific soybean developmental stages. Optimum air temperatures range from 19 to 25°C throughout all stages of development, and range from 20 to 22°C for soybean germination and emergence specifically. However, yield response to air temperature at planting was not measured in the study by Holmberg (1973).

Lower soil temperatures that occurred at earlier planting dates resulted in greater yields overall (Figure 3.4). No significant soybean yield-temperature relationship existed for the Carman 2014 site year. Yields from the lowest soil temperature treatment seeded on May 5 were similar to or greater than higher soil temperature treatments corresponding with mid to late May planting dates at Carman in 2014 (Figure 3.4A). A similar trend was seen at Melita in 2015, where yields of low temperature treatments were similar to or greater than yields at higher initial soil temperatures (Figure 3.4C). Overall, most soil temperatures within the range tested in this study (5 to 22°C) did not limit soybean yield. Holmberg (1973) identified the base air temperature range to be 6 to 7°C for soybean germination to occur, and 8 to 10°C for soybean emergence to occur. However, the effect of these low temperatures at early development stages on soybean yield is not reported in the literature.

It is important to note that the yield trend at Melita was altered due to weed competition early in the growing season. Heavy weed competition prior to the V4 stage caused yield reduction of the 6°C (April 28) and 9°C (May 2) soil temperature treatments. Soybeans are poor competitors against weeds, especially during development stages up to V4 (Van Acker et al., 1993). The two lowest soil temperature treatments might have produced the greatest yields if weather and soil conditions had allowed for timely control of weeds in these two treatments.

Planting date, rather than soil temperature at planting, likely influenced soybean yields in this study. Yield reduction caused by increasing soil temperature is the opposite of what we might expect, given the range of soil temperatures tested in this experiment. The lowest soil temperatures ranging from 7 (April 27) to 11°C (May 2) at Carman in

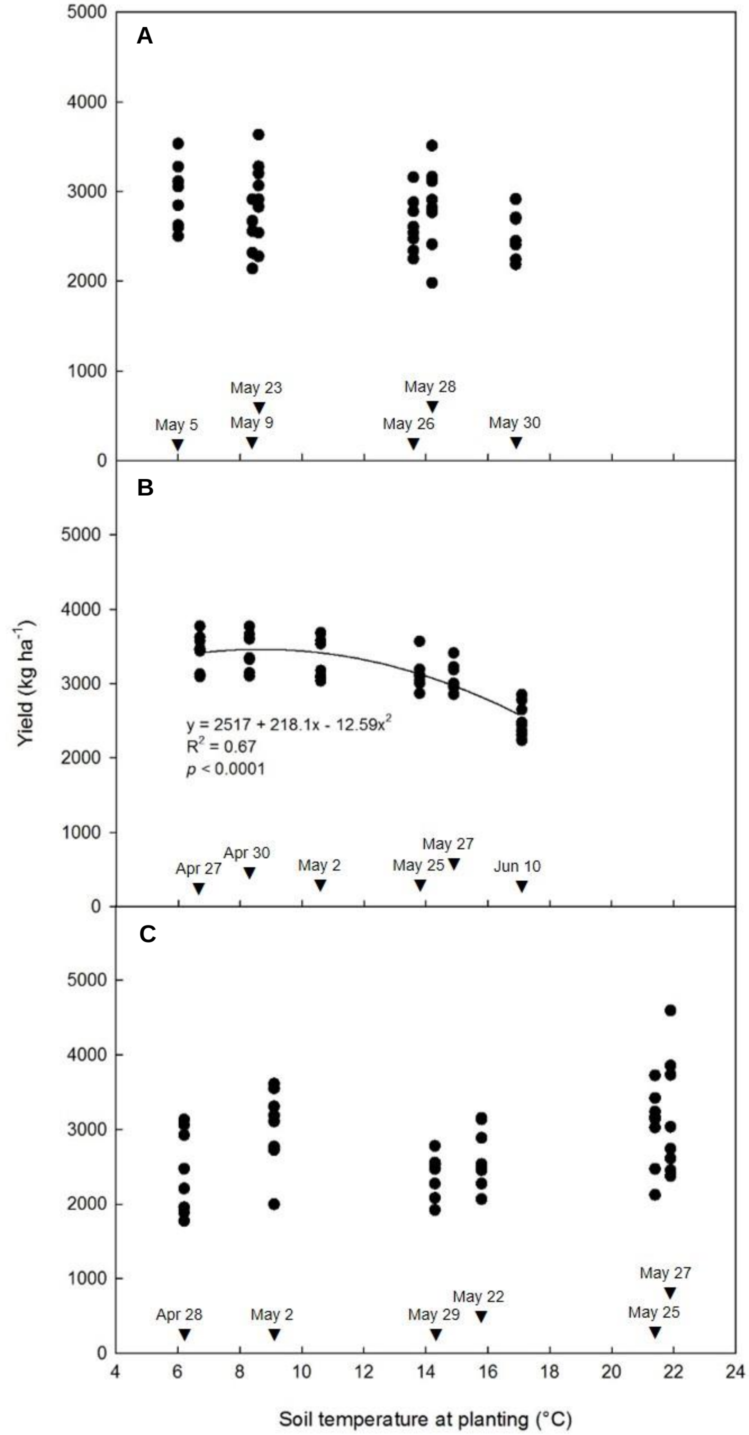

Figure 3.4. The relationship between soybean yield and soil temperature at planting at **(A)** Carman, MB in 2014, at **(B)** Carman, MB in 2015, and at **(C)** Melita, MB in 2015. Calendar dates for each corresponding soil temperature at planting are labeled for each planting date treatment.

2015 resulted in the highest soybean yields (Figure 3.4B). Beyond the first three planting date treatments, however, there is a greater likelihood that yield decline in the quadratic model was driven by the last planting date rather than warming soil temperature (Figure 3.4B). Soybean yield reduction from late planting was likely caused by fewer remaining growing degree-days left in the season. Yield decline with later planting has been well-documented in the literature (Bastidas et al., 2008; De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009). In addition, low soil temperatures tested in this study were within the range of base (6 to 10°C) air temperatures for soybean germination and emergence. Holmberg (1973) defined the base air temperature requirement for soybean plants as the temperature that would allow formation of reproductive organs and flowers (Holmberg, 1973). It is expected that base soil temperatures for soybean germination and emergence would likely be lower than air temperatures, as changes in soil temperature lag behind changes in air temperature (Brady and Weil, 2008).

When examining the distribution of calendar dates associated with each soil temperature, the lowest yields correspond with late planting (Figure 3.4). Planting was completed prior to the end of May for Carman 2014 and Melita 2015, whereas the warmest soil temperature treatment at Carman in 2015 was delayed until June (Figure 3.4). The significant quadratic relationship at Carman in 2015 was likely driven by late planting on June 10 due to the dramatic decline in yield compared to other site years (Figure 3.4B). Yield data from Melita in 2015 also was sorted according to actual temperature, causing certain calendar dates to fall out of chronological order (Figure 3.4C). Soil temperatures of 21 to 22°C corresponded with May 25 and May 26, whereas

14°C occurred afterward on May 29 (Figure 3.4C). Thus, it is likely that lower yields associated with 14°C are actually a result of later planting (Figure 3.4C).

The literature provides evidence to support the hypothesis that planting date has a greater influence on soybean yield than soil temperature at planting. Studies examining soybean planting date, row width, and varieties identified that planting date had the greatest impact on yield (Ryder and Beuerlein, 1979; Beaver and Johnson, 1981). Therefore, it is possible that soybean planting date also had a greater influence on soybean yield compared to soil temperature at planting. The late season period from flowering to physiological maturity was also reported to be more influential on soybean yield compared to the early season period from emergence to flowering (Schou et al., 1978). Planting date impacts the time in which soybean plants begin to flower due to its influence on photoperiod (Raper and Kramer, 1987). Photoperiod and growing season length decrease with later planting (Tanner and Hume, 1978), resulting in yield reduction (Hicks, 1978; Board, 2002). Compared to the late season effect of planting date, the influence of soil temperature at planting would likely be more isolated to the early part of the growing season.

3.4.2 Soybean Yield Response to Planting Date

To test the influence of planting date on soybean yield at Carman in 2015, the relationship between yield and planting date (Julian date) was examined. It was hypothesized that the relationship between soybean yield and Julian planting date would be similar to or stronger than the previously determined relationship with soil temperature. A negative linear relationship was identified between soybean yield and

Julian planting date, in which soybean yield declined with later planting (Figure 3.5). Due to a significant interaction between planting date and variety according to analysis of variance (Appendix A, Table 7.3), short and long season soybean varieties were presented separately (Figure 3.5). For the short season variety, soybean yield declined by 14 kg ha^{-1} with each day planting was delayed (Figure 3.5). The long season variety was slightly more responsive, in which soybean yield declined by 22 kg ha^{-1} with each one-day delay in planting (Figure 3.5). Relative to total soybean yields ranging from 2000 to 4000 kg ha^{-1}, yield decline ranged from 0.7 to 0.4% overall for the short season variety and 1.1 to 0.5% for the long season variety. However, soybean planting delayed by up to 30 days due to poor planting conditions, for example, could result in up to 30% yield loss. The linear model explained 51 and 73% of the soybean yield response to planting date for short and long season varieties, respectively (Figure 3.5).

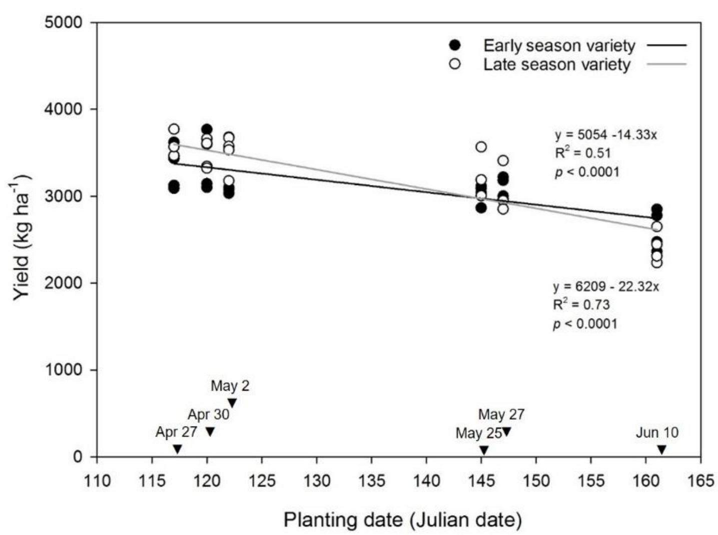

Figure 3.5. The relationship between soybean yield and planting date for short and long season soybean varieties at Carman in 2015.

The relationship between soybean yield and planting date differed slightly from the relationship between yield and soil temperature at Carman in 2015. Significant differences between short and long season varieties occurred when soybean yield was regressed with Julian planting date; however, it is unclear why differences between varieties were not observed for soil temperature. The quadratic model was not significant for the relationship between soybean yield and planting date; however, both models exhibited a declining trend in yield with later planting (Figure 3.5). High R^2 values were identified for yield response of short and long season soybean varieties to Julian planting date. These R^2 values were similar to or greater than the R^2 value of soybean yield response to soil temperature, supporting the hypothesis that planting date has a greater influence on yield than soil temperature.

Results from this study were similar to previous research. A study by Pedersen (2006) reported that 15 out of 18 experiments showed a significant positive yield response from early planting in the Midwestern United States. The other three experiments did not result in a negative yield response from early planting (Pedersen, 2006). Pedersen (2006) recommended that calendar date and seed bed conditions should be the primary focus for determining when to plant soybeans. The present study validates the importance of calendar date as a determinant for the time of soybean planting in Manitoba. Other factors such as the weather forecast following seeding, expected tolerance of soybean plants to late spring or early fall frosts, and timeline to complete seeding and harvest due to the short growing season in Manitoba should still be considered for determining when to plant soybeans. These factors are perhaps more influential than soil temperature at planting in Manitoba. Future research is required to compare the importance of calendar date, soil temperature, and weather conditions following seeding on soybean yield.

3.4.3 Frost

Early planting increases the risk of spring frost damage to soybean seedlings. Late spring frost events at Carman and Morden in 2015 may have influenced soybean yield. A frost event occurred at Carman on May 30, 2015, at which time only the first three soil temperature treatments had emerged. Surprisingly, the frost-affected treatments yielded the greatest. However, it is important to note that this frost event was mild with air temperatures reaching only -0.4 and -0.7°C for two hours, respectively. A more serious spring frost occurred on the same day at Morden, in which air temperatures dropped to -0.5, -1.6, and -0.5°C for three hours, respectively. The first four planting date treatments had emerged in Morden and were affected by the frost. By definition, this was not a “hard” or “killing” frost of -2.2°C that stops translocation of sugars and results in plant death (Brown and Blackburn, 1987; Bootsma and Brown, 1995). However, air temperature at Morden was closer to -2.2°C for one hour compared to the frost event at Carman. The impact of the frost at Morden on soybean yield is unknown, as yield data was not available from this site year. Although yield results from this study suggest otherwise, it is recommended to plant soybeans late enough to avoid high risk spring frost periods, and early enough for plants to reach the R7 stage prior to high risk fall frost periods (Table 3.2) (Calder et al., 1965; Judd et al., 1982).

Yield results from this study suggest that soybeans can be planted at almost any time during a one month planting period in Manitoba. This includes any calendar date from April 27 to May 30. One site year from this experiment highlighted the risk of yield decline from soybeans planted in June. Later planting reduces yield potential, as previously discussed. However, growers should be cautious when considering early planting of soybeans due to the risk of frost. Frost events experienced during this study were not considered “killing frosts” by definition, but the probability that a killing frost can occur during late April to early May is one in two years in Manitoba (Table 3.2). Summarized values in Table 3.2 are reported as the risk of a killing frost (-2.2°C) occurring every one in ten years (10% probability) and every one in two years (50% probability). There is risk of late spring killing frost at Carman, Melita, and Morden from May 15 to 20 every one in ten years, and April 30 to May 5 every one in two years. In this study, 12 and 6 out of 36 planting date treatments across all site years occurred prior to the date of last spring frost at 10 and 50% probability levels, respectively (Table 3.1; 3.2). Thus, soybean crops will be put at risk of freezing damage if seeded early, although this risk will often be taken by farmers with the potential to improve yield.

Table 3.2. Number of frost-free days, date of last spring frost, and date of first fall frost for 2014-2015 research sites at Carman, Melita, and Morden, Manitoba (Nadler, 2007).

Location	Frost-free days	Last spring frost	First fall frost
	--------------------------10% probability of -2.2°C--------------------------		
Carman	101-110	May 20-May 24	Sep 17-Sep 21
Melita	96-100	May 15-May 24	Sep 7-Sep 11
Morden	111-115	May 15-May 19	Sep 22-Sep 26
	--------------------------50% probability of -2.2°C--------------------------		
Carman	116-125	May 5-May 9	Oct 2-Oct 6
Melita	116-120	May 5-May 9	Sep 22-Sep 26
Morden	126-130	Apr 30-May 4	Oct 2-Oct 11

Late spring frost events occurred at two sites (Carman and Morden) in 2015; however, yield data was only available from one site (Carman). Frost did not appear to reduce soybean yields of affected treatments at Carman. The earliest planted soybeans affected by frost at one site year produced the highest yields, indicating that the best time to plant soybeans in Manitoba was as early as possible. It is expected that yield reduction would have occurred if freezing temperatures were lower and lasted for a longer period of time (Judd et al., 1982; Meyer and Badaruddin, 2001). Thus, frost risk is an important consideration for the development of recommendations for when to plant soybeans in Manitoba. Future research on the effect of hard frost events on field-grown soybeans in Manitoba is needed to develop stronger time of planting recommendations.

3.4.4 Soybean Emergence and Plant Establishment Response to Soil Temperature

Soybean emergence was examined to understand the effects of soil temperature early in the growing season. Emergence was evaluated using days to 50% emergence, maximum plant density at 100% emergence, and seedling mortality. In order to identify emergence measures, a non-linear sigmoidal logistic model was fitted to emergence data from 2015 site years. The logistic sigmoidal model had the best overall fit according to statistical criteria (Appendix A, Table 7.4). Overlapping 95% confidence intervals of equation parameters indicated there was no difference in the model between soybean varieties. Reported results are averaged across short and long season soybean varieties. The relationship between days after planting (DAP) and plant density in thousand plants ha^{-1} for soil temperature treatments of 2015 site years at Carman, Melita, and Morden, is depicted in Figure 3.6. Plant density increased at an increasing rate until it reached a point of inflection. Beyond this point of inflection, plant density began to increase at a decreasing rate until it reached a maximum plant density, or plateau at 100% emergence (Figure 3.6).

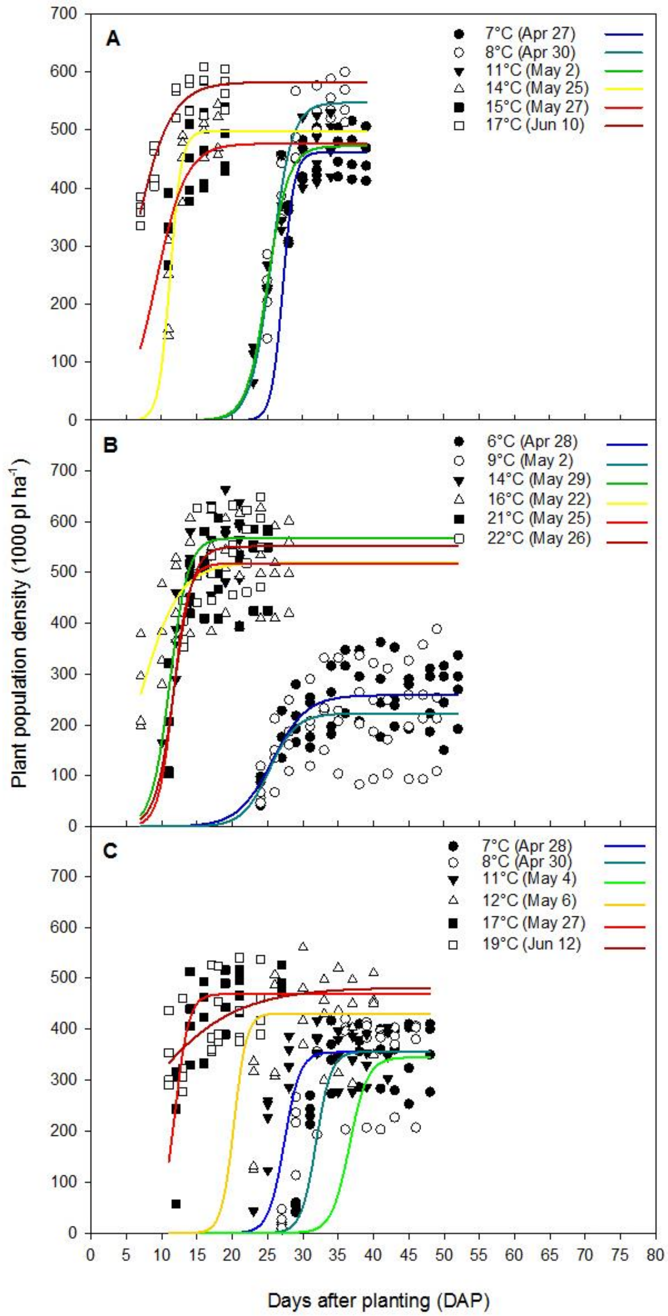

Figure 3.6. Soybean emergence represented as the relationship between plant density and days after planting for six soil temperature treatments at **(A)** Carman, MB in 2015, **(B)** Melita, MB, and **(C)** Morden, MB.

3.4.4.1 Days to 50% Soybean Emergence

The number of days to 50% emergence, or the point of inflection, was examined to determine how slowly or rapidly soybeans emerge under a range of cool to warm soil temperatures. Results from combined 2015 sites were analyzed for the relationship between soil temperature and days to 50% emergence. Groups of "cool" and "warm" soil temperatures were apparent. Cool soil temperatures ranged from 6 to 12°C, and warm soil temperatures ranged from 14 to 22°C (Figure 3.7). Soybean treatments seeded into cool soil temperatures (April 27 to May 6) required 24 to 35 days to reach 50% emergence. This is similar to a finding by Pedersen (2006) that reported that soybean emergence can be delayed by two to three weeks if planted during the last week of April and first week of May in the Midwestern United States. On the other hand, treatments seeded into warm soil temperatures (May 25 to June 12) reached 50% emergence within 4 to 16 days (Figure 3.7). This result indicates that a threshold soil temperature exists for soybean emergence. The threshold soil temperature in this study was 14°C or higher at 10:00 AM at a 5 cm depth, which resulted in more rapid emergence in the spring.

Linear models were tested to see if a relationship existed between days to 50% emergence and soil temperature within each soil temperature group (Figure 3.7). Days to 50% emergence values from the first two planting date treatments at Melita were excluded due to evidence of delayed soybean emergence from weed competition. A significant linear relationship was found between soil temperature and days to 50% emergence for the "cool" soil temperature group, but not for the "warm" soil temperature group (Figure 3.7). For cool soil temperatures, the number of days to reach 50% emergence decreased with increasing soil temperature (Figure 3.7). This accurately

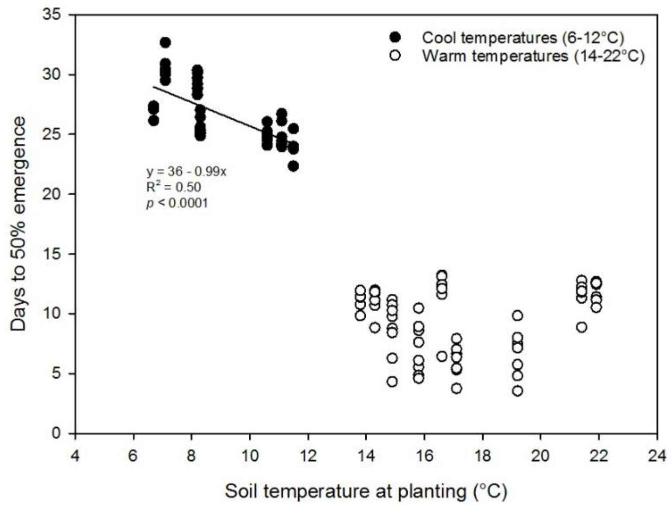

Figure 3.7. The relationship between days to 50% emergence and soil temperature for three combined 2015 site years. Treatments formed cool and warm temperature groups.

represented the expected relationship between the rate of emergence and warming soil temperature. Cold soils have been reported as the cause of delayed soybean emergence due to slowed rates of enzyme-mediated processes that take place during respiration and hydrolysis of seed food reserves, or slow translocation rates of metabolites (Raper and Kramer, 1987). Thus, soil temperatures ranging from 7 to 8°C at planting likely contributed to delayed soybean emergence, driving the relationship for the cool temperature group only (Figure 3.7).

Days to 50% soybean emergence were also influenced by factors other than soil temperature. The linear model fitted to the cool soil temperature group explained 50% (R^2 = 0.50) of the variation in days to 50% soybean emergence (Figure 3.7). Thus, the other 50% is influenced by other factors, such as soil moisture. Planting date also likely influenced the number of days to 50% emergence. Results from the present study are similar to others in the literature, in which soybeans planted in mid-May have been reported to emerge two to three weeks after planting, and three to five days if planted in early June in northern growing regions of the United States (Tanner and Hume, 1978). Weather conditions following planting may have also influenced the relationship between declining days to 50% emergence and increasing soil temperature. Andales et al. (2000) determined that both low and high soil moisture interacted with cold soil temperature, contributing to delayed soybean emergence. However, low soil moisture had a greater influence on delayed emergence than high soil moisture (Andales et al., 2000). Falk (1981) also reported that temperature is the most influential factor on time to soybean emergence when moisture is not limiting. Cutforth et al. (1985) also reported that the rate of corn germination increased with increasing soil water content. In the present study, rainfall events were infrequent immediately following the earliest planting dates in 2015 (Figure 3.1B; D; E). These conditions may have contributed to delayed emergence (Andales et al., 2000). However, the underlying mechanism which caused the decline in of days to 50% soybean emergence with increasing soil temperature is unknown for the cool temperature group.

Data from this study confirm our hypothesis that low soil temperatures, or earlier planting dates, delay soybean emergence. Delayed emergence increases the risk of seedling disease due to reduced effectiveness of seed treatment over time. Warmer soil temperatures at planting result in more rapid soybean emergence, which enhances the competitive ability of soybeans against weed populations. However, rapid emergence did not result in higher yields in this study (Figure 3.4; 3.5). This is similar to the finding by Egli (1993) in Kentucky who reported that variation in time of soybean emergence has little influence on yield. Cool and warm groups of soil temperature treatments did not occur in yield data of this study, indicating that other environmental factors throughout the growing season ultimately influenced soybean yield. These factors may include the timing of precipitation events or air temperatures at key development stages, such as flowering and pod fill. As yield data in this study were only available for three out of five site years, it is also important to note that the link between soybean emergence and yield might change with the inclusion of more site years.

3.4.4.2 Soybean Plant Density at 100% Emergence

Plant density at 100% emergence, or maximum plant density, was examined to determine the effect of soil temperature on seedling emergence in the spring. For individual site years in 2015, a significant relationship between maximum plant density and soil temperature was found only at Morden (Figure 3.8C). No significant relationships were found at Carman or Melita (Figure 3.8A; B). At Carman, maximum plant densities were similar across all soil temperature treatments (Figure 3.8A). At Melita, differences in maximum plant density were due to weed competition from poor weed control in the two lowest soil temperature treatments (Figure 3.8B); thus, weed infested treatments were excluded from the analysis. Previous studies have reported the qeffect of chilling injury on reduced soybean plant stands (Markowski, 1988b); however, it is unlikely that chilling injury occurred only at Morden, when all sites experienced similar temperatures at planting.

Factors other than soil temperature, however, also influenced the trend in plant stand establishment at Morden. At Morden, a significant positive linear relationship was found where plant density increased with increasing soil temperature (Figure 3.8C). The linear model described only 20% of the variation in maximum plant density response to

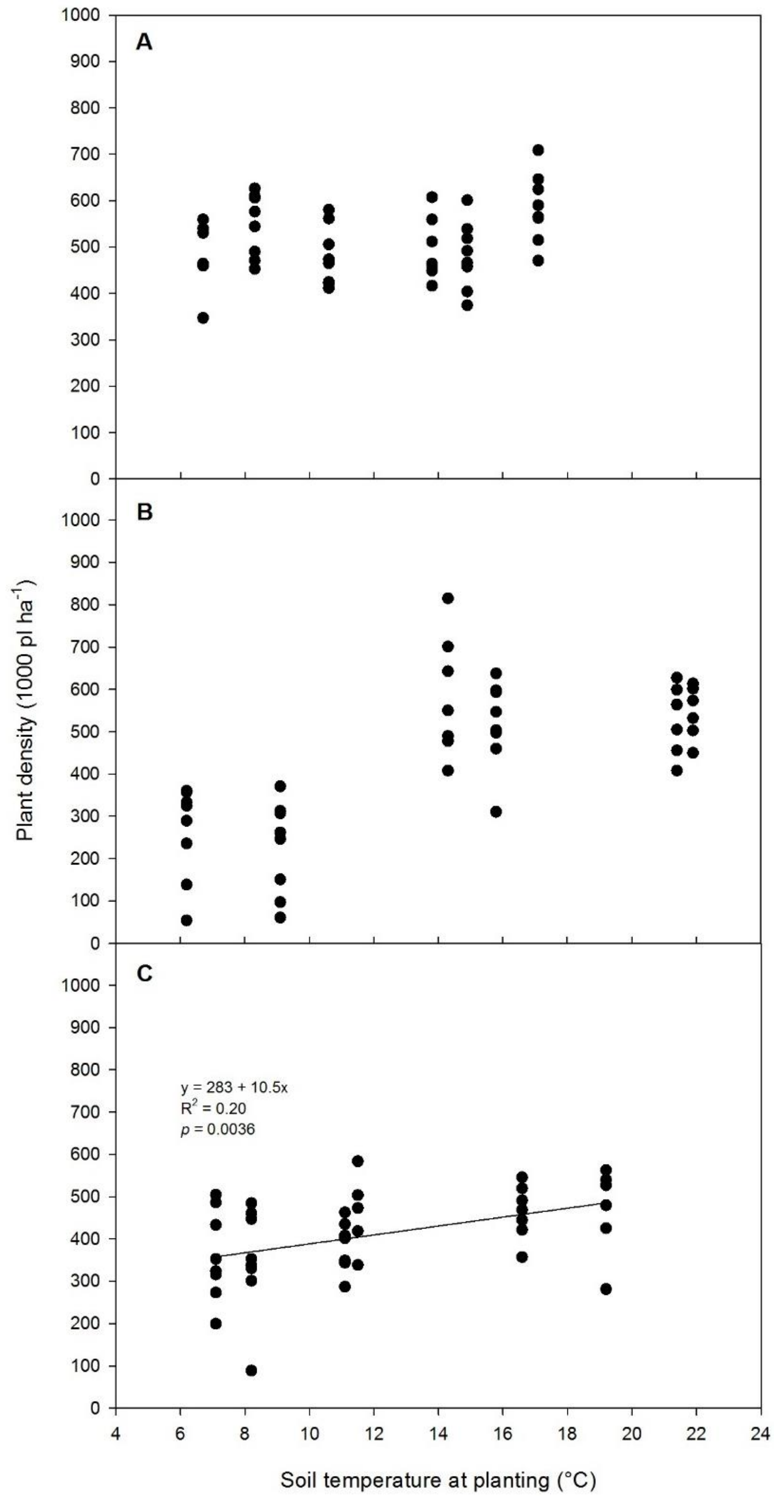

Figure 3.8. The relationship between maximum plant density at 100% emergence and soil temperature at planting at **(A)** Carman, MB, **(B)** Melita, MB, and **(C)** Morden, MB in 2015.

soil temperature; therefore, 80% of the variation was caused by other factors. The frost event experienced at Carman in 2015 was mild and had no significant effect on plant establishment (Figure 3.8A). However, lower freezing temperatures that occurred for one extra hour at Morden may have contributed to decreased emergence at the first two planting dates, which defined the significant relationship between plant density and soil temperature (Figure 3.8C). As discussed previously, only the first four soil temperature treatments (6, 8, 10 and 12°C target temperatures) at Morden had emerged at the time of the frost. Frost-exposed treatments at Morden showed visible signs of frost damage (Figure 3.9). Maximum soybean plant densities of frost-affected treatments appeared to exhibited greater variability and lower plant densities compared to treatments that emerged after the frost (Figure 3.8C). This result suggests that maximum soybean plant density may have been affected by frost, rather than low soil temperature at planting.

Figure 3.9. The range of necrotic tissue damage to soybean seedlings at Morden, MB on May 30, 2015 caused by air temperatures ranging from -0.5 to -1.6°C for a total of three hours.

Soybeans are considered to be moderately tolerant to frost (Badaruddin and Meyer, 2001; Meyer and Badaruddin, 2001). Soybean plants exhibit epigeal emergence, which causes the apical growing point and the axillary buds in the cotyledon node to move above the soil surface after emergence (Tanner and Hume, 1978; Miller et al., 2002). Freeze damage to the apical growing point above the soil surface can result in soybean seedling mortality and plant stand loss (Brown and Blackburn, 1987; Badaruddin and Meyer, 2001). Previous studies have identified the LT_{50} air temperatures for soybeans, in which 50% of seedlings are killed by freezing. The LT_{50} was reported at -4.5°C by Meyer and Badaruddin (2001) and -3°C by Hume and Jackson (1981a) for soybean seedlings. However, the duration of freezing temperatures influences the LT_{50} level, as soybean seedlings were exposed to freezing temperatures longer in the study by Hume and Jackson (1981a). Although LT_{50} temperatures reported in previous studies are quite low, temperatures below 0°C can affect soybean plant stands (Brown and Blackburn, 1987).

3.4.4.3 Soybean Seedling Mortality

Soybean seedling mortality response to soil temperature was analyzed to further examine soybean seedling emergence in the spring. No significant relationship between soybean seedling mortality and soil temperature was identified for the combined 2015 sites. However, analysis of individual site years revealed that only Morden in 2015 exhibited a significant negative linear relationship between soil temperature and soybean seedling mortality (Figure 3.10). High soybean seedling mortality coincided with low plant densities at 100% emergence of the first four soil temperature treatments that had emerged at the time of the frost at Morden (Figure 3.10; Figure 3.8C). This result suggests that late spring frost indeed had a greater influence on reduced plant density compared to soil temperature alone. In the absence of frost, there was no significant relationship between soybean seedling mortality and soil temperature at planting. Therefore, we can reject our hypothesis that low soil temperature and earlier planting results in reduced soybean plant density.

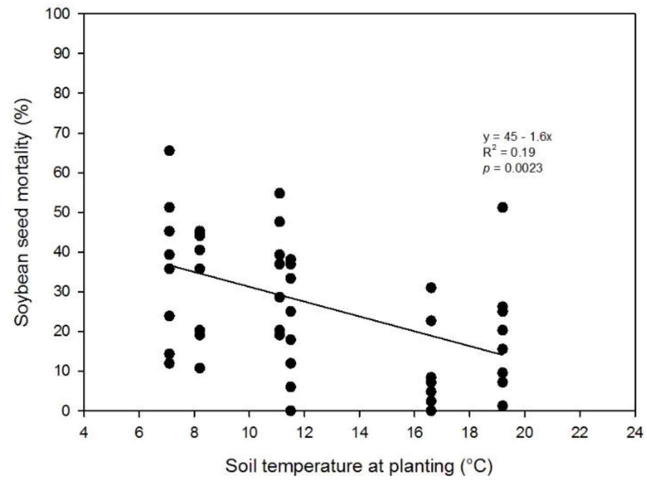

Figure 3.10. The relationship between percentage soybean seedling mortality and actual soil temperature at planting at Morden, MB in 2015.

3.4.5 Influence of Thermal Time on Soybean Emergence Models

There are limitations when interpreting modelled soybean emergence data as a relationship between plant density and days after planting (Figure 3.6). The thermal time unit of growing degree-days (GDD) was used to model emergence data as an alternative method of representing emergence response of soil temperature treatments. In the previous model, sigmoidal logistic models were fitted to the relationship between plant density and days after planting for each soil temperature treatment. Days after planting does not provide information on heat accumulation. Representation of emergence data with GDD allows for standardizing results across years, locations, and calendar dates. Growing degree-days in this study were calculated using air temperature.

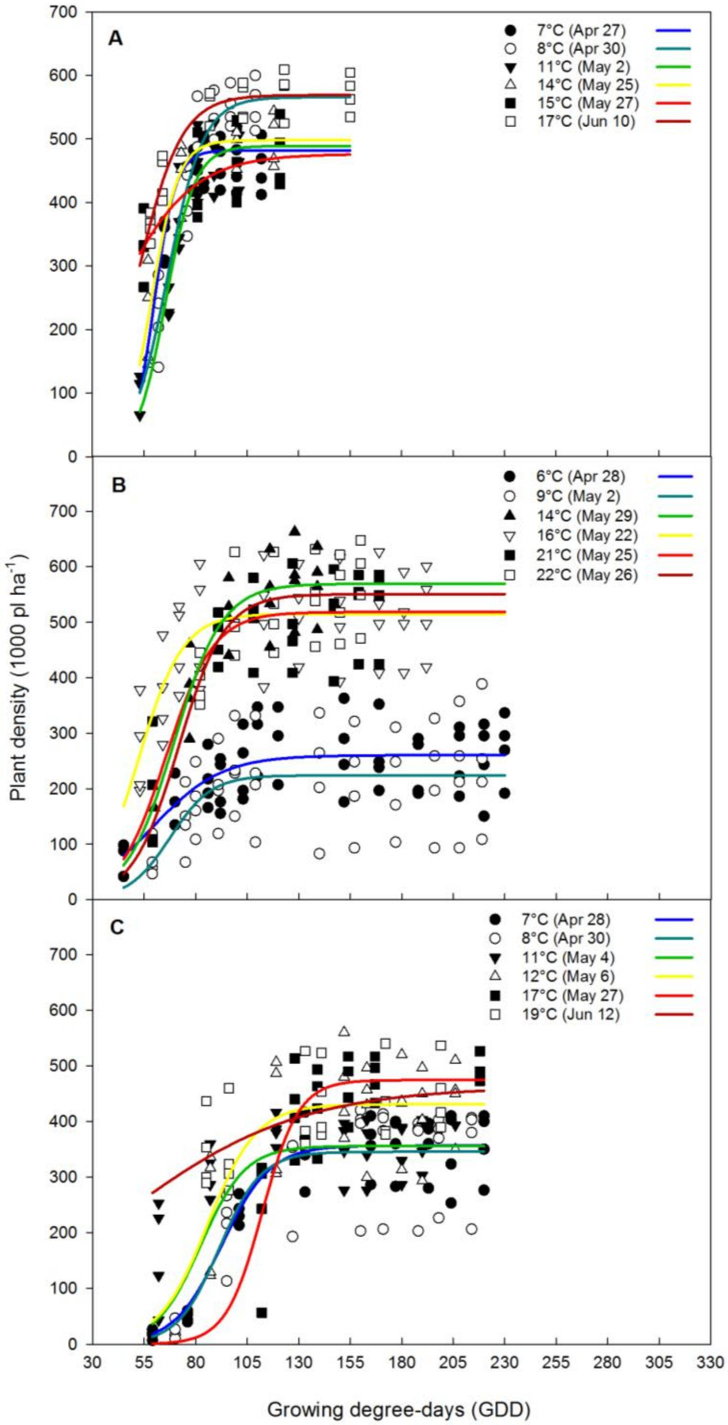

Figure 3.11. Soybean emergence represented as the relationship between plant population density and growing degree-days for six soil temperature treatments in 2015 at **(A)** Carman, MB, **(B)** Melita, MB, and **(C)** Morden, MB.

Results appeared to differ between the DAP and GDD emergence modelling methods, although emergence model parameters were not significantly different from each other (Appendix A, Table 7.5). The lack of significant difference between DAP and GDD emergence modelling was identified by overlapping 95% confidence intervals of all model parameters. Thus, plant densities, or emergence, of soil temperature treatments in response to GDD (Figure 3.11) followed similar patterns as the response to DAP (Figure 3.6). This result is most easily observed with the Carman and Morden locations in 2015, where lines fitted to each soil temperature treatment were much closer together compared to previous modelling (Figure 3.11A; C). Soil temperature groups appeared to remain for emergence data at Melita in 2015 (Figure 3.11B; however, separation between cool and warm soil temperature groups at Melita was likely due to weed competition.

Results varied between the DAP and GDD emergence modelling methods. Plant densities, or emergence, of soil temperature treatments in response to GDD (Figure 3.12) followed similar patterns as the response to DAP overall (Figure 3.6). The most notable difference was the elimination of “cool” and “warm” soil temperature groups (Figure 3.12; 3.6). This result is most easily observed with the Carman and Morden locations in 2015, where lines fitted to each soil temperature treatment are much closer together compared to previous modelling (Figure 3.12A; C). Soil temperature groups were still apparent for emergence data at Melita in 2015. However, the soil temperature group response at Melita was due to weed competition (Figure 3.12B).

For further analysis of emergence modelling methods, days to 50% emergence and plant density at 100% emergence values were also calculated from logistic model parameters using GDD. These parameters were derived from model fitting of each rep, variety, and soil temperature treatment, similar to previous methods. No significant relationship between days to 50% emergence and soil temperature at planting occurred when values were derived from GDD modelling (data not shown). In comparison, days to 50% emergence results from DAP modelling displayed distinct cool and warm temperature groups, and a significant linear relationship for cool temperatures (Figure 3.6; 3.7). However, the lack of separation between "cool" and "warm" soil temperature groups previously observed with DAP modelling, was not visible for GDD modelling (Figure 3.11).

It was expected that established plant stand results would be similar between the two modelling methods due to visual examination of data. Linear regression of the relationship between maximum plant density and soil temperature at planting for individual site years confirmed the similarity between GDD and DAP modelling. A significant positive linear relationship between total seedling emergence and soil temperature at planting only occurred at Morden in 2015 due to frost, as previously discussed (Figure 3.8C). Therefore, modelling of emergence data using GDD produced similar plant density results as DAP modelling.

3.4.6 Soybean Physiological Maturity in Response to Soil Temperature

The number of days required for soybeans to reach physiological maturity was examined to determine the effect of soil temperature on growing season length of soybeans in Manitoba. Linear models were tested to see if a relationship existed between days to maturity (DTM), measured as days after planting (DAP), and soil temperature. Significant interactions between soil temperature and site year, and variety and site year were identified by analysis of variance (Appendix A, Table 7.6). The interaction between soil temperature and site year was explored further using regression to examine the effects of soil temperature at planting on days to physiological soybean maturity. Thus, DTM results were presented for each of four site years separately (Figure 3.12).

Significant negative linear relationships were found for three out of four site years, in which DTM decreased with increasing soil temperature (Figure 3.12). The linear model explained 52 and 81% of the DTM response to soil temperature at planting at Carman in 2014 and 2015, respectively (Figure 3.12A; B). Every 1°C increase in soil temperature at planting lowered the number of DTM by 1.5 and 3.6 days at Carman in both 2014 and 2015 (Figure 3.12A; B). Thus, a stronger response of soybean DTM occurred at Carman in 2015. However, the linear model explained only 15% of the DTM variation at Melita in 2014 (Figure 3.12C; D). Every 1°C increase in soil temperature at planting reduced soybean DTM in Melita by 0.7 days in 2014 (Figure 3.12C; D). At Melita in 2015, soybean DTM did not respond to soil temperature at planting. Overall, days to physiological soybean maturity was more responsive to soil temperature at planting in Carman compared to Melita (Figure 3.12).

Calendar date likely had a greater influence on DTM response in this study than soil temperature at planting, as both calendar date and soil temperature are confounding factors. Due to the covariance between these two variables, colder soil temperatures occurred on earlier planting dates and warmer soil temperatures occurred on later planting dates. Thus, declining DTM with increasing soil temperature could be interpreted as a decline due to later planting. Secondly, photoperiod sensitivity influences the number of days required for soybeans to reach physiological maturity. Photoperiod,

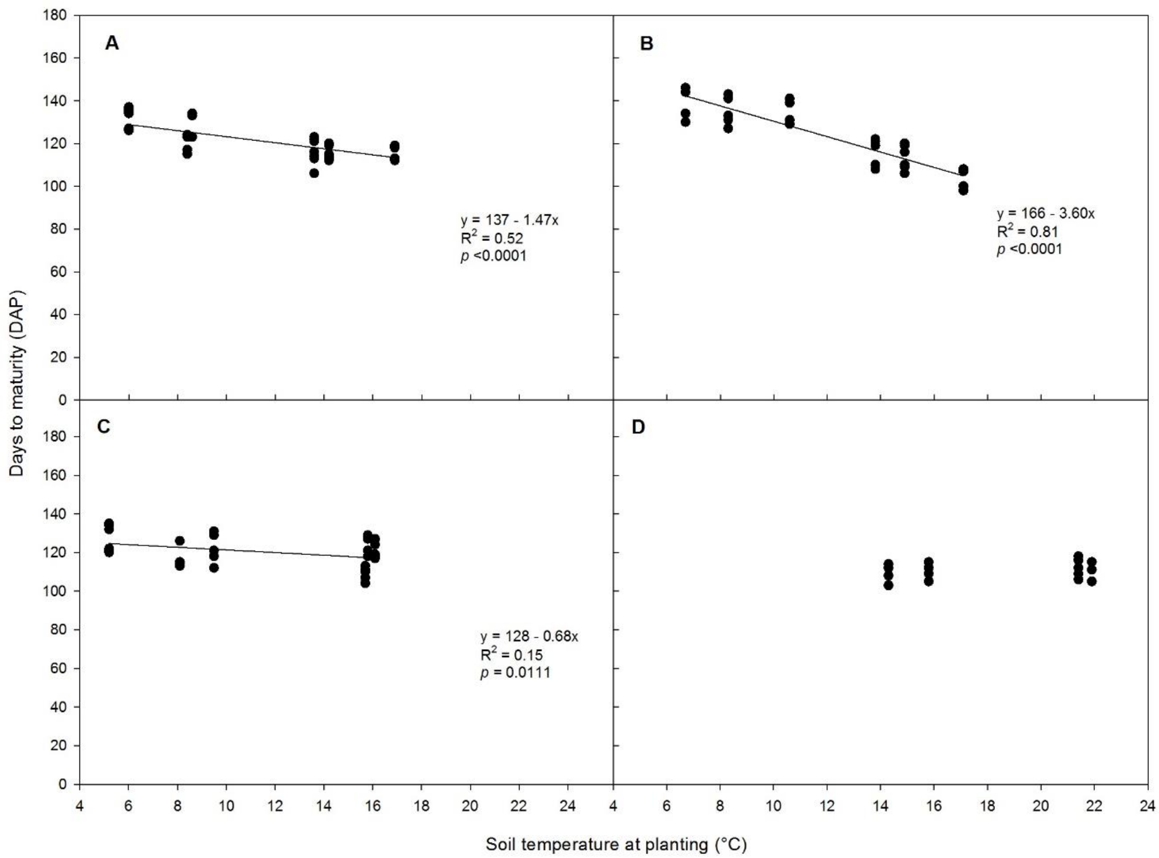

Figure 3.12. The relationship between the number of days from planting to physiological soybean maturity and soil temperature at planting at **(A)** Carman in 2014, **(B)** Carman in 2015, **(C)** Melita in 2014, and **(D)** Melita in 2015.

or day length, plays an important regulatory role in the time of soybean flowering (Sinclair et al., 1991). Soybean plants tend to flower at similar times within a region due to photoperiodic regulation (Steinberg and Garner, 1936). The summer solstice marks the shift from long photoperiod to short photoperiod, and this trigger will signal soybean plants to flower regardless of planting date (Steinberg and Garner, 1936; Hicks, 1978). Late-planted soybeans will "catch up" to the development stages of previously sown soybeans. However, differences in DTM as a result of calendar date are still apparent regardless of the photoperiod effect (Board and Hall, 1984). The remaining variation in DTM for each site year was caused by factors other than calendar date. Soil moisture is one possible factor. For example, low soil moisture during the seed-filling period can induce early maturation of soybeans. Moisture received in different site years also likely contributed to varying soybean DTM response to planting date across site years.

The amount of time required to reach physiological maturity of soybeans is a concern among growers in Manitoba due to the short growing season. Delayed maturity increases the risk of early fall frost exposure to soybeans. Fall frost damage is limited during the R7 to R8 stages of soybean development; however, significant yield loss can occur when soybeans are exposed to freezing temperatures of -2.2°C at the R6 stage or earlier (Judd et al., 1982). The risk of frost or freezing damage to soybeans is increased in the spring by early planting, and in the fall by late planting (Halvorson et al., 1995). This risk was surprisingly low for the varieties tested in this study; however, growers are still recommended to strike a balance between soybeans seeded late enough to avoid spring frost and early enough to avoid fall frost to ensure adequate DTM.

3.5 Conclusions

This study determined that the relationship between soil temperature at planting and soybean yield was significant for only one in three site years. Soybean yields at Carman in 2015 increased with increasing soil temperature and reached a maximum at 9°C at 10:00 AM at a 5 cm soil depth, beyond which yield declined with further increases in soil temperature. This soil temperature was much lower than the optimum air temperature range for soybean germination and emergence identified by Holmberg (1973) as 20 to 22°C.

Further analysis revealed that soybean yields were better explained by the influence of planting date, rather than soil temperature. At Carman in 2015, the relationship between soybean yield and Julian planting date was found to be significant, in which yield declined with later planting. According to analysis of variance, yield responses of short and long season varieties were significantly different for the relationship between soybean yield and Julian planting date. Soybean yield declined by 14 and 22 kg ha^{-1} with each one-day delay in planting for short and long season soybean varieties, respectively. Strong relationships were found between soybean yield and both soil temperature ($R^2 = 0.67$, varieties combined) and planting date ($R^2 = 0.51$ short season variety, 0.73 long season variety), confirming the strong influence of planting date on soybean yield.

Spring frost was responsible for greater soybean seedling mortality and reduced plant density in this study. Exposure of soybean seedlings to mild freezing temperatures for two hours in duration did not reduce plant stand or yield at Carman in 2015; however, a slightly harder frost for three hours in duration experienced at Morden in 2015 caused seedling mortality and reduced plant densities of affected treatments. Longer duration of freezing temperatures has been reported in the literature to result in greater seedling mortality at lower temperatures (Hume and Jackson, 1981a; Meyer and Badaruddin, 2001). It can be concluded from this study that soil temperature at planting had no effect on soybean seedling mortality and established plant densities, as no response was observed in the absence of frost. Frost damage associated with earlier planting poses a potential threat to soybean yields; thus, growers should consider this risk when determining soybean planting dates in Manitoba.

The comparison between DAP and GDD emergence modelling revealed that soil temperature at planting did not affect soybean emergence. Modelling emergence based on accumulated thermal time suggested that all treatments followed similar sigmoidal emergence patterns. Cool and warm soil temperature groups that initially occurred with DAP emergence modelling, indicated that cool soil temperatures caused delayed emergence and warm soil temperatures resulted in rapid emergence. These temperature groups were apparent for the number of days to 50% emergence. However, values derived from GDD emergence modelling revealed no differences in the number of growing degree-days required to reach 50% emergence across soil temperature treatments.

According to the results of this study, it is recommended to plant soybeans as early as possible during the planting period in Manitoba. Early soybean planting dates yielded the greatest overall, and low soil temperature treatments associated with early planting did not cause yield reductions. However, it is also recommended that growers consider the forecasted weather conditions following seeding, tolerance to loss from spring or fall frost, timeline to complete seeding and harvest, and seedbed conditions when determining soybean planting dates.

Future research should seek to adapt the operational definition of soil temperature used in this study to compare 10:00 AM as a representative time of day to other potentially representative hours of soil temperature, such as 11:00 AM or 12:00 PM. Growing degree-day calculations based on soil temperatures, rather than air temperatures, in future studies would more accurately model emergence data. The measurement of DTM as days from emergence, rather than days from planting, to physiological maturity would be more streamlined with DTM values used in the agriculture industry. Future studies could examine the effects of soil or air temperatures at key development stages throughout the season, such as flowering, on yields of soybeans grown in uncontrolled environments. Understanding temperature effects on key development stages might help explain yield differences that are not caused by planting date. Another future approach might be the examination of long-term soil temperature data to establish what calendar dates correspond with which soil temperatures.

Soybean planting date and plant density are agronomic decisions made simultaneously at the start of the growing season. In Chapter 4, the influence of soybean planting date on optimum soybean plant density was examined to contribute to the development of stronger soybean planting recommendations in northern growing regions of the NGP.

4.0 OPTIMUM SOYBEAN (*GLYCINE MAX*) PLANT DENSITIES FOR EARLY TO VERY LATE PLANTING DATES IN NORTHERN GROWING REGIONS OF THE NORTHERN GREAT PLAINS

4.1 Abstract

Soybean (*Glycine max* L. Merr.) producers in northern growing regions of the Northern Great Plains (NGP) can increase soybean yield and economic return in a short growing season by optimizing planting date and plant density. Despite recent increases in soybean acres, current information on soybean response to delayed planting and stand loss from environmental effects is limited. The objective of this study was to determine soybean plant densities for yield and profit maximization for different planting dates in northern growing regions of the NGP. Six plant densities ranging from 197,680 to 568,340 plants ha^{-1} were seeded on early to late planting dates at Carman, MB, and five plant densities ranging from 197,680 to 494,210 plants ha^{-1} were seeded on early to very late planting dates at Carrington, ND in 2014 and 2015. The combined analysis of all four site years determined that soybean yield-density relationships formed two planting date groups: early/mid, and late/very late. Maximum yield was greater for early/mid planting (4520 kg ha^{-1}) compared to late/very late planting (3242 kg ha^{-1}). However, soybean yield did not reach a true maximum within the range of established plant densities in this study, according to yield-density relationships. Soybean economic optimum seed densities (EOSDs) were 492,000 and 314,000 seeds ha^{-1} for early/mid and late/very late planting, respectfully. These EOSD values were sensitive to changes in soybean grain price and seed cost. From the results of this study, growers are advised to seed soybeans from early to mid planting dates (May 4 to May 26) at a profit-maximizing level, accounting for

price and cost fluctuations. However, as the influence of weed and disease dynamics were a limitation of the marginal cost analysis, growers are also advised to consider these factors when determining soybean plant or seed densities.

4.2 Introduction

Growers can manipulate soybean (*Glycine max* L. Merr.) planting date and plant density to maximize yield and economic return. Soybean growth and yield responses to plant density are influenced by planting date, environmental conditions, and maturity groups (De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009). As soybean production continues to increase in northern growing regions of the NGP, it is an ongoing effort to develop best management planting practices for soybeans due to the short growing season. Soybean plant density and planting date information is presently limited in northern production areas of the NGP.

Soybean plant density recommendations require improvement based on planting date in northern growing regions. It is currently recommended to achieve a target soybean plant density of 395,000 plants ha^{-1} based on recent research by Mohr et al. (2014). In North Dakota, the recommended target plant density is slightly lower than Manitoba at 371,000 plants ha^{-1} (NDSU, 2014). Research from the United States has indicated that soybean seed densities should be increased by 20% if planted before or after the optimum planting date (May 10 to 20) due to cold soil and shorter plants, respectively (Heatherly and Elmore, 2004). However, optimum soybean plant densities have not been determined for non-optimal planting dates in northern growing regions.

Economic return is an important consideration for soybean plant density and planting date management. A trade-off exists between crop yield maximization and seed cost minimization when determining economic optimum soybean plant density (Mohler, 2001; De Bruin and Pedersen, 2008a). Incorporating factors such as seed cost and commodity price into soybean seed density calculations gives a better indication of profitability (Wahab et al., 1986; Saindon et al., 1995; Jettner et al., 1999; De Bruin and Pedersen, 2008a), and may result in lower seed densities necessary to reach maximum yield. Given the recommendation to increase soybean seed densities with later planting, it is also unclear what effect this might have on economic return.

Previous studies have documented the ability of soybeans to exhibit compensatory growth or shade avoidance in response to low and high plant densities, respectively (Egli, 1993; Carpenter and Board, 1997; Andrade and Abbate, 2005; Hay and Porter, 2006). More soybean branches, reduced height, and pods closer to the soil surface have resulted from soybean seed densities as low as 148,000 seeds ha^{-1} (Beuerlein, 1988). High soybean seed density, however, have been reported to produce fewer soybean branches, taller plants, and increased height of the lowest pod (Weber et al., 1966; Beuerlein, 1988). The extent to which soybean plants compensate under low plant densities has not been reported for northern growing regions.

This study was initiated to identify soybean plant densities for yield maximization, and economic optimum seed densities for profit maximization, for early to late planting dates in northern growing regions of the NGP. It was also initiated to observe compensatory growth and shade avoidance responses to a range of soybean plant densities seeded in different planting windows. It was hypothesized that soybean plants would compensate in growth under low plant densities and compete in growth under high plant densities. Profit maximization as a goal for soybean production was hypothesized to result in lower optimum soybean plant density compared to that which maximizes yield, due to the incorporation of economic factors such as soybean seed cost and commercial price. Finally, optimum soybean plant densities were expected to be greater for later planting compared to early or mid planting.

4.3 Materials and Methods

4.3.1 Site Description

The field experiments were initiated in 2014 and 2015 at the Ian N. Morrison Research Station in Carman, Manitoba and the North Dakota State University Carrington Research Extension Center (CREC) in Carrington, North Dakota (47.508143, -99.120793). These locations encompassed differing agricultural regions within the northern Great Plains. A site description for Carman, Manitoba can be found in Section 3.3.1. The soil at Carrington, North Dakota is a Calcic Hapludoll of the Heimdal series with a silty loam texture. The soil had a pH of 6.4 and 2.9% organic matter.

4.3.2 Weather

Climatic conditions over the growing seasons were variable among site years and are summarized in Figure 4.1 below at Carrington, North Dakota in 2014 and 2015, respectively. Climatic conditions for Carman, Manitoba can be found in Section 3.3.2. Climatic data was obtained from Agriculture and Agri-Food Canada and Manitoba

Agriculture weather monitoring stations at Carman, Manitoba, and from the NDAWN weather monitoring station at Carrington, North Dakota.

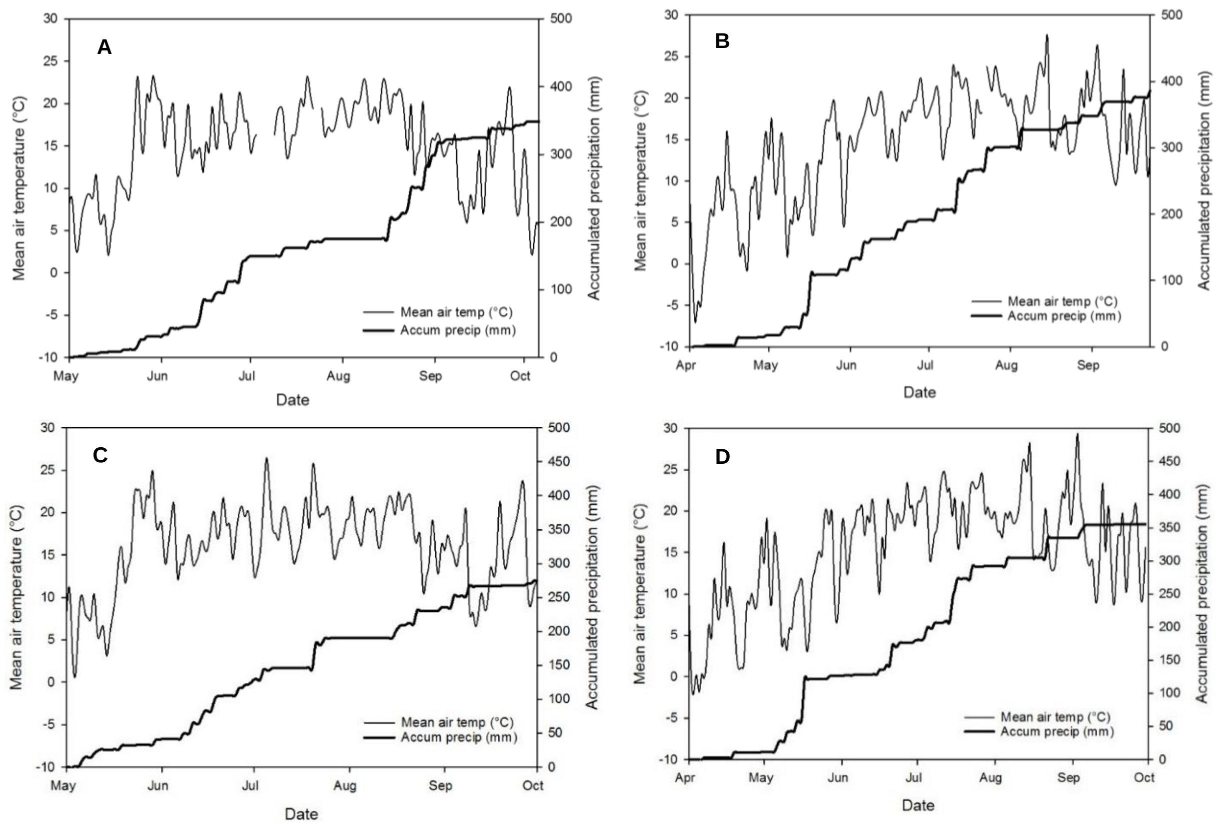

Figure 4.1. Mean daily air temperature and accumulated precipitation for the growing seasons at Carman, MB in **(A)** 2014 and **(B)** 2015, and Carrington, ND in **(C)** 2014 and **(D)** 2015.

4.3.3 Experimental Design

The experiment was arranged as a split plot design with four blocks. Planting date served as the main plot and target plant density served as the sub plot. Individual sub plots measured 2 m x 8 m at Carman, Manitoba, and 5 m x 9 m at Carrington, North Dakota. Treatment levels varied between the two sites based on growing season length. At Carman, treatments consisted of six target plant densities seeded on 1) early, 2) mid and 3) late planting dates (Table 4.1). Target plant densities at Carman consisted of 197,680; 271,820; 346,950; 420,080; 494,210; and 568,340 pl ha $^{-1}$. At Carrington, treatments consisted of five target plant densities seeded on 1) early; 2) mid; 3) late; and 4) very late planting dates (Table 4.1). The lowest five target plant densities were used at Carrington. All planting dates were spaced approximately two weeks apart (Table 4.1). Soybean varieties were Dekalb 24-10RY (MG 00.5) and Dairyland Seeds 0404 (MG 0.4) at Carman and Carrington, respectively.

Table 4.1. Summary of planting dates at Carman, MB and Carrington, ND in 2014 and 2015.

	Carman		Carrington	
Planting Date	2014	2015	2014	2015
Early	-†	May 04	-	May 05
Mid	May 26	May 22	May 23	May 19
Late	Jun 09	Jun 10	Jun 05	Jun 02
Very Late	-	-	Jun 23	Jun 16

† Missing values indicate treatment was not in the protocol.

4.3.4 Crop Management

See Section 3.4.4 for crop management information at Carman, Manitoba. At Carrington, North Dakota, multiple passes with a cultivator were used to prepare the seedbed prior to the first seeding date. At Carrington in 2014, one extra tillage pass was done prior to the last planting date due to soil surface crusting. Soybean seed densities were adjusted for seed lot germination and 20% mortality to reach the intended target plant densities. Granular inoculant was applied with the seed. Seeding operations were performed with a cone plot seeder (Wintersteiger Plotseed XL, Ried im Innkreis, Austria) with 35.6 cm row spacing. For pre-emergent weed control, ethafluralin (Sonalan 10G®, Dow AgroSciences, Indianapolis, IN) was applied at a rate of 2.81 L ha^{-1} (2268 g a.i./22,680 g of product) and incorporated with tillage. Two in-season glyphosate (Roundup PowerMax®, Monsanto, St. Louis, MS) applications were made each year prior to flowering at a rate of 1.75 L ha^{-1} (540 g a.e./L). Herbicide was applied using a three-point tractor mounted sprayer (River Bend, Moorhead, MN). Plots were harvested by main plot, as each planting date reached maturity. Harvest operations were performed with a plot combine (Hegel 150, Zürn Harvesting, Waldenburg, Germany).

4.3.5 Data Collection

4.3.5.1 Plant Population and Emergence

At Carman, soybean plant density was determined just prior to harvest on both sides of a marked 1-m length in each plot in 2014, and 3-m length in 2015. At Carrington, plant counts were conducted in 1-m lengths at two weeks after planting and again in mid-July for final plant stand assessment.

4.3.5.2 Main Stem Branching

Five soybean plants were randomly selected at the R5 stage of development from each plot for main stem branch counts. All branches extending from the main stem were considered in the counts, including immature or dead branches (Paul Gregoire, personal communication). Second order soybean branches were not considered in these counts. Main stem branching values were averaged for each plot.

4.3.5.3 Biomass

Soybean biomass was harvested at the R5 stage of development. Plants were cut at the soil level and removed from each plot. Biomass sample sizes were 1 m x 2 rows. Plants were oven dried at 60°C for at least 48 hours before they were weighed.

4.3.5.4 Lowest Pod Height

At the R8 stage of development, lowest pod height was measured on three random soybean plants per plot. The distance from the soil surface to the node of the lowest pod was measured at Carman. The length from the soil to the bottom of the lowest pod was measured at Carrington. Lowest pod height values were averaged for each plot.

4.3.5.5 Plant Height

Final soybean plant height was recorded just prior to harvest, at the R8 stage of development. Soybean plant heights were measured from the soil surface to the top node of the plant. At Carman, plant height was recorded for three random plants per plot. Plant height values were averaged for each plot. At Carrington, an average height of plants across each entire plot was recorded.

4.3.5.6 Days to Maturity

Plots were monitored every two days for physiological maturity once plants began to turn yellow. One average maturity rating was recorded for each plot. The calendar date in which physiological maturity was reached was recorded for each plot. At Carrington, physiological maturity was defined as 50% brown pod. At Carman, physiological maturity was defined as 95% brown pod.

4.3.5.7 Lodging Ratings

Entire plots were assessed for lodging in 2015. Each plot was given one lodging score on a scale of 1 to 9 (1 = erect; 9 = fully lodged) (Wang et al., 2016).

4.3.5.8 Yield

A description of soybean harvest and yield data collection for both sites can be found in Section 3.3.5.9. Methodology for soil moisture measurements at Carman in 2014 and 2015 can also be found in Section 3.3.5.9. At Carrington, seed moisture was tested with a Steinlite SL 95 moisture meter (Steinlite, Atchison, KS).

4.3.6 Statistical Analysis

4.3.6.1 Analysis

Analysis of variance (ANOVA) was used to compare treatment means of all response variables as a preliminary statistical analysis tool using the mixed procedure (PROC MIXED) of SAS 9.4 (SAS Institute Inc., Cary, NC). It was used to assess the significance of fixed effects and interactions prior to regression analysis. Analysis of variance was also used to assess significance of parameters derived from the rectangular hyperbolic model that described the soybean yield-density relationship. For individual site years, planting date treatment means were analyzed within site years due to unbalanced data. For combined site years, 95% confidence intervals were used in conjunction with analysis of variance also due to unbalanced data.

4.3.6.2 Regression Modelling

Statistical analysis involved regression of the relationships between response variables and actual plant density based on harvest plant density counts. Linear, quadratic, and non-linear models were tested for the relationship between soybean yield and plant density (Appendix B, Table 7.12). Non-linear models, including the rectangular hyperbola (Cousens, 1985) and exponential (Edwards and Purcell, 2005) model, were tested to fit soybean yield data using the NLIN procedure of SAS 9.4 (SAS Institute Inc., Cary, NC). The criteria for choosing the appropriate model for the yield-density relationship included model convergence for all treatments, the Akaike Information Criterion (AIC) (Akaike, 1974), R^2 and pseudo R^2 values, biological relevance, and overall model simplicity (Motulsky and Christopolis, 2003). The following equation was used to calculate an approximation of the coefficient of determination for the non-linear regression:

$$\text{Pseudo } R^2 = 1 - \text{SS } (\mathit{Residual}) / \text{SS } (\mathit{Total}_{\mathit{Corrected}}) \qquad [1]$$

where SS ($Residual$) is the residual sum of squares, and SS ($Total_{Corrected}$) is the corrected total sum of squares for the non-linear regression (Bowley, 1999).

The rectangular hyperbola model represented the soybean yield-density relationship for this study:

Rectangular hyperbola: $f(x) = y = Ix/(1 + (Ix/a))$ [2]

where y is the yield of grain in kg ha^{-1}, x is the plant density in 1000 pl ha^{-1}, I is the rate of change in yield for each increment in plant density per hectare (kg 1000 pl^{-1}) as plant density approaches zero, and a is maximum yield.

Treatment differences among equation parameters from the rectangular hyperbola model were determined by analysis of variance using the mixed procedure (PROC MIXED) in SAS. Analysis of variance was used to compare parameter values derived from models fitted to each replicate of plant density treatments for each of the planting date treatments. These parameters included the soybean plant density at 95% of maximum predicted yield (1000 pl ha^{-1}), maximum soybean yield (a) (kg ha^{-1}), and rate of change in yield (I). To calculate soybean plant density at 95% of maximum yield, all known variables were substituted into the original rectangular hyperbola equation, including 95% of maximum yield.

4.3.7 Economic Analysis

4.3.7.1 Marginal Cost Analysis

Marginal cost analysis was conducted to determine economic optimum seed density recommendations for soybeans in different planting windows, incorporating both seed cost and grain revenue (Baumol and Blinder, 2015). The rectangular hyperbola equation parameters for each planting date in each site year were first used to estimate yield for a range of simulated plant densities (Table 4.2). The relationship between marginal cost (MC) and marginal revenue (MR) for simulated plant densities were represented in two ways: 1) total cost (TC) and total revenue (TR) (Shirtliffe and Johnston, 2002; Lawley, 2004; Baumol and Blinder, 2015); and 2) the first derivative, or slope, of the yield-density relationship (French et al., 1994; Jettner et al., 1999; Lawley, 2004; Baumol and Blinder, 2015). The greatest distance between TC and TR represents the greatest profit, whereas the intersection between MC and MR represents the point of profit maximization.

Table 4.2. Summary of rectangular hyperbola yield functions ($y = Ix/(1 + (Ix/a))$) and parameters used to estimate yield for a simulated range of plant densities.

Site Year	Planting Date	Rectangular Hyperbola Yield Function
Carman 2014	Mid + Late	y = 52.92x/(1 + (52.92x/3036))
Carman 2015	Early + Mid	y = 102.3x/(1 + (102.3x/4105))
	Late	y = 49.96x/(1 + (49.96x/3185))
Carrington 2014	Mid	y = 95.33x/(1 + (95.33x/4882))
	Late	y = 10.69x/(1 + (10.69x/6527))
Carrington 2015	Early + Mid + Late + Very Late	y = 82.17x/(1 + (82.17x/3385))
All Site Years Combined	Early + Mid	y = 46.06x/(1 + (46.06x/4474))
	Late + Very Late	y = 63.91x/(1 + (63.91x/3264))

The marginal cost analysis is based on empirical data from the current experiment and necessary assumptions to complete the model. The assumptions, listed in Table 4.3, included a soybean seed cost of $0.36 per thousand seeds, soybean grain price of $0.37 kg^{-1}, and average soybean seedling mortality across planting dates in each site year. Soybean seed cost per thousand seeds was derived from the base seed cost of $50 per unit of soybean seed, in which one unit is equal to 140,000 seeds. The base seed cost excluded the cost of seed treatment. Using these assumptions, a profit function was developed to calculate economic optimum seed density (EOSD) at 95% of maximum yield for each soybean planting date in each site year, and for combined site years (Equation 1). The profit function involved both total revenue and total cost functions, which incorporated soybean plant density, seedling mortality, seed cost, yield, and grain revenue.

Profit function: $f(\mathrm{x}) = TR(\mathrm{x}) - TC(\mathrm{x})$ [1]

Total revenue function: $TR(\mathrm{x}) = \mathrm{y} * P$ [2]

Total cost function: $TC(\mathrm{x}) = [\mathrm{x} * (1 + m)] * C$ [3]

Economic optimum seed density: $EOSD = \frac{a}{I}\left[\sqrt{\frac{P*I}{C(1+m)}} - 1\right]$ [4]

where *TR* is the total revenue of soybean grain in \$ ha^{-1}, y is soybean yield in kg ha^{-1} derived from the rectangular hyperbola equation, *P* is the commercial price of soybeans in \$ kg^{-1}, *TC* is the total cost of soybean seed in \$ 1000 seeds^{-1}, x is the simulated plant density in 1000 plants ha^{-1}, m is soybean seedling mortality in 1000 plants ha^{-1}, *C* is the cost of soybean seed in \$ 1000 seeds^{-1}, and *EOSD* is the economic optimum seed density in seeds ha^{-1}, where *Y* is 95% of maximum yield and *I* is the parameter from the rectangular hyperbola model.

Table 4.3. Summary of assumptions used to calculate economic optimum seed densities (EOSDs) of soybeans at different planting dates.

Assumption	Value	Source
Soybean seed cost in 2015	\$0.36 thousand seeds^{-1}†	Dennis Lange, Manitoba Agriculture, Food and Rural Development - Pulse Specialist, Personal Communication (2015)
Soybean commercial price in 2015	\$0.37 kg^{-1}	Dennis Lange, Manitoba Agriculture, Food and Rural Development - Pulse Specialist, Personal Communication (2015)
Soybean seedling mortality	Carman 2014 average for all planting dates: 40%	Experiment data collection
	Carrington 2014 average for mid-planting: 11% Carrington 2014 average for late planting: 6%	
	Carman 2015 average for all planting dates: 22%	
	Carrington 2015 average for all planting dates: 32%	
	Combined site year average: 29%	

† Seed cost derived from \$50 unit^{-1} (1 unit = 140,000 soybean seeds), excluding the cost of seed treatment.

4.3.7.2 Sensitivity Analysis

A sensitvity analysis was conducted to test the influence of assumptions made to calculate economic optimum soybean seed densities. The EOSD for each planting date in each site year was calculated over a range of soybean seed costs and commercial prices. Seed cost values ranging from \$0.29 to \$0.50 1000 seeds^{-1}, and commercial price values ranging from \$0.18 to \$0.73 kg^{-1} were substituted into the EOSD equation, holding all other factors constant.

4.4 Results and Discussion

4.4.1 Plant Establishment

Actual soybean plant densities varied among site years and treatments. The comparison between target and actual soybean plant densities are summarized in Figure 4.2 for each planting date and site year. Actual plant densities at both site years in Carman and Carrington in 2015 increased with increasing target plant densities, as expected (Figure 4.2A; C; D). At Carman, all actual plant densities were close to target densities. At Carrington in 2015, all actual plant densities were close to target densities except for the early planting date, which resulted in lower actual plant densities (Figure 4.2D). In contrast, the Carrington 2014 site year showed a relatively flat trend in actual plant density with increasing target plant density (Figure 4.2 B; D). Data from very late planting at Carrington in 2014 were not included in plant growth and development analyses due to the unexpected trend in actual soybean plant density and the occurrence of frost, preventing plots from reaching maturity. In all site years, actual plant densities were similar to or greater than the lower target densities, whereas upper target densities were generally not reached (Figure 4.2). Variation in soybean plant establishment among locations, years, and environmental conditions have been previously reported (Helms et al., 1996).

Analysis of variance was used to compare treatment means of percentage soybean seedling mortality for each planting date in each site year. Significant differences in soybean mortality were found at Carrington in 2014 and 2015. At Carrington in 2014, very late planting resulted in significantly greater soybean seedling mortality (44%) compared to mid (11%) and late planting (6%) (Table 4.4). The opposite result in

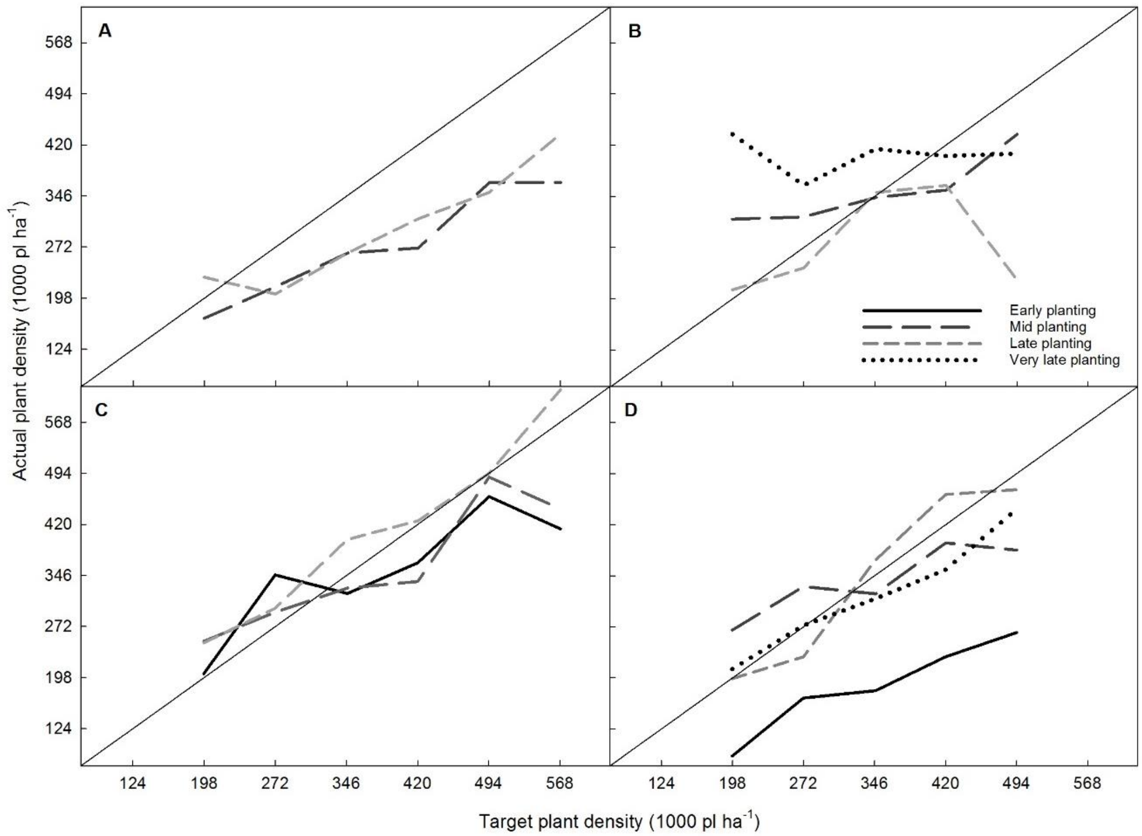

Figure 4.2. Actual versus target plant densities at **(A)** Carman, MB in 2014 for mid to late planting dates, at **(B)** Carrington, ND in 2014 for mid to very late planting dates, at **(C)** Carman, MB in 2015 for early to late planting dates, and at **(D)** Carrington, ND in 2015 for early to very late planting dates. The 1:1 line represents y = x for each plant density.

soybean seedling mortality occurred at Carrington in 2015. Early planting resulted in significantly higher percentage seedling mortality (50%) compared to all other planting dates, in which mortality ranged from 24 to 28% (Table 4.4).

High seedling mortality at Carrington was driven by environmental conditions (Table 4.4). Dry soil conditions at Carrington in 2014 likely caused poor plant establishment and greater mortality with late planting due to a lack of rainfall following planting (Figure 4.1A). Previous studies have shown that late planting can cause reduced soybean plant density due to dry soil conditions during imbibition (Helms et al., 1996; Hamman et al., 2002). An extended period of cold weather and dry conditions during emergence at Carrington in 2015 likely reduced plant stands of early-seeded soybeans (Figure 4.1). The opposite result was determined by De Bruin and Pedersen (2008a), in which early planting had no negative effect on soybean plant density. However, this finding was specific to the Midwestern United States, where weather conditions experienced by early-planted soybeans are more favourable compared to northern growing regions. According to the literature, factors such as variation in sowing depth and surface crop residue can also reduce soybean plant density (Fehr et al., 1973; Egli and TeKrony, 1996).

Table 4.4. Soybean seedling mortality for early to very late planting dates of individual and combined site years.

	Carman				Carrington			
Planting Date	2014		2015		2014		2015	
	----------------% soybean seedling mortality-----------------							
Early	-		25	**a**	-		50	**a**
Mid	41	**a**†	26	**a**	11	**b**	24	**b**
Late	38	**a**	15	**a**	6	**b**	27	**b**
Very Late	-		-		44	**a**	28	**b**
Source of Variation								
Planting Date	ns		ns		0.0033		0.0011	

† Means within a column followed by the same letter are not significantly different at p<0.05 according to Fischer's protected LSD test.

Significant differences in percentage soybean seedling mortality between planting dates of combined site years was assessed using analysis of variance. Overlapping 95% confidence intervals between planting dates indicated that no significant differences occurred across seeding dates of four combined site years. The average soybean seedling mortality of combined site years and planting dates was 28%. The predicted soybean mortality of 20% factored into seed density calculations for this study was slightly less than average mortality of combined site years. Seven out of 12 planting dates were within 10% of the predicted mortality used in calculations, suggesting that it is an acceptable level for seed density calculations. This is especially valuable for soybean growers who have not established an expected soybean mortality level for their farm.

4.4.2 Soybean Plant Growth and Development Response to Plant Density

4.4.2.1 Main Stem Branching

Soybean main stem branch number, was assessed to determine the growth and development response of soybean plants to plant density at different planting dates. No significant interactions between soybean planting date and plant density were identified by analysis of variance at any sites for soybean branching (Appendix B, Table 7.7). Thus, results were averaged across planting dates for all site years. Significant negative linear relationships between the number of main stem soybean branches and plant density were found in all site years except Carrington in 2014 (Figure 4.3). Carrington in 2014 had a small range in actual soybean plant densities (Figure 4.2B), which may have been responsible for the lack of branching response (Figure 4.3B). The linear model explained 16 to 35% of the variation in branch number at Carman in 2014 and 2015, respectively, whereas the model explains only 10% of the branching response at Carrington in 2015 (Figure 4.3). The weaker relationship between branching and plant density at Carrington in 2015 may be caused by the lack of high plant densities established (Figure 4.2D).

Soybean branch number reduction with increasing plant density was smaller than expected in this study. The number of main stem branches decreased by 0.5 to 1 with every 100,000 plants ha^{-1} increase across all three site years (Figure 4.3). Previous research has also reported slight branching responses. A study by Cox et al. (2010) determined that a soybean seed density of 358,000 seeds ha^{-1} resulted in 0.9 more branches compared to 469,000 seeds ha^{-1} in 19 cm row spacing.

Soybean branching response to plant density similar to previous findings. A study by Carpenter and Board (1997) determined that average soybean branch dry matter per plant and the number of soybean branch nodes were greater at reduced plant densities. Caprenter and Board (1997) also found that additional branches improved the ability of soybean plants to generate more leaf area. More leaf area allows for greater interception of solar radiation and increased photosynthetic capacity (Hay and Porter, 2006). High soybean plant densities have also been reported to reduce the number of soybean branches (Hay and Porter, 2006). Adjacent plants in close proximity to each other can prevent branches from developing beyond the bud stage, or cause premature plant death (Hay and Porter, 2006).

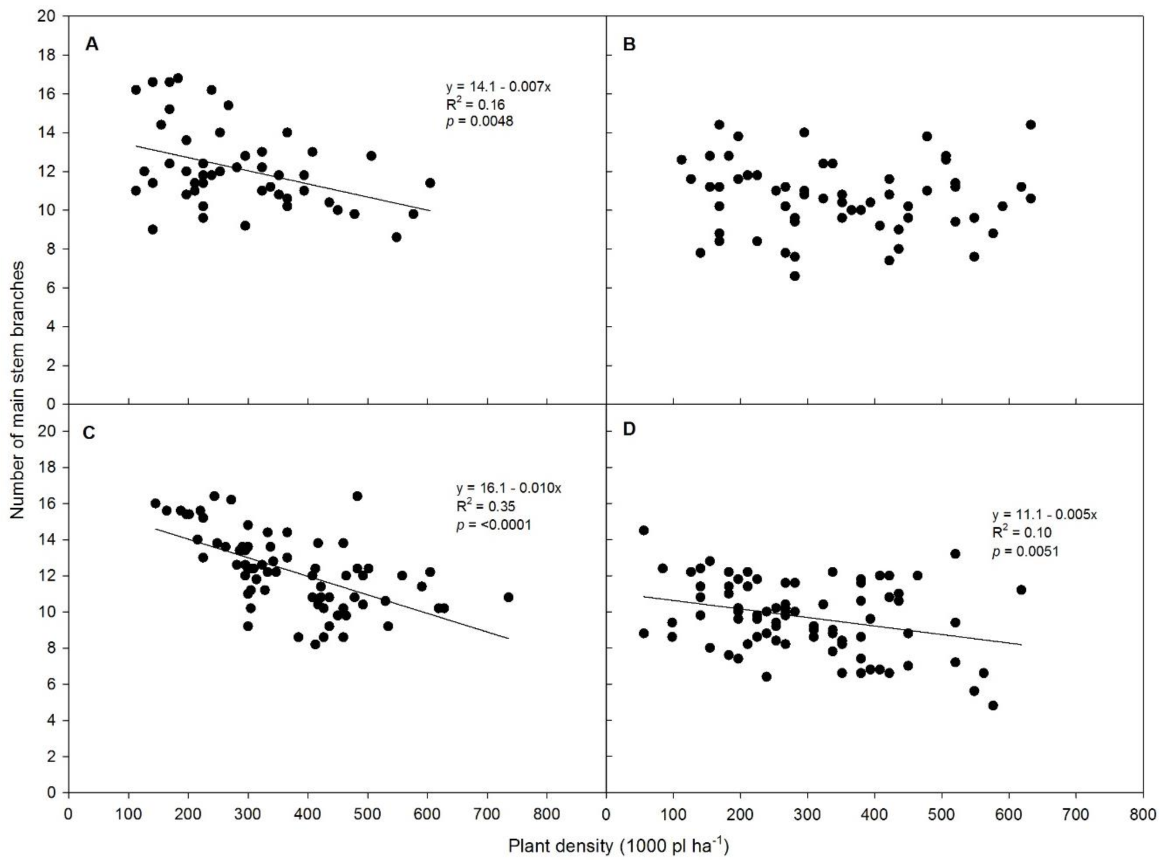

Figure 4.3. The relationship between number of main stem soybean branches and plant density at **(A)** Carman, MB in 2014, at **(B)** Carrington, ND in 2014 for combined ideal to late planting dates, at **(C)** Carman, MB in 2015 for combined early to late planting dates, and at **(D)** Carrington, ND in 2015 for combined early to very late planting dates.

4.4.2.2 Biomass

Soybean biomass was another response variable assessed in this study to determine the growth response of soybeans to a range of plant densities seeded at different planting dates. Positive linear relationships between dry soybean biomass and plant density were found at Carman and Carrington in 2015 only (Figure 4.4). No significant interaction between soybean planting date and plant density was identified for soybean biomass at Carman in 2015 (Appendix B, Table 7.8); thus, soybean biomass response was averaged across all planting dates. However, a significant interaction was found at Carrington in 2015 resulting in planting dates analyzed separately (Appendix B, Table 7.8). Biomass increased by 2 kg ha^{-1} with every increase in 1000 plants at Carman (Figure 4.4A). At Carrington, soybean biomass responses to plant density ranged from 3 to 8 kg ha^{-1} with every increase in 1000 plants (Figure 4.4B; Table 4.5). Biomass from the earliest planting date at Carrington in 2015 was the most responsive to increasing plant density, whereas very late planting was the least responsive (Figure 4.4B; Table 4.5). The linear model explained only 15% of the biomass response to plant density at Carman in 2015 (Figure 4.4A).

At Carrington in 2015, the linear model explained 67% of the biomass response to plant density for early planting, indicating a stronger linear relationship (Figure 4.4B). The linear model explained 32, 30, and 27% of the variation in soybean biomass for mid, late, and very late planting dates, respectively (Table 4.5). It is unclear why biomass did not respond to plant density at Carman in 2014, as an adequate range of low to high plant densities were established (Figure 4.2A). However, the lack of range in plant density at Carrington in 2014 could explain why biomass did not exhibit a response (Figure 4.2B).

Results from this study differ from previous research on soybean biomass response to plant density. A study by Cox et al. (2010) in New York reported that no linear relationship existed between soybean biomass per plant and three soybean seed densities of 385,000, 469,000 and 580,000 seeds ha^{-1} at the R5 stage. In addition, the lowest seed density in this study produced 20% more biomass, and the highest seed density produced 10% less biomass, compared to the intermediate seed density, despite the lack of linear relationship. Soybean yields were similar in the study by Cox et al. (2010), regardless of different biomass levels.

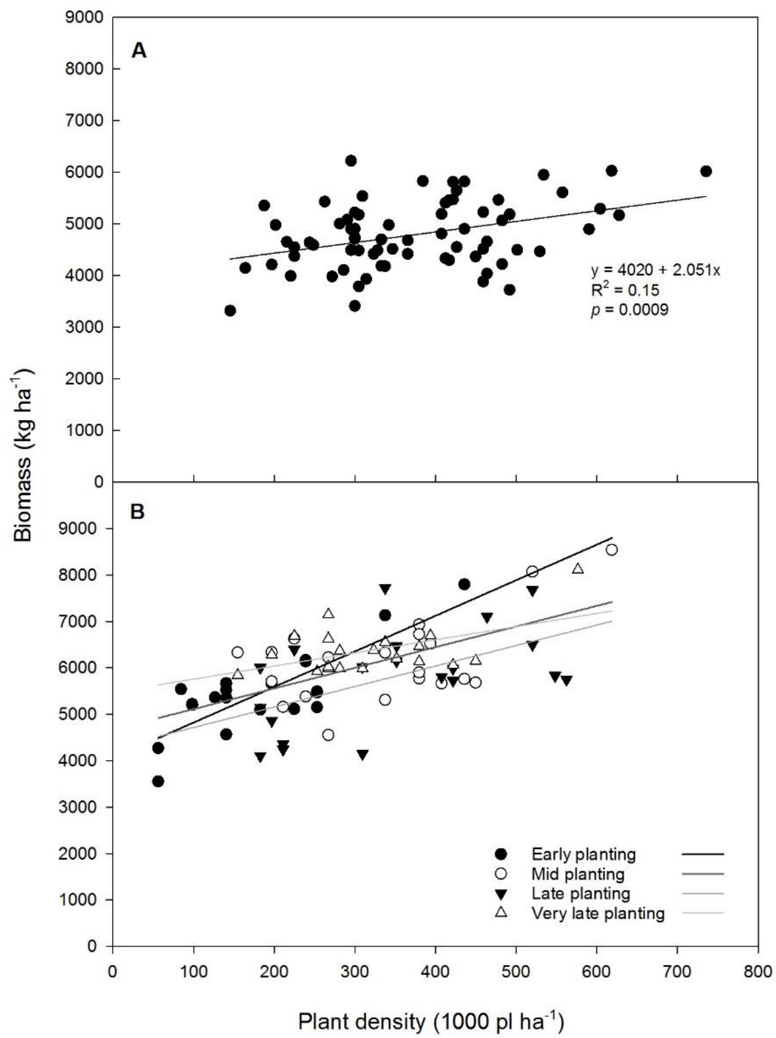

Figure 4.4. The relationship between dry soybean biomass and plant density at **(A)** Carman, MB in 2015 for combined early to late planting dates, and at **(B)** Carrington, ND in 2015 for early to very late planting dates.

Table 4.5. Parameters and goodness of fit statistics for the linear model (y = *a* + *b*x) to describe the relationship between soybean biomass (kg ha^{-1}) and plant density (plants ha^{-1}) for early to very late planting dates at Carrington in 2015. The parameter *a* represents the intercept and parameter *b* represents the slope.

Planting date	*a*	*b*	*p*-Value	R^2
Early	4057	7.660	<0.0001	0.67
Mid	4669	4.442	0.0091	0.32
Late	4276	4.410	0.0131	0.30
Very late	5475	2.828	0.0187	0.27

Previous research by Bhatia et al. (1999) indicated that reduced soybean biomass from late planting contributed to soybean yield loss. From the two site years of this study with significant relationships between soybean biomass and plant density, differences between planting dates occurred at one site (Figure 4.4). However, biomass levels were similar across all planting dates in this study. Differences in soybean biomass between planting dates occurred only for the slope, or response to plant density.

4.4.2.3 Lowest Pod and Plant Height

Height of the lowest soybean pod and soybean plant height prior to harvest were measured to further examine the growth and development response of soybean plants to plant density at different planting dates. Lowest pod height and plant height responded to plant density at only one in four site years at Carman in 2015 (Figure 4.5). Soybean pod and plant height did not respond to plant density at other site years. No significant interactions between soybean planting date and plant density were identified for pod and plant height at Carman in 2015 (Appendix B, Table 7.9; 7.10); thus, results were averaged across planting dates. Both pod and plant height increased with increasing plant density at Carman in 2015 (Figure 4.5), due to intraspecific competition among plants (Mohler, 2001). It is important to note that the linear model explained only 11 and 9% of the variation in soybean pod and plant height, respectively (Figure 4.5). A great deal of variability was also observed for lowest soybean pod height at Carman in 2015. This indicates that other factors, such as moisture throughout the growing season, also influenced these relationships.

Changes in soybean pod and plant height were very minimal. Every increase in 100,000 soybean plants ha^{-1} resulted in soybean pod and plant height increases of 0.7 and 1.2 cm, respectively (Figure 4.5). Smaller ranges in plant density established in site years other than Carman 2015 may explain the lack of soybean pod and plant height response to plant density overall (Figure 4.2). It is also possible that soybean plant densities were not high enough in this study to induce pod and plant height responses in most cases.

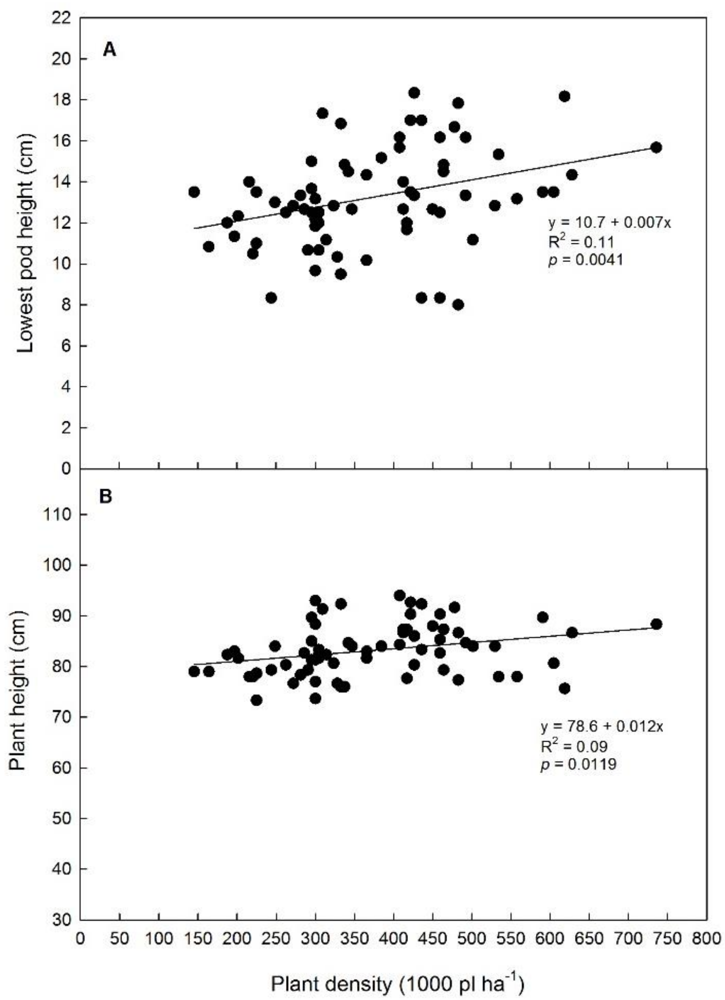

Figure 4.5. The relationship between soybean plant density and **(A)** average height of the lowest soybean pod, and **(B)** soybean plant height at Carman, MB in 2015.

Soybean plants at low densities can compensate in growth; however, lower pod height associated with reduced plant stands is less desirable for soybean growers during harvest due to the heightened risk of machinery damage from soil intake into the combine. However, the results of this study suggest that it would not be beneficial for growers to increase soybean plant density to achieve higher pods due to the overall lack of response.

The results from this study agree with previous research that determined lower seed densities produce shorter plants with more branches and lower pods (Beuerlein, 1988), and higher seed densities result in taller plants with fewer branches and raised height of the lowest pod (Weber et al., 1966; Beuerlein, 1988). The shade avoidance response of soybeans to adjacent plants under high plant densities is the result of increased rate of internode elongation and alteration in the pattern of dry matter allocation (Aphalo and Ballaré, 1995). However, tall plants grown in high plant densities tend to have weak stems, increasing the risk of lodging and development of disease in the crop canopy (Weber et al., 1966; Cooper, 1971; Beuerlein, 1988). Lodging was observed at Carman in 2015 where plants were taller overall, compared to other site years. However, no significant relationship between lodging and plant density was found (Appendix B, Figure 7.3).

4.4.3 Yield Response to Plant Density

Yield is an important variable for determining the yield-maximizing plant density for soybeans. Many growers aim to maximize yield, which is important for minimizing weed competition (Mohler, 2001). However, it is understood that growers must also consider profit when determining the plant density due to high soybean seed costs. The relationship between soybean yield and plant density in this study was asymptotic, where yield increased due to increasing plant density until it reached a plateau at maximum yield. The asymptotic rectangular hyperbola model (Cousens, 1985) was found to be significant for all planting dates of individual and combined site years (Figure 4.6; Figure 4.7). Compared to other yield models such as the linear and quadratic, the asymptotic rectangular hyperbola model and exponential models (Edwards and Purcell, 2005) converged for all treatments and site years. The rectangular hyperbola and exponential models produced similar AIC values across planting date groups and site years (Appendix B, Table 7.2); however, the rectangular hyperbola was chosen because the shape of the function had the best fit with the yield-density relationship of the plotted data.

It was hypothesized that late planting would result in different soybean yield responses to plant density compared with early to mid planting dates. Differences between soybean planting date treatments were determined by evaluating 95% confidence intervals for each model. No significant differences in soybean yield-density relationships were found between mid and late planting dates at Carman in 2014 (Figure 4.6A), and early, mid, late, and very late planting dates at Carrington in 2015 (Figure 4.6D). However, planting date differences were observed at Carrington in 2014 and Carman in 2015. Yield-density relationships were significantly different between mid and late planting dates at Carrington in 2014 (Figure 4.6B). At Carman in 2015, soybean yield-density relationships for early to mid planting dates behaved similarly, whereas late planting was significantly different (Figure 4.6C).

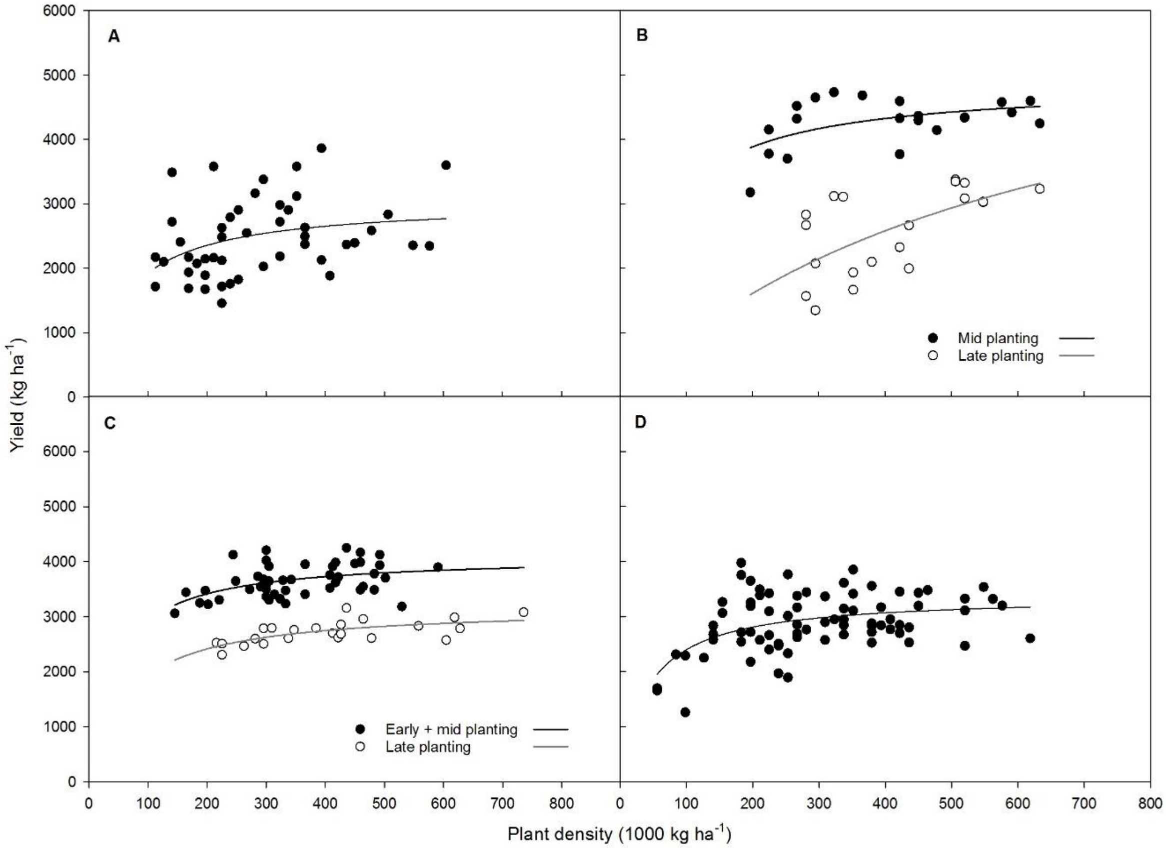

Figure 4.6. The relationship between soybean yield and actual plant density fitted with the rectangular hyperbola model ($y = Ix/(1 + (Ix/a))$) at **(A)** Carman, MB in 2014 for combined mid to late planting dates, **(B)** Carrington, ND in 2014 for mid and late planting dates, at **(C)** Carman, MB in 2015 for combined early to mid, and late planting dates, and at **(D)** Carrington, ND in 2015 for combined early to very late planting dates.

Table 4.6. Parameters and goodness of fit statistics for the rectangular hyperbola model ($y = Ix/(1 + (Ix/a))$) to describe the relationship between soybean yield and plant density for early to very late planting dates of individual and combined site years. Sample size indicates *n* (planting date × plant density × replicate) for each model.

Site Year	Planting Date	*a*	*I*	P-Value	AIC	Sample Size
Carman 2014	Mid + Late	3036	52.9	<0.0001	323	48
Carman 2015	Early + Mid	4105	102.3	<0.0001	288	48
	Late	3185	50.0	<0.0001	243	24
Carrington 2014	Mid	4882	95.3	<0.0001	278	20
	Late	6527	10.7	<0.0001	299	20
Carrington 2015	Early + Mid + Late + Very Late	3385	82.2	<0.0001	326	80
Combined Site Years	Early + Mid	4474	46.1	<0.0001	352	132
	Late + Very Late	3264	63.9	<0.0001	342	128

The soybean yield-density relationship for late planting at Carrington in 2014 exhibited a different trend compared to all other planting dates and site years. Yield appeared to continue trending upward with increasing plant density, although the highest plant densities exceeded 600,000 pl ha^{-1} (Figure 4.6B). This result suggests that soybean plant densities were not high enough for yield to reach a plateau. No yield data was available for the very late planting date at Carrington in 2014 due to a killing frost on October 3rd that prevented plots from reaching physiological maturity.

Soybean yields of all four combined site years were analyzed to determine the response to plant density across a larger northern growing region. The combined site year analysis resulted in two significantly different planting date groups: 1) early/mid, and 2) late/very late. Planting date groups were identified using overlapping 95% confidence intervals of both equation parameters for soybean yield-density relationships among early to mid, and late to very late planting dates, respectively. No overlap of 95% confidence intervals occurred among planting date groups. The rectangular hyperbola model was fitted to each planting date group, in which soybean yield increased with increasing plant density until a plateau was reached (Figure 4.7). Strong soybean yield-density relationships were found for combined site year planting date groups, similar to individual site years. The yield-density relationship for late/very late planting appeared to reach a plateau, whereas yield appeared to continue to increase with increasing plant density for the early/mid planting date group (Figure 4.7).

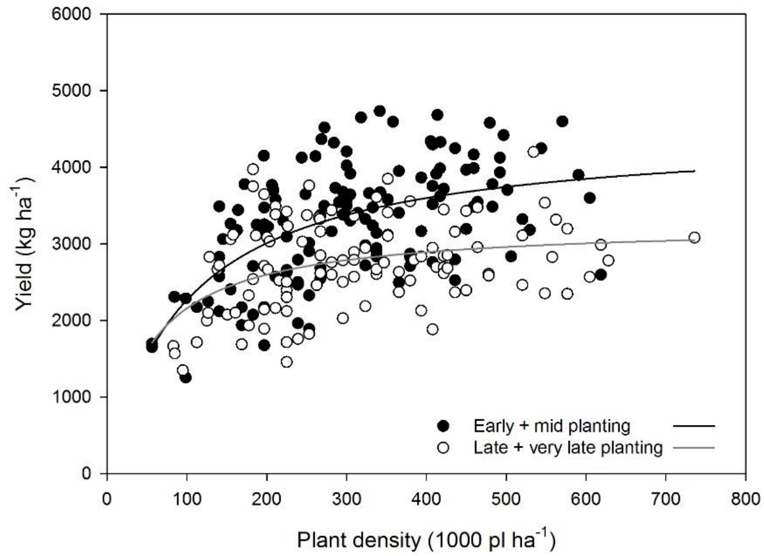

Figure 4.7. The relationship between soybean yield and actual soybean plant density for early to mid, and late to very late planting date ranges fitted with the rectangular hyperbola model (y = $Ix/(1 + (Ix/a))$) for combined site years.

Similar to the literature, the soybean yield-density relationship in this study was described as asymptotic. Previous studies conducted across the United States used the exponential (Parvez et al., 1989; Edwards and Purcell, 2005; Popp et al., 2006; De Bruin and Pedersen, 2009) or Mitscherlich (Lee et al., 2008) models to describe the soybean yield-density relationship. The rectangular hyperbola model followed a similar pattern as the other asymptotic models, where soybean yield increased with increasing plant density until a plateau was reached at maximum yield. However, the rectangular hyperbola appeared to reach a plateau at a higher plant density compared to the exponential and Mitscherlich models. In contrast, a study conducted by Mohr et al. (2014) in Manitoba described the soybean yield-density relationship using a parabolic quadratic model, which depicted a decline in soybean yield beyond the plant density which maximized yield.

Rectangular hyperbola model parameters examined in this study were maximum soybean yield and the initial rate of change in soybean yield as plant density approaches zero (Cousens, 1985). Significant differences between planting date treatments were evaluated using analysis of variance. Statistical comparisons could only be made for site years where yield-density relationships were significantly different between planting dates, which included Carrington in 2014 and Carman in 2015 (Table 4.7). For late planting at Carrington in 2014, model convergence did not occur for all reps. Due to this unbalanced data set, analysis of variance between mid and late planting dates could not be completed (Table 4.7). The only significant difference between planting date groups of individual site years occurred for maximum soybean yield at Carman in 2015 (Table 4.7). Maximum yield at Carman in 2015 was greater for early/mid planting compared to late planting, as expected (Table 4.7). A similar result was observed for combined site years, where early/mid planting yielded significantly greater than late/very late planting (Table 4.7).

Soybean yield parameters derived from the rectangular hyperbola model differed between planting date groups of the combined data set (Table 4.7). The early/mid planting date group yielded significantly greater than the late/very late planting date group (Table 4.7). However, a significantly greater initial rate of change in soybean yield was determined for late/very late planting compared to early/mid planting. This result indicated that soybean yield was more responsive to plant density at late/very late planting dates. However, the greater initial slope did not result in increased soybean yield, as late/very late planting dates yielded significantly less than early/mid planting dates. Contrary to our hypothesis, the results from individual and combined site years

Table 4.1. Parameters derived from the rectangular hyperbola model ($y = Ix/(1 + (Ix/a))$) to describe the relationship between soybean yield and plant density for planting date groups at each site year.

Site Year	Planting Date	Maximum Yield (a)		Rate of Change in Yield (I) †	
		-----kg ha^{-1}-----		---yield 000 pl^{-1}---	
Carman 2014	Mid + Late	3036	**-**	52.92	**-**
Carman 2015	Early + Mid	3949	**a**	113.2	**a**
	Late	3076	**b**	139.4	**a**
Carrington 2014	Mid	5238	**a**	103.1	**-**
	Late	4701	**a**	-	**-**
Carrington 2015	Early + Mid + Late + Very Late	3385	**-**	82.17	**-**
All Site Years Combined	Early + Mid	4520	**a**	46.05	**b**
	Late + Very Late	3242	**b**	70.48	**a**

† Rate of change in yield as plant density approaches zero.

‡ Means within a column followed by the same letter are not significantly different at $p<0.05$ according to Fischer's protected LSD test.

indicated that no yield benefit would result from increasing soybean plant density with later planting. However, this finding should be tested further with additional site years.

One of the most important findings from this study was that no optimum, or yield-maximizing, soybean plant densities were identified for any planting dates and site years. No optimum plant densities were identified because soybean yield did not reach a true plateau within the range of established plant densities in this study (Figure 4.6; 4.7). This was likely caused by the nature of the rectangular hyperbola model describing the yield-density relationship. As previously discussed, other asymptotic models used to describe soybean yield-density in previous studies appeared to reach a plateau at lower soybean plant densities than the rectangular hyperbola model (Parvez et al., 1989; Edwards and Purcell, 2005; Popp et al., 2006; Epler and Staggenborg, 2008; De Bruin and Pedersen, 2009). Due to this lack of yield maximization, the results from this study suggest that soybean plant densities should be increased beyond the current recommendation of 395,000 plants ha^{-1} (Mohr et al., 2014). However, yields in this study were very close to the point in which the expected plateau would occur. In other words, further yield increases with increasing plant density beyond the highest established plant stand in this study would be minimal. Thus, growers should aim for greater plant densities to achieve higher yields and improved competition against weeds, but it would not be necessary to increase plant density beyond the maximum stand established in this study.

The continued increase in soybean yield with increasing plant density described by the rectangular hyperbola model suggests an overall lack of intraspecific competition among soybean plants. Mohler (2001) reported that the relationship between crop yield and plant density should be described as a parabolic relationship, where yield increases with increasing plant density, reaches a maximum level, then declines with further increases in plant density due to intraspecific competition. In contrast, most studies examining the soybean yield response to plant density have reported an asymptotic relationship where yield does not decline at high plant densities. The results from this study agree with other soybean yield-density research, suggesting an overall lack of soybean sensitivity to intraspecific competition.

The effect of planting date on maximum soybean yield in this study agrees with previous research. In this study, soybeans planted prior to the end of May resulted in greater yields compared to late planting in June (Table 4.7). In a study by De Bruin and Pedersen (2008a), early planting of MG II soybean varieties from late April to early May consistently yielded greater than planting from late May to early June in Indiana. Wilcox and Frankenberger (1987) in Indiana found a yield advantage to indeterminate MG II soybean varieties planted in early May compared to planting dates ranging from late May to mid-June. Robinson et al. (2009) determined that soybeans seeded from April 10 to May 9 in Indiana resulted in the greater yields compared to late March and early June seeding dates. Finally, a meta-analysis of nine planting date studies by Egli and Cornelius (2009) reported that soybean yield rapidly declined when planting was delayed beyond May 27, regardless of maturity group in the southeastern United States.

In the literature, several factors contribute to soybean yield reduction from late planting, including: reduced total biomass, pod number per plant, plant height, branch number (Bhatia et al., 1999), seed number and mass (Egli, 1975; Parker et al., 1981; Egli et al., 1987; Bhatia et al., 1999), soil moisture as the season progresses (Tanner and Hume, 1978), insolation, or solar radiation, received during the reproductive growth phase (Egli and Bruening, 1992), and time from planting to flowering and maturity (Bhatia et al., 1999).

Soybean yield-density results from this study are different from the literature due to the use of the rectangular hyperbola model describing this relationship. Other studies have identified yield-maximizing soybean plant densities using the exponential and Mitscherlich models; however, no yield-maximizing plant densities were identified within the range of established plant densities in this study due to the rectangular hyperbola model. A study by Mohr et al. (2014) identified an optimum soybean plant density of 395,000 plants ha^{-1} for maximized yield in Manitoba. This study employed a parabolic quadratic equation to describe the soybean yield-density relationship at 13 site years. Studies conducted across the United States examining MG II to IV identified yield-maximizing soybean plant densities ranging from 108,000 to 618,000 plants ha^{-1}. Yield-maximizing plant densities from the yield-density model exceeded the maximum plant density of 736,000 plants ha^{-1} established in this field study (Figure 4.7). The yield-maximizing plant density from the model is also well above the range reported in the literature.

Soybean yield-density relationships from this study challenge results in the literature by pointing to the benefit of increased plant densities to increase soybean yield. However, high seed costs limit the extent to which growers can economically increase seed density. Yield-maximizing plant densities reported in this study would be too expensive for growers; thus, factors such as commerical soybean grain price, soybean seed cost, and seedling mortality need to be accounted for to determine the profit-maximizing plant or seed density level.

4.4.4 Economic Optimum Seed Densities

4.4.4.1 Marginal Cost Analysis

Development of seed density, or seeding rate, recommendations involves the trade-off between seed cost minimization and crop yield maximization (Wahab et al., 1986; Saindon et al., 1995; De Bruin and Pedersen, 2008a). Growers are interested in reducing seed densities as much as possible to avoid associated costs. Regardless, growers are interested in maximizing profit. A marginal cost analysis incorporating both seed cost and grain revenue was used to determine economic optimum seed density (EOSD) recommendations for soybeans (Jettner et al., 1999; Lawley, 2004). A set of necessary assumptions were used to calculate the EOSD of soybeans for each site year (Dennis Lange, Personal Communication). These assumptions are listed in Table 4.3.

The response of total soybean seed cost and total soybean grain revenue to simulated plant density for each site year and planting date group is depicted in Figure 4.8. The trend in total cost was similar for all site years; however, total revenue appeared to vary across site years and planting dates (Figure 4.8). The maximum distance between total cost (TC) and total revenue (TR), represented the EOSD or point of profit maximization (Figure 4.8). Total revenue followed a slightly different trend for late planting at Carrington in 2014 (Figure 4.8B) due to its unique yield-density relationship (Figure 4.6B).

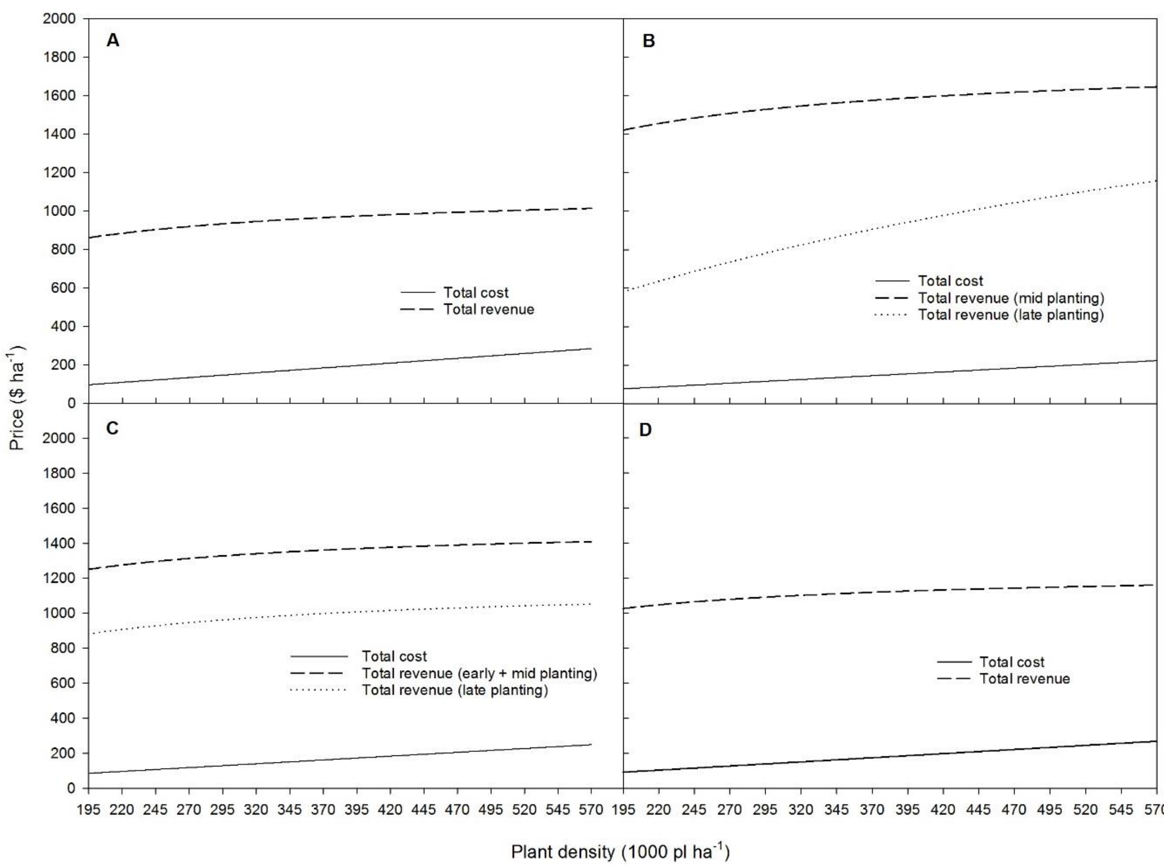

Figure 4.8. The relationship between soybean plant density and total cost and total revenue at **(A)** Carman, MB in 2014 for combined mid and late planting dates, and **(B)** Carrington, ND in 2014 for mid and late planting dates, at **(C)** Carman, MB in 2015 for combined early to mid, and late planting dates, and at **(D)** Carrington, ND in 2015 for combined early to very late planting dates.

The response of marginal soybean seed cost and marginal soybean grain revenue to simulated soybean plant density is depicted in Figure 4.9. Both marginal cost and marginal revenue represent the change in total cost and total revenue, respectively, for each one-unit increase in plant density per unit of area, or 1000 plants ha^{-1}. The intersection point between MR and MC depicts the point of profit maximization, or EOSD. In all cases, marginal cost remains constant with increasing plant density, whereas marginal revenue decreases at a decreasing rate with increasing plant density (Figure 4.9). Intersection points occurred for all site years and planting dates except late planting at Carrington in 2014. Soybean EOSD was hypothesized to be greater for late planting. This hypothesis could only be tested for Carman 2015 where there were significant differences in soybean yield-density relationships between early/mid and late planting date groups (Figure 4.6C). However, similarity between intersection points of MC and MR for planting date groups at Carman in 2015 do not support the recommendation to increase seed density with late planting (Figure 4.9C).

A combined marginal cost analysis of all four site years was conducted to determine EOSDs for the two planting date groups previously identified: early/mid and late/very late. Differences in EOSD were apparent between early/mid, and late/very late planting date groups, as both the maximum distance between TC/TR and MC/MR intersection points aligned at different plant densities for the two planting date groups (Figure 4.10). The MC/MR intersection point of the early/mid planting date group occurred at a higher plant density, indicating that it was more economical to increase soybean seed density for early/mid-planting, rather than for late/very late planting.

Higher maximum yields were likely the cause of greater TR generated from early/mid planting compared to late/very late planting (Table 4.7).

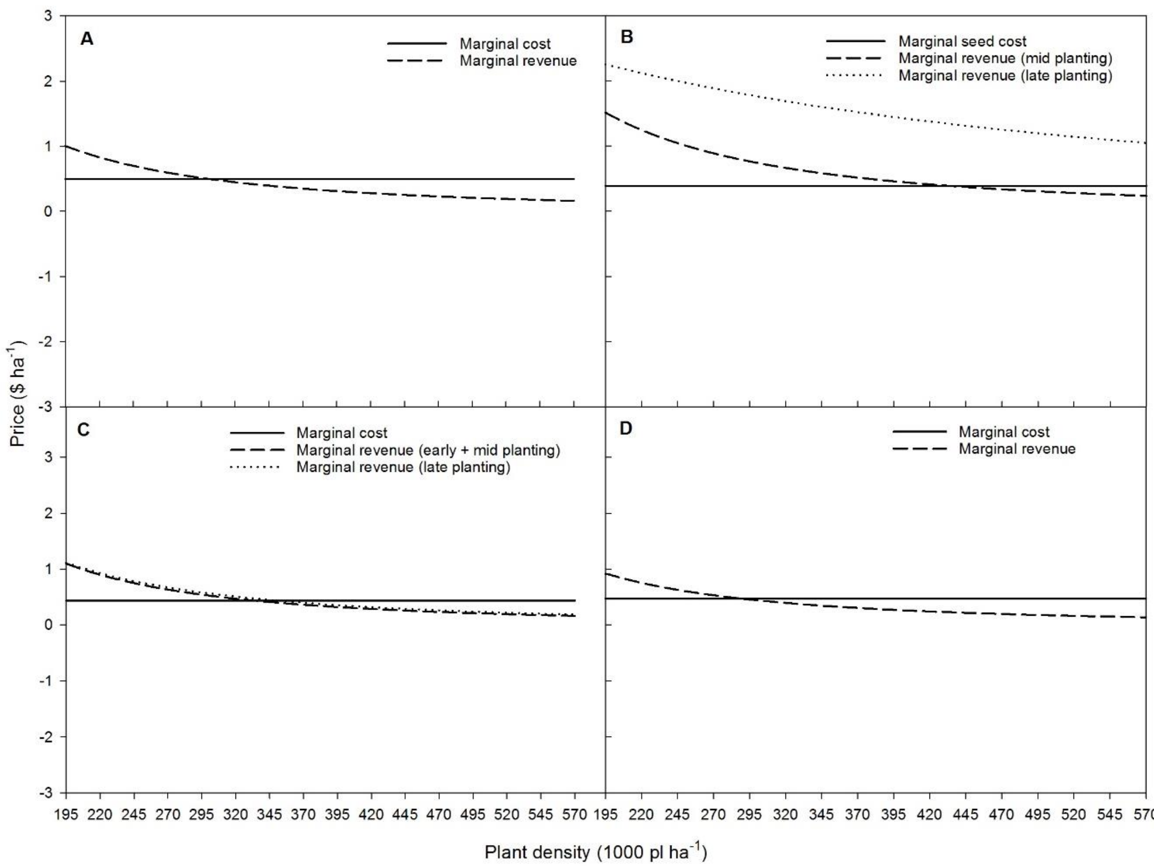

Figure 4.9. The relationships between soybean plant density and marginal seed cost and marginal grain revenue at **(A)** Carman, MB in 2014 for combined mid to late planting dates, and **(B)** Carrington, ND in 2014 for the mid planting date, at **(C)** Carman, MB in 2015 for combined early to mid, and late planting dates, and at **(D)** Carrington, ND in 2015 for combined early to very late planting dates.

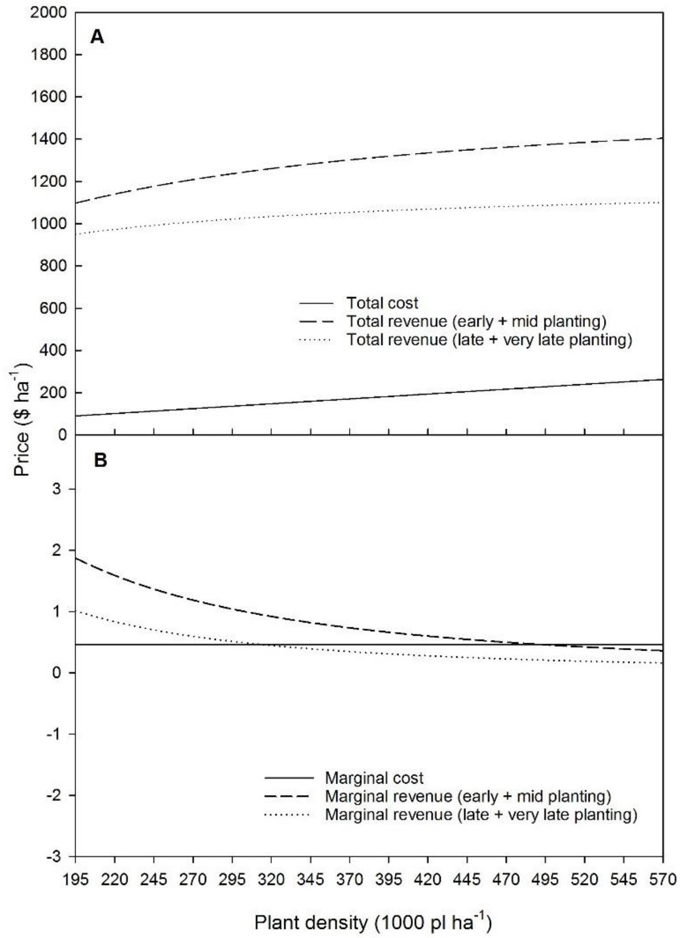

Figure 4.10. The relationships between soybean plant density and **(A)** total cost and total revenue, and **(B)** marginal cost and marginal revenue, for early/mid, and late/very late planting date groups from combined site years.

A profit function incorporating yield, grain revenue, soybean seed cost, plant density, and seedling mortality (Section 4.3.7) was used to calculate EOSDs for planting date groups, and both individual and combined site years (Table 4.8). The EOSD for combined mid/late planting at Carman in 2014 was 300,000 seeds ha^{-1}, 430,000 seeds ha^{-1} for mid planting at Carrington in 2014, 333,000 seeds ha^{-1} for combined early/mid planting dates at Carman in 2015, and 313,000 seeds ha^{-1} for combined early to very late planting at Carrington in 2015 (Table 4.8). In contrast, EOSDs for late planting were as high as 350,000 and 1,356,000 seeds ha^{-1} at Carman in 2015 and Carrington in 2014, respectively (Table 4.8). However, the EOSD from late planting at Carrington in 2014 was also considered to be an anomaly due to the unique yield-density relationship (Figure 4.6B).

Table 4.8. Economic optimum seed densities (EOSDs) of soybeans for different planting date groups of individual and combined site years.

Site Year	Planting Date	Economic Optimum Seed Density
		------000 seeds ha^{-1}------
Carman 2014	Mid + Late	300
Carman 2015	Early + Mid	333
	Late	350
Carrington 2014	Mid	430
	Late	1356
Carrington 2015	Early + Mid + Late + Very Late	313
Combined Site Years	Early + Mid	492
	Late + Very Late	314

Economic optimum seed densities of soybeans differed between planting date groups of all site years combined. The EOSDs for early/mid and late/very late planting were 492,000 and 314,000 seeds ha^{-1}, respectively (Table 4.8). This result suggests that it would not be economical to increase soybean seed density with later planting. However, it is suspected that environmental conditions influenced these profit maximizing values and additional site years are needed to test this finding.

Soybean EOSDs in Table 4.8 were overall lower than the recommended plant density of 395,000 plants ha^{-1} for Manitoba (Mohr et al., 2014). Exceptions to this were mid planting at Carrington in 2014 and early/mid planting of combined site years. It is important to highlight that profit-maximizing values in this study were reported as seed density, rather than plant density, due to the incorporation of seed cost into calculations.

For soybean yield-density relationships described by the rectangular hyperbola model (Figure 4.6; 4.7), the EOSDs calculated in this study provided an indication of where the slope approaches zero. It is suspected that the point in which slope approaches zero would equate approximately to the point where soybean yield was maximized by plant density, as in previous studies examining soybean yield-density (Edwards and Purcell, 2005; De Bruin and Pedersen, 2008b; Lee et al., 2008). Thus, EOSD values in this study were similar to optimum soybean plant densities at 95% of maximum predicted yield reported in the literature (Section 2.6.2, Table 2.3).

In this study, stark differences were observed between yield-maximizing plant density and profit maximizing seed density. Soybean yield-density relationships pointed to the benefit of increasing soybean plant density for greater yield, although yield did not reach a true maximum within the established range of plant densities in this study. In contrast, soybean EOSDs that resulted in maximum profit were similar to or slightly less than current recommendations, and more realistic from a grower perspective. Optimum soybean plant densities were also greater than economic optimums in previous studies. A study by Lee et al. (2008) in Kentucky determined that economic optimum soybean plant densities ranged from 76,000 to 241,000 plants ha^{-1}. These economic optimums were 7 and 33% lower than plant densities that maximized yield, respectively. Another study by De Bruin and Pedersen (2008a) in Iowa determined the economic optimum soybean plant density of 171,000 plants ha^{-1} was lower than the range of soybean plant densities which achieved 95% of maximum predicted yield, ranging from 194,000 to 291,000 plants ha^{-1}. However, it is important to note that these optimum soybean plant densities were all identified under weed-free conditions.

One limitation of this economic analysis was that the influence of weed dynamics on soybean EOSDs was not accounted for. Conventional wisdom has highlighted the efficiency of reduced soybean plant densities due to high seed costs. However, reduced plant densities increase the risk of herbicide-resistant weed development in glyphosate-resistant, or Roundup Ready, cropping systems (Dewerff et al., 2014; Heap, 2014), as soybeans are poor competitors against weeds (Van Acker et al., 1993). Although the mutation frequency is low for glyphosate, the widespread use in current soybean cropping systems has increased the risk of resistance selection for many weed species (Harker et al., 2012; Heap, 2014). Profit maximization is an important practical aspect of crop production for growers; however, the presence of glyphosate resistant weeds would likely have a greater long-term economical impact compared to increased soybean seed densities to help prevent this issue. Increased plant density of soybeans could be one component of an integrated weed management strategy to reduce the risk of further glyphosate-resistant weed development in current soybean cropping systems (Harker et al., 2012; Mortensen et al., 2012; Vencill et al., 2012; Dewerff et al., 2014). Alternatively, high plant densities can increase the risk of disease development within the crop canopy. Thus, both disease and weed dynamics should be considered as components of an integrated management strategy when determining optimum soybean plant density.

4.4.4.2 Sensitivity Analysis

A sensitvity analysis was conducted to test the influence of assumptions made in order to calculate soybean EOSDs. To observe the overall trend in EOSD sensitivity to changing commercial soybean price, EOSD values were calculated over a range of prices from \$0.10 to \$0.08 kg^{-1} to represent fluctuating market prices for soybean grain. As the commercial grain price of soybeans increased, EOSD increased at a decreasing rate (Figure 4.11). Trends appeared to be similar for all planting date groups and site years.

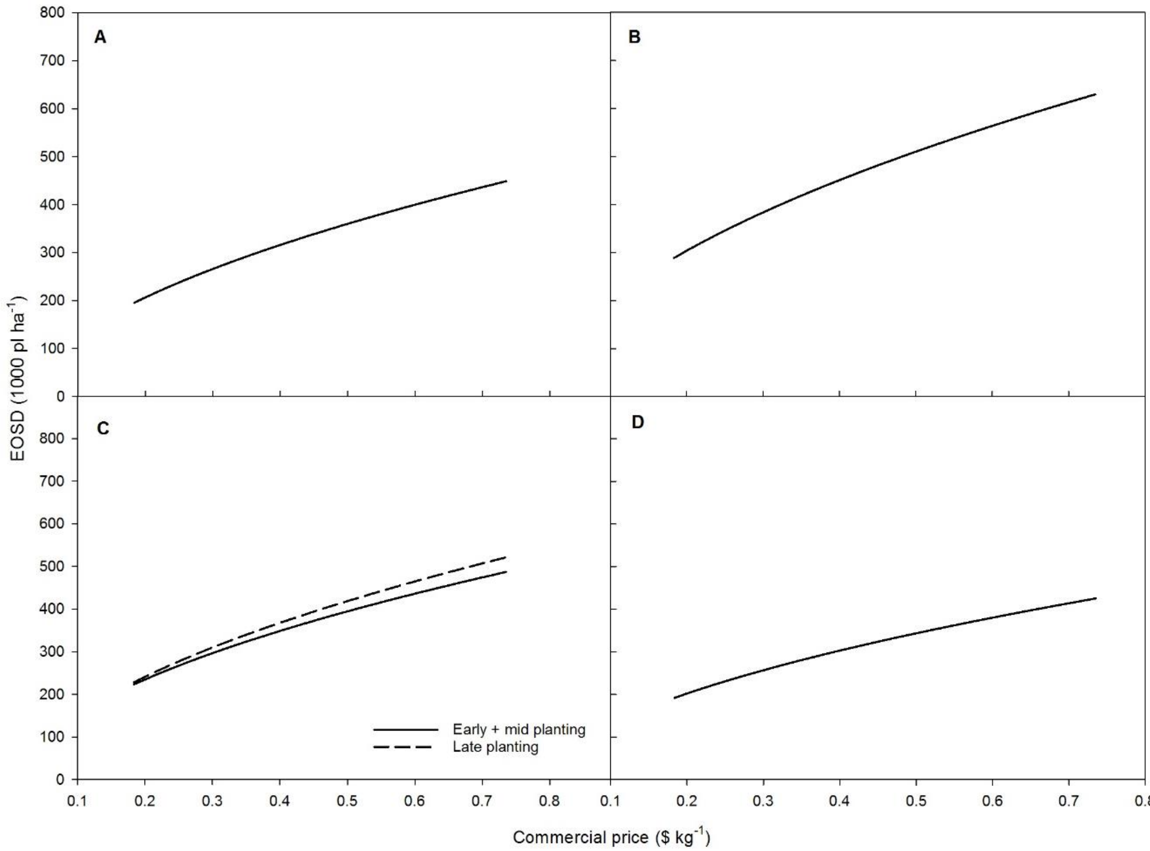

Figure 4.11. Sensitivity of economic optimum soybean seed density to changes in commercial soybean price at **(A)** Carman, MB in 2014 for combined mid and late planting dates, and **(B)** Carrington, ND in 2014 for the mid planting date, at **(C)** Carman, MB in 2015 for combined early to mid, and late planting dates, and at **(D)** Carrington, ND in 2015 for combined early to very late planting dates. Note: Values of EOSD for late planting at Carrington in 2014 far exceeded the plant density range depicted in price sensitivity graphs.

Table 4.9. Percentage change in economic optimum seed density (EOSD) of soybeans for planting date groups at individual and combined site years with realistic extremes in commercial soybean grain price and seed cost to test the sensitivity of assumptions.

Site Year	Planting Date	20% decrease in price† ($0.29 kg^{-1})	20% increase in price ($0.44 kg^{-1})	10% increase in cost‡ ($0.39 1000 seeds^{-1})	20% increase in cost ($0.43 1000 seeds^{-1})	30% increase in cost ($0.46 1000 seeds^{-1})
		% change in EOSD				
Carman 2014	Mid + Late	-12.6	11.4	5.4	11.2	16.6
Carman 2015	Early + Mid	-11.8	12.5	5.2	10.7	15.8
	Late	-10.7	11.3	5.4	11.3	16.7
Carrington 2014	Mid	-11.8	15.3	5.2	10.7	15.8
	Late	-10.7	13.8	6.7	14.3	21.4
Carrington 2015	Early + Mid + Late + Very Late	-12.1	10.9	5.2	10.8	16.0
Combined Site Years	Early + Mid	-12.6	12.3	5.4	11.4	16.8
	Late + Very Late	-11.4	11.1	5.3	11.0	16.3

† The 20% change in commercial soybean grain price from the assumed price of $0.37 kg^{-1}.
‡ The 10, 20, and 30% increases in soybean seed cost from the assumed minimum seed cost of $0.36 1000 seeds^{-1}.

The sensitivity of EOSD values to changing assumptions of commercial soybean grain price were numerically assessed using the percentage change in EOSD based on realistic price extremes. The lowest and highest values for soybean grain price experienced in Canada over the past 10 years were identified as \$0.29 and \$0.44 kg^{-1}, respectively (Dennis Lange, personal communication). These prices represented a 20% change in soybean price from the assumed price of \$0.37 kg^{-1}, and are summarized in Table 4.9. Using early/mid planting at Carman in 2015 as an example (Figure 4.11), EOSD decreased by 11.8% with a 20% decrease in price and increased by 12.5% with a 20% increase in price (Table 4.9). This result suggests that economic optimum soybean seed densities calculated in this study are sensitive to changing commercial soybean grain price. Thus, soybean EOSDs should be adjusted for changes in commercial soybean grain price.

A similar method was used to determine the trend in EOSD sensitivity to changing soybean seed cost. Economic optimum soybean seed density was calculated over a range seed costs from \$0.25 to \$0.55 per thousand seeds. Soybean EOSD decreased at a decreasing rate with increasing soybean seed cost (Figure 4.12). Trends appeared to be similar across all planting date groups and site years (Figure 4.12). The response of soybean EOSDs to changing commercial soybean grain price and soybean seed cost from combined site years was similar to those of individual site years (Figure 4.13).

The sensitivity of soybean EOSDs to different assumptions of seed cost was calculated as the percentage change in EOSD with realistic changes in soybean seed cost. Soybean seed costs of \$0.39, \$0.43, and \$0.46 per thousand seeds were used to calculate

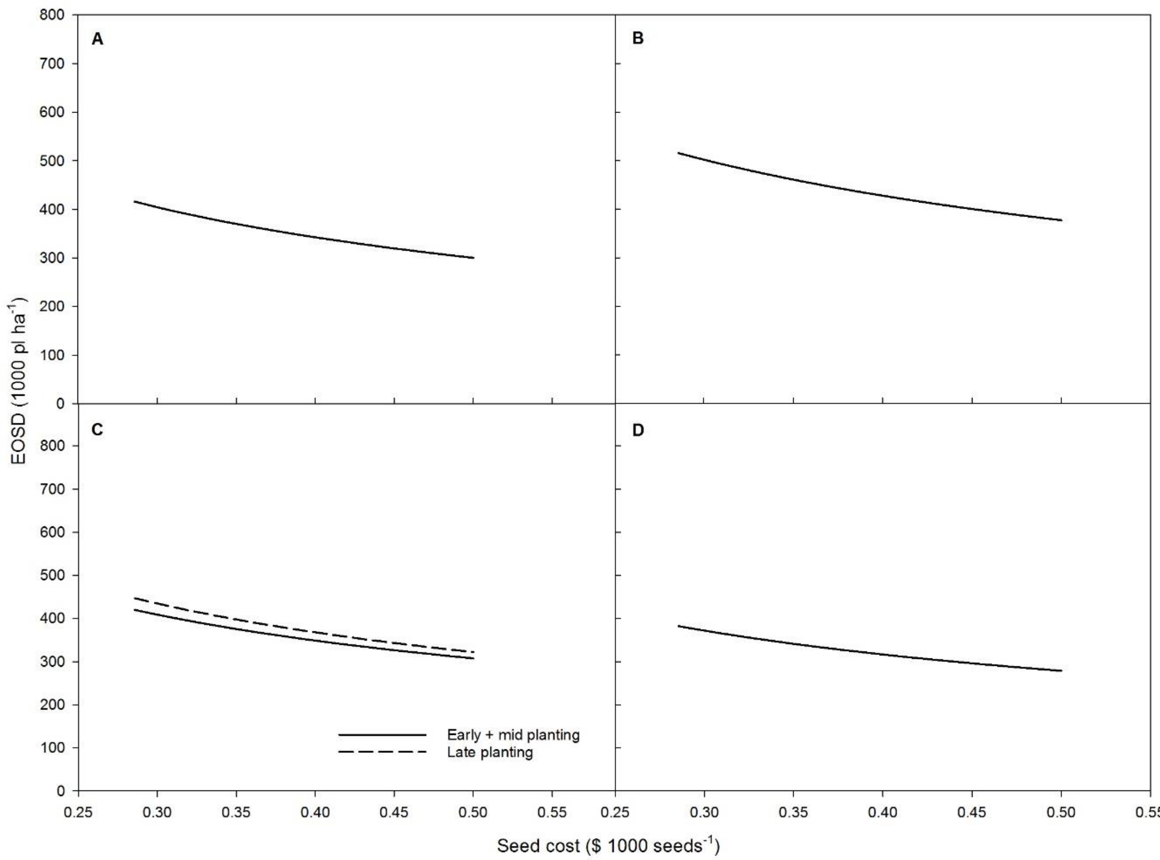

Figure 4.12. Sensitivity of economic optimum soybean seed density to changes in soybean seed cost at **(A)** Carman, MB in 2014 for mid and late planting dates combined, and **(B)** Carrington, ND in 2014 for the mid planting date, at **(C)** Carman, MB in 2015 for combined early to mid, and late planting dates, and at **(D)** Carrington, ND in 2015 for early to very late planting dates combined. Note: Values of EOSD for late planting at Carrington in 2014 far exceeded the plant density range depicted in cost sensitivity graphs.

EOSD sensitivity, summarized in Table 4.9. These soybean seed cost values represent 10, 20, and 30% increases in seed cost compared to the base price of $0.36 per thousand seeds assumed in the model. Each percentage increase represents the additional cost of fungicide seed treatment, insecticide seed treatment, and both fungicide and insecticide seed treatment, respectively. Again using early/mid planting at Carman in 2015 as an example (Figure 4.12), EOSD decreased by 5.2, 10.7, and 15.8% with 10, 20, and 30% increases in soybean seed cost, respectively. The percentage EOSD change in response to increasing soybean seed cost was substantial, indicating that profit-maximizing seed densities were sensitive to seed cost changes. Thus, soybean EOSDs need to be adjusted for changing soybean seed cost.

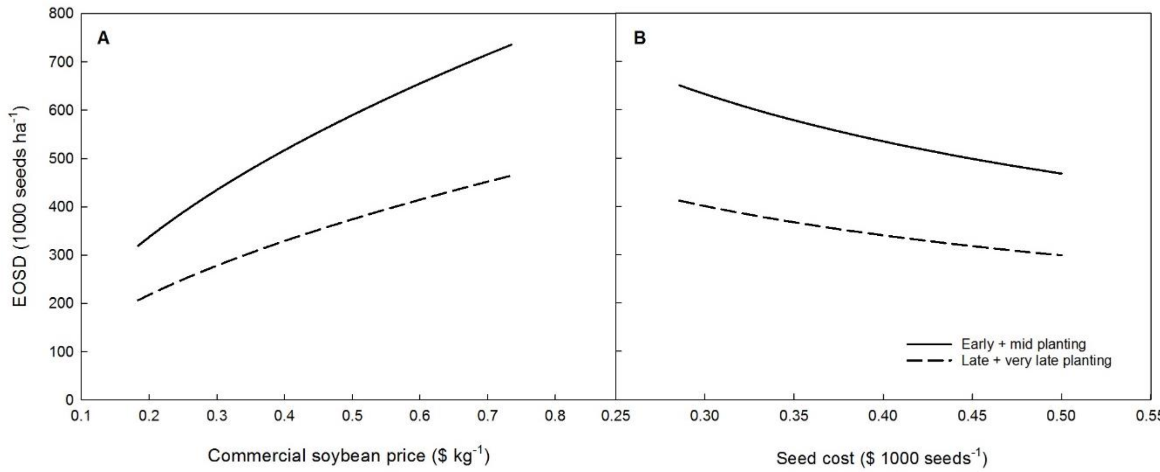

Figure 4.13. Sensitivity of economic optimum soybean seed density to **(A)** changes in commercial soybean price, and **(B)** soybean seed cost for early to mid, and late to very late planting date groups of all site years combined.

The responsiveness of soybean EOSDs to grain price and seed costs changes is another limitation of this economic analysis. Due to this sensitivity, growers would need to calculate profit-maximizing soybean seed densities based on their seed costs and current grain prices. Thus, results from this study would be most useful in the form of a seeding rate calculator for growers. However, the need to adjust EOSDs based on agronomic factors not included in the marginal cost analysis, such as weed or disease dynamics, remains a limitation of this calculator, as previously discussed.

4.4.5 Conclusions

Significant relationships between soybean yield and plant density were identified for all planting dates and site years in this study. Soybean yield-density relationships were described by the rectangular hyperbola model in all cases, following a similar asymptotic pattern where soybean yield increased with increasing plant density until a plateau, or yield maximum. An important finding from this study was that soybean yields did not reach a true maximum within the range of established plant densities. This result suggests that greater plant densities have the potential to increase yield; however, actual yields in this study were near the yield plateau level. It also confirms that soybeans do not easily exhibit intraspecific competition, as soybean yield continued to increase with increasing plant density.

Soybean yield-density relationships were sensitive to planting date. The relationship between soybean yield and plant density was significantly different between planting dates at two out of four individual site years. The combined analysis of all four site years determined that soybean yield-density relationships formed two planting date groups: 1) early/mid (May 4 to 26), and 2) late/very late (June 2 to 23). However, soybean yield-density relationships were similar within each planting date group. Maximum yield of early/mid planting was significantly greater than late/very late planting. Maximum yields were 4520 and 3242 kg ha^{-1} for each planting date group, respectively. However, late/very late planting exhibited a greater initial rate of change in soybean yield with increasing plant density.

Soybean EOSDs in this study were within the range of optimum soybean plant densities reported in the literature (Section 2.6.2, Table 2.3). The economic optimum seed density (EOSD) of soybeans was 492,000 seeds ha^{-1} for early/mid planting, greater than the EOSD for late/very late planting at 314,000 seeds ha^{-1}. However, profit-maximizing soybean seed densities were much lower than predicted yield-maximizing plant densities in this study. This result suggests that the trade off between seed cost minimization and yield maximization was more dramatic than expected. However, it may be unrealistic and too expensive for growers to target plant densities greater than those established in this study to achieve maximum yield.

This study was conducted under weed-free conditions with limited disease pressure. Both of these factors would influence a grower’s seed density decision, and thus remains a limitation of this marginal cost analysis to determine EOSDs. When considering reduced plant or seed densities for profit maximization, weed competition can reduce yield due to the naturally poor competitive ability of soybean crops. Widespread use of glyphosate increases the risk of herbicide resistance and reduced soybean seed densities would further increase resistance selection pressure. In contrast, the risk of disease development, such as white mould (*Sclerotinia sclerotiorum*), within the crop canopy increases when considering increased soybean plant or seed densities. Thus, future research should be designed to allow for these components to be included as factors in marginal cost analysis to determe profit-maximizing soybean plant or seed densities.

Future research should seek to incorporate additional site years of data to determine optimum soybean plant densities for different planting dates. Individual site years provided evidence for increased soybean plant densities with later planting; however, combined site years did not. Results may change with different years and environmental conditions. Economic analyses in future studies should also seek to adapt optimum soybean plant or seed density calculations for increased competition against weeds, and mitigation of disease development.

5.0 GENERAL DISCUSSION

This research aimed to strengthen soybean planting date and plant density recommendations for northern growing regions of the Northern Great Plains (NGP) due to the continuing expansion in soybean production. Northern growing regions of the NGP experience short growing seasons, an increased risk of spring and fall frost, and cold soil temperatures at planting. Thus, the window for planting soybeans in northern growing regions is constrained, as soybeans are a long season crop.

Soybean planting date and plant density are closely related agronomic decisions. Planting date and plant density decisions are made simultaneously at the beginning of the growing season and can both be managed to increase soybean yield and economic return. Several studies that examined soybean planting date also examined plant density (Parvez et al., 1989; Oplinger and Philbrook, 1992; Ball et al., 2000; De Bruin and Pedersen, 2008a). However, soybean planting date and plant density responses vary across locations, years, and varieties (Tanner and Hume, 1978; Pedersen, 2003; De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009), and plant density responds to planting date (De Bruin and Pedersen, 2008a). The overall objectives of this research were to determine the effects of soybean planting dates based on soil temperature, and identify the optimum soybean plant densities for different planting dates, in the development of stronger soybean planting recommendations in northern growing regions of the NGP.

5.1 The Effect of Soybean Planting Dates Based on Soil Temperature in Manitoba

The main objective of this experiment was to determine if soil temperature at planting was an influential factor on early season factors such as days to emergence and plant stand establishment, and late season factors such as days to maturity and soybean yield. A major finding from this study was that soil temperature at planting did not influence soybean yield, the opposite of what was hypothesized. Only one out of three site years resulted in a significant negative soybean yield response to soil temperature; however, further analysis of this significant relationship identified that soybean yield at that site had a significant negative response to planting date. The significant relationship between soybean yield and planting date from one site year was examined separately for short and long season varieties due to a significant interaction between planting date and variety. For each soybean variety, the earliest planting dates resulted in the greatest yields and yield declined with later planting.

From the results of this study, it is recommended that growers should plant soybeans as early as possible during the planting period for maximized soybean yield. When determining the time to plant soybeans, growers are also advised to assess: 1) the risk of both spring and fall frost, 2) seedbed conditions, 3) weather conditions following seeding, and 4) their personal timeline to complete seeding and harvest of all crops. Both spring and fall frost damage have negative implications for soybean yield, although yield reduction from spring frost causing high seedling mortality in this study could not be validated. Seedbed conditions should be adequate for successful soybean seed placement, germination, and plant establishment in the spring. Chilling injury during imbibition still poses a risk to soybean plant establishment if seeded early, although soil temperatures were not actually low enough in this study to cause injury by chilling. Finally, the yield potential of other crops grown in northern regions, such as spring wheat (*Triticum aestivum* L.) (Nass et al., 1975; Hunt et al., 1996) and canola (*Brassica napus* L.) (Scott et al., 1973; Ma et al., 2016), can also decline rapidly if seeded later in May. Thus, growers should also consider appropriate planting dates of other crops when determining the time to plant soybeans.

5.2 Soybean Plant Densities for Early to Very Late Planting Dates in Northern Growing Regions of the NGP

The main objective of this study was to identify soybean plant densities for yield maximization, and economic optimum seed densities for profit maximization, for early to very late planting dates in northern growing regions of the NGP. Significant asymptotic soybean yield-density relationships were identified for all planting dates and site years in this study. Soybean yield-density relationships from combined site years formed two planting date groups: 1) early/mid (May 4 to 26), and 2) late/very late (June 2 to 23). Maximum yield was greater for early/mid planting at 4520 kg ha^{-1} compared to 3242 kg ha^{-1} for late/very late planting. An important finding from this study was that yield continued to increase with increasing plant density beyond the upper limit of established plant densities for all planting dates and site years. This result indicated a lack of true yield maximization and intraspecific competition among soybean plants. However, it may be too expensive for growers to aim for plant densities greater than those established in this study, and actual yields were near the predicted maximum level based on the rectangular hyperbola model.

Economic optimum seed density (EOSD) of soybeans was much lower than predicted yield-maximizing plant densities in this study. Soybean EOSDs that maximized profit were 492,000 and 314,000 seeds ha^{-1} for early/mid and late/very late planting dates, respectively. Contrary to the hypothesis, EOSD was greater for early/mid compared to late/very late planting. However, it is suspected that additional site years accounting for a wider range in environmental conditions would influence this outcome.

According to the results of this study, it is recommended that growers should plant soybeans on early to mid planting dates (May 4 to 26) at profit-maximizing seed densities, as yield-maximizing plant densities would not likely be an economical option. However, as EOSDs were sensitive to changes in soybean grain price and seed cost, growers are also advised to adjust these profit-maximizing values accordingly. The influence of weed and disease dynamics are important considerations for soybean seed density decisions. However, the marginal cost analysis of this study did not account for weed pressure under reduced plant densities, nor disease pressure under high plant densities. Thus, growers are advised to consider all potential outcomes when determining soybean EOSDs.

5.3 Soybean Yield Response to Planting Date

Both experiments in this thesis tested a range of planting dates. A combined analysis of both experiments was conducted to address the emerging theme that calendar date is the most important factor for determining when to plant soybeans in northern growing regions to maximize yield. For the combined analysis, soybean yield data from all soil temperature/planting date treatments at Carman in 2014 and 2015 were included from the first experiment in Chapter 3. Additional data from the second experiment in Chapter 4 was included by selecting planting date treatments with similar target plant densities from Carman 2014 and 2015. Target plant densities were 420,080 and 444,790 plants ha^{-1} from the first and second experiments, respectively. Statistical analysis involved regression of the relationship between soybean yield and planting date using PROC REG in SAS.

To help focus the direction for future research, the relationship between soybean yield and planting date was tested to see if yield responded to Julian planting date across all experiments and site years. A significant negative linear relationship occurred between soybean planting date and yield, in which soybean yield declined with later planting (Figure 5.1). Each one-day delay in planting date resulted in a soybean yield decline of 16 kg ha^{-1} for planting dates ranging from April 27 to June 22 (Figure 5.1). This relationship was similar to the previously identified response of soybean yield to planting date from the first experiment at Carman in 2015 (Figure 3.5). The combined analysis of 21 planting dates across six site years provided greater statistical power compared to individual site years, although the linear model in this relationship explained only 19% of the variation in soybean yield. Thus, planting date has a significant effect on declining soybean yield potential with later planting. This finding affirms the importance soybean planting date examination for northern growing regions in the future.

Results from this research highlight the yield benefit from planting early. These results are supported by previous studies that also determined a yield advantage to soybean planting from late April to early May across the United States (Wilcox and Frankenberger, 1987; Kane and Grabau, 1992; Pedersen, 2003; De Bruin and Pedersen, 2008a; Robinson et al., 2009). Greater yields from earlier planting may be attributed to more nodes per plant and more pods (Beaver and Johnson, 1981; Wilcox and Frankenberger, 1987) and seeds per unit of area (Pedersen and Lauer, 2004b).

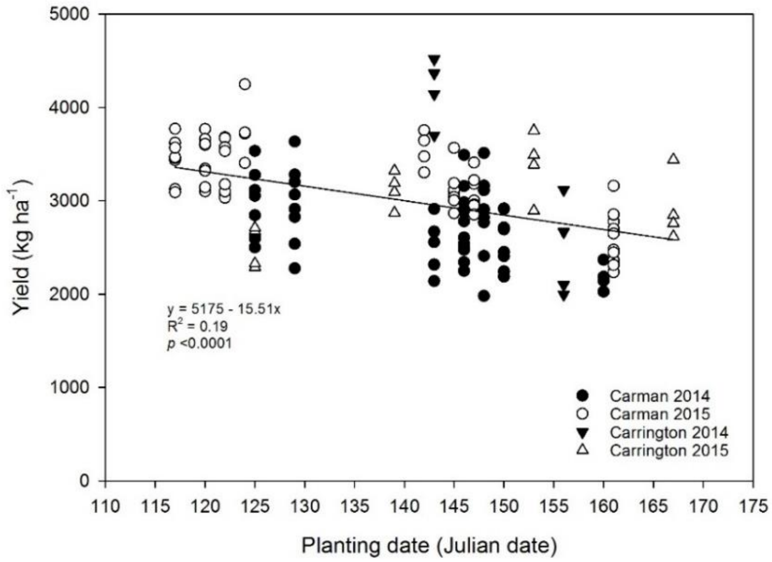

Figure 5.1. Soybean yield response to planting date at Carman and Carrington in 2014 and 2015. The Julian date range of 115 to 165 corresponded with calendar dates ranging from April 27 to June 16.

In contrast, soybean yield decline in response to June planting has also been widely documented across the United States (Bastidas et al., 2008; De Bruin and Pedersen, 2008a; Egli and Cornelius, 2009). Yield decline with later planting has been attributed to reduced plant height (Heatherly and Elmore, 2004), seed number and mass (Egli, 1975; Parker et al., 1981; Egli et al., 1987), plant height (Heatherly and Elmore, 2004), soil moisture as the season progresses (Tanner and Hume, 1978), and insolation, or solar radiation, during the reproductive growth phase (Egli and Bruening, 1992). In addition, soybeans flower at the same time regardless of planting date due to the trigger of shorter photoperiod (Hicks, 1978). The shortened vegetative growth period of late-planted soybeans caused by flower initiation can reduce soybean yield (Hicks, 1978; Board, 2002).

According to the combined results of this study, it is recommended to plant soybeans as early as possible during the short planting period in northern growing regions of the NGP. A distinct declining trend in soybean yield with later planting occurred, regardless of year, location, and variety differences. Recommendations from this research are similar to studies conducted in the United States that have addressed the interest to plant soybeans earlier. Wilcox and Frankenberger (1987) reported the yield advantage of soybeans sown in early May compared to mid-May or early June in the United States. More recently, Robinson et al. (2009) determined that planting dates from April 10 to May 9 resulted in the greatest yields in Indiana.

5.4 Conclusions and Recommendations

Soil temperature at planting was not an influential factor on soybean yield in the first experiment of this study. The significant soybean yield response to soil temperature at one in three site years was instead a response to planting date, in which yield declined with later planting and the earliest planting dates resulted in the greatest yields. From the results of this study, it is recommended to plant soybeans as early as possible during the planting period for maximized soybean yield. However, soybean growers are also advised to asses the risk of both spring and fall frost, seedbed conditions, weather conditions following seeding, and their personal timeline to complete seeding and harvest of all crops.

In the second experiment of this study, the combined analysis of all four site years indicated that two planting date groups occurred for the relationship between soybean yield and plant density: 1) early/mid (May 4 to 26), and 2) late/very late (June 2 to 22). Based on the chosen soybean yield-density model, true yield maximization did not occur within the range of established plant densities. However, actual soybean yields were near the predicted maximum level, or plateau of the yield-density relationship. Economic optimum soybean seed densities that maximized profit were 492,000 and 314,000 seeds ha^{-1} for early/mid and late/very late planting date groups, respectively. However, EOSDs were sensitive to changes in soybean grain price and seed cost. Early/mid planting dates yielded greater than late/very late planting dates overall. The overall recommendation from this study is to plant soybeans during the early/mid planting window (May 4 to 26) at a profit-maximizing seed density. However, growers are also advised adjust soybean EOSDs for changing grain price and seed cost, and to assess the influence of weed and disease pressures when considering low or high plant densities.

In conclusion, earlier soybean planting dates in northern growing regions of the NGP result in maximized soybean yield. The combined analysis of both experiments indicated that soybean yield declined by 16 kg ha^{-1} with each one-day delay in planting date from planting dates ranging from April 27 to June 22 at Carman and Carrington in 2014 and 2015. However, high yields of early seeded soybeans may be reduced by late spring frost damage, and the yield potential of other crops, such as wheat and canola, can dramatically decrease with later planting date. In order to mitigate risk, soybean growers in northern regions should seek to achieve a range of soybean planting dates, rather than plant all soybeans early or late. Thus, the combined recommendation from the two experiments of this thesis would be to plant soybeans anytime before the end of May at a profit-maximizing plant or seed density from Carrington, North Dakota to Carman, Manitoba.

Findings from the first experiment of this study should be tested with additional site years to validate whether or not soil temperature influences soybean yield. Further testing could also involve adaptation of the operational definition of soil temperature used in this study. The time of 10:00 AM could be compared to other times of day such as 11:00 AM or 12:00 PM, to determine which would serve as the most representative time for average soil temperature. Future studies could also examine the effects of soil or air temperatures on key development stages, ranging from flowering to physiological maturity, on yields of field-grown soybeans in Manitoba. Examination of long-term soil temperature data could also provide a clearer picture of calendar dates that correspond with soil temperatures, to establish an association between soil temperature and planting date.

Future research should expand on the investigation into soybean planting date effects. Incorporation of more locations, years, and varieties into each experiment of this study would encompass a wider range of environmental conditions and yield potentials of the northernmost growing regions of the NGP, for the development of stronger soybean planting date recommendations. Additional locations in the western, northern, or eastern peripheries of Manitoba would encompass shorter growing season length compared to the Red River Valley. Locations between Carman and Carrington would provide information on the gradient of soybean yield potential extending southward. Further research is also needed to rank the influence of multiple factors influencing decisions about the time of soybean planting. Factors to compare include calendar date, soil temperature, and weather conditions following seeding. The individual influence and interaction between these factors would help soybean growers determine when to plant in Manitoba.

Another approach to strengthening soybean planting recommendations in the future might be to rank the importance of early planting for different crops grown in northern growing regions. For example, the rates of yield decline with later planting could be compared between soybeans and other crops, such as canola and wheat, to validate which crops should be planted the earliest.

Future studies should also assess the interaction between soybean seedling diseases and planting date. The incidence of soybean seedling disease is expected to increase in the future due to repetitive production and movement of pathogens. Thus, delayed emergence and reduced effectiveness of seed treatment caused by early soybean planting increases the susceptibility of soybeans to seedling diseases, such as root rots. Finally, both planting date and plant density recommendations should be improved in the future for maximized competition against herbicide resistant weeds. Future analyses could incorporate the effect of increasing weed densities and prevalence of disease or insect pressures into marginal cost analyses for optimum soybean plant or seed density calculations.

6.0 LITERATURE CITED

AAFC. 2015. Canadian soy: the healthy alternative. Agric. Agri-Food Canada. Available at http://www.agr.gc.ca/eng/industry-markets-and-trade/?id=1360881916382 (verified 20 April 2016).

Akaike, H. 1974. A New Look at the Statistical Model Identification. Autom. Control. IEEE Trans. 19(6): 716–723.

Andales, A.A., W.D. Batchelor, and C.E. Anderson. 2000. Modification of a soybean model to improve soil temperature and emergence date prediction. Trans. ASAE 43(1): 121–129.

Anderson, L.R., and B.L. Vasilas. 1985. Effects of planting date on two soybean cultivars: seasonal dry matter accumulation and seed yield. Crop Sci. 25(6): 999–1004.

Andrade, F.H., and P.E. Abbate. 2005. Response of maize and soybean to variability in stand uniformity. Agron J. 97(4): 1263–1269.

Andric, L., T. Teklic, M. Vrataric, A. Sudaric, and V. Duvnjak. 2007. Soybean seed vigour and field emergence under influence of cultivar, seed age and planting date. Cereal Res. Commun. 35(2): 177–180.

Aphalo, P.J., and C.L. Ballaré. 1995. On the importance of information-acquiring systems in plant-plant interactions. Funct. Ecol. 9(1): 5–14.

Archontoulis, S. V., and F.E. Miguez. 2015. Nonlinear regression models and applications in agricultural research. Agron. J. 107(2): 786–798.

Badaruddin, M., and D.W. Meyer. 2001. Factors modifying frost tolerance of legume species. Crop Sci. 41(6): 1911–1916.

Ball, R.A., L.C. Purcell, and E.D. Vories. 2000. Optimizing soybean plant population for a short-season production system in the southern USA. Crop 40: 757–764.

Bastidas, A.M., T.D. Setiyono, A. Dobermann, K.G. Cassman, R.W. Elmore, G.L. Graef, and J.E. Specht. 2008. Soybean sowing date: The vegetative, reproductive, and agronomic impacts. Crop Sci. 48(2): 727–740.

Baumol, W.J., and A.S. Blinder. 2015. Microeconomics: principles and policy. 13th ed. Centage Learning. Boston, MA.

Beaver, J.S., and R.R. Johnson. 1981. Response of determinate and indeterminate soybeans to varying cultural practices in the northern USA. Agron. J. 73(5): 833–838.

Bernard, R.L. 1972. Two genes affecting stem termination in soybeans. Crop Sci. 12(2): 235-239.

Beuerlein, J.E. 1988. Yield of indeterminate and determinate semidwarf soybean for several planting dates row spacings and seeding rates. J. Prod. Agric. 1(4): 300–303.

Bhatia, V.S., S.P. Tiwari, and O.P. Joshi. 1999. Yield and its attributes as affected by planting dates in soybean (*Glcine max*) varieties. Indian J. Agric. Sci. 69(10): 696–699.

Birch, C.P.D. 1999. A new generalized logistic sigmoid growth equation compared with the Richards growth equation. Ann. Bot. 83: 713–723.

Board, J.E. 2002. A regression model to predict soybean cultivar yield performance at late planting dates. Agron. J. 94(3): 483–492.

Board, J.E., and W. Hall. 1984. Premature flowering in soybean yield reductions at nonoptimal planting dates as influenced by temperature and photoperiod. Agron. J. 76: 700–704.

Bootsma, A., and D.M. Brown. 1995. Risk analyses of crop heat units available for corn and other warm-season crops in Ontario. Agric. Agri-Food Canada, Tech. Bull.

Bowley, S.R. 1999. A hitchhiker's guide to statistics in plant biology. Any Old Subject Books Plants et al., Inc., Guelph, ON.

Brady, N.C., and R.R. Weil. 2008. Soil aeration and temperature. p. 276–309. *In* The Nature and Properties of Soils. 14th ed. Pearson Education, Inc., Upper Saddle River, NJ.

Bramlage, W.J., A.C. Leopold, and D.J. Parrish. 1978. Chilling stress to soybeans during imbibition. Plant Physiol. 61(4): 525–529.

Brown, D.M., and W.J. Blackburn. 1987. Impacts of freezing temperatures on crop production in Canada. Can. J. Plant Sci. 67(4): 1167–1180.

Brown, R.F., and D.G. Mayer. 1988. Representing cumulative germination. 1. A critical analysis of single value indices. Ann. Bot. 61: 117–125.

Burris, J.S. 1976. Seed/seedling vigor and field performance. J. Seed Technol. 1: 158–174.

Buss, T. 2015. To seed or not to seed: Early season worries with soybeans. Manitoba Agric. Food Rural Dev. Crop. Eastman Webinar. Available at https://www.youtube.com/watch?v=jbOvhB2ACnc&list=PLD7OiKfhYvB9GOFDK_GeBLXsFoZQK_fML&index=2 (verified 29 September 2016).

Calder, F.W., L.B. Macleod, and L.P. Jackson. 1965. Effect of soil moisture content and stage of development on cold-hardiness of the alfalfa plant. Can. J. Plant Sci. 45(3): 211–218.

Carpenter, A.C., and J.E. Board. 1997. Branch yield components controlling soybean yield stability across plant populations. Crop Sci. 37(3): 885–891.

CGC. 2014. Test weight for Canadian grains. Canadian Grain Commission. Available at https://www.grainscanada.gc.ca/guides-guides/weight-poids/itwm-mrps-eng.htm (verified 5 October 2016).

Chen, G., and P. Wiatrak. 2010. Soybean development and yield are influenced by planting date and environmental conditions in the southeastern coastal plain, United States. Agron. J. 102(6): 1731–1737.

Chow, W.S., D.J. Goodchild, C. Miller, and J.M. Anderson. 1990. The influence of high levels of brief or prolonged supplementary far-red illumination during growth on photosynthetic characteristics, composition and morphology of *Pisum sativum* chloroplasts. Plant. Cell Environ. 13(2): 135–145.

Conley, S., and J. Gaska. 2008. Predicting when soybeans will emerge. Cool Bean Advisor: University of Wisconsin-Extension. Available at www.coolbean.info (verified 8 August 2016).

Conley, S.P., and J.B. Santini. 2007. Crop management practices in Indiana soybean production systems. Crop Management doi: 10.1094/CM-2007-0104-01-RS.

Cooper, R.L. 1971. Influence of early lodging on yield of soybean (*Glycine max* L. Merr.). Agron. J. 63(3): 449-450.

COPA. 2015. Oilseed crushing statistics. Canadian Oilseed Processors Association. Available at http://copacanada.com/crush-oil-meal-production/ (verified 29 September 2016).

Cousens, R. 1985. A simple model relating yield loss to weed density. Ann. Appl. Biol. 107(2): 239–252.

Cox, W.J., J.H. Cherney, and E. Shields. 2010. Soybeans compensate at low seeding rates but not at high thinning rates. Agron. J. 102(4): 1238–1243.

Cutforth, H.W., C.F. Shaykewich, and C.M. Cho. 1985. Soil water-soil temperature interactions in the germination and emergence of corn (*Zea mays* L.). Can. J. Soil. Sci. 65: 445–455.

De Bruin, J.L., and P. Pedersen. 2008a. Soybean seed yield response to planting date and seeding rate in the upper Midwest. Agron. J. 100(3): 696–703.

De Bruin, J.L., and P. Pedersen. 2008b. Effect of row spacing and seeding rate on soybean yield. Agron. J. 100(3): 704–710.

De Bruin, J.L., and P. Pedersen. 2009. New and old soybean cultivar responses to plant density and intercepted light. Crop Sci. 49(6): 2225–2232.

Dewerff, R.P.., S.P.. Conley, J.B.. Colquhoun, and V.M.. Davis. 2014. Can soybean seeding rate be used as an integrated component of herbicide resistance management? Weed Sci. 62(4): 625–636.

Dornbos, D.L., and R.E. Mullen. 1992. Soybean seed protein and oil contents and fatty-acid composition adjustments by drought and temperature. J. Am. Oil Chem. Soc. 69: 228–231.

Duke, S.H., L.E. Schrader, C. a Henson, J.C. Servaites, R.D. Vogelzang, and J.W. Pendleton. 1979. Low root temperature effects on soybean nitrogen metabolism and photosynthesis. Plant Physiol. 63(5): 956–962.

Edey, S.N. 1977. Growing degree-days and crop production in Canada. Agriculture Canada Publication 1635. Available at http://publications.gc.ca/collections/collection_2013/aac-aafc/agrhist/A53-1635-1977-eng.pdf (verified 27 May 2016).

Edje, O.T., and J.S. Burris. 1971. Effects of soybean seed vigor on field performance. Agron. J. 63: 536–538.

Edwards, J.T., and L.C. Purcell. 2005. Soybean yield and biomass responses to increasing plant population among diverse maturity groups: I. Agronomic characteristics. Crop Sci. 45(5): 1770–1777.

Egli, D.B. 1975. Rate of Accumulation of Dry Weight in. Science (80-.). 55: 215–219.

Egli, D. 1988. Plant density and soybean yield. Crop Sci. 28(6): 977–981.

Egli, D.B. 1993. Relationship of uniformity of soybean seedling emergence to yield. J. Seed Technol. 17(1): 22–28.

Egli, D.B., and W. Bruening. 1992. Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO. Agric. For. Meteorol. 62(91): 19–29.

Egli, D.B., and P.L. Cornelius. 2009. A regional analysis of the response of soybean yield to planting date. Agron. J. 101(2): 330–335.

Egli, D.B., R.D. Guffy, and J.J. Heitholt. 1987. Factors associated with reduced yields of delayed plantings of soybean. J. Agron. Crop Sci. 159: 176–185.

Egli, D.B., R.D. Guffy, and J.E. Leggett. 1985. Partitioning of assimilate between vegetative and reproductive growth in soybean. Agron. J. 77: 917–922.

Egli, D.B., and D.M. TeKrony. 1996. Seedbed conditions and prediction of field emergence of soybean seed. J. Prod. Agric. 9(3): 365–370.

Egli, D.B., and I.F. Wardlaw. 1980. Temperature response of seed growth characteristics of soybeans. Agron J. 72(3): 560–564.

Elmore, R.W. 1990. Soybean cultivar response to tillage systems and planting date. Agron. J. 82(1): 69–73.

Elmore, R.W. 1998. Soybean cultivar responses to row spacing and seeding rates in rainfed and irrigated environments. J. Prod. Agric. 11(3): 326–331.

Endres, G. 2016. Soybean planting date. Center Points North Dakota State University Carringt. Research Extension Center. Available at https://www.ag.ndsu.edu/CarringtonREC/center-points (verified 1 April 2016).

Epler, M., and S. Staggenborg. 2008. Soybean yield and yield component response to plant density in narrow row systems. Crop Management doi:10.1094/CM-2008-0925-01-RS.

Erickson, E.H. 1975. Variability of floral characteristics influences honey bee visitation to soybean blossoms. Crop Sci. 15: 767–771.

Falk, G. 1981. Environmental factors affecting soybean growth in Manitoba. M.Sc. Thesis. University of Manitoba. Winnipeg, MB.

Fehr, W.R., J.S. Burris, and D.F. Gilman. 1973. Soybean emergence under field conditions. Agron. J. 65(5): 740–742.

Fehr, W., and C. Caviness. 1977. Stages of soybean development. Cooperative Extension Service Iowa State University Special Report 80. 1–12.

Finkelstein, R.R., and M.L. Crouch. 1984. Precociously germinating rapeseed embryos retain characteristics of embryogeny. Planta 162(2): 125–131.

Forcella, F. 1993. Seedling emergence model for velvetleaf. Agron. J. 85: 929–933.

French, R.J., K. McCarthy, and W.L. Smart. 1994. Optimum plant population densities for lupin (*Lupinus angustifolius* L.) in the wheatbelt of western Australia. Aust. J. Exp. Agric. 34(4): 491–497.

Gass, T., A. Schori, A. Fossati, A. Soldati, and P. Stamp. 1996. Cold tolerance of soybean (*Glycine max* (L.) Merr.) during the reproductive phase. Eur. J. Agron. 5(1–2): 71–88.

Gibson, L., and R. Mullen. 1996. Influence of day and night temperature on soybean seed yield. Crop Sci. 36(1): 98–104.

Goto, K., and T. Yamamoto. 1972. Studies on cool injury in bean plants. Abnormalities in the reproductive processes relating to pod dropping as affected by cool temperature before anthesis in soybean plants. Res. Bull. Hokkaido Natl. Agric. Exp. Stat. 100: 14–19.

Grabe, D.F., and R.B. Metzer. 1969. Temperature-induced inhibition of soybean hypocotyl elongation and seedling emergence. Crop Sci. 9(3): 331–333.

Grau, C.R., E.S. Oplinger, E.A. Adee, E.A. Hinkens, and M.J. Martinka. 1994. Planting date and row width effect on severity of brown stem rot and soybean productivity. J. Prod. Agric. 7(3): 347–351.

Halvorson, M.A., T.C. Helms, and J.W. Enz. 1995. Evaluation of simulated fall freeze, planting date, and cultivar maturity in soybean. J. Prod. Agric. 8(4): 589–594.

Hamman, B., D.B. Egli, and G. Koning. 2002. Seed vigor, soilborne pathogens, preemergent growth, and soybean seedling emergence. Crop Sci. 42(2): 451–457.

Harker, K.N., J.T. O'Donovan, R.E. Blackshaw, H.J. Beckie, C. Mallory-Smith, and B.D. Maxwell. 2012. Our view. Weed Sci. 60(2): 143–144.

Hatfield, J.L., and D.B. Egli. 1974. Effect of temperature on rate of soybean hypocotyl elongation and field emergence. Crop Sci. 14(3): 423–426.

Hay, R., and J. Porter. 2006. Development and phenology. p. 7–29. *In* The Physiology of Crop Yield. 2nd ed. Wiley-Blackwell. Hobokin, NJ.

Heap, I. 2014. Global perspective of herbicide-resistant weeds. Pest Manag. Sci. 70(9): 1306–1315.

Heatherly, L.G., and R.W. Elmore. 2004. Managing inputs for peak production. p. 452–525. *In* Boerma, H.R., Specht, J.E., Soybeans: Improvement, Production, and Uses. 3rd ed. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Helms, T.C., E. Deckard, R.J. Goos, and J.W. Enz. 1996. Soybean seedling emergence influenced by days of soil water stress and soil temperature. Agron. J. 88(4): 657–661.

Hicks, D.R. 1978. Growth and development. p. 17–41. *In* Norman, A.G., Soybean Physiology, Agronomy and Utilization. Academic Press, New York, NY.

Hobbs, P.R., and R.L. Obendorf. 1972. Interaction of initial seed moisture and imbibitional temperature on germination and productivity of soybean. Crop Sci. 12(5): 664-667.

Holmberg, S.A. 1973. Soybeans for cool temperate climates. Agri Hort. Genet. 31(1–2): 1–20.

Hu, M., and P. Wiatrak. 2012. Effect of planting date on soybean growth, yield, and grain quality: Review. Agron. J. 104(3): 785–790.

Hume, D.J., and A.K.H. Jackson. 1981a. Frost tolerance in soybeans. Crop Sci. 21(5): 689–692.

Hume, D.J., and A.K.H. Jackson. 1981b. Pod formation in soybeans at low temperatures. Crop Sci. 21(6): 933–937.

Hunt, L.A., S. Pararajasingham, and J.V. Wiersma. 1996. Effects of planting date on the development and yield of spring wheat: Simulation of field data. Can. J. Plant Sci. 76: 51–58.

Inouye, J. 1979. Effects of temperature and daylength on flowering of some photo-insensitive soybean varieties. Japanese J. Trop. Agric. 22(4): 167–171.

Jettner, R.J., K.H.M. Siddique, S.P. Loss, and R.J. French. 1999. Optimum plant density of desi chickpea (*Cicer arietinum* L.) increases with increasing yield potential in south-western Australia. Aust. J. Agric. Res. 50(6): 1017–1025.

Johnson, R.R., and L.M. Wax. 1979. Soybean stand establishment and yield as affected by herbicides and cultural-practices. Agron. J. 71(5): 880–884.

Johnson, L.A., P.J. White, and R. Galloway. 2008. Soybeans - Chemistry, Production, Processing, and Utilization, Volume 2. AOCS Press, Urbana, IL.

Judd, R., D.M. TeKrony, D.B. Egli, and G.M. White. 1982. Effect of freezing temperatures during soybean seed maturation on seed quality. Agron. J. 74(4): 645–650.

Kandel, H., and A. Akyüz. 2012. Growing degree day model for North Dakota soybean. Crop and Pest Report. North Dakota State University. Available at https://www.ag.ndsu.edu/cpr/plant-science/growing-degree-day-model-for-north-dakota-soybean-6-28-12 (verified 1 April 2016).

Kane, M. V., and L.J. Grabau. 1992. Early planted, early maturing soybean cropping system - Growth, development, and yield. Agron. J. 84(5): 769–773.

Kane, M. V., C.C. Steele, and L.J. Grabau. 1997a. Early-maturing soybean cropping system. I. Yield responses to planting date. Agron. J. 89(3): 454–458.

Kane, M. V., C.C. Steele, L.J. Grabau, C.T. MacKown, and D.F. Hildebrand. 1997b. Early-maturing soybean cropping system: III. Protein and oil contents and oil composition. Agron. J. 89(3): 464–469.

Katanda, Y. 2014. Hog manure-recovered struvite as a phosphorus source for enhanced phosphorus use efficiency and reduced seedling toxicity in canola. M.Sc. Thesis. University of Manitoba. Winnipeg, MB.

Khan, A.Z., P. Shah, H. Khan, S. Nigar, S. Perveen, M.K. Shah, Amanullah, S.K. Khalil, S. Munir, and M. Zubair. 2011. Seed quality and vigor of soybean cultivars as influenced by canopy temperature. Pakistan J. Bot. 43(1): 643–648.

Knypl, J.S., and K.M. Janas. 1979. Increasing low-temperature resistance of soybean, *Glycine max* (L.) Merr., by exposure of seeds to water saturated atmosphere. 21(4): 291–297.

Larson, L.A. 1968. The effect soaking pea seeds with or without seedcoats has on seedling growth. Plant Physiol. 43(2): 255–259.

Lawley, Y. 2004. Determining optimum plant population densities for three annual green manure crops under weedy and weed-free conditions. M.Sc. Thesis. University of Saskatchewan. Saskatoon, SK.

Lee, C.D., D.B. Egli, and D.M. TeKrony. 2008. Soybean response to plant population at early and late planting dates in the Mid-South. Agron. J. 100: 971–976.

Littlejohns, D. a., and J.W. Tanner. 1976. Preliminary studies on the cold tolerance of soybean seedlings. Can. J. Plant Sci. 56(2): 371–375.

Loss, S.P., R. Jettner, K.H.M. Siddique, and L.D. Martin. 1998. Responses of faba bean (*Vicia faba* L.) to sowing rate in south-western Australia. I. Seed yield and economic optimum plant density. Aust. J. Agric. Res. 49(6): 989.

Lueschen, W.E., J.H. Ford, S.D. Evans, B.K. Kanne, T.R. Hoverstad, G.W. Randall, J.H. Orf, and D.R. Hicks. 1992. Tillage, row spacing, and planting date effects on soybean following corn or wheat. J. Prod. Agric. 5(2): 254–260.

Ma, B.L., H. Zhao, Z. Zheng, C. Caldwell, A. Mills, A. Vanasse, H. Earl, P. Scott, and D.L. Smith. 2016. Optimizing seeding dates and rates for canola production in the humid eastern Canadian agroecosystems. Agron. J. 108(5): 1869–1879.

MAFRD. 2016a. Current crop topics. Manitoba Agriculture Food and Rural Development. Available at http://www.gov.mb.ca/agriculture/crops/seasonal-reports/current-crop-topics.html (verified 20 June 2005).

MAFRD. 2016b. Soybeans - production. Manitoba Agriculture Food Rural Development. Available at http://www.gov.mb.ca/agriculture/crops/production/soybeans.html (verified 20 June 2005).

Mague, T.H., and R.H. Burris. 1972. Reduction of acetylene and nitrogen by field-grown soybeans. New Phytol. 71(2): 275–286.

Markowski, A. 1988a. Sensitivity of different species of field crops to chilling temperature. Part I. Interaction of initial seed moisture and imbibition temperature. Acta Physiol. Plant. 10(3): 265–274.

Markowski, A. 1988b. Sensitivity of different species of field crops to chilling temperature. Part II. Germination, growth and injuries of seedlings. Acta Physiol. Plant. 10(3): 275–283.

MASC. 2016. Seeding dates and yield information. Manitoba Agricultural Services Corporation. Available at http://www.mmpp.com/mmpp.nsf/mmpp_seeding_dates.html (verified 20 June 2004).

Mederski, H.J. 1983. Effects of water and temperature stress on soybean plant growth and yield in humid, temperate climates. p. 35–48. *In* Raper, C.D., Kramer, P.J. (eds.), Crop reactions to water and temperature stresses in humid, temperate climates. ed. Westview Press, Boulder, CO.

Meyer, D.W., and M. Badaruddin. 2001. Frost tolerance of ten seedling legume species at four growth stages. Crop Sci. 41(6): 1838–1842.

Miller, P.R., B.G. McConkey, G.W. Clayton, S.A. brandt, J.A. Staricka, A.M. Johnston, G.P. Lafond, B. Schatz, D.D. Baltensperger, and K. Neill E. 2002. Pulse crops adaptation in the Northern Great Plains. Agron. J. 94(2): 261–272.

Mohler, C.L. 2001. Enhancing the competitive ability of crops. p. 269–321. *In* Liebman, M., Mohler, C.L., Staver, C.P. (eds.), Ecological Management of Agricultural Weeds. Cambridge University Press, Cambridge, UK.

Mohr, R., B. Irvine, G. Finlay, M. Sandercock, C. Linde, P. Halibicki, R. Burak, J. Kostuik, and S. Chalmers. 2014a. Effect of row spacing and seeding rate on soybean growth, yield and quality in Manitoba. Manitoba Agronomist Conference Poster, Winnipeg, MB.

Mohr, R., B. Irvine, M. Sandercock, G. Finlay, C. Linde, P. Halibicki, R. Burak, J. Kostuik, and S. Chalmers. 2014b. Agronomic management of soybeans in Manitoba. Final report for experiment 1: Effects of row spacing and seeding rate on soybean.

Mortensen, D.A., J.F. Egan, B.D. Maxwell, M.R. Ryan, and R.G. Smith. 2012. Navigating a Critical Juncture for Sustainable Weed Management. Source Biosci. Biosci. 62(75): 75–84.

Motulsky, H., and A. Christopolis. 2003. Fitting models to biological data using linear and nonlinear regression: A practical guide to curve fitting. Oxford University Press, New York, NY.

MPSG. 2016a. The bean report - May 13, 2016. Manitoba Pulse and Soybean Growers. Available at http://www.manitobapulse.ca/production/the-bean-report/ (verified 30 June 2016).

MPSG. 2016b. Soybean maturity guide. Available at http://www.manitobapulse.ca//wp-content/uploads/2015/08/Soybean-MATURITY-GUIDE_8_19_15_F.pdf.

Musser, R.L., S.A. Thomas, and P.J. Kramer. 1983. Short and long term effects on root and shoot chilling of Ransom soybean. Plant Physiol. 73: 778–783.

Nadler, A.J. 2007. An agroclimatic risk assessment of crop production on the Canadian prairies. M.Sc. Thesis. University of Manitoba. Winnipeg, MB.

Nass, H.G., H.W. Johnston, J.A. Macleod, and J.D.E. Sterling. 1975. Effects of seeding date, seed treatment and foliar sprays on yield and other agronomic characters of wheat, oats and barley. Can. J. Plant Sci. 55(1): 41–47.

NDSU. 2014. Soybean production - field guide for North Dakota and northwestern Minnesota. North Dakota State Univ. Ext. Serv.: 1–25. Available at https://www.ag.ndsu.edu/publications/landing-pages/crops/soybean-production-guide-a-1172 (verified 20 June 2005).

NDSU. 2015. Freeze free days (1981-2010). North Dakota State Climate Office. Available at https://www.ndsu.edu/ndsco/data/30yearaverage/freezefree/#c343132 (verified 1 May 2016).

Nykiforuk, C.L., and A.M. Johnson-Flanagan. 1998. Low temperature emergence in crop plants. J. Crop Prod. 1(1): 249–289.

Obendorf, R.L., and P.R. Hobbs. 1970. Effect of seed moisture on temperature sensitivity during imbibiton of soybean. Crop Sci. 10(5): 563-566.

Ohnishi, S., T. Miyoshi, and S. Shirai. 2010. Low temperature stress at different flower developmental stages affects pollen development, pollination, and pod set in soybean. Environ. Exp. Bot. 69(1): 56–62.

Oplinger, E.S., and B.D. Philbrook. 1992. Soybean planting date, row width, and seeding rate response in three tillage systems. J. Prod. Agric. 5(10): 94–99.

Parker, M.B., W.H. Marchant, and B.J. Mullinix. 1981. Date of planting and row spacing effects on four soybean cultivars. Agron. J. 73(5): 759–762.

Parrish, D.J., and A.C. Leopold. 1977. Transient changes during soybean imbibition. Plant Physiol. 59(6): 1111–1115.

Parvez, A.Q., F.P. Gardner, and K.J. Boote. 1989. Determinate- and indeterminate-type soybean cultivar responses to pattern, density, and planting date. Crop Sci. 29: 150–157.

Pedersen, P. 2003. Soybean agronomic response to management systems in the upper Midwest. Agron. J. 95: 1146– 1151.

Pedersen, P. 2006. Soybean planting date. Integrated Crop Management Iowa State University. Available at http://www.ipm.iastate.edu/ipm/icm/2006/4-3/soyplant.html (verified 26 May 2016).

Pedersen, P., and J.G. Lauer. 2004a. Soybean growth and development in various management systems and planting dates. Crop Sci. 44(2): 508–515.

Pedersen, P., and J.G. Lauer. 2004b. Response of soybean yield components to management system and planting date. Agron. J. 96(5): 1372–1381.

Pendleton, J.W., and E.E. Hartwig. 1973. Management. Soybeans: Improvement, production, and uses. p. 211–237. *In* Caldwell, B.E. (ed.), Agronomy 16. 1st ed.

Piper, E.L., and K.J. Boote. 1999. Temperature and cultivar effects on soybean seed oil and protein concentrations. J. Am. Oil Chem. Soc. 76(10): 1233–1241.

Podolsky, K. 2015. Soybean maturity: it’s complicated. Yield Manitoba. 18–20. Available at http://www.mmpp.com/mmpp.nsf/ym_2015_06_soybean_maturity.pdf.

Popp, M.P., J.T. Edwards, L.C. Purcell, and P.M. Manning. 2006. Profit-maximizing seeding rates and replanting thresholds for soybean: Maturity group interactions in the Mid-South. Agric. Syst. 91(3): 211–228.

Powell, A.A. 1988. Seed vigor and field establishment. Adv. Res. Technol. Seeds 11: 29–61.

Rahman, M.M., J.G. Hampton, and M.J. Hill. 2005. The effect of time of sowing on soybean seed quality. Seed Sci. Technol. 33(3): 687–697.

Raper, C.D., and P.J. Kramer. 1987. Stress physiology. p. 589–640. *In* Wilcox, J.R. (ed.), Soybeans: improvement, production and uses. 2nd Ed. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. Madison, WI.

Raven, P.H., R.F. Evert, and S.E. Eichhorn. 2005. Biology of plants. 7th ed. W.H. Freeman and Company Publishers, New York, NY.

Robinson, A.P., S.P. Conley, J.J. Volenec, and J.B. Santini. 2009. Analysis of high yielding, early-planted soybean in Indiana. Agron. J. 101(1): 131–139.

Rowntree, S.C., J.J. Suhre, N.H. Weidenbenner, E.W. Wilson, V.M. Davis, S.L. Naeve, S.N. Casteel, B.W. Diers, P.D. Esker, J.E. Specht, and S.P. Conley. 2013. Genetic gain × management interactions in soybean: I. Planting date. Crop Sci. 53(3): 1128.

Ryder, G.J., and J.E. Beuerlein. 1979. Study of soybean production systems. Ohio Rep. Res. Dev. 64(2): 19–22.

Saindon, G., H.C. Huang, and G.C. Kozub. 1995. White-mold avoidance and agronomic attributes of upright common beans grown at multiple planting densities in narrow rows. J. Am. Soc. Hortic. Sci. 120(5): 843–847.

Saito, M., T. Yamamoto, K. Goto, and K. Hashimoto. 1970. The influence of cool temperature before and after anthesis, on pod-setting and nutriens in soybean plants. Crop Sci. Soc. Japan Proc. 39(4): 511–519.

Schou, J.B., D.L.C. Jeffers, and J.G. Streeter. 1978. Effects of reflectors, black boards, or shades applied at different stages of plant development on yield of soybeans. Crop Sci. 18(1): 29-34.

Schulz, F.A., and D.F. Bateman. 1968. Temperature response of seeds during early phases of germination and its relation to injury by *Rhizoctonia solani*. Phytopathology 58(8): 1067.

Scott, R.K., E.A. Ogunremi, J.D. Ivins, and N.J. Mendham. 1973. Effect of sowing date and season on growth and yield of oilseed rape (*Brassica napus*). J. Agric. Sci. 81(Oct): 277–285.

Seddigh, M., and G.D. Jolliff. 1984. Night temperature effects on morphology, phenology, yield and yield components of indeterminate field-grown soybean. Agron J. 76(5): 824–828.

Shirtliffe, S.J., and A.M. Johnston. 2002. Yield-density relationships and optimum plant populations in two cultivars of solid-seeded dry bean (*Phaseolus vulgaris* L.) grown in Saskatchewan. Can. J. Plant Sci. 82(3):521-529.

Shurtleff, W., and A. Aoyagi. 2010. History of soybeans and soyfoods in Canada (1831-2010): Extensively annotated bibliography and sourcebook. Soyinfo Center, Lafayette, CA.

Simon, E.W., A. Minchin, M. McMenamin, and J.M. Smith. 1976. The low temperature limit for seed germination. New Phytol. 77: 301–311.

Sinclair, T.R., S. Kitani, K. Hinson, H.J. Bruniard, and T. Horie. 1991. Soybean flowering date: Linear and logistic models based on temperature and photoperiod. Crop Sci. 31: 786–790.

Sionit, N., B.R. Strain, and E.P. Flint. 1978. Interaction of temperature and CO2 enrichment on soybean: growth and dry matter partitioning. Can. J. Plant Sci. 67(1): 59–67.

Skrudlik, G., and J. Kościelniak. 1996. Effects of low temperature treatment at the seedling stage on soybean growth, development and final yield. J. Agron. Crop Sci. 176(2): 111–117.

Smith, P.J., A. Bootsma, and A.D. Gates. 1982. Heat units in relation to corn maturity in the Atlantic region of Canada. Agric. Meterology 26: 201–213.

Spears, J.F., D.M. TeKrony, and D.B. Egli. 1997. Temperature during seed filling and soybean seed germination and vigour. Seed Sci. Technol. 25(2): 233–244.

StatCan. 2009. The soybean, agriculture's jack-of-all-trades, is gaining ground across Canada. Statistics Canada. Available at http://www.statcan.gc.ca/pub/96-325-x/2007000/article/10369-eng.htm (verified 1 April 2016).

StatCan. 2016. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in imperial units. Statistics Canada. Available at http://www5.statcan.gc.ca/cansim/a01?lang=eng (verified 1 April 2016).

Steinberg, B.R.A., and W.W. Garner. 1936. Response of certain plants to length of day and temperature under controlled conditions. J. Agric. Res. 52(12): 943–960.

Stewart, C.R., B.A. Martin, L. Redding, and S. Cerwick. 1990. Seedling growth, mitochondrial characteristics and alternative respiratory capacity of corn genotypes differing in cold tolerance. Plant Physiol. 92: 761–766.

Tanner, J.W., and D.J. Hume. 1978. Management and production. p. 158–216. *In* Norman, A.G. (ed.), Soybean Physiology, Agronomy, and Utilization. Academic Press, Ann Arbor, MI.

Taylor, A.O., and J.A. Rowley. 1971. Plants under climate stress. I. Low temperature, high light effects on photosynthesis. Plant Physiol. 47: 719–725.

Thomas, J.F., and C.D. Raper. 1978. Effect of day and night temperatures during floral induction on morphology of soybeans. Agron. J. 70: 893–898.

Thomas, J.F., C.D. Raper, and W.W. Weeks. 1981. Day and night temperature effects on nitrogen and soluble carbohydrate allocation during early reproductive growth in soybeans. Agron. J. 73(4): 577–582.

Torres, M., and G. Frutos. 1989. Analysis of germination curves of aged fennel seeds by mathematical models. Environ. Exp. Bot. 29(3): 409–415.

Torres, M., and G. Frutos. 1990. Logistic function analysis of germination behaviour of aged fennel seeds. Environ. Exp. Bot. 30(3): 383–390.

Tremblay, G.J., J.M. Beausoleil, P. Filion, and M. Saulnier. 2006. Response of three soybean cultivars to seeding date. Can. J. Plant Sci. 86(4): 1071–1078.

USDA. 2016. Crop production annual summary. United States Department of Agriculture. Available at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1000 (verified 20 April 2016).

Van Acker, R.C., C.J. Swanton, and S.F. Weise. 1993. The Critical Period of Weed Control in Soybean (*Glycine max* L. Merr.). Weed Sci. 41: 194–200.

Vencill, W.K., R.L. Nichols, T.M. Webster, J.K. Soteres, C. Mallory-Smith, N.R. Burgos, W.G. Johnson, and M.R. McClelland. 2012. Herbicide resistance: Toward an understanding of resistance development and the impact of herbicide-resistant crops. Weed Sci. 60(sp1): 2–30.

Wahab, M.N.J., D.H. Dabbs, and R.J. Baker. 1986. Effects of planting density and design on pod yield of bush snap bean (Phaseolus vulgaris L). Can. J. Plant Sci. 66(3): 669–675.

Wang, C., T. Wu, S. Sun, R. Xu, J. Ren, C. Wu, B. Jiang, W. Hou, and T. Han. 2016. Seventy-five years of improvement of yield and agronomic traits of soybean cultivars released in the Yellow-Huai-hai River Valley. Crop Sci. 56(5): 2354–2364.

Weber, C.R., R.M. Shibles, and D.E. Byth. 1966. Effect of plant population and row spacing on soybean development and production. Agron. J. 58(1): 99-102.

Wells, R. 1991. Soybean growth rspns to plant density: Relationships among canopy photosynthesis, leaf area, and light interception. Crop Sci. 31: 755–761.

Whigham, K., D. Farnham, J. Lundvall, D. Tranel, E. Edwards, and S. Sailer. 2000. Soybean replant decisions. Iowa State University Extension. Available at http://www.soybeanresearchinfo.com/pdf_docs/Replant_IA_PM1851.pdf (verified 30 December 2016).

Whigham, D.K., and H.C. Minor. 1978. Agronomic characteristics and environmental stress. p. 78–116. *In* Norman, A.G. (ed.), Soybean Physiology, Agronomy and Utilization. Academic Press, New York, NY.

Wiggans, R.G. 1939. The influence of space and arrangement on the production of soybean plants. Jour Amer Soc Agron 31(4): 314–321.

Wilcox, J.R., and J.F. Cavins. 1992. Normal and low linolenic acid soybean strains: Response to planting date. Crop Sci. 32(5): 1248–1251.

Wilcox, J.R., and E.M. Frankenberger. 1987. Indeterminate and determinate soybean responses to planting date. Agron. J. 79(6): 1074–1078.

Willey, R.W., and S.B. Heath. 1969. Quantitative relationships between plant population and crop yield. p. 281–321. *In* Advances in Agronomy Vol. 21. Academic Press, New York, NY.

Wuebker, E.F., R.E. Mullen, and K. Koehler. 2001. Flooding and Temperature Effects on Soybean Germination. Crop Sci. 41(6): 1857–1861.

Yaklich, R.W., B. Vinyard, M. Camp, and S. Douglass. 2002. Analysis of seed protein and oil from soybean northern and southern region uniform tests. Crop Sci. 42(5): 1504–1515.

Zhang, Q., Q. Gao, S.J. Herbert, Y. Li, and a M. Hashemi. 2010. Influence of sowing date on phenological stages, seed growth and marketable yield of four vegetable soybean cultivars in North-eastern USA. African J. Agric. Res. 5(18): 2556–2562.

7.0 APPENDICES

APPENDIX A: The Effects of Planting Dates Based on Soil Temperature on Soybean Emergence, Maturity, and Yield in Manitoba

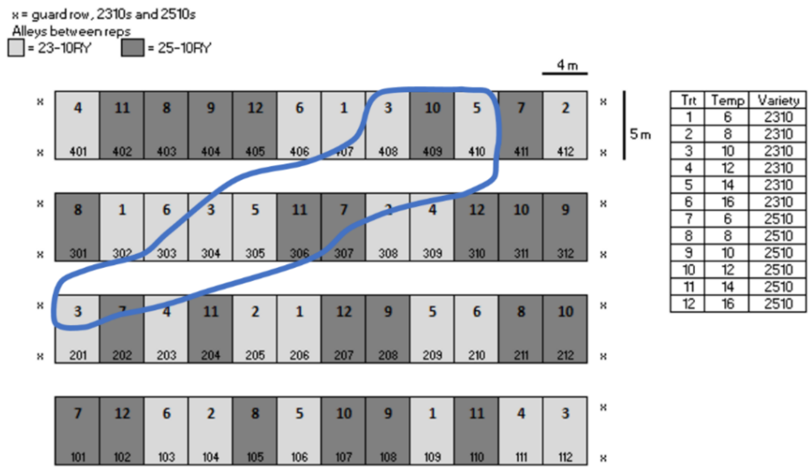

Figure 7.1. Image of plot plan at Morden, MB in 2015 depicting the area where early maturation of soybeans took place, spanning three replicates and 14 plots.

Table 7.1. Significance of fixed effects for the dependent variable soybean yield from three site years. The model factors included: site year (siteyear), soybean variety (variety) and target soil temperature (soiltemp). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 3. An effect was considered significant at $p < 0.05$.

Source of Variation	*p*-value
Siteyear	0.0120
Variety	0.0040
Siteyear × Variety	0.0064
Soiltemp	<0.0001
Siteyear × Soiltemp	0.0007
Variety × Soiltemp	0.1859
Siteyear × Variety × Soiltemp	0.4558

Table 7.2. Significance of fixed effects for the dependent variable soybean yield at Carman, MB in 2014 and 2015, and Melita in 2015. The model factors included: soybean variety (variety) and target soil temperature (soiltemp). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 3. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2014	Carman 2015	Melita 2015
	--------------------------	*p*-value	--------------------------
Variety	0.0068	0.2339	0.5071
Soiltemp	0.0371	<0.0001	0.0425
Soiltemp × Variety	0.2857	0.2301	0.0952

Table 7.3. Significance of fixed effects for the dependent variable soybean yield at Carman, MB in 2015. The model factors included: soybean variety (variety) and Julian planting date (date). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 3. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2015
Variety	0.0227
Date	<0.0001
Date × Variety	0.0442

Table 7.4. Comparison of logistic, Mitscherlich, and gompertz non-linear sigmoidal model parameters and statistical goodness of fit criteria for the relationship between soybean seedling emergence and days after planting at Carman, Melita, and Morden, MB in 2015.

		Logistic $E = M / (1 + \exp(-kt + b))$					Mitscherlich $E = M(1-\exp(-k(t-z)))$					Gompertz $E = M(\exp(-\exp(-kt+b)))$				
Site Year	Soil Temperature Treatment (°C)	M	k	b	AIC	RMSE	M	k	z	AIC	RMSE	M	k	b	AIC	RMSE
Carman 2015	6	462	1.24	33.7	225	67.1	462	1.10	26.8	225	67.1	462	1.17	31.6	225	67.1
	8	547	0.68	17.5	228	205.4	557	0.41	23.8	228	72.2	551	0.54	13.3	228	72.4
	10	473	0.67	16.9	209	48.4	511	0.26	22.3	210	49.6	483	0.45	11.0	209	48.4
	12	498	1.24	13.9	226	83.8	500	0.86	10.3	226	83.8	499	1.04	11.2	226	63.4
	14	477	0.47	4.3	224	80.6	480	0.37	7.8	224	80.6	478	0.42	3.6	224	80.6
	16	583	0.38	2.2	236	86.4	591	0.27	3.6	236	86.4	586	0.33	1.6	236	86.5
Melita 2015	6	259	0.41	10.5	265	106.5	261	0.25	22.5	265	106.3	260	0.33	7.9	265	106.4
	8	223	0.53	13.3	258	95.2	225	0.31	22.8	258	95.2	224	0.41	10.0	258	95.2
	10	519	0.36	2.5	257	102.3	523	0.25	4.2	257	102.7	520	0.30	1.7	257	102.4
	12	517	0.94	10.9	237	80.4	520	0.61	10.3	237	80.2	518	0.76	8.4	237	80.3
	14	551	0.75	8.9	246	104.9	553	0.61	11.0	246	104.8	552	0.68	7.7	246	104.8
	16	568	0.77	8.6	250	123.0	581	0.40	9.2	251	123.3	572	0.58	6.0	250	123.1
Morden 2015	6	356	1.05	31.9	248	93.5	370	0.25	27.1	251	98.2	357	0.74	22.0	249	93.7
	8	345	1.27	36.6	257	116.2	351	0.42	26.8	257	115.9	348	0.74	20.7	257	115.9
	10	355	1.11	27.3	229	67.7	359	0.46	22.8	230	68.3	357	0.75	18.1	229	67.7
	12	431	0.88	20.2	245	94.4	431	0.71	22.0	245	94.4	431	0.79	17.8	245	94.4
	14	469	0.99	11.8	235	83.7	473	0.64	10.9	235	83.4	471	0.80	9.3	235	83.6
	16	482	0.15	0.9	236	84.9	504	0.10	-0.4	236	84.9	491	0.12	0.4	236	84.9

Table 7.5. Comparison of 95% confidence intervals of DAP and GDD logistic model parameters for soybean emergence at Carman, Melita, and Morden, MB in 2015.

		DAP Model Parameters						GDD Model Parameters					
Site Year	Soil Temperature Treatment (°C)	M		k		b		M		k		b	
Carman 2015	6	462	± 25.8	1.24	± 2.05	33.7	± 57.4	462	± 30.1	0.19	± 0.37	11.5	± 23.9
	8	547	± 33.0	0.68	± 0.28	17.5	± 7.21	566	± 46.4	0.11	± 0.04	7.6	± 2.86
	10	473	± 24.4	0.67	± 0.18	16.9	± 4.53	489	± 32.5	0.14	± 0.04	9.3	± 2.68
	12	498	± 46.7	1.24	± 0.87	13.9	± 9.71	498	± 46.1	0.16	± 0.11	9.1	± 6.30
	14	477	± 81.7	0.47	± 0.74	4.3	± 7.92	476	± 85.5	0.05	± 0.09	2.1	± 4.71
	16	583	± 58.9	0.38	± 0.33	2.2	± 2.41	569	± 39.3	0.09	± 0.11	4.9	± 6.28
Melita 2015	6	259	± 27.1	0.41	± 0.37	10.5	± 9.81	261	± 29.3	0.06	± 0.05	3.5	± 3.14
	8	223	± 24.6	0.53	± 0.55	13.3	± 14.1	224	± 25.5	0.10	± 0.09	6.7	± 6.25
	10	519	± 34.3	0.36	± 0.22	2.5	± 1.85	515	± 30.0	0.09	± 0.06	5.0	± 3.35
	12	517	± 28.2	0.94	± 0.50	10.9	± 5.60	519	± 29.2	0.09	± 0.05	5.7	± 2.83
	14	551	± 44.5	0.75	± 1.04	8.9	± 13.6	551	± 44.9	0.09	± 0.13	6.4	± 10.6
	16	568	± 56.1	0.77	± 0.64	8.6	± 7.55	570	± 61.5	0.09	± 0.08	6.0	± 5.59
Morden 2015	6	356	± 28.3	1.05	± 0.75	31.9	± 22.9	357	± 28.8	0.09	± 0.06	8.0	± 5.42
	8	345	± 35.0	1.27	± 1.47	36.6	± 42.2	346	± 35.8	0.10	± 0.11	9.0	± 9.92
	10	355	± 21.2	1.11	± 1.04	27.3	± 25.9	356	± 21.7	0.09	± 0.08	7.7	± 7.18
	12	431	± 31.2	0.88	± 1.04	20.2	± 24.0	431	± 32.3	0.08	± 0.10	7.2	± 9.02
	14	469	± 33.6	0.99	± 0.70	11.8	± 8.52	475	± 37.2	0.11	± 0.07	12.7	± 8.45
	16	482	± 210	0.15	± 0.36	0.9	± 3.01	463	± 119	0.02	± 0.05	1.0	± 3.52

Table 7.6. Significance of fixed effects for the dependent variable days to physiological soybean maturity from four combined site years in Manitoba. The model factors included: site year (siteyear), soybean variety (variety) and target soil temperature (soiltemp). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 3. An effect was considered significant at $p < 0.05$.

Source of Variation	Pr > F
Siteyear	<0.0001
Variety	<0.0001
Siteyear × Variety	0.0043
Soiltemp	<0.0001
Siteyear × Soiltemp	<0.0001
Variety × Soiltemp	0.0014
Siteyear × Variety × Soiltemp	0.5903

APPENDIX B: Optimum Soybean Plant Densities for Early to Very Late Planting Dates in Northern Growing Regions of the Northern Great Plains

Table 7.7. Significance of fixed effects for the dependent variable soybean main stem branch number at Carman, MB, and Carrington, ND in 2014 and 2015. The model factors included: soybean planting date (date) and target soybean plant density (density). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 4. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2014	Carman 2015	Carrington 2014	Carrington 2015
	------------------------------*p*-value------------------------------			
Date	0.0128	0.0131	0.6162	0.5587
Density	<0.0001	<0.0001	<0.0001	0.0016
Date × Density	0.0565	0.9147	0.6366	0.0709

Table 7.8. Significance of fixed effects for the dependent variable soybean biomass at Carman, MB in 2014 and 2015, and Carrington, ND in 2014 and 2015. The model factors included: soybean planting date (date) and target soybean plant density (density). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 4. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2014	Carman 2015	Carrington 2014	Carrington 2015
	------------------------------*p*-value------------------------------			
Date	0.0219	0.0048	0.0203	0.1231
Density	0.0651	0.5201	0.6228	0.0143
Date × Density	0.7592	0.8603	0.6557	0.0398

Table 7.9. Significance of fixed effects for the dependent variable soybean pod height at Carman, MB in 2014 and 2015, and Carrington, ND in 2014 and 2015. The model factors included: soybean planting date (date) and target soybean plant density (density). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 4. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2014	Carman 2015	Carrington 2014	Carrington 2015
	------------------------------*p*-value------------------------------			
Date	0.0032	0.0135	0.3335	0.2946
Density	0.0005	<0.0001	0.0211	0.0028
Date × Density	0.0106	0.8446	0.0346	0.2470

Table 7.10. Significance of fixed effects for the dependent variable soybean plant height at harvest at Carman, MB in 2014 and 2015, and Carrington, ND in 2014 and 2015. The model factors included: soybean planting date (date) and target soybean plant density (density). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 4. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2014	Carman 2015	Carrington 2014	Carrington 2015
	------------------------------*p*-value------------------------------			
Date	0.1682	0.2837	0.2905	0.0052
Density	0.1843	0.0067	0.1482	0.4571
Date × Density	0.0785	0.8709	0.3277	0.0856

Table 7.11. Significance of fixed effects for the dependent variable soybean lodging at Carman, MB and Carrington, ND in 2015. The model factors included: soybean planting date (date) and target soybean plant density (density). Analysis of variance was conducted using PROC MIXED prior to the regression analysis in Chapter 4. An effect was considered significant at $p < 0.05$.

Source of Variation	Carman 2015	Carrington 2015
	----------*p*-value----------	
Date	0.8777	0.1052
Density	0.3573	0.0002
Date × Density	0.6040	0.0236

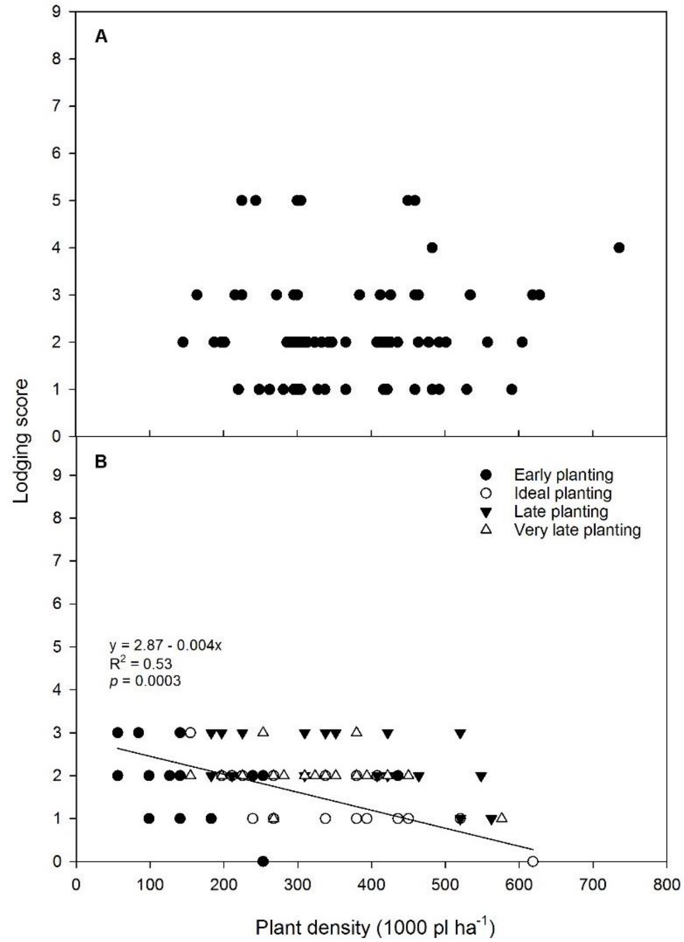

Figure 7.2. Soybean lodging response to soybean plant density at **(A)** Carman, MB and **(B)** Carrington, ND in 2015. The linear model was only significant for the mid planting date at Carrington in 2015.

Table 7.12. Comparison of linear, quadratic, rectangular hyperbola, and exponential model parameters and statistical goodness of fit criteria for the relationship between soybean yield and plant density under weed-free conditions at Carman, MB and Carrington, ND in 2014 and 2015.

		Linear $y = a + bx$				Quadratic $y = a + bx + cx^2$					Rectangular Hyperbola $y = Ix/(1 + (Ix/a))$				Exponential $y = a(1\text{-}\exp^{(-bx)})$			
Site Year	Planting Date	a	b	*p*-value	AIC	*a*	*b*	*c*	*p*-value	AIC	*a*	*I*	*p*-value	AIC	*a*	*b*	*p*-value	AIC
Carman 2014	Mid + Late	2024	1.54	0.0258	568	-	-	-	0.0721	599	3036	52.9	<0.0001	323	2683	0.011	<0.0001	324
Carman 2015	Early + Mid	3228	1.20	0.0034	530	2644	-	-	0.0045	530	4105	102.3	<0.0001	288	3766	0.012	<0.0001	288
	Late	2259	1.25	0.0142	279	1640	-	-	0.0293	280	3185	50.0	<0.0001	243	2871	0.008	<0.0001	243
Carrington 2014	Mid	-	-	0.0716	239	2565	-	-	0.0539	237	4882	95.3	<0.0001	278	4469	0.010	<0.0001	275
	Late	1065	3.70	0.0037	253	-	-	-	0.0156	255	6527	10.7	<0.0001	299	4360	0.002	<0.0001	299
Carrington 2015	Early + Mid + Late + Very Late	2482	1.39	0.0018	993	1835	6.23	-0.008	0.0002	987	3385	82.2	<0.0001	326	3040	0.015	<0.0001	325
Combined Site Years	Early + Mid	2335	3.07	<0.0001	1695	1383	9.98	-0.011	<0.0001	1684	4474	46.1	<0.0001	352	3730	0.008	<0.0001	352
	Late + Very Late	2349	1.22	0.0022	1370	1808	4.84	-0.005	0.0010	1368	3264	63.9	<0.0001	342	2912	0.012	<0.0001	341