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Suitability of winter canola (*Brassica napus*) for enhancing summer annual crop rotations in Iowa

by

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Program of Study Committee:

Mary Wiedenhoeft, Co-Major Professor
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ABSTRACT

Winter canola (*Brassica napus)* could be a good candidate for enhancing cropping systems in Iowa because of its potential to provide environmental benefits and produce a marketable crop compatible with existing grain production and distribution schemes. However, it is still uncertain whether this crop would be suitable for helping balance environmental and financial goals of conventional cropping systems under the environmental and market conditions unique to Iowa. The work presented in this thesis is an effort to assess the suitability of winter canola for providing environmental benefits while fitting within the logistic and economic constrains of current cropping systems. Based on observations from experimentation in field plots, it is determined that canola can be successfully established in the fall, survive the winter, and regrow in the spring, but adequate conditions during fall growth are crucial. It is estimated that seeding by 31 Aug in the north to 12 Sep in the southeast will allow enough time for adequate growth of canola during the fall in at least half of the years in Iowa. Because these seeding date requirements will likely conflict with standing crops during most years, adjustments to the rotation schemes of conventional rotations are needed. Therefore, two alternative systems are proposed, and their economic profiles are studied. Findings from this economic analysis suggest that these rotation alternatives produce relatively less net returns than the conventional corn (*Zea mays* L.)-soybean (*Glycine max* (L) Merr.) rotation, throughout a range of market and canola yield scenarios. Based on these results, it is determined that although winter canola can provide some environmental and economic enhancements to summer annual crop rotations in Iowa, but the specific situations in which canola can fit these rotations are limited. Nonetheless,

more research is needed to fully understand the productivity of winter canola, before counting these as feasible alternatives for Iowa producers.

CHAPTER 1.

GENERAL INTRODUCTION

Iowa's natural endowment of fertile soils and favorable climate has afforded the development of one of the most productive agricultural systems in the world. During the last 70 years, this region has seen tremendous advances in crop production through the deployment of superior genetics, sophisticated inputs and infrastructure, and improved farm management. In recent years, these intensified systems have been central to the discussion on how to provide enough food to a growing global population while allocating sufficient land for bioenergy production and environmental services (Jackson, 2008; National Research Council, 2009; Altieri, 2009; Gomiero et al., 2011; Heaton et al., 2013; Liebman et al., 2013). A major point of controversy is the environmental consequences that have accompanied the gains in crop production, whose effects reach beyond farm fields. This contention is epitomized by the recent announcement by the municipal utility Des Moines Water Works of its intent to file a lawsuit against drainage districts in three northwestern Iowa counties over nitrate pollution in the Raccoon River (Meinch, 2015), which is a source of drinking water for about a half million people in central Iowa.

A major contributing factor of nutrient exports to water bodies and other related environmental impacts is that agricultural fields remain fallow with little or no vegetative cover after the harvest of summer annual crops, namely corn (*Zea mayz* L.) and soybean (*Glycine max* (L) Merr.). During this period, residual fertilization as well as crop residue decomposition processes result in the nitrification of the soil N pools, which renders fallow fields prone to nitrate leaching into underground waters or drainage systems (Dinnes et al., 2002; Li et al., 2013). This nitrate ultimately makes its way into the water supply. Furthermore, without the presence of plant cover, unprotected topsoil is susceptible to unsustainable amounts of erosion, (Stocking, 1988; Pimentel and Kounang, 1998; Zhou et al., 2009; Cox et al., 2011), and water bodies become vulnerable to eutrophication and sediment deposition (Dinnes, 2004; Strock et al., 2011; Rao et al., 2012).

Extending and diversifying rotations with the inclusion of winter annual or perennial crops has been suggested to address the pitfalls of these "inherently" leaky systems. These crops may be included as cover crops between the harvest and planting of cash crops (Reeves, 1994; Strock et al., 2004; Fageria et al., 2005; Dabney et al., 2010; Kaspar and Singer, 2011), as alternative grain crops (Schwarte et al., 2005; Heggenstaller et al., 2008), as forage crops (Liebman et al., 2008, 2013; Picasso et al., 2008; Davis et al., 2012), or as replacing annual crops in strategic field areas (Heaton et al., 2013; Liebman et al., 2013). Yet, even when the above strategies have great potential to reduce nutrient exports while providing a suite of other environmental services (Dinnes, 2004; McLellan et al., 2015), these practices are still not prevalent among producers in Iowa. Only about 1% of all Iowa corn and soybean land was under cover crops in 2013 (Iowa Dept. of Ag. and Land Stewardship, 2014), and extended rotations accounted for only approximately 6% of all agricultural land in the state from 2006 to 2010 (Iowa Dept. of Ag. and Land Stewardship, 2013, Section 2.2, page 17). A possible reason for low adoption of cover crops is that a large portion of Midwestern farmers still regard them as practices whose agronomic benefits do not reliably translate into short-term economic returns to justify their use (Singer et al., 2007; Chellemi, 2009; Muth, 2014). Therefore, it is crucial to evaluate alternatives from environmental, agronomic, and economic perspectives. If economic advantages of diversification are demonstrated along with the agronomic and environmental benefits, perhaps the adoption of such strategies might be increased.

Winter canola (*Brassica napus)* could be a particularly good candidate for enhancing cropping systems in Iowa because of its potential to provide environmental benefits. Being a winter annual crop, winter canola could provide ground cover to reduce erosion and living roots to uptake nitrates during the winter fallow period. In addition, Iowa-grown canola could produce a marketable crop compatible with existing grain production and distribution schemes. Thus, the need for additional machinery and infrastructure might be limited (Brown et al., 2008; Boyles et al., 2012). However, it is still uncertain whether this crop would be suitable for helping balance environmental and financial goals of conventional cropping systems under the environmental and market conditions unique to Iowa.

The work presented in this thesis is an effort to explore the alternative of diversifying the predominant corn-soybean based rotations in Iowa with the inclusion of winter canola. The suitability of this crop for providing environmental and economic enhancements to the conventional summer annual cropping systems was studied throughout. The first stage was to assess the agronomic feasibility of growing winter canola in Iowa by studying the effect of seeding date on its ability to successfully overwinter and provide winter cover benefits. This information was then used to establish reliable seeding dates for this crop throughout the state. Building on the knowledge gained through experimentation in field plots and laboratory settings, the economic feasibility of integrating winter canola into summer annual rotations was also studied. The overarching framework used is depicted in Figure 1.1.

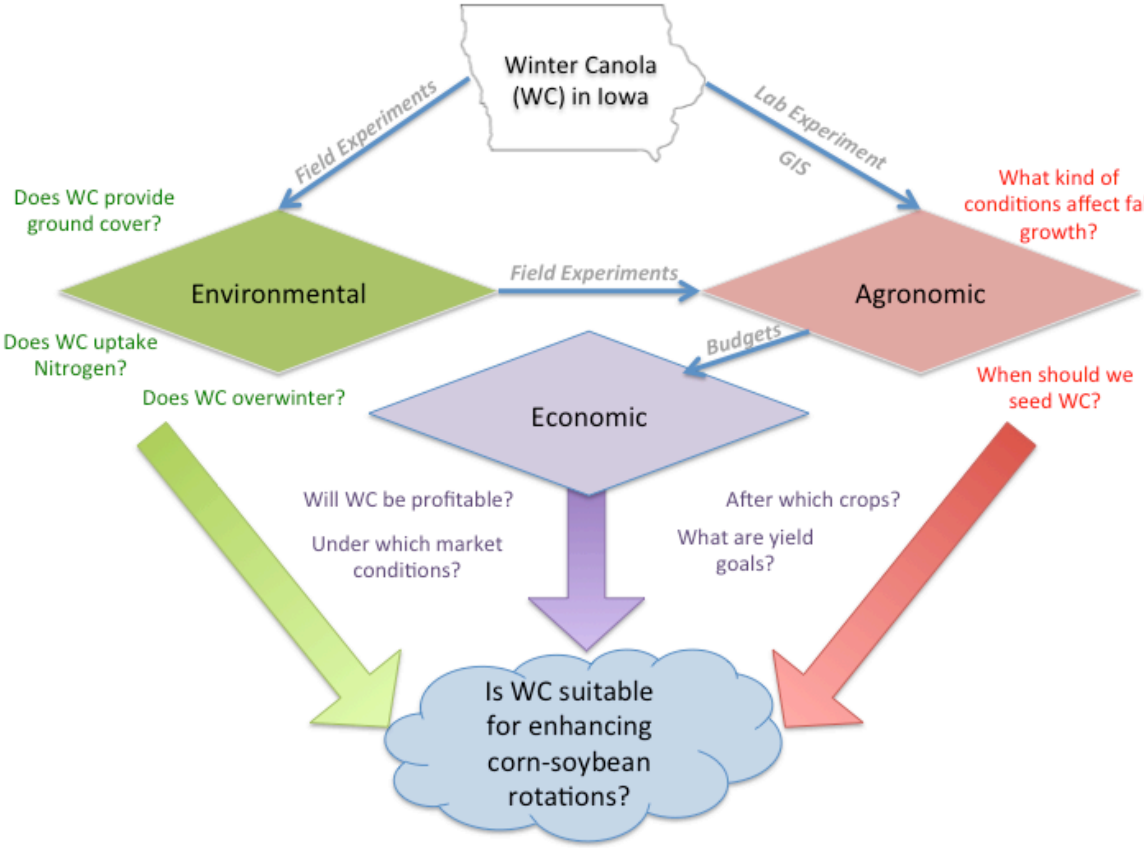

Figure 1.1 *Diagram of the framework used for assessing the suitability of winter canola for enhancing conventional summer annual rotations from environmental, agronomic, and economic perspectives*

Thesis Organization

This thesis is organized into six chapters. Chapter 1 is this general introduction. Chapter 2 constitutes an analysis of the effect of seeding date on winter canola's ability to successfully overwinter and provide adequate environmental benefits. Chapters 3 and 4 discuss an empirical approach for estimating reliable seeding dates for winter canola in Iowa. Chapter 3 focuses on determining the thermal time requirement for optimal fall growth of winter canola based on data collected from field plots and laboratories, while Chapter 4 uses this requirement to estimate the latest reliable seeding date across the state using Geographic Information Systems. The discussion is followed by an economic analysis of incorporating winter canola into summer annual rotations, which is included in Chapter 5. This analysis addresses the target oilseed yields and the market conditions under which integration would be economically competitive with conventional summer annual rotations. Lastly, Chapter 6 aims to synthesize the knowledge gained from the work done, and lay out suggested next steps to further develop this crop into a feasible alternative for Iowa.

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CHAPTER 2.

THE EFFECT OF SEEDING DATE ON THE PERFORMANCE OF WINTER CANOLA AS A WINTER COVER CROP IN CENTRAL IOWA

A manuscript to be submitted to Agronomy Journal

Abstract

Growing winter canola (*Brassica napus*) as a cover crop could provide soil and water conservation benefits, but winter survival represents a challenge in the cooler climates of the Upper Midwest. Timing of seeding can greatly affect winter canola's ability to successfully overwinter. Therefore, we conducted field experiments during 2012-2013 and 2013-2014 growing seasons to investigate the effect of seeding date on the performance of winter canola as a cover crop in central Iowa. Evidence is provided on the effect of seeding date on four indicators of cover crop performance: above ground biomass (AGB) production, N accumulation, canopy cover, and winter survival. Our results indicate that only canola seeded in early September in 2012, and in early and mid-September in 2013, produced sufficient AGB, canopy cover and N accumulation to provide adequate cover crop benefits during fall growth. However, because of unseasonable harsh winter conditions experienced during the winter of 2013-2014, which caused the death of plants for all seeding date treatments, this study was inconclusive about the effect of seeding date on winter survival and spring cover crop performance across different environments. Nonetheless, the results of this study indicate the importance of timely seeding for successfully establishing a winter canola cover crop in Iowa.

Introduction

Fields under conventional cropping systems in Iowa often remain bare with little or no cover between the harvest of crops in the fall and before the development of the next crop canopy in the spring. This practice renders agricultural land susceptible to unsustainable levels of soil erosion (Stocking, 1988; Cruse et al., 2006; Kaspar and Singer, 2011), and water bodies vulnerable to nutrient pollution (Cooper and Lipe, 1992; Schilling and Libra, 2000; Dinnes et al., 2002). Winter cover crops can be grown to cover the soil during periods between the harvest and establishment of summer annual crops, namely corn (*Zea mays* L.) and soybean (*Glycine max* (L) Merr.). While growing cover crops has many benefits (Kaspar and Singer, 2011), most adopters in the U.S. Corn belt use them with the objective of reducing soil erosion and enhancing nutrient cycling (Singer et al., 2007; Singer, 2008). In Iowa, cereal rye (*Secale cereale* L.) is frequently used as cover crop preceding the establishment of corn, while the use of non-grass species is much less common (Singer, 2008).

In general, winter cereal cover crops have a neutral effect on the yield of the subsequent corn crop (Miguez and Bollero, 2005). Yet in Iowa, yield decreases sometimes have been observed following rye cover crops, which deters growers from adopting this practice. Although the nature for the occasional yield decrease is not entirely understood, the problem may be related with the asynchronous nitrogen (N) release from the rye cover crop biomass and the needs of the subsequent crop (Miguez and Bollero, 2006; Kaspar and Singer, 2011; Pantoja, 2013), common pathogens shared between rye and corn seedlings (Schenck et al., 2013) or other factors which are currently under investigation. Including non-grass cover crop species into rotations, either as monocultures or in “cocktail” mixes, is being examined as a strategy for reducing the risk for corn yield decreases and for boosting the benefits related with the use of cover crops (Finney et al., 2013). Thus, information is needed for characterizing the performance of alternative cover crops grown under Iowa conditions to provide farmers and researchers with viable alternatives to the most commonly used cover crops in this state.

Winter canola (*Brassica napus*) is a winter annual crop that has been grown as cover crop in some areas of the Pacific Northwest and the Midwest, mainly in rotation with vegetable crops (Clark, 2007). In Idaho, *Brassica* cover crops have been seen to provide up to 80% canopy cover, and winter canola has been reported to accumulate as much as 3.0 to 8.2 Mg ha^{-1} of aboveground biomass at termination in the spring (Boydston and Hang, 1995; Al-khatib et al., 1997; Eberlein et al., 1998; Haramoto and Gallandt, 2004). Canola can also scavenge substantial amounts of N during fall growth and spring regrowth, reducing NO_3 –N movement into water sources (Dabney et al., 2010). Research in irrigated corn in Spain found that nitrogen leaching was reduced as much as 80% under a winter rape (*Brassica rapa*) cover crop treatment (Salmerón et al., 2010).

The extent to which canola can provide cover crop benefits is related to the amount of crop growth achieved during the fall rosette stage and in the spring, prior to its termination. Therefore, if the crop fails to overwinter, its usefulness as a winter cover crop may be limited. One of the main factors affecting winter canola growth and overwintering potential in northern latitudes has been found to be seeding date (Velicka et al., 2006; Lääniste et al., 2007; Holman et al., 2011). It has been reported that late seeding dates may result in small plants that do not store sufficient reserves during fall growth, reducing winter hardiness (Holman et al., 2011; Boyles et al., 2012). In central Iowa, preliminary data suggest that winter canola seeded in early September can survive the winter and produce acceptable oilseed yields during most years (Gailans and Wiedenhoeft, 2013). But, if canola were grown as cover crop after soybean or corn, direct seeding would have to be delayed until the standing crop is harvested, typically in early to mid-October. Therefore, we conducted a study to investigate the effect of timing of seeding on the performance of winter canola as a cover crop in central Iowa. Evidence is provided on the effect of seeding date on four indicators of cover crop performance: above ground biomass (AGB) production, N accumulation, canopy cover, and winter survival.

Materials and Methods

Environment and treatment description

Two field experiments were carried out during the 2012-2013 and 2013-2014 growing seasons at the Iowa State University Agricultural Engineering and Agronomy Farms in Boone County, Iowa (42.02°N, 93.74°W). In the 2012-2013 season, experimental plots were established at Sorenson Farm (SOR) in a field with Nicollet loam (Aquic Hapludolls) and Clarion loam (Typic Hapludolls) as predominant soil series and 3.6% organic matter (OM). In the 2013-2014 season, experimental plots were established at Bruner Farm (BRU), in a field with Clarion loam and Webster silty clay loam (Typic Endoaquolls) as predominant soil series, and 3.5% OM. Both sites were located within 1.0 km from each other.

Weather information for both seasons was recorded at a site (weather station Ames-8-WSW; 42.02°N, 93.77°N) located within 4 km from tests plots. Data were obtained from the Iowa Environmental Mesonet online database, and included values on daily precipitation, daily high and low temperatures, daily growing degree-days (GDD) (Base = 4.5°C, Max = 30°C), and snow depth from 1 September to 1 June. The factor environment characterized the effects of site and season.

In both site-years, a soybean crop had been growing during the summer and was removed in late August using a silage chopper. Then, fields were tilled with a tandem disk harrow, and fertilized by topdressing a 26.9 kg N ha^{-1}, 89.6 kg P_2O_5 ha^{-1}, 33.6 kg K_2O ha^{-1}, 22.4 kg S ha^{-1} and 2.2 kg Zn ha^{-1} at SOR and 22.4 kg N ha^{-1}, 67.2 kg P_2O_5 ha^{-1}, 22.4 kg K_2O ha^{-1} and 22.4 kg S ha^{-1} at BRU. Fields were tilled a second time to incorporate the fertilizer.

At every site-year, experimental plots were established in a completely randomized block design with four repetitions. A seeding date treatment was randomly assigned to each plot. Treatments for seeding dates were: early September (P1), mid September (P2), early October (P3), mid-October (P4). In SOR, seeding dates corresponded to 31 Aug (244 day of the year [DOY]), 17 Sep (261 DOY), 1 Oct (275 DOY) and 12 Oct (286 DOY), respectively. In a similar manner, in BRU, seeding dates corresponded to 3 Sep (246 DOY), 13 Sep (256 DOY), 1 Oct (275 DOY) and 14 Oct (287 DOY). At each seeding date, winter canola "Baldur" was seeded using a 3-meter wide grain drill in 19 cm rows, at a rate of 7 kg ha^{-1} and depth of 2.0 cm. Baldur (DL Seeds Inc. & Rubisco Seeds LLC) is a medium maturity, medium height and high yielding non-GM hybrid, with generally good winter hardiness (Stamm and Dooley, 2014).

Data collection

To assess the ability of winter canola to provide winter cover benefits under each seeding date treatment, four cover crop performance indicators were estimated for each plot at the end of fall growth and at termination in the spring. Indicators were: above ground biomass (AGB), canopy cover, N accumulation, and winter survival. At SOR, samples and observations were collected on 4 Nov (309 DOY) and 20 May (140 DOY), while at BRU, samples and observations were collected on 8 Nov (312 DOY) and 15-Apr (105 DOY).

Data was collected from half-meter sample areas using a 76 × 66 cm frame laid at three random points throughout experimental plots. The position of the frame was adjusted to fit four rows across its longest side. The average of the three areas was used as the estimate for the whole plot. Digital photographs of the areas were obtained and were used to estimate canopy cover. Number of plants was recorded and plants were clipped at the soil surface. The harvested aboveground portion of the plants was dried in a forced-air oven at 60°C until constant weight and weights were recorded. Dry weights were used to estimate the AGB expressed in kg ha^{-1}. Biomass samples were grinded using a Wiley mill (1 mm sieve), or a coffee grinder (home appliance) if the samples were too small (typically <5.0 g). The biomass samples were analyzed in laboratory to determine % N and % C content, which in turn was used to estimate a C:N of the biomass. Total N accumulation in the biomass was calculated as the product of % N content and the estimate of the AGB, and was expressed in kg ha^{-1}.

Percent canopy cover of each sample area was estimated by overlaying a 100-intersections point grid object on top of the digital photograph. The grid was created using Microsoft PowerPoint, and was adjusted every time to fit entirely within the sample area. The number of grid intersections that were superimposed over living canola canopy were counted and expressed as percentage. The grid was repositioned within the sample area, and the process was repeated a second time. The average of the two counts was the estimate of the % canopy cover of each image.

Number of plants per sample area was used to estimate plant density of experimental plots. Percent winter survival was calculated by dividing the estimated plant density of plots in the spring by the estimated plant density of plots in the fall. If spring density was greater than fall density, then winter survival was considered to be 100%.

Statistical analysis

Prior to conducting analyses, data was transformed when testing significant using a Bartlett's tests ($\alpha = 0.05$) to ensure homogeneity of variances. Above ground biomass and N accumulation data were transformed using a logarithmic transformation ($ty = \ln[y + 1]$), and canopy cover and winter survival were transformed with an angular transformation ($ty = \text{Arcsin}[\sqrt{y}]*180\pi^{-1}$).

The combined data for both environments was analyzed using the following model:

$$Y_{ijk} = \mu + Env_i + Blk_{(i)j} + Trt_k + Env{\times}Trt_{ik} + \varepsilon_{(i)jk}$$

(Model 2.1)

where: Y_{ijk} is the response variable (AGB, N accumulation, canopy cover, winter survival), μ the overall mean, Env_i is the effect of the ith environment, $Blk_{(i)j}$ is the effect of the jth block within the ith environment, Trt_k is the effect of the kth treatment, $Env{\times}Trt_{ik}$ is the interaction effect of the ith level of environment with the kth level of treatment, and $\varepsilon_{(i)jk}$ is the experimental error (NID (0, F^2)).

The factor environment was considered to be random, while the factor treatment was considered as fixed. Data was analyzed using Analysis of Variance (ANOVA), with the F-ratios determined by Mclntosh (1983) to test for factor effects. Test of hypothesis for the effect of Trt was calculated using $Env{\times}Trt$ as error term, while the effect of $Env{\times}Trt$ was calculating using $\varepsilon_{(i)jk}$ as error term.

When the $Env{\times}Trt$ term was found significant (p-value < 0.05), then data from both environments were also analyzed separately as a completely randomize block design using the following model:

$$Y_{ijk} = \mu + Blk_i + Trt_j + \varepsilon_{ij}$$

(Model 2.2)

Mean comparison procedure used was Fisher's protected Least Significant Difference (LSD) test with a comparison-wise error rate of $\alpha = 0.05$.

Results

Weather conditions

In general, fall growing conditions in both years featured dryer and warmer weather than normal in the early fall, and about normal temperature and moisture conditions in mid and late fall. Winter conditions were about normal for 2012-2013 (SOR), while extremely cold for 2013-2014 (BRU). Spring conditions in both environments remained fairly cool and moist, as cold weather lingered until early to mid April.

During 2012-2013 (SOR) (Figure 2.1), plots experienced seven days with air temperatures above 30°C, and received 47.0 mm of precipitation in the month of September, about 48% below the climatic normal. Most of the September precipitation was clustered on the first two weeks of the month and conditions remained dry for the last half of the month, challenging the establishment of canola seeded at P2. October and November weather conditions stayed about normal, with 59.5 mm and 23.9 mm of monthly precipitation, respectively, and air temperatures within normal ranges. The first occurrence of temperatures below -4.5°C was registered on 7 Oct (281 DOY), but temperatures remained relatively mild until late November and the first snow accumulation did not occurred until 20 Dec (355 DOY). This rendered growing conditions ideal for canola during mid and late fall. Winter conditions at SOR were within normal ranges for central Iowa, with 73 days of snow cover and four days with low temperatures under -20°C. The lowest air temperature recorded at SOR was -22°C on 2 Feb (33 DOY). The last occurrence of temperatures below -4.5°C was registered on 2 Apr (92 DOY), but conditions remained cool and wet through the rest of the spring with snow accumulations occurring as late as 3 May (123 DOY).

During 2013-2014 (BRU) (Figure 2.2), plots experienced even hotter and dryer conditions in September than SOR; for eleven days the air temperatures reached above 30°C, with the local weather station registering only 30.2 mm of precipitation (about 76% below the climatic normal). October and November weather conditions were about normal, with 63.5 mm and 40.4 mm of monthly precipitation respectively and air temperatures within normal ranges. The first occurrence of temperatures below -4.5°C was registered on 25 Oct (298 DOY), and first snow accumulation occurred on 22 Nov (326 DOY). Winter conditions at BRU were exceptionally cold with 93 days of snow cover and 29 days with low temperatures under -20°C. The lowest air temperature recorded at BRU was -29°C on 11 Feb. The last occurrence of temperatures below -4.5°C was registered on 15 April, and temperatures remained cool and wet until early April.

Cover crop performance indicators

Fall growth

In this study, an overall effect of the seeding date treatment on fall AGB production (p-value=0.0385) was observed across environments (Table 2.1). However, the ANOVA also revealed a strong interaction of *Env×Trt* (p-value <0.0001), suggesting that the effect of seeding date on fall growth differed between environments (Table 2.2). The data from SOR followed a distinct trend in which the fall AGB production was much greater for early-seeded canola, with 1144 kg ha^{-1} for P1, 109 kg ha^{-1} for P2, 14.0 kg ha^{-1} for P3 and 4.75 kg ha^{-1} for P4 (Table 2.3). At BRU, however, the effect was not as generalized. In fact, a Fisher's protected LSD test found no significant difference in the transformed values of fall AGB between P1 and P2. The ABG production in BRU was 695 kg ha^{-1} for P1 and P2, and 39.8 kg ha^{-1} for P3, while canola seeded at P4 failed to emerge.

The story was similar for N accumulation. An overall effect of the seeding date treatment on the fall N accumulation of winter canola (p-value=0.0286) was found along with a strong interaction of *Env×Trt* (p-value <0.0001), which suggest that the effect was different between environments. SOR total fall N accumulation estimates were 52.8 kg ha^{-1} for P1, 5.33 kg ha^{-1} for P2, 0.71 kg ha^{-1} for P3 and trivial amounts for P4. Like AGB, at BRU, P1 values of N accumulation were not different than P2. BRU total fall N accumulation estimates were 28.1 kg ha^{-1} for P1 and P2, and trivial amounts for P3 and P4 (Table 2.3).

The effect of seeding date on fall canopy cover at the sampling date (p-value=0.0752) does not seem to be as strong as for AGB and N accumulation. However, the effect of the interaction of *Env×Trt* tested highly significant (p-value <0.0001), meaning that the overall effect of the seeding date treatment was significantly dependent on the environment. At SOR, canopy cover at P1 was much greater than at other treatments, while at BRU, P1 transformed values of canopy cover were not different than P2 but both were drastically greater than the other treatments. The SOR canopy cover fall estimates were 72% for P1, 14% for P2, 5.3% for P3 and 1.8% for P4. The BRU canopy cover fall estimates were 53% for both P1 and P2 combined, and 8% for P3.

Winter survival

No prevailing effect of seeding date on winter survival across environments (p-value=0.5). Rather, a strong interaction between factors *Env×Trt* was observed (p-value <0.0001). This is because extremely harsh weather conditions during at BRU the winter of 2013-2014 made conditions unsuitable for survival, causing the death of all canola plants regardless of seeding date. At SOR, however, we were able to observe an effect of seeding date on winter survival (p-value <0.0001). Winter survival of canola was greater when seeded in P1, and sharply decreased if seeding was delayed. Seeding in P1 achieved winter survival of nearly 84% of their fall plant densities, with spring stands with an average of 44.7 plants m^{-2}. On the contrary, treatment P2 only reached 12.0% survival, having uneven spring stands that averaged below 10 plants m^{-2}. Treatments P3 and P4 did not survive the winter.

Spring regrowth

At SOR, spring regrowth appeared to follow a similar trend as observed for fall growth, with a strong effect of seeding date treatment on indicators AGB, N accumulation and canopy cover. Only P1 produced abundant AGB (3079 kg ha^{-1}), provided adequate canopy cover (71%), and accumulated abundant N (59.9 kg ha^{-1}) at termination in the spring. Delaying seeding to P2 severely reduced the AGB (102 kg ha^{-1}), canopy cover (10%) and N accumulation (2.3 kg ha^{-1}). The C:N of the winter canola biomass at termination was approximately 18:1 for P1, and 15:1 for P2. Since all BRU plots winter killed, no spring regrowth at BRU was recorded.

Discussion

The analysis of the data suggests that seeding date had a significant effect on the production of AGB and N accumulation during fall growth. It was observed that, in general, early seeding dates produced more AGB and N accumulation than later seeding dates. The trend is explained by the fact that early-seeded canola was exposed to greater amounts of GDD needed to realize growth. Winter canola seeded at P1 received on average about 0.45 times more heat units during fall growth (measured from seeding to sampling date), than canola seeded in P2, and about 1.66 and 4.12 times more than when seeded in P3 and P4, respectively. Less heat units available for growth were clearly reflected in a steep decline in the production of AGB and N accumulation at SOR. For instance, delaying seeding from P1 to P2 reduced the production of AGB by about a 10.5 fold. For the N accumulation the effect was similar, with P1 accumulating about 9.9 times more N than P2. Delayed cover crop establishment meant smaller plants that produced less AGB and accumulated less N during fall growth, which agrees with much of the evidence provided in the literature (Sidlauskas and Rife, 2004; Wysocki et al., 2005; Lääniste et al., 2007; Brown et al., 2008; Holman et al., 2011; Velicka et al., 2011).

Nonetheless, early seeding does not completely eliminate the risk for delayed establishment if adverse conditions are experienced in the early fall. This seemed to be the case at BRU, where delaying seeding from P1 to P2 decreased the total amount of heat units by about 20%, but no actual difference in AGB production and N accumulation between the treatments was observed. This presumably was due to the lack of soil moisture experienced during the early fall, were the first rainfall event recorded after P1 seeding was not until 13 days after seeding. This inhibited the germination of canola seeds, causing emergence to occur simultaneously with P2. On the contrary, the total amount of rainfall received by SOR P2 plots after seeding was about 42% less than P1 (measured from seeding to the sampling date). As expected, the drastic reduction of heat units and moisture available for growth (both included in the factor environment) notably affected the establishment of canola seeded at P2 at SOR.

A number of studies have described that adverse weather conditions in the early fall can significantly hinder the establishment and growth of winter canola. For instance, Balodis and Gaile (2011) found that *B. napus* germination and growth was affected by the amount of precipitation and air temperatures around the time of seeding and that a hydrothermal coefficient (a water stress indicator) was useful for explaining the emergence rate of seedlings (Balodis and Gaile, 2011). They also observed slower establishment and development of the fall rosette during drought years. Likewise, previous research has also demonstrated the importance of soil moisture and temperature in the emergence of canola seedlings (Blackshaw, 1991; Vigil et al., 1997). In general, research indicates that canola seedling emergence may be substantially delayed under dry and/or cold weather conditions.

Although the canopy cover is typically related to the amount of growth achieved by the crop, the analysis of data collected in this study was not able to verify a general trend of seeding date on the amount of canopy cover provided by canola in the fall. This was due to the large variability experienced across the two environments. However, both at SOR and BRU, the effect of seeding date on canopy cover during the fall seems to be significant. At SOR, P1 provided the most canopy cover (72%), followed by P2 (14%), while at BRU P1 and P2 provided the most amount of cover (52%). Conventionally, at least 30% of ground cover to is recommended to protect soil against wind and water erosion (Daniel et al., 1999). However, it is yet unknown whether the canopy cover provided by a canola monoculture provides the same relative erosion protection as surface residue. This is because, in contrast to the fibrous roots and dense vegetative structures of grasses, the architecture of the canola rosette, with wide, limp leaves and deep but thin taproot, may not be entirely favorable to protect the soil, especially if ground has been tilled prior to seeding. Anecdotal observations at BRU, where soil movement seemed to be greater in the cover crop plots than on untilled control plots, indicated a need to further investigate this issue.

Only P1 at SOR, and P1 and P2 at BRU, produced sufficient AGB, canopy cover and N accumulation to provide adequate cover crop benefits during fall growth. This suggests that to maximize cover crop benefits during the fall in central Iowa, delaying seeded beyond early September should be avoided. Mid-September seeding may still provide a feasible cover crop, but the risk of uneven establishment and poor growth is substantial. Other research has also found that early-seeded canola typically shows greater fall vigor and higher fall crown height (Holman et al., 2011). However, excessive growth during the fall has been also found detrimental for winter survival (Lääniste et al., 2007). This is often attributed to excessive use of water and nutrients during fall growth, and to the development of a higher crown that exposes the growing point to more cold stress and desiccation during the winter (Brown et al., 2008). Thus, seeding too early is also not recommended.

The effect of seeding date on winter survival was evident at SOR; a sharp decline in survival was observed when seeding was delayed. However, seeding date made no difference in the survival of canola at BRU, where extreme weather conditions experienced during the winter of 2013-2014 caused complete winterkill. Thus, the overall effect of seeding date on canola winter survival in central Iowa is still questionable. Failure of the canola plants to survive at BRU also made it difficult to measure the overall effect of seeding date on AGB, N accumulation and canopy cover in the spring. Only P1 at SOR resulted in ample AGB production (3.1 Mg ha^{-1}), N accumulation (59.9 kg ha^{-1}) and canopy cover (70%) at termination in the spring.

Complete winterkill, regardless of the growth stage achieved in the fall, seems to be an occasional risk faced in colder climates. *B. napus* cultivars can tolerate temperatures as cold as -19 °C after adequate cold acclimation, but cold hardiness has also been found to vary among cultivars (Waalen et al., 2011). While this temperature is not uncommon during the winter in Iowa, snow cover often provides some protection from external air temperatures. However, snow cover in Iowa is inconsistent and can widely fluctuate during the winter and across the landscape, thus the cover crop might still be exposed to detrimental external air temperatures. Plant death under cold stress often occurs by desiccation or the loss of cell membrane integrity (Smallwood and Bowles, 2002; Gusta and Wisniewski, 2012).

Winter canola has been seen to inconsistently overwinter in geographic regions within Plant Hardiness Zone 5 (USDA-ARS) (Rife and Zeinali, 2003), although in recent years improved cold tolerance of cultivars has been achieved. The inland region of the Baltic republic of Estonia faces similar challenges as central Iowa due to its cold winters. Recent research from this area has also reported complete winterkill regardless of fall growth in one out of three experiment years, although an overall trend of decreased survival with delayed seeding was observed (Lääniste et al., 2007).

While for some canola seed growers the risk for complete failure may be intolerable, canola may still be useful as a winter cover crop in Iowa. As demonstrated here, a winter canola monoculture can provide ample AGB production, N accumulation, canopy cover and achieved sufficient survival in Iowa during the fall and spring, if the right conditions for establishment, growth and overwintering occur. The risk of cover crop failure might be further reduced by incorporating canola in binary and cocktail mixes as suggested by Finney et al, (2013). In our study, signs of increased performance of early seeding dates were detected in spite of the great variation observed between both environments. Although more investigation is needed to solidly confirm the effect on survival and canopy cover, the results of this study speak to the importance of timely seeding for successfully establishment of a winter canola cover crop in Iowa.

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Figures and Tables

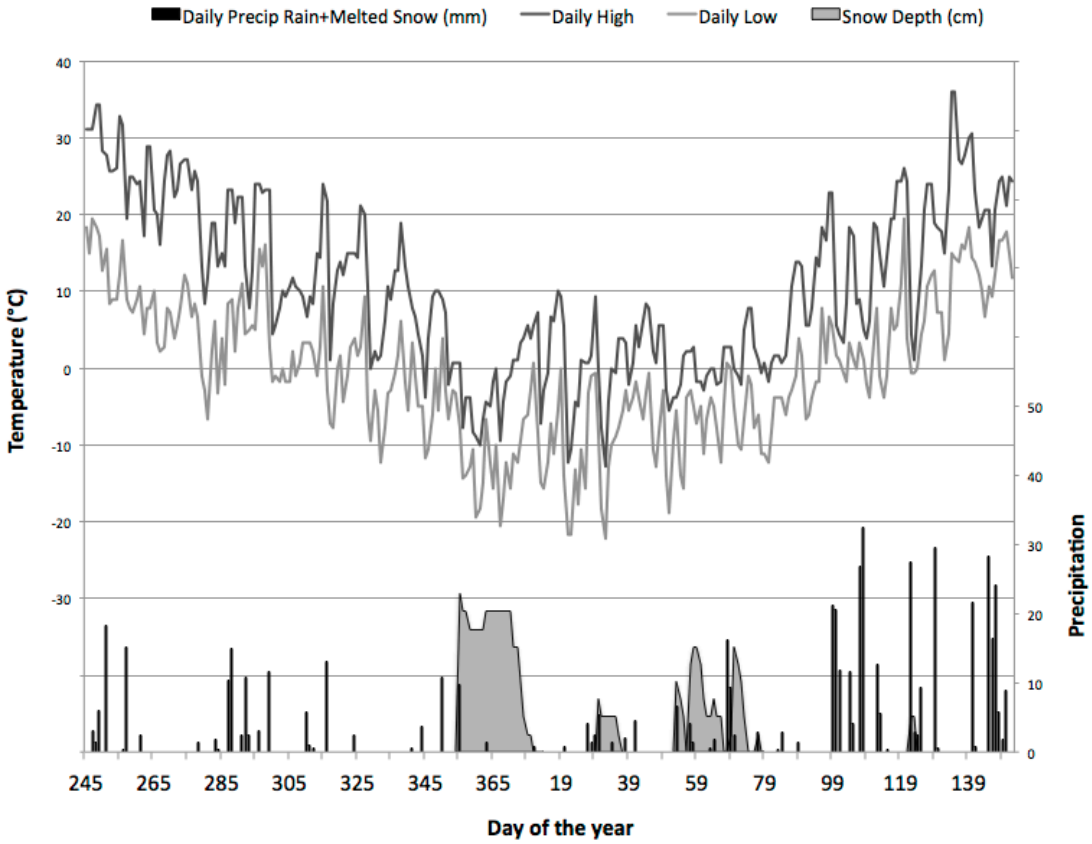

Figure 2.1 *Weather conditions at Sorenson Farm (2012-2013)*

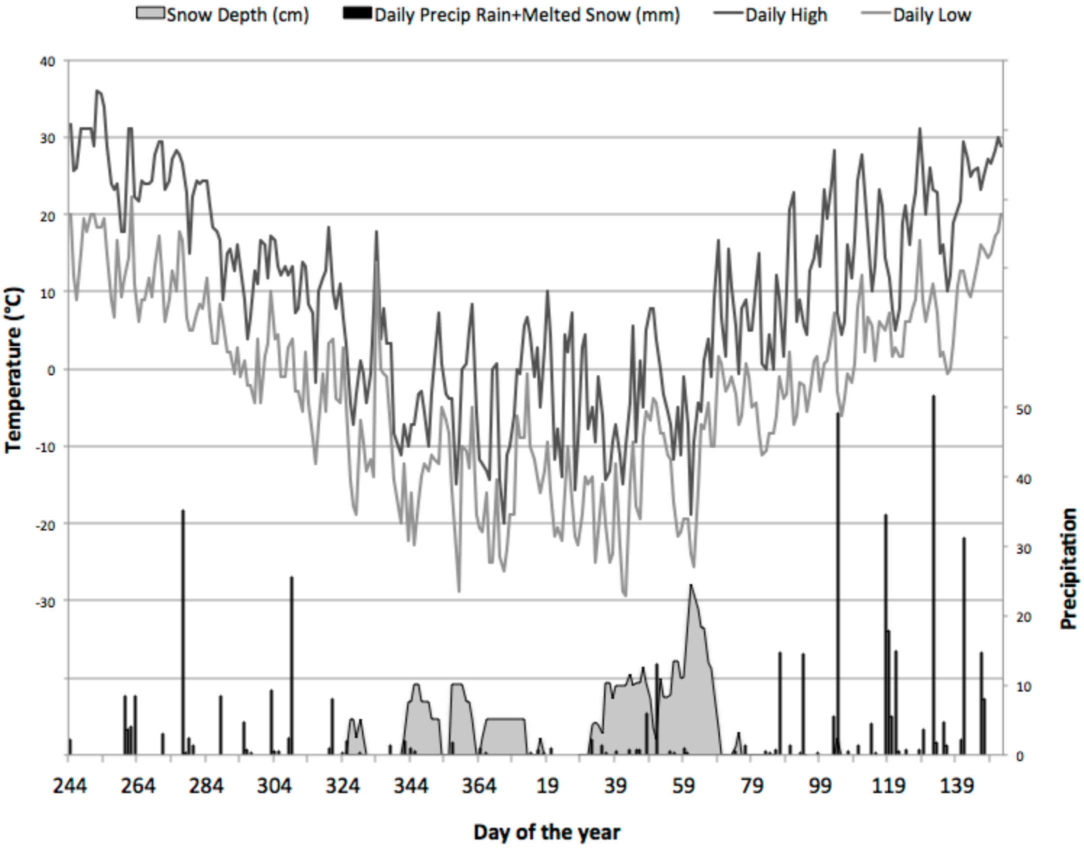

Figure 2.2 *Weather conditions at Bruner Farm (2013-2014)*

Table 2.1 *Overall effect of seeding date treatment (TRT) and environment×treatment (ENV×TRT) interaction on cover crop performance indicators during fall growth. *Tests of hypotheses for Trt use the Env×Trt as an error term. **Tests of hypothesesfor Env×Trt use the Trt×Blk as an error term. ^{ns} Indicates factor that tested to have a non effect at the significance level α=0.05.*

		TRT*	**ENV×TRT****
Indicator	***Transformed Units***	***Pr > F***	***Pr > F***
Above Ground Biomass (AGB)	ln[kg ha^{-1} + 1 kg ha^{-1}]	0.0385	< 0.0001
N accumulation	ln[kg ha^{-1} + 1 kg ha^{-1}]	0.0286	< 0.0001
Canopy Cover	Arcsin[√(% Canopy Cover)] ×180 π^{-1}	0.0752^{ns}	< 0.0001
Winter Survival	Arcsin[√(% Winter Survival)] ×180 π^{-1}	0.50 ^{ns}	< 0.0001

Table 2.2 *Effect of seeding date treatment on the cover crop performance indicators at each environment.*

			Environment	
			SOR	***BRU***
Indicator	***Transformed Units***	***Season***	***Pr > F***	***Pr > F***
Above ground biomass	ln[kg/ha + 1 kg/ha]	Fall	<0.0001	<0.0001
		Spring	<0.0001	-
N accumulation	ln[kg/ha + 1 kg/ha]	Fall	<0.0001	<0.0001
		Spring	<0.0001	-
Canopy cover	Arcsin[√(% Canopy Cover)]	Fall	<0.0001	<0.0001
		Spring	<0.0001	-
Winter survival	Arcsin[√(% Winter Survival)]	-	<0.0001	-

Table 2.3 *Estimates for cover crop performance indicators. *Treatments with the same letter are not significantly different at α = 0.05*

Indicator	*Units*	*Season*	*Environment*	*Seeding Date Treatment*			
				P1	***P2***	***P3***	***P4***
Above Ground Biomass	**kg ha^{-1}**	**Fall**	SOR	1144	109	14.0	4.75
			BRU*	744a	646a	39.8b	0
		Spring	SOR	3079	102	0	0
			BRU	0	0	0	0
Canopy Cover	**%**	**Fall**	SOR	72.0	13.5	5.25	1.75
			BRU*	53.3a	52.0a	7.75b	0
		Spring	SOR	71	10.25	0	0
			BRU	0	0	0	0
N accumulation	**kg ha^{-1}**	**Fall**	SOR	52.8	5.33	0.71	0.25
			BRU*	30.3a	25.9a	1.32b	0
		Spring	SOR	59.9	2.3	0	0
			BRU	0	0	0	0
Winter Survival	**%**	**-**	SOR	84.5	12	0	0
			BRU	0	0	0	0

CHAPTER 3.

THERMAL TIME REQUIREMENTS FOR OPTIMUM FALL GROWTH OF WINTER CANOLA IN IOWA

A manuscript to be submitted to Crop Science

Abstract

Numerous studies have concluded that winter canola plants need to develop a healthy, robust rosette of at least five leaves before the onset of winter to maximize potential survival. However, no information is available about the growth of winter canola under Iowa conditions. Therefore, investigation was conducted to track the growth of winter canola during the fall and to estimate its thermal time requirement for achieving the fifth stage in Iowa. The conditions that can affect the timely establishment of winter canola were also examined. The accrual of thermal time is an adequate predictor of emergence and growth for winter canola during the fall, and leaf development, plant weight and N accumulation are tightly correlated to the accrual of growing degree days (GDD) from emergence. The development of five leaves was estimated to require the accrual of 491 to 542 GDD after seeding under normal growing conditions. At this stage, canola plants weighted between 176 and 1324 mg and contained between 2.14 and 8.93 mg of N in the shoot. It was also observed that emergence can be substantially delayed if conditions for germination and emergence are unfavorable. Seedlings placed at the soil surface were the most vulnerable to experiencing uneven and delayed emergence, while seeding below depths beyond 2 cm can also delay emergence.

Introduction

In the Midwest, establishing overwintering crops between the harvest and planting of summer annual crops has been proven to be a successful strategy to help slow down soil erosion and runoff, and scavenge residual N (Dinnes et al., 2002; Snapp et al., 2005; Kaspar and Singer, 2011). Growth during the fall, persistence through the winter, and subsequent regrowth in the spring, provide a living cover that shelters the soil and recycles nutrients during times where summer annual crops, such as soybean (*Glycine Max* L. Merr.) or corn (*Zea mays* L.), cannot grow. Winter canola (*Brassica napus var.* Baldur) may be grown in Iowa successfully for this purpose, but providing adequate conditions for a timely establishment in the fall is crucial (Chapter 2). This is because canola's ability to survive the winter and deliver the pursued soil cover benefits has been seen to be associated to the degree of plant development achieved before the onset of winter (Velicka et al., 2006; Lääniste et al., 2007). Yet, currently there is no information available about the growth of winter canola under Iowa conditions, so characterizing the fall development of this crop in this environment is critical.

Numerous studies have concluded that winter canola cultivars reach an optimal growth stage for survival when the rosette develops between five to eight leaves (Sidlauskas and Rife, 2004; Wysocki et al., 2005; Velicka et al., 2006; Lääniste et al., 2007; Balodis and Gaile, 2011; Boyles et al., 2012). Less developed plants typically do not store sufficient reserves for survival, and thus are at greater risk of winterkill (Boyles et al., 2012). On the other hand, overgrown plants may develop an elevated and more exposed apical bud or use excessive amount of nutrients during fall growth, which can also be detrimental for survival (Lääniste et al., 2007; Holman et al., 2011).

Plant development is driven by the environmental conditions to which plants are exposed (i.e. temperature, moisture, nutrients), but these can vary widely among specific locations and between years. For instance, under favorable conditions, winter canola can develop five or six leaves within four weeks after seeding, but under unfavorable conditions, canola may only develop one or two leaves in the same timeframe (Daniels et al., 1986; Sidlauskas and Rife, 2004). Lack of soil moisture and cold soil temperatures have been seen to significantly inhibit the emergence of canola and delay establishment and growth (Nuttall, 1982; Blackshaw, 1991; Vigil et al., 1997). Likewise, extremely hot or cold air temperatures, or lack of soil moisture during the fall can also slow down growth, even if timely emergence is achieved (Sidlauskas and Rife, 2004; Balodis and Gaile, 2011). However, in general, canola fall development can be effectively predicted by the amount of thermal time (i.e. temperature over time) accrued after seeding or emergence (Gabrielle et al., 1998; Miller et al., 2001; Sidlauskas and Rife, 2004).

The greatest challenge for establishing canola in Iowa is that achieving this optimum growth stage (considered to be more than five leaves herein) is limited by a progressive decline in the thermal time available for growth as the winter approaches. This time frame is particularly limited if growing canola after summer annual crops is desired. Therefore, an estimate of the thermal time required for reaching optimum growth under Iowa weather conditions is needed to determine a reliable timeframe for seeding canola. Here, we characterize winter canola’s fall growth under Iowa weather conditions, and attempt to define winter canola’s thermal time requirement for emergence and optimum fall growth. These requirements were estimated using empirical data from experiments in field plots and were supplemented by data collected from experiments in controlled environments.

Materials and Methods

In this study, we defined the optimum fall growth as a rosette that develops at least five leaves. Two distinctive phases were considered to occur during fall growth: I) seeding to emergence, and II) emergence to optimum growth. To define the thermal time requirement for developing this optimum growth, these two phases of development of winter canola plants var. Baldur, were studied under field plot conditions and controlled environments.

Thermal time definition and units

Thermal time is defined as the accrual of temperature over time and is often used to study the rate of development in plants (Munns et al., 2010). In North America, the unit most commonly used to measure thermal time is growing-degree-day (GDD). Daily observations of GDD were calculated using the second method outlined by Mcmaster and Wallace (1997). To calculate the GGD accrued on a given day, the average of the daily maximum temperature (T_{max}) and the daily minimum temperature ($T_{\min}$) was computed, and a base temperature (T_{BASE}) was subtracted from the average. In this study, T_{BASE} was considered the minimum temperature which canola plant development is considered to be measurable. Likewise, a maximum temperature (T_{MAX}) in which further increases in rate of development were not considered significant was also included in the calculation. For this study, the values $T_{BASE} = 4.5$ °C and $T_{MAX} = 30$ °C (Habekotte, 1997; Vigil et al., 1997; Gabrielle et al., 1998; Balodis and Gaile, 2011) were used. The equation to calculate daily GGD was:

$$GDD = \left[\frac{T_{max} - T_{\min}}{2}\right] - T_{BASE}$$

(Equation 3.1)

where, if $T_{min} < T_{BASE}$, then $T_{min} = T_{BASE}$; and if $T_{max} < T_{BASE}$, then $T_{max} = T_{BASE}$. Similarly, if $T_{max} > T_{MAX}$, then $T_{max} = T_{MAX}$; and if $T_{min} > T_{MAX}$, then $T_{min} = T_{MAX}$.

Field experiments

To estimate the thermal time requirement for optimum growth of winter canola, two field experiments were carried out during the fall of 2012 and 2013 at the Iowa State University Agronomy and Agricultural Engineering Farms in Boone County, Iowa (42.02°N, 93.74°W). In 2012, experimental plots were established at Sorenson Farm (SOR) in a field with Nicollet loam (Aquic Hapludolls) and Clarion loam (Typic Hapludolls) as predominant soil series, and 3.6% organic matter (OM). In 2013, experimental plots were established at Bruner Farm (BRU) in a field with Clarion loam and Webster silty clay loam (Typic Endoaquolls) as predominant soil series, and 3.5% OM. Sites in the two years were located within 1.0 km from each other.

At SOR and BRU, a soybean crop had been previously established, so it was removed in late August using a silage chopper because it had not matured. Then, fields were tilled with a tandem disk harrow, and were fertilized by topdressing a dry fertilizer mix at a rate of 26.9 kg N ha^{-1}, 89.6 kg P_2O_5 ha^{-1}, 33.6 kg K_2O ha^{-1}, 22.4 kg S ha^{-1} and 2.2 kg Zn ha^{-1} at SOR and 22.4 kg N ha^{-1}, 67.2 kg P_2O_5 ha^{-1}, 22.4 kg K_2O ha^{-1} and 22.4 kg S ha^{-1} at BRU. Fields were tilled a second time to incorporate the fertilizer. Experimental plots at both site-years were established in a completely randomized block design with four repetitions. Winter canola variety “Baldur” was seeded at three dates using a 3-meter wide grain drill in 19 cm rows, at a rate of 7 kg ha^{-1} and depth of 2.0 cm. Baldur (DL Seeds Inc. & Rubisco Seeds LLC) is a medium maturity, medium height and high yielding non-GM hybrid, with generally good winter hardiness (Stamm and Dooley, 2014). Seeding dates corresponded to 31 Aug (244 day of the year [DOY]), 17 Sep (261 DOY) and 1 Oct (275 DOY), at SOR, while at BRU, seeding dates corresponded to 3 Sep (246 DOY), 13 Sep (256 DOY) and 1 Oct (274 DOY).

Date of emergence for each seeding date was determined visually and recorded. Plant samples were collected on 5 Oct (279 DOY), 11 Oct (285 DOY), 24 Oct (298 DOY) and 4 Nov (309 DOY), at SOR and on 3 Oct (276 DOY), 18 Oct (291 DOY) and 8 Nov (312 DOY) at BRU. Data samples were collected from half-meter areas using a 76 × 66 cm frame laid at three random points throughout the experimental plots, and average of the three observations was used as the estimate for the whole plot. From each sample area, six plants were randomly selected and number of true leaves was counted. The number of plants was counted and plants were clipped at the soil surface. The harvested aboveground portion of the plants was dried in a forced-air oven at 60°C until constant weight, and weights were recorded. Average plant weight was calculated by dividing the dry weight by the number of plants. Biomass samples were grinded using a Wiley mill (1 mm sieve) or a coffee grinder (home appliance) if the samples were too small (typically <5.0 g). Biomass samples were analyzed in laboratory to determine % N, which in turned was used to estimate average plant N accumulation in the biomass as the product of % N content and biomass weight, divided by the number of plants. Nitrogen content was expressed in mg plant^{-1}.

Weather observations for both seasons were recorded at a location (weather station Ames-8-WSW; 42.02°N, 93.77°N) within 4 km from tests plots. Weather data were obtained from the Iowa Environmental Mesonet online database (Iowa Environmental Mesonet, 2014) and daily minimum and maximum temperatures, and precipitation from 215 to 365 DOY for 2012 and 2013.

Experiment under controlled environments

To understand the extent to which environmental conditions affect the thermal time requirement for emergence of winter canola, an experiment in controlled temperature and moisture conditions was performed, with a methodology similar to those of previous canola seedling emergence studies (Blackshaw, 1991; Vigil et al., 1997). The growing medium used in this experiment was a loam soil with 30% sand and 26% clay, and a dry bulk density of 1.12 g cm^{-3}. Soil was pre-sieved using a 4 mm mesh to break soil aggregates and remove gravel and large organic material. Then, soil was sieved with a 2 mm mesh to homogenize soil particles and remove large weed seeds. Soil was air-dried in large pans until constant moisture (~0.05 g g^{-1}) and stored in stable conditions. A soil moisture treatment was applied by spreading soil on a large tray, moistening it with an aspirator bottle and mixing it with a small tool. Applied gravimetric moisture levels were 0.14 g g^{-1}, 0.18 g g^{-1} and 0.22 g g^{-1}. In this particular soil, water potential approached permanent wilting point (~ -1.5 MPa) at 0.14 g g^{-1}, while at 0.22 g g^{-1} water potential was near field capacity (~ -0.33 MPa), according to the equations derived by Saxton and Rawls (2006). To be able to work properly with the moisten soil and avoid compaction when mixing, the 0.22 g g^{-1} treatments were initially applied enough water to reach the 0.18 g g^{-1} level. The balance of the moisture was later applied at seeding by spraying water directly on top of soil using the aspirator bottle. Individual samples corresponded to paper cups of 260 ml in capacity filled with approximately 150 g of wet soil and covered with individual plastic bags to prevent loss of soil moisture (Figure 3.1).

Temperature treatments were applied using a dark incubation chamber and were maintained constant during the incubation period. Levels of temperature were 10, 16, 22 and 28 °C, which were meant to represent a range of soil temperatures typical during the early fall in Iowa Prior to seeding, cups of soil were placed in the incubation chamber at the corresponding temperature level for at least 24 hours to ensure homogeneous conditions throughout the soil. Twenty winter canola seeds variety “Baldur” (92% germination as indicated by supplier) were placed with tweezers at four seed depths: 0, 1, 2 and 3 cm. Eight small perforations were made to plastic bags to allow some gas exchange. Then, samples were placed back in incubation. The depth and moisture treatments were applied in a 2 × 3 factorial arrangement with four repetitions within the incubation chamber, and the temperature treatment was replicated in two different incubation chambers. Observations on the number of seedlings emerged (hypocotyl and cotyledons visible above the soil level) were collected daily until emergence in most experimental units plateaued.

Statistical methods

Data from field experiments were analyzed with various simple regression analyses. To demonstrate the correlation between leaf development and plant growth, simple linear regression analyses of the number of leaves ($leaves$) on the average plant weight ($weight$) and N accumulation ($Naccum$) were conducted (Model 3.1a and 3.1b). Data on $weight$ and $Naccum$ were transformed using a $y = \ln{(x)}$ form to ensure homoscedasticity. A regression analysis of GDD accrued from emergence (GDD) on $leaves$, $Naccum$ and

$weight$ was performed to describe the effect of thermal time on growth of emerged canola plants (models 3.2a, 3.2b and 3.2c).

The simple regression models were:

$$\ln(weight) = \beta_0 + \beta_1 leaves$$

(Model 3.1a)

$$\ln(Naccum) = \beta_0 + \beta_1 leaves$$

(Model 3.1b)

$$leaves = \beta_0 + \beta_1 GDD$$

(Model 3.2a)

$$\ln(weight) = \beta_0 + \beta_1 GDD$$

(Model 3.2b)

$$\ln(Naccum) = \beta_0 + \beta_1 GDD$$

(Model 3.2c)

where $wieght$ is the average plant weight (mg); $leaves$ is the number of true leaves; $Naccum$ is the average plant Nitrogen accumulation in the shoot (mg); β_0, β_1 are regression coefficients; and *GDD are the g*rowing degree-days °C [Base = 4.5, Max=30] accrued after seeding.

Data collected from the experiment under controlled environments were analyzed by calculating percent emergence (PE) for each sample at the end of incubation period (Equation 3.2), where:

$$PE = \frac{Emerged\ Seedlings}{Number\ of\ seeds} \times 100$$

(Equation 3.2)

Percent of total emergence (PTE) (Equation 3.3) was also calculated for daily observations at every sample with:

$$PTE = \frac{Emerged\ Seedlings}{PE} \times 100$$

(Equation 3.3)

PTE responses were averaged by experimental unit (cross-factor of temperature, incubation chamber, moisture and depth; n=96), and then a Gompertz Growth Model (Equation 3.4) was fitted using a self-starting function (SSgompertz) with GDD as explanatory variable, all within the Nonlinear Least Squares function in R statistical software (version 3.1.1). The model fitted had the form:

$$y = A\ e^{-b_2 b_3^x}$$

(Equation 3.4)

where y is the response variable of PTE; A, b_2 and b_3 are model parameters; and x is the independent variable of GDD. The GDD requirement for 50% emergence (GDD_{50}) was calculated by solving Equation 3.4 for GDD with a predicted PTE of 50%.

The effects of treatments on the log-transformed units of GDD_{50} were analyzed using a Linear Mixed-effects Model (*lme*) function from the Linear and Nonlinear Mixed Effects Model (*nlme*) package in R statistical software. The model included the soil moisture

($moist$) and seed depth ($depth$) and their interaction ($moist{\times}depth$) as fixed factors, and incubation chamber ($incub$) nested within temperature ($temp$) as a random factors:

$$ln(GDD_{50})_{ijkl} = \mu + temp_i + incub_{(i)j} + moist_k + depth_l + moist{\times}depth_{kl} + \varepsilon_{(i)jkl}$$

(Model 3.3)

where $\ln(GDD_{50})_{ijkl}$ is the response variable of log-transformed units of accrued growing degree-days °C [Base = 4.5, Max=30] after seeding; μ is the overall mean; $temp_i$ is the random effect of the ith temperature; $incub_{(i)j}$ is the random effect of the jth incubator within the ith temperature; $moist_k$ is the effect of the kth soil moisture treatment; $depth_l$ is the effect of the lth seed depth treatment; $moist{\times}depth_{kl}$ is the interaction effect of the kth level of moisture with the kth level of depth; and $\varepsilon_{(i)jkl}$ is the experimental error (NID (0, F^2)).

In addition, to test the effect of temperature, soil moisture and seed depth on the probability of emergence of canola seedlings, a Multiple Logistic Regression analysis was performed on the sample observations of PE (Model 3.4). The model was fitted using the Fitting Generalize Linear Models function (glm) in R statistical software. The distribution family used in the regression analysis was quasi-binomial with an empirical scale parameter, in order to account for overdispersion. The model used for the analysis is outlined was:

$$logit(\pi) = \beta_0 + \beta_1 moist + \beta_2 depth + \beta_3 temp + \beta_4 temp^2 + \beta_5 moist{\times}depth$$

(Model 3.4)

where $logit(\pi)$ is the response variable of log-odds of successful emergence for individual seedlings; β_0 , $\beta_1, \dots, \beta_5$ are regression coefficient; $moist$ is the explanatory variable of gravimetric soil moisture content (g g^{-1}); $depth$ is the explanatory variable of seed depth (cm); $temp$ is the explanatory variable of temperature (°C); and $moist \times depth$ is the explanatory variable of the interaction of soil moisture and seed depth.

Results and Discussion

Weather conditions during field experiments

In general, growing conditions in 2012 at SOR and in 2013 at BRU were dryer and warmer than normal in the early fall, and about normal temperature and moisture conditions in mid and late fall. At SOR (Figure 3.2A), plots experienced seven days with air temperatures above 30°C, and received only 47.0 mm of precipitation (about 48% below the climatic normal) during the month of September. Most of the precipitation was clustered in the first two weeks, and conditions remained dry for the last half of the month. October and November weather conditions stayed normal with 59.5 mm and 23.9 mm of monthly precipitation, respectively, and air temperatures within normal ranges. The first occurrence of temperatures below the -4.5°C threshold was on 7 Oct (281 DOY), but temperatures remained relatively mild until late November and the first snow accumulation did not occurred until 20 Dec (355 DOY). Thus, the conditions were ideal for growth of canola during mid and late fall.

In BRU (Figure 3.2B), plots experienced even hotter and dryer conditions in September than in SOR; the local weather station recorded seven days with air temperatures above

30°C, and only 30.2 mm of precipitation (about 76% below the climatic normal) in September. October and November weather conditions were normal, with 63.5 mm and 40.4 mm of monthly precipitation respectively, and air temperatures were within normal ranges. The first occurrence of temperatures below the -4.5°C threshold was on 25 Oct (298 DOY), and the first snow accumulation occurred on 22 Nov (326 DOY).

Emergence under field conditions

Observed thermal times accrued from seeding to emergence for every seeding date treatment in both experiments are reported in Table 3.1. In most treatments, emergence occurred within 12 to 16 days after seeding, with the exception of canola seeded on 3 Sep at BRU, where the emergence was presumably delayed by abnormally dry conditions experienced in early September. Likewise, with the exception of the aforementioned case, canola required between 129 to 223 GDD after seeding for emergence. In both years, the thermal time required for emergence was greater for earlier-seeded canola, but in a simple linear regression analysis, the effect of seeding date tested non significant (P-value=0.085). Thus, at least based on the data presented here, the thermal time required for emergence appears to be constant irrespective of seeding date. However, the lack of power of the test (df = 4) may indicate the need for further investigation to confirm or reject this claim.

The median value of the thermal time accrued from seeding date to emergence in this study was 168.5 GDD, which may be interpreted as an estimate for the thermal time requirement for emergence. Yet, since substantial experimental error among seeding date treatments was detected ($\sigma^2 = 6162.27$), we could consider this to be a weak estimate. Nonetheless, emergence of *B. napus* has been estimated to occur around similar ranges in

Saskatchewan (Miller et al., 2001) and Idaho (Wittman, 2005). In general, it has been reported that emergence can be detected in the field anywhere from 4 to 12 days after seeding, but this widely depends on conditions (Vigil et al., 1997; Boyles et al., 2012).

A study in Latvia determined that a hydrothermal coefficient, that is, one that accounts for temperature and precipitation, was useful for predicting a delay in emergence of canola under drought conditions (Balodis and Gaile, 2011). The study found that dry conditions delayed emergence up to 15 to 16 days after seeding. Emergence has been also reported to be substantially delayed by dry and cold conditions in field experiments in southern Alberta (Blackshaw, 1991), and to certain extent by seed depth in controlled environments (Vigil et al., 1997). Therefore, we deemed necessary to further investigate the factors that may affect the thermal time requirement for emergence of canola and their respective magnitudes. This will be discussed further below.

Growth under field conditions

Analysis of the combined data from both field experiments using models 3.1a and 3.1b confirmed that the factor $leaves$ was well correlated with the log-transformed units of $weight$ ($r^2 = 0.923$) and $Naccum$ ($r^2 = 0.945$). During the growth of the fall rosette, development of each leaf was associated with a 98% average increase in plant weight and an 88% average increase in N accumulation. Using the regression equation from model 3.1a and 3.1b, it is estimated that a five-leaf fall rosette weighted on average 483 mg (95% CI: 176, 1324 mg) and accumulated about 4.38 mg (95% CI: 2.14, 8.93 mg) of N in the shoot.

These results indicate that plants that develop more leaves tend to have greater biomass (Figure 3.3A), accumulate greater amounts of N in the shoot (Figure 3.3B), and thus, may be better prepared for overwintering. Velicka et al. (2006) found that number of leaves was associated with other biometric indicators such as diameter of the root collar, height of the apical bud, and the chemical composition of leaves and apical buds. In that study, canola plants with greater number of leaves typically contain greater concentrations of nutrients and sugars in leaves and apical buds and had better winter survival, although winter survival was also related to stand density (Velicka et al., 2006). *In vitro* analyses have observed that increased concentration of nutrients in tissues can improve cold hardiness, by inhibiting intracellular ice crystal formation and helping preserve membrane integrity (Teutonico et al., 1993; Rife and Zeinali, 2003; Waalen et al., 2011; Gusta and Wisniewski, 2012).

In our study, fall growth was tightly correlated to the amount of thermal time to which plants were exposed. Analysis of model 3.2a revealed that the accrued thermal time from emergence was an accurate predictor of the development of leaves of the fall rosette ($r^2 = 0.982$) (Figure 3.4A). On average, the development of one leaf required 69.1 GDD (95% CI: 64.6, 74.8 GDD). Based on the regression equation of Model 3.2a, it is estimated that the development of a five-leaf rosette required an accrual of 345 GDD (95% CI: 323, 374 GDD) after emergence. Likewise, analysis of Models 3.2b and 3.2c suggests that thermal time was also a reasonable predictor of the log-transformed units of average plant weight ($r^2 = 0.918$) (Figure 3.4B) and average N accumulation in the shoot ($r^2 = 0.934$) (Figure 3.4C).

Similar to our findings, Balodis and Gaile (2011) found that the accrual of thermal time was linearly correlated, not only to the number of leaves, but to other biometric indicators such as dry weight of leaves, height of the apical bud, root mass and root length. In our study, the accrual of 100 GDD resulted in 142% (95% CI: 118, 165 %) increase in average plant weight, and with a 136% (95% CI: 114, 159 %) increase in the N accumulation in the shoot.

The predicted thermal time requirement for the estimated average weight (483 mg) and N accumulation (4.38 mg) of a five-leaf rosette was 347 GDD (95% CI: 259, 436 GDD) and 344 GDD (95% CI: 273, 415 GDD), respectively.

Factors affecting emergence of canola seedlings

To increase the confidence in the thermal time requirement for emergence estimated with our field data, we investigated the conditions that may affect emergence of canola and their respective magnitudes. Others have studied the time and thermal time requirement for emergence of canola (Nuttall, 1982; Blackshaw, 1991; Vigil et al., 1997) but the range of temperatures examined have typically aimed to represent environments with lower temperatures (<16°C), which are more characteristic to those experienced in early spring. Here, we present the results for an experiment in a controlled environment under temperature treatments ranging from 10 to 28 °C, typical temperatures for fall seeding.

We were able to successfully fit Gompertz growth models on the collected data of the percent of total emergence (PTE) in 86 out of all 96 experimental units. Most of the failures to fit a model were due to the fact that no or very little PE was achieved under these treatments. Model parameters, root mean square errors and the predicted GDD_{50} of the resulting models are reported on Table 3.2.

The analysis of these data with Model 3.3 revealed that all fixed factors, $moist$, $depth$, and the interaction $moist \times depth$, had a significant effect ($\alpha = 0.05$) on the log-transformed thermal time requirements of winter canola seedlings. The factor $moist$ had a strong effect on the GDD_{50} (p-value <0.0001), while the effect of $depth$ was much weaker (p-value = 0.0442). The mean response of $moist$ was 87.4, 67.3 and 66.7 GDD at the 0.14, 0.18 and 0.22 g g^{-1} moisture levels, respectively. The mean response of $depth$ was 74.4, 66.6, 70.0 and 77.9 GDD seeded at 0.0, 1.0, 2.0 and 3.0 cm, respectively. Moreover, the high significance of $moist \times depth$ (p-value = 0.0041) indicates that the response was different depending on the level of moisture and depth, suggesting a non-linear response of these factors.

As shown in Figure 3.5A, at 0.14 and 0.18 g g^{-1}, the thermal time requirement was greater for depth 0.0 cm, followed by 3.0, 2.0 and 1.0 cm, respectively. However, at 0.22 g g^{-1}, seedlings required the most thermal time when seeded at 3.0 cm, followed by 2.0, 1.0 and 0.0 cm. At seed depths below 0.0 cm, seedlings tended to require greater thermal time to emerge as depth increased (Figure 3.5B). The GDD_{50} tended to be the greatest at moisture level of 0.14 g g^{-1}, followed by 0.22 and 0.18 g g^{-1}, respectively. The requirements for the 0.22 and 0.18 g g^{-1} moisture levels resulted in small numerical differences. The slightly grater GDD_{50} at the 1.0, 2.0 and 3.0 cm depths may be due to water saturation in the soil surrounding the seeds after the remaining water was applied at seeding in the 0.22 g g^{-1} treatment. This might have inhibited germination of seeds during the first hours of incubation, which resulted in a small delay in emergence.

Averaged across all levels of moisture and depth, emergence of canola seedlings occurred in this experiment about 72.2 GDD (95% CI: 68.7, 75.7 GDD) after seeding. This thermal time requirement was as much as 30% higher for canola grown under 0.14 g g^{-1} than canola under moisture levels of 0.18 and 0.22 g g^{-1}. The general trend of depth, however, was more complex. While it seems that in general deeper seeded seedlings require more thermal time to emerge, presumably because of the distance that the hypocotyl has to expand in order to reach the soil surface, this effect is influenced by moisture. At the driest level and medium moisture levels, increasing depth from 0 to 1 cm reduced GDD_{50}. However, increasing depth from 1 to 3 cm increased GDD_{50} by about 17%. This seems to indicate that while seeds placed at the soil surface seem to have an advantage for rapid emergence if soil moisture approaches field capacity, this may also result in significant delay in emergence if soil conditions tend to dryness. This has important implications when considering broadcasting as a seeding method. Other practices that decrease soil moisture in the top layer of the soil, such as tillage or removal of residues could also have a negative impact if rainfall fails. Broadly speaking, the analysis suggests that seeding depth between 1 and 2 cm would result in the most predictable thermal time requirement for emergence, and therefore seeding at this range of depths would be recommended.

Environmental factors seem to play a role, not only in the thermal time requirement for emergence, but also in the total emergence that a winter canola stand may achieve. The analysis of Model 3.4 revealed that $moist$, $depth$, $moist \times depth$, $temp$ and the $temp^2$ had a significant effect on the emergence of canola seedlings ($\alpha=0.05$). The significance of $temp^2$ (p-value <0.0001) evidences that the effect of temperature follows a curvilinear response. The model equation of a simple linear regression of $temp$ and $temp^2$ on the PE estimates that optimum temperature for emergence of canola was 17.4°C, where the predicted mean emergence was 83%. Observed values peaked at 85.2% in 16°C, while at 28°C mean PE only reached 50% (Figure 3.2A).

The strongest effect to the response of PE was given by $moist$. However, the moisture treatment of 0.14 g g^{-1} was the only one that exhibited a reduction on PE, in which the mean response was observed to be nearly 42%, compared with 81% and 83% observed in the 0.18 and 0.22 g g^{-1} treatments, respectively (Figure 3.6B and 3.6C). On the other hand, the effect of $depth$ was much weaker. Emergence was observed to be the lowest at the 0 cm depth and 0.14 g g^{-1}, achieving only a response of nearly 18% emergence. The significance of the $moist \times depth$ term is indication of the non-linearity of the responses.

Overall, the analysis of Model 3.4 suggests that the odds of successful emergence of individual canola seedlings may be mostly influenced by soil moisture and to a lesser degree by temperature and depth. Practically speaking, PE will be probably affected if hot and dry soil conditions are encountered, with PE likely being severely reduced if seeds are placed on the soil surface under these conditions.

Thermal time requirement for optimal overwintering growth

Our results demonstrate that the accrual of thermal time can be used effectively to track the development of winter canola. All of the metrics studied in our field experiments (leaf development, plant weight and N accumulation) were found to be correlated, not only to each other, but to the thermal time accrued from emergence. In both experiments, canola seeded in early September was exposed to sufficient thermal time to develop five or more leaves before the onset of winter, whereas delaying seeding generally resulted in smaller plants with typically fewer leaves.

With the analysis of field data, we conclude that the thermal time requirement from emergence date to the development of a five-leaf rosette of canola plants grown under similar conditions should be between 323 and 374 GDD, as calculated with the regression equation of Model 3.2a. Similarly, the thermal time required from seeding date to emergence estimated with our field data was 168.5 GDD. Although this value is more than double what was found to be in our experiments in controlled environments, it should be noted that emergence in laboratory experiments was determined when the hypocotyl and cotyledons were barely visible above the soil level. In the field experiments, the date of emergence was estimated by visually inspecting plots every other day. In addition, large soil aggregates and the presence of crop residues could have also reduced the emergence speed of seedlings. Since our field estimate is not substantially different from other research (Miller et al., 2001; Wittman, 2005), we are confident in using this value.

Based on these field data, we approximate that achieving the optimum growth for overwintering should be expected once 491 to 542 GDD after seeding have been accumulated. Nonetheless, as learned through the analysis of the experiment in controlled environments, the emergence of canola may be delayed as much as 30%. Consequently, the development of the fifth leaf in canola may take as much as 592 GDD, if adverse conditions such as low soil moisture are encountered at seeding.

Comparable estimates have been provided in similar studies on canola and rapeseed varieties in other parts of the world. For instance, Lääniste et al. (2007) showed that 416 GDD (Base = 5 °C) from seeding was sufficient to develop a strong root system and prepare rapeseed for overwintering in Estonia. Sidlauskas and Rife (2004) noted that the fifth leaf reached maximum expansion after the accrual of about 550 GDD (Base = 5 °C) after seeding in Lithuania. Results from field studies in Idaho report that the development of two leaves occurred after the accrual of 237 to 314 GDD (Base = 4 °C) after seeding (Wittman, 2005).

Conclusions

Based on our analyses, we conclude that the accrual of thermal time is an adequate predictor of emergence and growth for winter canola during the fall. Leaf development, plant weight and N accumulation are tightly correlated to the accrual of GDD from emergence. We estimate that a five-leaf rosette, that is, the minimum development stage that maximizes potential winter hardiness, weighs between 176 and 1324 mg, contains between 2.14 and 8.93 mg of N in the shoot, and requires the accrual of 491 to 542 GDD after seeding under normal growing conditions to achieve such growth. However, emergence should be expected to be substantially delayed if conditions for germination and emergence are not adequate. Seedlings placed at the soil surface seem to be especially vulnerable to delayed emergence and uneven stands if low soil moisture conditions are encountered. Additionally, seeding at depths below 2.0 cm may also delay emergence of canola seedlings. Thus it is recommended to seed winter canola between 1.0 to 2.0 cm to provide for most reliable, uniform and rapid emergence.

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Figures and Tables

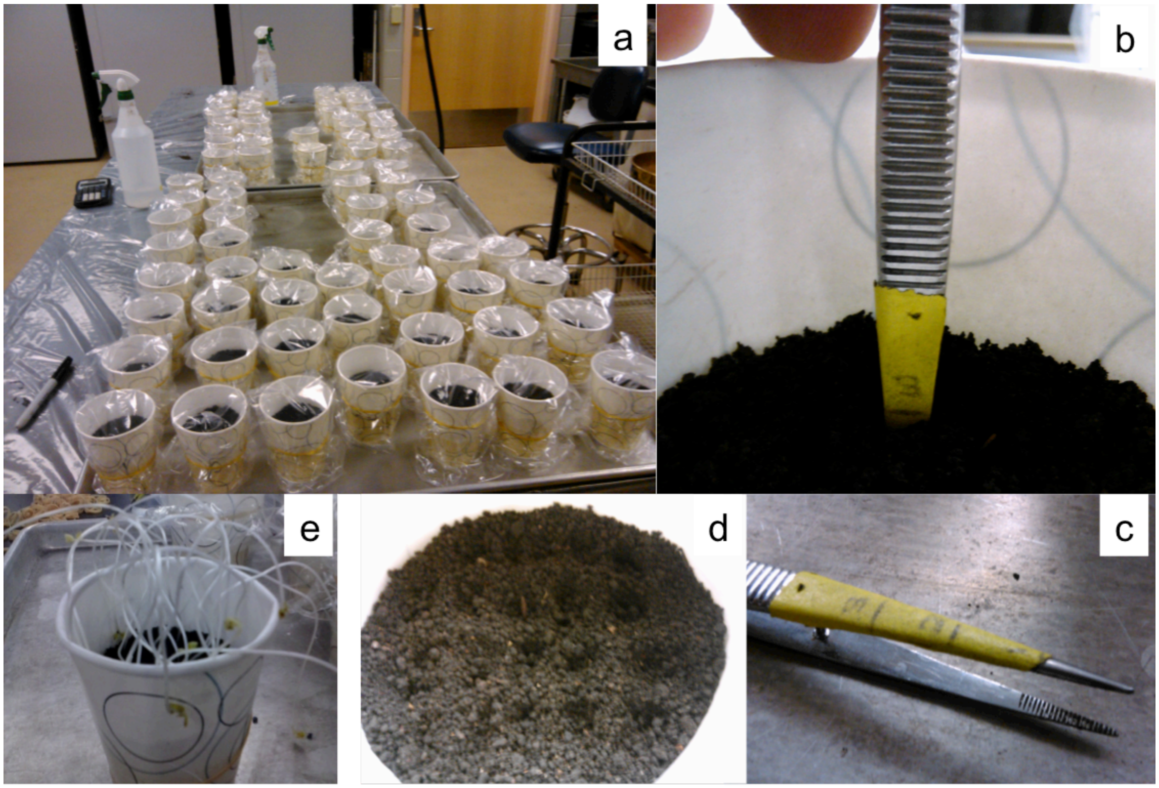

Figure 3.1 *Applying moisture and depth treatments to samples in experiments under controlled environment. (a) Samples were filled with ~150 g of wet soil, covered with individual plastic bags and incubated at constant temperature for at least 24 hours prior seeding. (b) Seeding was done by placing seeds in soil with tweezers. (c) Tweezers were marked at every centimeter to guide depth treatments. (d) In each sample, 20 seeds were placed in a grid-like arrangement. (e) Samples were incubated at constant temperature and emerged seedlings were counted daily for each sample until number of emerged seedlings plateaued, as shown in this picture.*

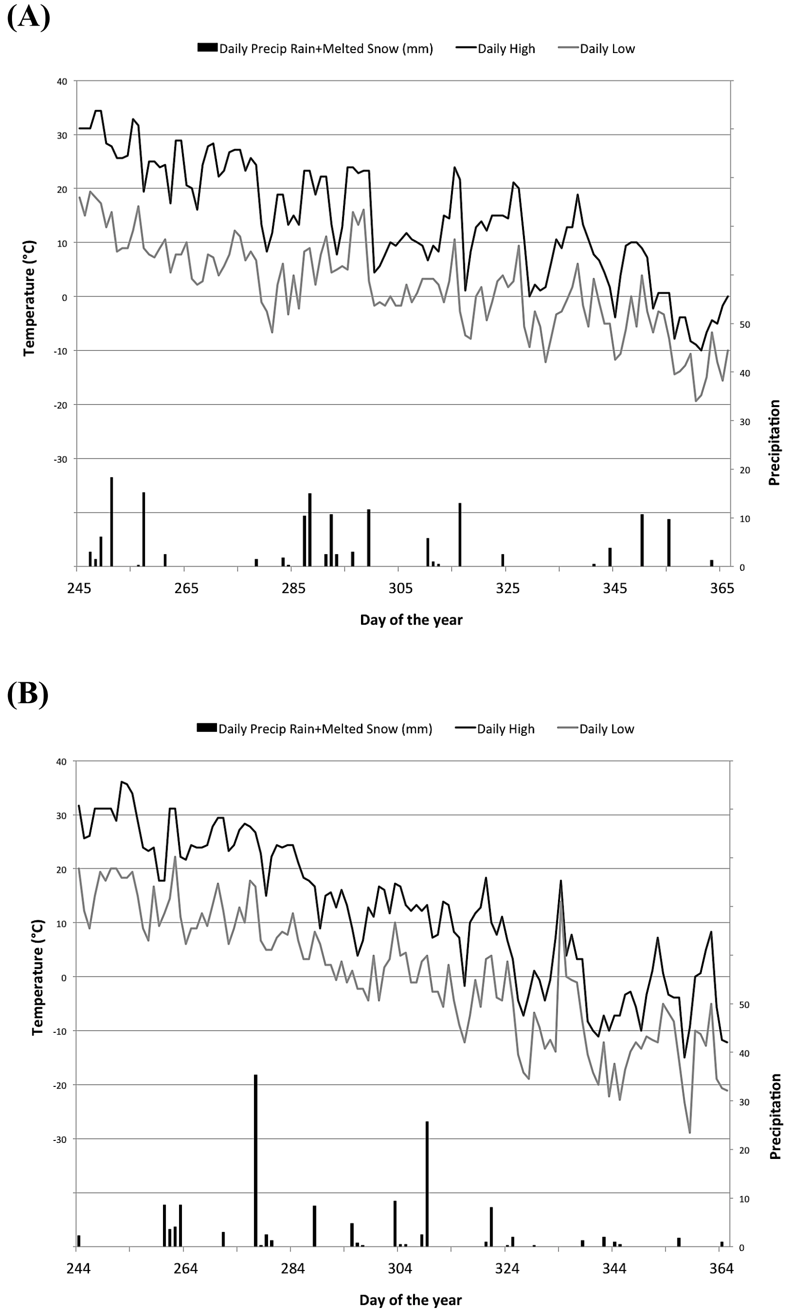

Figure 3.2 *Fall weather conditions at (A) Sorenson Farm (SOR), 2012, and at (B) Bruner Farm (BRU), 2013.*

Table 3.1 *Observed time and thermal time required for emergence of winter canola under field conditions.*

Site	*Seeding Date*	*Emergence Date*	*Days to Emergence*	*GDD to Emergence*
SOR 2012	31 Aug	13 Sep	13	223
	17 Sep	3 Oct	16	181
	1 Oct	17 Oct	16	129
BRU 2013	3 Sep	25 Sep	22	345
	13 Sep	25 Sep	12	156
	1 Oct	14 Oct	13	156

	Mean	***15.3***	***198.3***
	Median	***14.5***	***168.5***

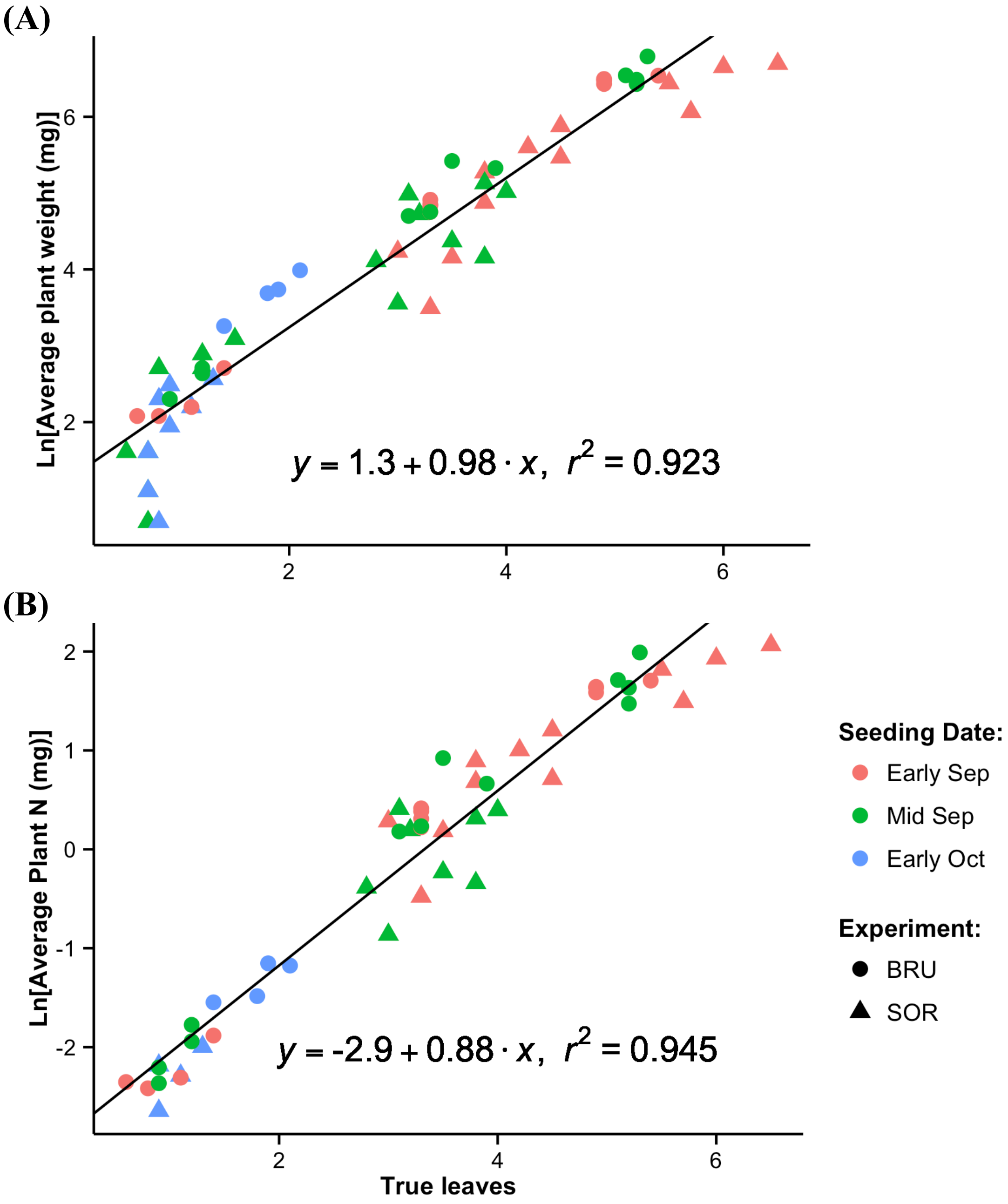

Figure 3.3 *(A) Correlation between leaf development and average plant weight and (B) correlation between leaf development and average plant N accumulation.*

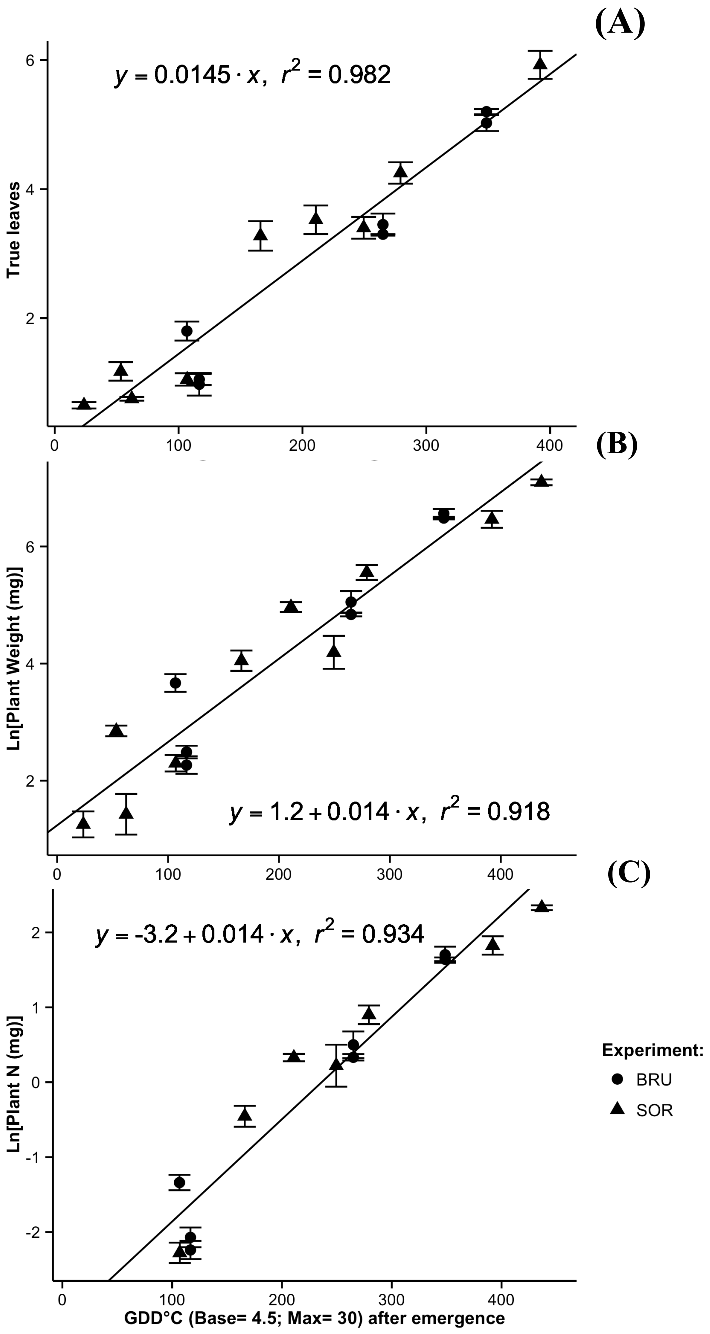

Figure 3.4 (A) Canola leaf development, (B) plant growth and (B) plant N accumulation correlation to thermal time. Note: Error bars denote standard error of the mean.

Table 3.2 *Model parameters and GDD_{50} prediction for experimental units.*

Factors				*Model Parameters*				*Predicted GDD to 50% total emergence*
Temp (°C)	*Incubator*	*Moist (g/g)*	*Depth (cm)*	*A*	*b2*	*b3*	*RMSE*	
10	1	0.14	0	NA	NA	NA	NA	NA
			1	NA	NA	NA	NA	NA
			2	NA	NA	NA	NA	NA
			3	109.9	901.7	0.9	6.0	85.8
		0.18	0	101.3	513.4	0.9	4.2	59.5
			1	101.0	24.9	0.9	3.5	59.9
			2	97.1	272.1	0.9	4.3	55.9
			3	101.4	63.3	0.9	5.2	63.1
		0.22	0	101.0	86.8	0.9	2.8	49.1
			1	98.8	137.4	0.9	1.6	53.7
			2	99.0	81.3	0.9	4.8	54.6
			3	100.1	103.4	0.9	1.8	64.6
	II	0.14	0	NA	NA	NA	NA	NA
			1	172.7	12.5	1.0	9.9	83.1
			2	104.4	1344.8	0.9	5.5	78.0
			3	124.1	154.1	0.9	7.4	89.3
		0.18	0	102.4	271.1	0.9	5.3	58.1
			1	89.9	1778.4	0.9	8.2	52.3
			2	99.7	44.5	0.9	3.9	60.3
			3	99.9	144.9	0.9	3.2	59.2
		0.22	0	100.1	105.4	0.9	2.5	52.1
			1	102.6	38.2	0.9	1.6	56.0
			2	102.2	115.0	0.9	2.5	57.3
			3	103.5	45.0	0.9	2.8	64.2
16	I	0.14	0	NA	NA	NA	NA	NA
			1	104.8	59.1	0.9	5.7	67.1
			2	99.9	1196.3	0.9	2.0	70.2
			3	100.0	595.7	0.9	3.0	72.5
		0.18	0	103.9	1343.0	0.9	6.6	77.7
			1	98.1	69.2	0.9	6.7	59.9
			2	100.4	52.5	0.9	2.1	66.8
			3	99.1	901.4	0.9	3.9	68.9
		0.22	0	105.9	14.1	1.0	3.7	60.0
			1	101.8	51.4	0.9	5.4	59.9
			2	99.7	95.9	0.9	3.3	62.9
			3	103.5	86.6	0.9	3.0	71.8
	II	0.14	0	106.9	46.2	1.0	3.9	98.3
			1	96.2	64.6	0.9	4.0	64.5
			2	99.3	691.4	0.9	2.3	68.0
			3	95.6	157.9	0.9	4.6	73.3
		0.18	0	97.1	45.7	0.9	2.7	66.8
			1	97.5	27.2	0.9	4.1	59.2
			2	98.8	41.6	0.9	4.6	64.8
			3	98.5	41.4	0.9	4.9	66.1
		0.22	0	100.8	16.5	0.9	5.2	50.6
			1	97.4	14.6	0.9	4.4	58.5
			2	99.0	32.7	0.9	4.1	66.9
			3	100.0	35.4	0.9	3.2	74.1
22	I	0.14	0	100.7	14.4	1.0	10.0	97.3
			1	98.5	3073.8	0.9	3.1	66.1
			2	98.4	46.0	0.9	3.8	77.4
			3	100.5	91.9	0.9	2.1	88.9
		0.18	0	99.3	26.9	1.0	3.7	72.8
			1	98.5	26.5	0.9	4.0	55.3
			2	100.0	23.3	1.0	2.4	70.6
			3	98.6	115.8	0.9	3.5	70.2
		0.22	0	98.8	117.9	0.9	3.8	57.8
			1	100.2	16.6	0.9	3.5	62.0
			2	100.6	13.2	1.0	2.1	69.3
			3	98.9	31.9	0.9	5.1	74.2
	II	0.14	0	NA	NA	NA	NA	NA
			1	98.4	80.7	0.9	4.0	81.0
			2	96.0	800.3	0.9	5.9	78.5
			3	102.2	27.0	1.0	3.9	104.9
		0.18	0	101.9	16.8	1.0	1.4	83.5
			1	96.2	15.6	0.9	4.7	61.6
			2	98.8	31.1	0.9	2.7	61.0
			3	91.8	169.5	0.9	7.1	69.0
		0.22	0	97.6	16.8	0.9	3.7	59.7
			1	100.9	17.7	1.0	2.0	64.9
			2	98.5	25.7	0.9	3.5	69.4
			3	100.0	30.1	1.0	2.7	74.7
28	I	0.14	0	NA	NA	NA	NA	NA
			1	NA	NA	NA	NA	NA
			2	NA	NA	NA	NA	NA
			3	NA	NA	NA	NA	NA
		0.18	0	102.8	23.3	1.0	3.9	102.1
			1	96.1	45.1	0.9	6.6	72.7
			2	96.6	125.8	0.9	3.5	70.3
			3	96.0	41.5	0.9	5.0	76.3
		0.22	0	99.8	11.4	1.0	3.1	62.1
			1	98.2	45.4	0.9	3.1	70.9
			2	99.3	23.5	1.0	3.8	77.6
			3	102.0	20.7	1.0	1.3	89.0
	II	0.14	0	110.0	34.6	1.0	10.2	151.7
			1	100.4	2968.1	0.9	1.1	99.4
			2	99.5	99.6	1.0	3.0	111.8
			3	99.3	34.2	1.0	5.7	114.8
		0.18	0	99.5	10.1	1.0	4.4	79.0
			1	99.9	12.6	1.0	5.4	72.5
			2	97.3	46.9	0.9	4.9	63.0
			3	98.1	17.1	1.0	3.3	75.5
		0.22	0	99.5	15.1	1.0	3.7	74.9
			1	100.0	13.2	1.0	1.9	84.6
			2	101.3	13.4	1.0	2.1	87.0
			3	102.9	17.1	1.0	3.1	100.6

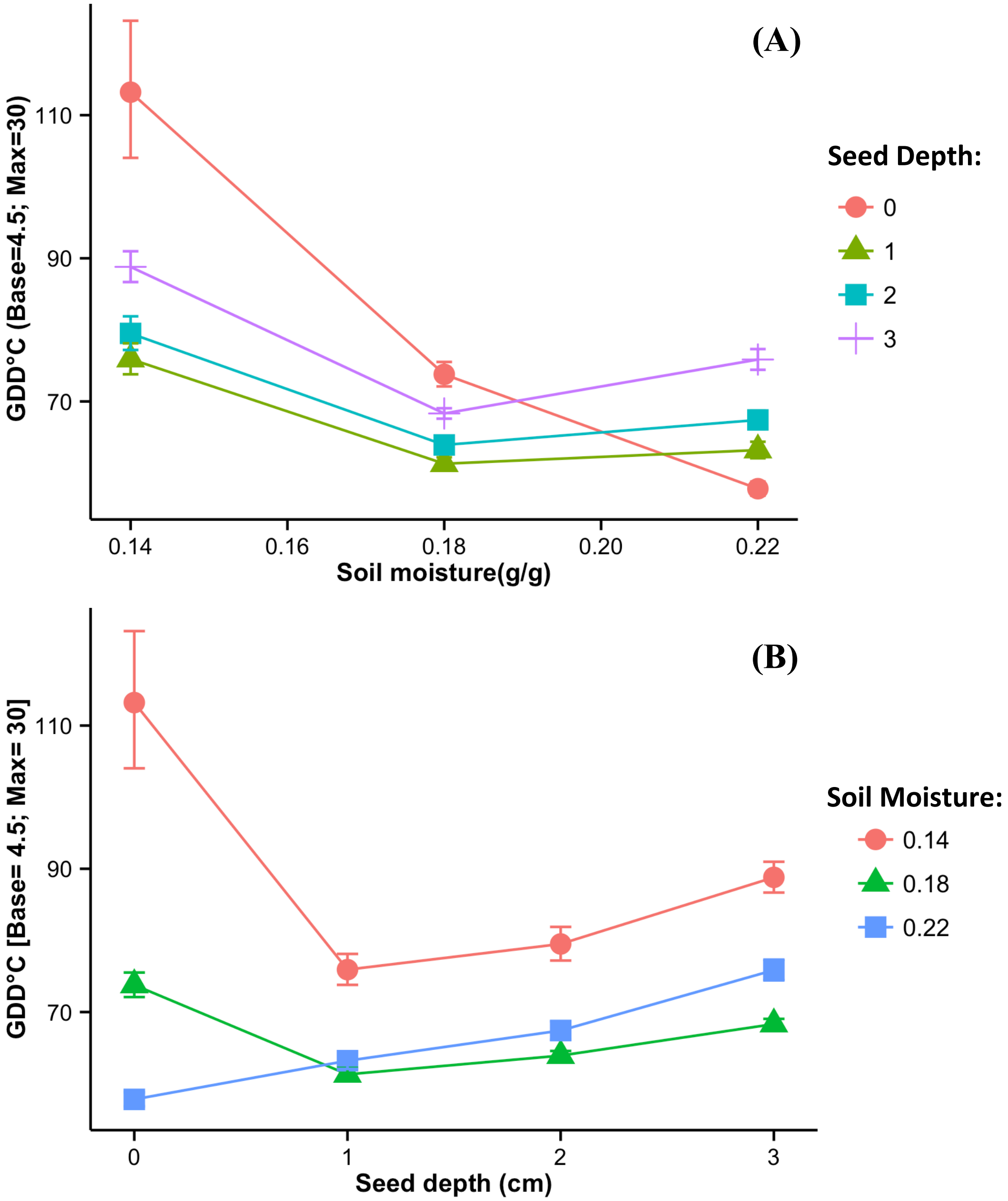

Figure 3.5 *The effect of (A) soil moisture and (B) seed depth on thermal time requirement for 50% emergence of winter canola seedlings under controlled environments.*

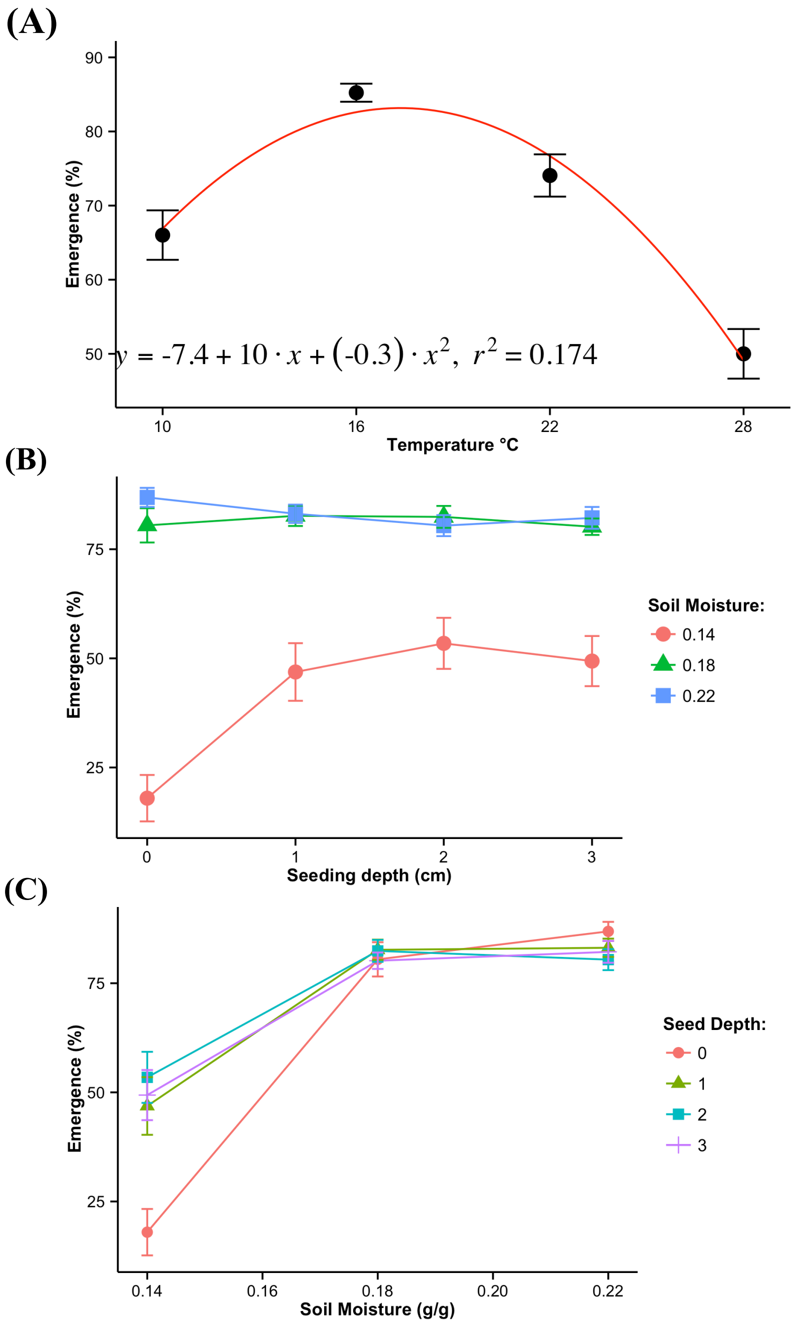

Figure 3.6 *The effect of (A) soil temperature, (B) seed depth (C) and soil moisture on emergence of winter canola seedlings under controlled environments.*

CHAPTER 4.

ESTIMATING THE LATEST RELIABLE SEEDING DATES FOR WINTER CANOLA IN IOWA

A report submitted as a requirement for the Geographic Information Systems Graduate Certificate

Abstract

Currently, it is recommended to seed winter canola (*Brassica napus*) at least six weeks before the first occurrence of temperatures below -4.5ºC in the fall to allow sufficient growth to maximize potential winter survival. However, the environmental conditions that drive plant growth vary widely among specific locations and between years, thus a more precise method that takes into account the local climatic conditions is needed. In this study, we propose a method that estimates the latest reliable seeding dates (LRSD) using the thermal time requirement for winter canola. We aimed to characterize the differences between the results of these two methods, and determined which method is more adequate for estimating reliable seeding timing for winter canola in this region. Meteorological data at 110 Iowa locations from 1972-2011 was used to calculate LRSD by both methods, and were summarized by locations at three probability levels (0.1, 0.5 and 0.9) of their empirical distribution functions. The results were compared through statistical and geostatistical analyses. The analysis revealed that the conventional six-week recommendation (CONV) method produced estimates that generally underestimated the actual thermal time requirements of winter canola by an average of 2.4, 10.8 and 17.5 days at the 0.1, 0.5 and 0.9

probability levels, respectively. Furthermore, the CONV method produced relatively less stationary data that was poorly suited for ordinary kriging (OK) interpolations, resulting in relatively higher surface prediction errors. In contrast, the proposed thermal time (PROP) method resulted in spatially coherent estimates that produced predictions surfaces with greater confidences when interpolated with OK. In Iowa, it is concluded that winter canola seeded *by* 31 Aug in the north to 12 Sep in the southeast would had been be exposed to enough thermal time to develop at least five leaves under adequate growing conditions during at least half of the years between 1927 and 2011 in Iowa. Therefore, seeding beyond these dates is not advisable.

Problem Definition

Winter survival remains one of the most important factors limiting the cultivation of winter canola (*Brassica napus*) in northern latitudes (Rife and Zeinali, 2003). Seeding timing has been seen to greatly affect winter canola's ability to successfully overwinter (Holman et al., 2011; Velicka et al, 2011). This is because, to maximize potential winter survival, canola plants need to develop a healthy, robust rosette with between five to eight leaves before the onset of winter conditions (Sidlauskas and Rife, 2004; Wysocki et al., 2005; Lääniste et al., 2007; Balodis and Gaile, 2011; Boyles et al., 2012). It has generally been recommended to seed at least six weeks before the day of first occurrence of temperatures at or below -4.5ºC ($DFO_{-4.5^{o}C}$) at a given location, to allow enough time for canola to achieve this optimal growth for winter survival (Boyles et al., 2012). Yet, crops almost never grow following the linear accumulation of time; development is also very much dependent on the environmental conditions to which they are exposed. Conditions can vary widely among specific locations and throughout time, and consequently, this recommended number of days before the DFO$_{-4.5^{\circ}C}$ may be insufficient for optimal growth in some locations or years when growing conditions are unfavorable (Daniels et al., 1986). Thus, a more precise method for estimating seeding dates of winter canola would be beneficial.

Plant development can be accurately predicted by measuring the accrual of thermal time, that is, the accumulation of temperature over time (Munns et al., 2010). In winter canola, thermal time has been seen to be tightly correlated to its phenological development, as well as to other biometric indicators such as dry weight of the shoot, diameter of the root collar, height of the apical bud, root mass and length, and the chemical composition of leaves and apical buds (Gabrielle et al., 1998; Sidlauskas and Rife, 2004; Velicka et al. 2006). In previous research, we have estimated the thermal time requirement for the development of a five-leaf rosette under fall field conditions in Iowa (Chapter 3), which, as stated above, is the minimum growth stage that maximizes potential winter survival. Thus, an alternative method for estimating a seeding time frame for a given location can be done by determining the number of days before the DFO$_{-4.5^{\circ}C}$ that are needed for the accrual of this requirement. Yet, it is still unclear whether allowing enough time for the thermal time requirement would produce different results than the six-week recommendation during most years in Iowa.

Therefore, the objective of this investigation is to characterize the differences between the results of these two methods and to determine which method is more adequate for estimating reliable seeding timing for winter canola in this region. To do this, we calculated the latest reliable seeding dates (LRSD) at 110 locations across the state during 40 years using both approaches. Their results were summarized at three levels of probability, and compared using statistical and geostatistical techniques to assess their performance.

Based on the results of these analyses, the best performing method was chosen to prepare a winter canola seeding date atlas for the state of Iowa.

Spatial questions

1. *Does the conventional six-week recommendation allow for the accumulation of the thermal time requirement for the development of five leaves during most years across Iowa?*
2. *Which method produces estimates that are more suitable for geostatistical interpolation?*
3. *What is the latest reliable date for seeding winter canola across Iowa?*

Research Design and Methods

Area of study

The area studied in this analysis covered the State of Iowa, located in the Central United States. The studied area covers 145,743 km^2. Iowa is delimited on the north by a straight line along 43.5 °N latitude, on the south by the Des Moines River and a straight line approximately along the 40.58 °N latitude, on the east by the Mississippi River, and by the Missouri and Big Sioux Rivers on the west. Iowa's topography is characterized mostly by rolling hills across the southern and eastern portions of the state, and by plains in the central and northwestern regions. Smaller areas of hills and valleys exist in the northeast, and a loess-derived hill range runs along most of the Missouri River valley on the west. Altitudes range from 146 m above the sea level at the confluence of the Des Moines and Mississippi rivers in the southeast, to 509 m in the northwest near its northern border (Figure 4.1).

Iowa has a humid continental climate (*Dfa* in the Köppen-Geiger classification) (Peel et al., 2007), with a climatic gradient in which cooler and drier conditions are more common in the northwest, and warmer and wetter conditions prevail in the southeast. This gradient is thought to have existed in this region for at least the last 16,500 years (Wayne, 1988). Average annual temperatures and precipitation normals range from 7.2 °C and 660 mm in the northwest to 11.1 °C and 964 mm in the southeast (NOAA). Autumnal weather conditions tend to be mild and relatively drier than summer and spring months, which is ideal for crop dry-down and ready access to fields for harvest.

Data sources

Meteorological dataset was compiled from the values reported in the Iowa Environmental Mesonet online database, which included mostly observed values, although a small portion were quality controlled or estimated in order to avoid missing values (IEM, 2014). Data included daily observations of minimum and maximum air temperatures for the period between the 200th to 360th day of the year (DOY), as well as the $\mathrm{DFO}_{-4.5°\mathrm{C}}$ for years 1972 to 2011, expressed in DOY. Data were obtained from 110 weather stations, which were distributed with reasonable uniformity across the area of study. The spatial distribution of the sample points is shown in Figure 4.1.

Thermal time units and calculation

In North America, the unit most commonly used to measure thermal time is the growing-degree day (GDD), in which only temperatures that fall within a defined “growing range” are counted. Daily observations of GDD were calculated using the second method outlined by Mcmaster and Wallace (1997). To calculate the GGD accrued on a given day, the average of the daily maximum temperature (T_{max}) and the daily minimum temperature ($T_{\min}$) was computed, and a base temperature (T_{BASE}) was subtracted from the average. The T_{BASE} is considered the minimum temperature under which canola plant development is not considered to occur. Likewise, a maximum temperature (T_{MAX}), or the temperature above which further increases in rate of development are not considered significant, was also included in the calculation. For this study, the values fro $T_{BASE} = 4.5\ °\mathrm{C}$ and $T_{MAX} = 30\ °\mathrm{C}$ were used.(Habekotte, 1997; Vigil et al., 1997; Gabrielle et al., 1998; Balodis and Gaile, 2011). The equation to calculate daily GGD was:

$$GDD = \left[\frac{T_{max} - T_{\min}}{2}\right] - T_{BASE}$$

(Equation 4.1)

where, if $T_{min} < T_{BASE}$, then $T_{min} = T_{BASE}$, and if $T_{max} < T_{BASE}$, then $T_{max} = T_{BASE}$; if $T_{max} > T_{MAX}$, then $T_{max} = T_{MAX}$, and if $T_{min} > T_{MAX}$, then $T_{min} = T_{MAX}$.

Latest reliable seeding date calculation methods

Estimates for the LRSD at every year-location (n=4400) were calculated using two approaches: i) the conventional six-week (CONV) method and ii) the proposed thermal time (PROP) method. Under the CONV method, the LRSD for each year-location was calculated by subtracting 42 days from the DFO$_{-4.5°C}$ as shown below (Equation 2). The result was expressed in DOY.

$$LRSD = DFO_{-4.5°C} - 42$$

(Equation 4.2)

Under the PROP method, the LRSD at each year-location was determined by counting the number of days backwards in time, starting from the $DFO_{-4.5°C}$, until the accrual of daily values of thermal time (TT_{daily}) equaled the thermal time requirement for the development of five leaves (TT_R) (Equation 4.3). Based on data from field experiments, it has been determined that the development of a five-leaf rosette in Iowa requires of the accrual of 491 - 542 GDD °C (T_{BASE} = 4.5, T_{MAX} = 30) after seeding (Chapter 3). For this study, the mid-value from this range was used so that TT_R= 515 GDD °C. The result from the calculation was expressed in DOY.

$$\sum_{LRSD}^{DFO_{-4.5°C}} (TT_{daily}) = TT_R$$

(Equation 4.3)

In both methods, the $DFO_{-4.5°C}$ is the day that represents the end of the growing season. Although mild temperatures and growth can still occur after the incidence of frosts (Li et al., 2012), it has been observed that exposure of winter canola plants to cycles of cold temperatures contribute to initiate cold acclimation mechanisms that ultimately result in the cessation of growth and preparation for overwintering (Rife and Zeinali, 2003).

Data summarization

The calculations resulted in families of 40 LRSD estimates (each one corresponding to a year) at every location and method. The resulting values of each family were summarized at the 0.1, 0.5 and 0.9 probability levels of their empirical distribution functions, using the discontinuous sample quantiles method described by Hyndman and Fan (1996). Probability levels describe the risk of not achieving enough time or thermal time associated to a given DOY. For values calculated with the PROP method, on the DOY that corresponded to the 0.1 probability level ($CONV_{0.1}$), there were 42 or more days before the $DFO_{-4.5°C}$ in 90% of the cases from 1972 to 2011, while at the DOY that corresponded to the 0.5 ($CONV_{0.5}$) and 0.9 ($CONV_{0.9}$) probability levels, there were 42 or more days in 50% and 10% of the cases, respectively. Similarly for values calculated with the PROP method, on the DOY that corresponded to the 0.1 probability level ($PROP_{0.1}$), there were 515 or more GDD °C before the $DFO_{-4.5°C}$ in 90% of the cases from 1972 to 2011, while at the DOY that corresponded to the 0.5 ($PROP_{0.5}$) and 0.9 ($PROP_{0.9}$) probability levels, there were 515 or more GDD °C in 50% and 10% of the cases, respectively. The summarized values for every method and probability level were assigned as the Z value for each location resulting in six distinct datasets, which were analyzed separately henceforth.

Statistical analysis

As preliminary analysis, the empirical distribution of each dataset was explored in search of outliers by generating histograms. Then, the difference between the Z values calculated with the CONV method minus those calculated with the PROP method at each probability level were calculated for every location. To detect differences between their results of both methods, one-sample T-tests on the differences were performed, with a null hypothesis of sample mean being significantly greater than zero at the significance level of α=0.05. Statistical analysis was conducted with R statistical software.

Geostatistical analysis

To determine which method is more adequate for estimating a reliable seeding timing for winter canola in Iowa, each dataset was analyzed using geostatistical procedures. It was assumed that methods that produced more spatially coherent data with less degree of error when fitted with geostatistical models would be more adequate to estimate the LRSD across the state.

The resulting datasets were analyzed to determine whether data presented positive *spatial autocorrelation*, which represents the degree to which similar values tend to be cluster together in space (Tobler, 1970). This is because in general, climatic variables (e.g. climatic normals) often tend to be positively spatially autocorrelated (Lapen and Hayhoe, 2003). Spatial autocorrelation is related to the degree that data is stationary, that is, that the covariance between values is dependent on the distance between them. Data stationarity was assess by performing Voronoi map analyses, in which Theissen polygons were calculated for each location using Euclidian distances, and an entropy values were assigned to each polygon. The entropy (E) of the i^{th} polygon was computed as follows:

$$E_i = - \sum_{j=1}^{5} \frac{n_j}{N_i} \ln\left(\frac{n_j}{N_i}\right)$$

(Equation 4.4)

where N_i is the number of neighbors of the i^{th} polygon; and n_j is the number of neighbors assigned to the j^{th} class. Values were divided into five classes using the geometrical intervals method, thus entropy values ranged from 0 to 2.32. Voronoi map analyses were conducted in ArcGIS10.2. desktop package software.

Further analysis was conducted by fitting geostatistical models through each dataset and calculating the degree of error associated with each procedure. Because multiple geostatistical interpolation methods exist, the following is a discussion on the selection of an interpolation procedure.

Selecting an interpolation procedure

Interpolation procedures fit a model through a set of known points to predict values at unmeasured locations. Broadly speaking, interpolation procedures are divided into two main categories: deterministic and geostatistical. Deterministic procedures use mathematical functions to estimate the value of unsampled points. For instance, the commonly used Inverse Distance Weighted (IDW) procedure assumes that the spatial relationship between two points is inversely related to the distance between these points, weighed by a certain parameter (Res et al., 1999; Lu and Wong, 2008). The IDW procedure has been used to interpolate meteorological and climatic variables in a number of studies, including air temperatures in Israel (Res et al., 1999), snow distribution in the Colorado Rocky Mountains (Erxleben et al., 2002), precipitation in Taiwan (Lu and Wong, 2008) and the preparation of a frost atlas of the Fars province in Iran (Didari et al., 2011). However, despite their popularity, IDW and other deterministic procedures have several limitations such as: i) the weight parameter cannot be empirically determined, ii) variances of predicted values at unsampled locations cannot be estimated, and iii) the weight parameter is applied uniformly throughout the study area without consideration of the spatial distribution of the data (Lu and Wong, 2008). Therefore, the application of deterministic procedures is limited to situations where the estimation of uncertainty is not sought.

Geostatistical procedures combine mathematical and statistical approaches to predict values and assess uncertainty at unsampled locations. A powerful geostatistical procedure commonly used in climate studies and geosciences is kriging. As with deterministic procedures, this procedure weighs surrounding measured values to derive a prediction for each location. However, kriging uses not only the distance between points, but also the overall spatial arrangement among measured points (Johnston et al., 2001). Accordingly, kriging assumes that the location and the spatial distribution of sample points reflect a spatial correlation that can be used to explain variation in a surface (Jarvis and Stuart, 2001; Childs, 2004). Kriging fits a model through a specific number of location points or points within a specific radius using a semivariogram to determine a prediction at unsampled locations (Johnston et al., 2001; Webster and Oliver, 2007).

Several types of kriging procedures have been proposed over the years, which make different assumptions about the input data, and are used for a variety of applications. For a detail discussion of the range of kriging procedures the reader is referred to Webster and Oliver (2007). From all of the available procedures, ordinary kriging (OK) is one of the common types in practice because of its reportedly robustness and flexibility (Li and Heap, 2011). In this procedure, the predictions are weighed linear combinations of the data, and it is assumed that the data have a constant but unknown mean.

Multiple examples exist of researches that studied the use of OK interpolation to estimate surfaces of measurements derived from air temperatures. For instance, Lapen and Hayhoe (2003) interpolated air temperatures across the southern shore of Lake Huron in Ontario. In that study, OK was deemed adequate to estimate annual maximum and minimum temperatures in that region (Lapen and Hayhoe, 2003). Alternatively, Benavides et al. (2007) noted that OK did not achieve satisfactory predictive power when interpolating noisy mean air temperatures across a mountainous region in Northern Spain. Nonetheless, the addition of elevation as an auxiliary variable was seen to substantially improve predictions (Benavides et al., 2007). However, general consensus of a preferred procedure for interpolating these types of data has not been reached (Li and Heap, 2011). The accuracy of each procedure seems to depend more on the nature of the data: how sample points are spatially distributed, whether the data present any trends, or the extent of variation between sample points (Johnston et al., 2001; Webster and Oliver, 2007; Benavides et al., 2007; Li and Heap, 2011).

Ordinary kriging interpolation

Ordinary kriging was selected to perform geostatistical interpolations in this study. This is because OK is a flexible estimator that provides prediction surfaces, as well as estimates of uncertainty of those predictions. The spatial autocorrelation of the LRSD values was characterized by estimating their respective empirical semivariograms. A semivariogram measures the increase in dissimilarity between pairs of points separated by a distance or lag h. The semivariance $\hat{\gamma}(h)$ is calculated as half the average of the squared difference of values z between data pairs located in u_i and $u_i + h$. The empirical semivariogram was estimated by:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(u_i) - z(u_i + h)]^2$$

(Equation 4.5)

where $N(h)$ is the number of data pairs separated by a h lag (Webster and Oliver, 2007).

Ordinary kriging is often known as the “best linear unbiased estimator” since its estimates are weighted *linear* combinations of the available data; it tries to have an *unbiased* error equal to 0; and it minimizes the variance of the errors giving the *best* prediction (Isaaks and Srivastava, 1989). The procedure is based on the assumption that the values Z at locations u are equal to an unknown constant μ and some error $\varepsilon(u)$, as shown below:

$$Z(u) = \mu + \varepsilon(u)$$

(Equation 4.6)

and prediction of $\hat{Z}$ at locations u_0 is given by:

$$\hat{Z}(u_0) = \sum_{i=1}^{n} \lambda_i \, Z(u_i)$$

(Equation 4.7)

where λ_i is the weight of the measured value Z at location u_i. To ensure that the estimates are unbiased, the sum of the weights λ_i must be equal to one:

$$\sum_{i}^{n} \lambda_i = 1$$

(Equation 4.8)

The empirical semivariogram calculated above was then replaced by a continuous function based on the Gaussian semivariogram model. The semivariogram is described as,

$$\hat{\gamma}(h) = C_0 + C\left[1 - exp\left(-\frac{3\,h^2}{r^2}\right)\right];$$

(Equation 4.9)

where C_0 is the nugget, C is the partial sill, and r is the range. For a more detailed discussion on OK and semivariogram models the reader is referred to Isaaks and Srivastava (1989) and Webster and Oliver (2007).

The OK model and search neighborhood parameters were determined independently for each dataset. This was done through an iterative approach that pursued to optimize the model prediction errors statistics provided by cross validations. During the model selection process, minimizing the root-mean-square prediction error (RMSE) was given the greatest priority, while a mean standardized error (MSE) close to zero was used to determine that the model predictions were unbiased (i.e. centered on the true value). To assess whether the estimated variability of the predictions was valid, root-mean-square standardized errors (RMSSE) approaching to 1 was also sought. Likewise, average standard errors (ASE) numerically close to the RMSE were favored. Further deliberation was done based on visual inspections of scatterplots of predicted versus measured values and normal quantile-quantile

(QQ) plots. All of the OK interpolations were performed within the Geostatistical Analyst tool environment of the ArcGIS 10.2.2 Desktop package software. Resulting geostatistical analysis prediction and error layers were exported to raster grid layers with a spatial resolution of 5.0 km for further comparison and analysis.

Results And Discussion

Statistical comparison

The LRSDs calculated with both methods exhibited spatial trends in which the lowest values predominated in the north and northwest, and higher values in the southeast (Figure 4.2). These trends seem to reflect the aforementioned northwest-southeast climatic gradient. The LRSD ranged from 233 to 263 DOY for $CONV_{0.1}$, from 249 to 276 DOY for $CONV_{0.5}$, and from 264 to 292 DOY for $CONV_{0.9}$. The mean LRSDs were 242.8, 260.1 and 274.5 DOY, for $CONV_{0.1}$, $CONV_{0.5}$ and $CONV_{0.9}$, respectively (Table 4.1). In comparison, the LRSD ranged from 232 to 254 DOY for $PROP_{0.1}$, from 241 to 263 DOY for $PROP_{0.5}$, and from 249 to 267 DOY for $PROP_{0.5}$. The mean LRSDs were 240.4, 249.3 and 257.0 DOY, for $PROP_{0.1}$, $PROP_{0.5}$ and $PROP_{0.9}$, respectively (Table 4.1).

To compare the results between the two methods, the difference between the values calculated by the CONV and PROP methods were computed at every location. At all three probability levels, the mean difference resulted significantly greater than zero, as suggested by performed T-tests (α=0.05). Thus, an observable difference between the results of both methods was found. For $CONV_{0.1}$, LRSD values calculated with this method tended to significantly underestimate the time needed for the accrual of the TT_R (as calculated with the

PROP method) by an average of 2.38 days (95% CI: 1.74, 3.02 days). The disagreement between both methods was substantially larger for $\mathrm{CONV}_{0.5}$ and $\mathrm{CONV}_{0.9}$, where LRSD values calculated with the CONV method tended to significantly underestimate the time needed for the TT_R by an average of 10.8 days (95% CI: 10.2, 11.4 days) and 17.5 days (95% CI: 16.8, 18.3 days), respectively. Figure 4.3 displays the empirical distribution functions of the calculated differences of both methods at the three probability levels. Differences of as much as 35 days in some cases were observed, although the magnitude of the differences seemed to be weakly spatially autocorrelated, as suggested by preliminary spatial analyses whose results are not presented here.

Geostatistical comparison

Voronoi map analyzes suggested that the local variation was relatively higher for the LRSD values calculated with CONV across all three probability levels (Figure 4.5). Lower entropy values assigned to polygons indicated lower local variation, while higher entropies indicated the opposite. The general local variation in the data produced with the CONV method could not be attributed to the presence of outliers. In contrast, the LRSD values calculated with the PROP method seemed to produce relatively more spatially coherent data (Figure 4.5). Specifically, the $\mathrm{PROP}_{0.5}$ and $\mathrm{PROP}_{0.9}$ produced the most stationary data, while the $\mathrm{PROP}_{0.1}$ produced data with slightly higher local variation.

A possible explanation for the increased local variation under the CONV method is that it relies solely on the $\mathrm{DFO}_{-4.5^{\circ}\mathrm{C}}$ to calculate the LRSD values. In this study, the CONV method included 40 years at every location. Yet, daily minimum temperatures are highly variable, thus it is expected that the $\mathrm{DFO}_{-4.5^{\circ}\mathrm{C}}$ for a particular location will be generally different from year to year, increasing the variability of the output. Conversely, the PROP method accounted not only for DFO$_{-4.5°C}$, but also included the daily observations of GDD during the accrual of the TT_R, thus a most robust estimate was achieved. Jarvis and Stuart (2001) determined that OK interpolations are most suited for spatially coherent variables, so data with lower local variability is preferred. Perhaps under the CONV method, increasing the sample size of DFO$_{-4.5°C}$ at every location could be considered for producing more stationary estimates.

Spatial interpolations

Ordinary kriging assumes that the input Z values for a spatial interpolation are normally distributed (Webster and Oliver, 2007). However, this assumption seems to be violated with the LRSD values calculated with both methods at all of the three probability levels, which seemed non-normally distributed. Another assumption made by the OK interpolation procedure is that the data should exhibit no spatial trends (Webster and Oliver, 2007). In this case, deviation from normality across all probability levels seemed to be linked to the spatial trends present on the observed original meteorological data, which was previously discussed. Particularly, it may relate to the fact that the rate of loss of temperature during the fall is not uniform across all locations. In northern locations, the temperature decrease during the fall is much steeper than in southern locations, which is associated to the relationship of latitude and the degree of fluctuation of insolation throughout the year (Gabler et al., 2009). This implies that between two points located at the same distance, the difference in the DFO$_{-4.5°C}$ (for the CONV method) or time needed to accrue the TT_R (for the PROP method) in northern latitudes would tend to be lesser than in southern locations. Therefore, the distribution of these data appeared non symmetrical and skewed to the left (Figures 4.6A and 4.6B).

To correct this, it was required to detrend the datasets prior to performing the interpolations. Exploratory trend analyses suggested that all but one dataset presented a second order global trend, while the $\mathrm{CONV}_{0.1}$ exhibited a first order global trend. The method used to remove trends prior to the OK procedure was the global polynomial (GP) interpolation procedure. The OK interpolation was performed on the GP model residuals at every sample points whose empirical distribution functions resembled to be closer to normal (Figures 4.6C and 4.6D). Thus, further data transformations on the GP residuals were deemed unnecessary. Estimates were returned to their original scale after OK interpolations.

Procedure summaries for the OK interpolations are shown in Table 4.2. In all cases, a number of at least 10 and at most 15 neighbors were considered, although the searching neighborhood shape and type differed among procedures. Likewise, the Gaussian semivariogram produced the lowest errors and thus it was used in all cases. The lag size and number of lags of the empirical semivariogram, and the range and nugget of the modeled semivariogram were optimized to produce the lowest errors. The semivariogram models for the OK interpolations of LRSD calculated with the CONV method are shown in 4.7A, while the modeled semivariograms of the LRSD calculated with the PROP method are shown in Figure 4.7B.

In both LRSD calculation methods, the RMSSE and the MSE were generally optimal. This was with the exception of $\mathrm{CONV}_{0.1}$ where a minimum RMSSE of 1.016 and a MSE of -0.014, a moderate deviation from the optimal values, could be achieved. However, the RMSE of the OK interpolations of the LRSDs calculated with the PROP method were substantially lower than those calculated with the CONV method (Table 4.3). This resulted in predictions that had considerably greater confidence and reduced error when the sample values were calculated with the PROP method. Additionally, the PROP method produced LRSD values that improved semivariogram fitness during the interpolation procedures. This is shown as predicted versus measured regression equations that are closer to that of the $y=x$ reference line (i.e. slope ~ 1 and intercept ~ 0). In all cases, the semivariogram tended to overestimate earlier dates, while it generally underestimated later seeding dates (Figure 4.8).

For this analysis, this means that the CONV method provided estimates that were generally poorly suited for OK interpolation procedures. On the other hand, the PROP method provided estimates that were generally better suited for OK interpolation procedures. Nonetheless, accuracy of interpolation procedures seemed to be dependent on probability level. The $\text{CONV}_{0.5}$ achieved the lowest errors in the CONV method, while both $\text{PROP}_{0.5}$ and $\text{PROP}_{0.9}$ produced similarly acceptable errors in the PROP method. Evidence for this is provided on Figures 9A and 9B, where maps of the resulting predictions as well as their prediction standard errors are displayed.

Reliable Seeding date atlas for winter canola in Iowa

To prepare a reliable seeding date atlas for winter canola in Iowa, the predicted values and standard error maps of the OK interpolation with $\text{PROP}_{0.5}$ dataset were used. This data set was chosen because of three main reasons: i) the GP interpolation residuals that were used for the OK interpolation appeared to be the most normally distributed, and therefore the error maps could be the most trusted; ii) the resulting OK interpolation produced acceptable errors statistics that were only exceeded by the LRSD values calculated with the $\text{PROP}_{0.9}$;

and iii) the $PROP_{0.5}$ provided a simpler and more concise interpretation than that of the $PROP_{0.9}$ (i.e. >50% vs. >10% of the cases).

The prediction and the error raster outputs were used to calculate the lower limit 95% confidence interval at every cell of the resulting raster, using the following equation:

$$LRSD_{atlas} = P - 1.96 * SE$$

(Equation 4.10)

where P is the predicted cell value and SE is the standard error of the prediction. This produced a surface that can be interpreted as the DOY by which seeding would have provided enough time for the accumulation of the TT_R of 515 GDD °C before the $DFO_{-4.5°C}$ during half of the years between 1972 and 2011, with a confidence of 97.5%. The prepared seeding date atlas is displayed on Figure 4.10. This estimated surface values are in between 28 Aug to the 16 Sep, which agrees with empirical evidence provided in a recent study that found that in the Midwest, planting dates in mid to late August and early September are the more beneficial for survival than late September or October(Assefa et al., 2014).

Nonetheless, the predictive power of the PROP method, and to the same extent the CONV method, relies on the assumption that the next 40 years will be similar on average to the years from 1972-2011. However, research suggests that, in fact, climatic conditions in this region are changing. For instance, steady increases in the length of the growing season in the contiguous United States have been observed to be increasing for more than three decades (Kunkel et al., 2004) This trend will likely continue and perhaps accelerate; yet it is uncertain how the change of the regional climate is likely to affect the predictive power of approach here described.

Conclusions

Through our analysis, it was evident that the CONV method was not accurate for estimating reliable seeding dates for winter canola in Iowa. This method produced estimates that generally underestimated the time required for the development of five leaves. Moreover, the CONV method also produced estimates that were relatively non-stationary, which renders them poorly suited for OK interpolation procedures. The resulting prediction surfaces included substantial degree of error, thus the confidence in these predictions is low. This suggests that the conventional six-week recommendation may be ill suited for locations in Iowa, since it does not match the actual thermal time requirements of this crop. In contrast, the PROP method provided spatially coherent data that produced more accurate predictions when interpolated with OK procedures.

Based on the results of the OK interpolation of the $PROP_{0.5}$ data it is estimated that winter canola seeded *by* 31 Aug in the north to 12 Sep in the southeast was exposed to enough thermal time to develop at least five leaves under adequate growing conditions during at least half of the years between 1972-2011 in Iowa. Assuming that the next 40 years in Iowa will be *on average* similar to the studied period, then seeding beyond these dates may not be advisable.

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Figures and Tables

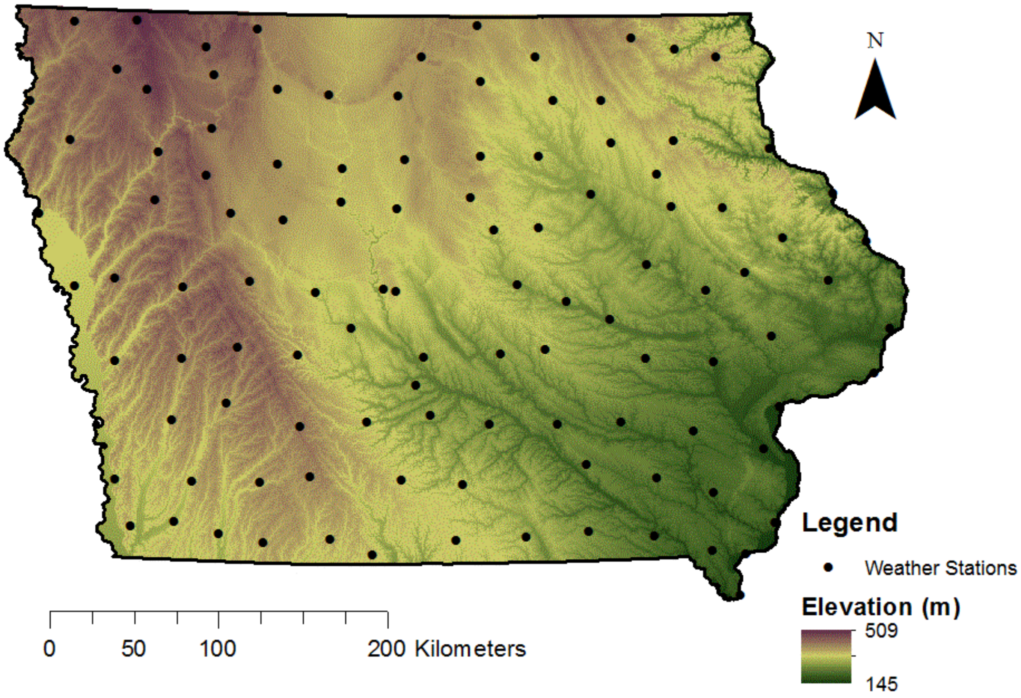


Figure 4.1 *Location of the study area and sample points.*

Table 4.1 *Distribution of latest reliable seeding date (LRSD) values (in DOY) calculated by the conventional (CONV) and proposed (PROP) methods at three probability levels.*

	Probability Level	*Interval*			*Median*	*Mean*
	0.1	233	-	263	242	242.7
CONV	**0.5**	249	-	276	260	260.1
	0.9	264	-	292	273	274.5
	0.1	232	-	254	240	240.4
PROP	**0.5**	241	-	263	248.5	249.3
	0.9	249	-	267	257	257
	0.1	-5	-	16	2	2.38
Difference	**0.5**	4	-	22	11	10.83
	0.9	7	-	35	17	17.53

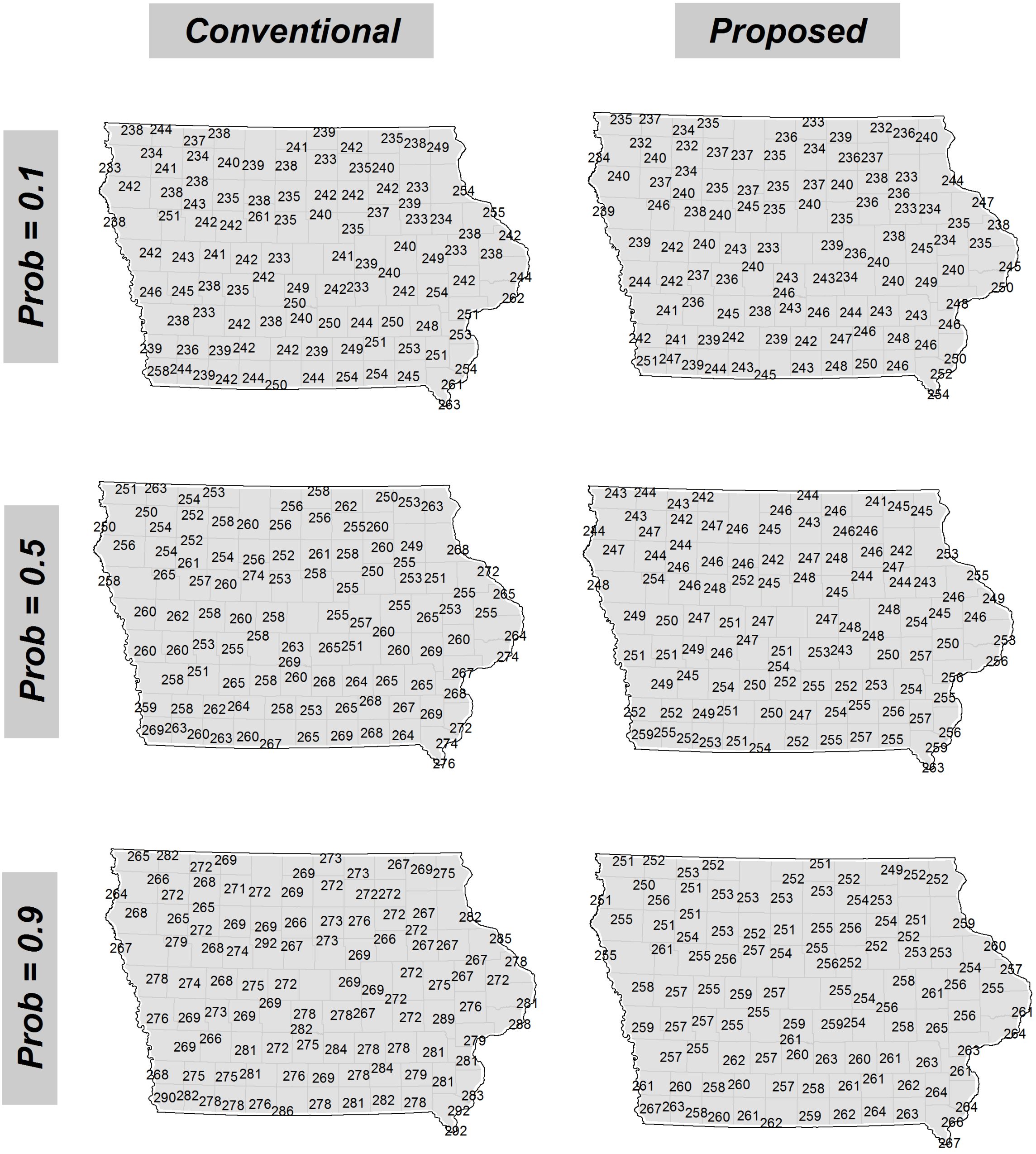


Figure 4.2 *Latest reliable seeding date (LRSD) values calculated with the conventional (CONV) method and the proposed (PROP) method at three probability levels.*

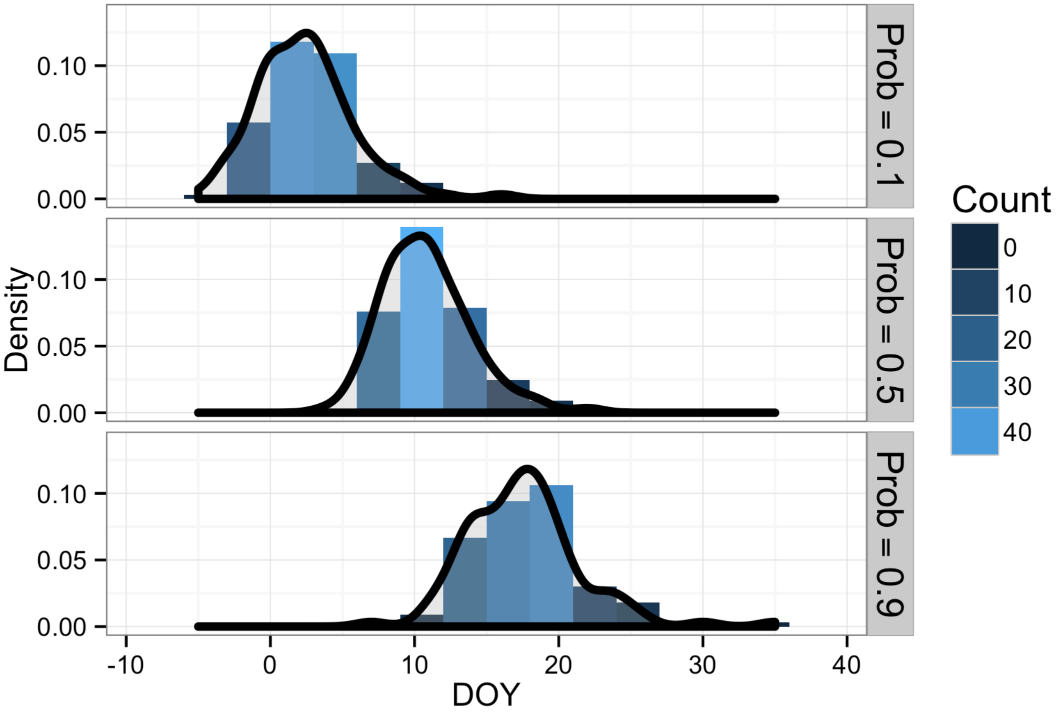


Figure 4.3 *Distribution of the differences of latest reliable seeding date values in day of the year (DOY) calculated with the conventional and proposed methods at three probability levels.*

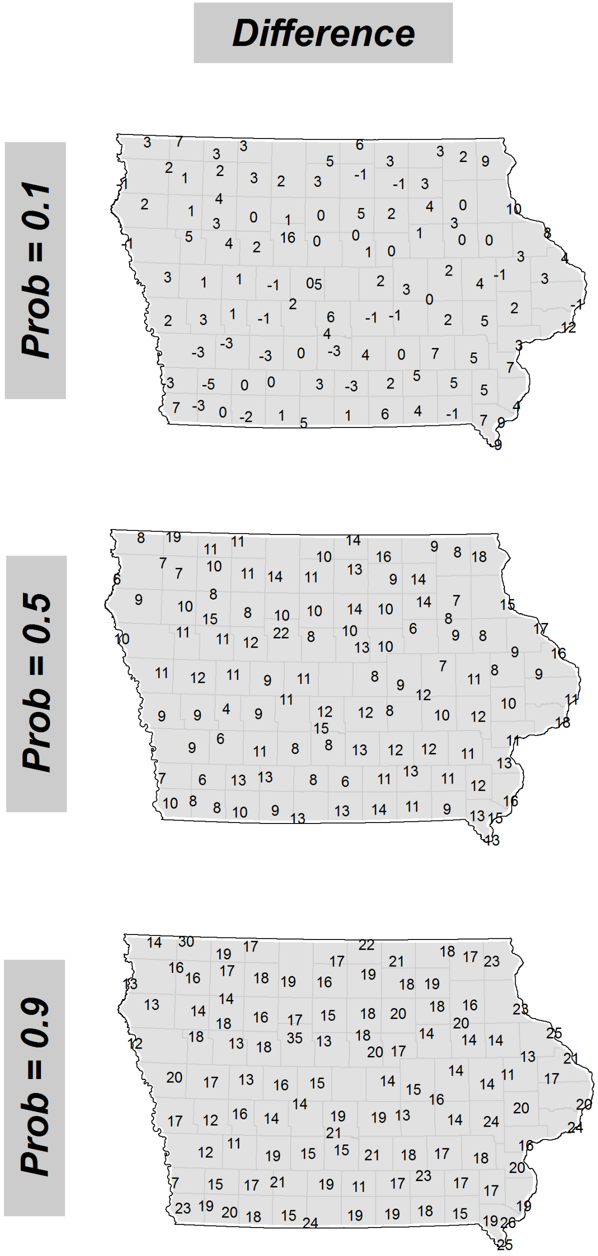


Figure 4.4 *Differences between the latest reliable seeding fate values calculated with the conventional and the proposed methods at three probability levels.*

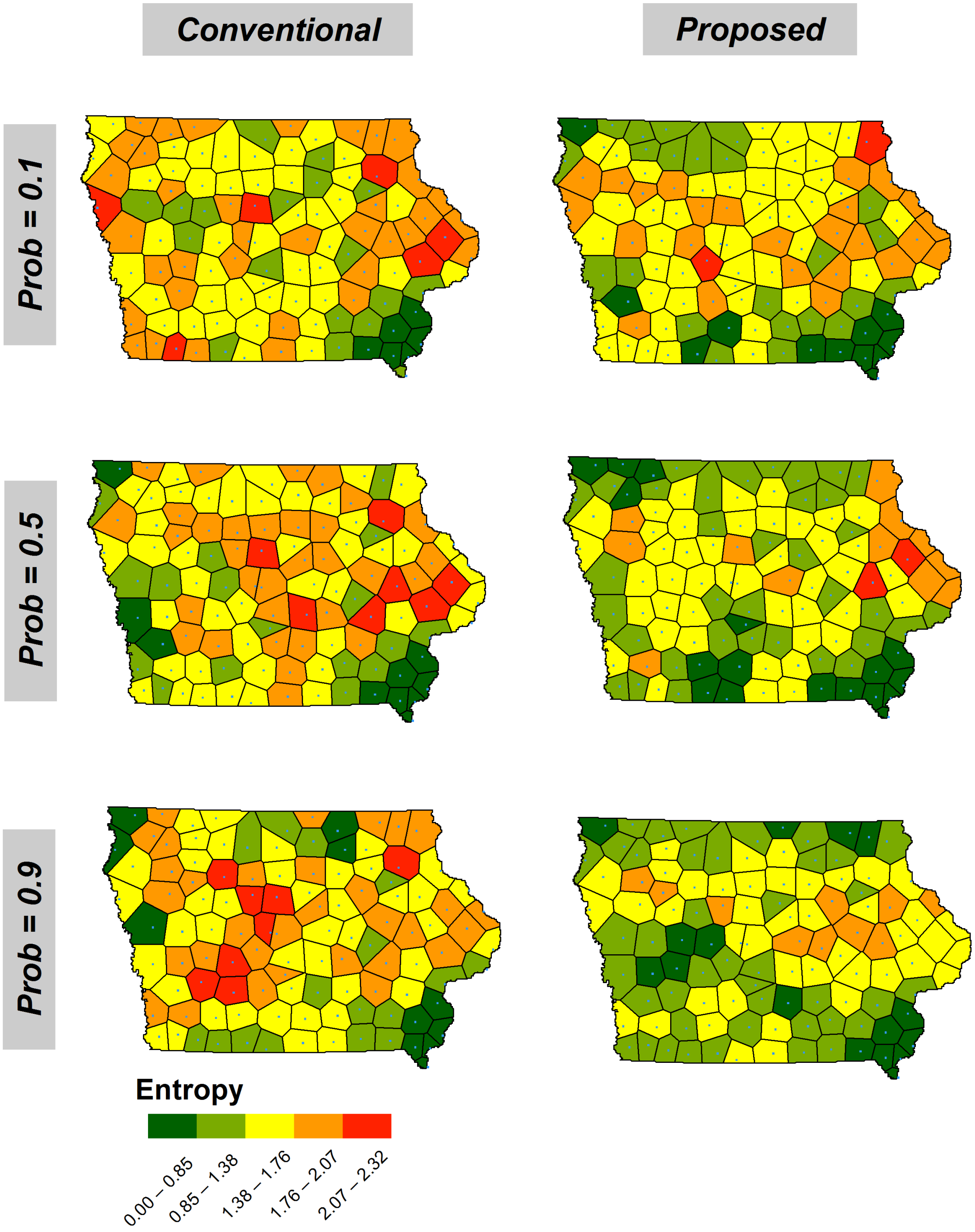


Figure 4.5 *Voronoi entropy maps of the latest reliable seeding date values calculated with the conventional and proposed methods.*

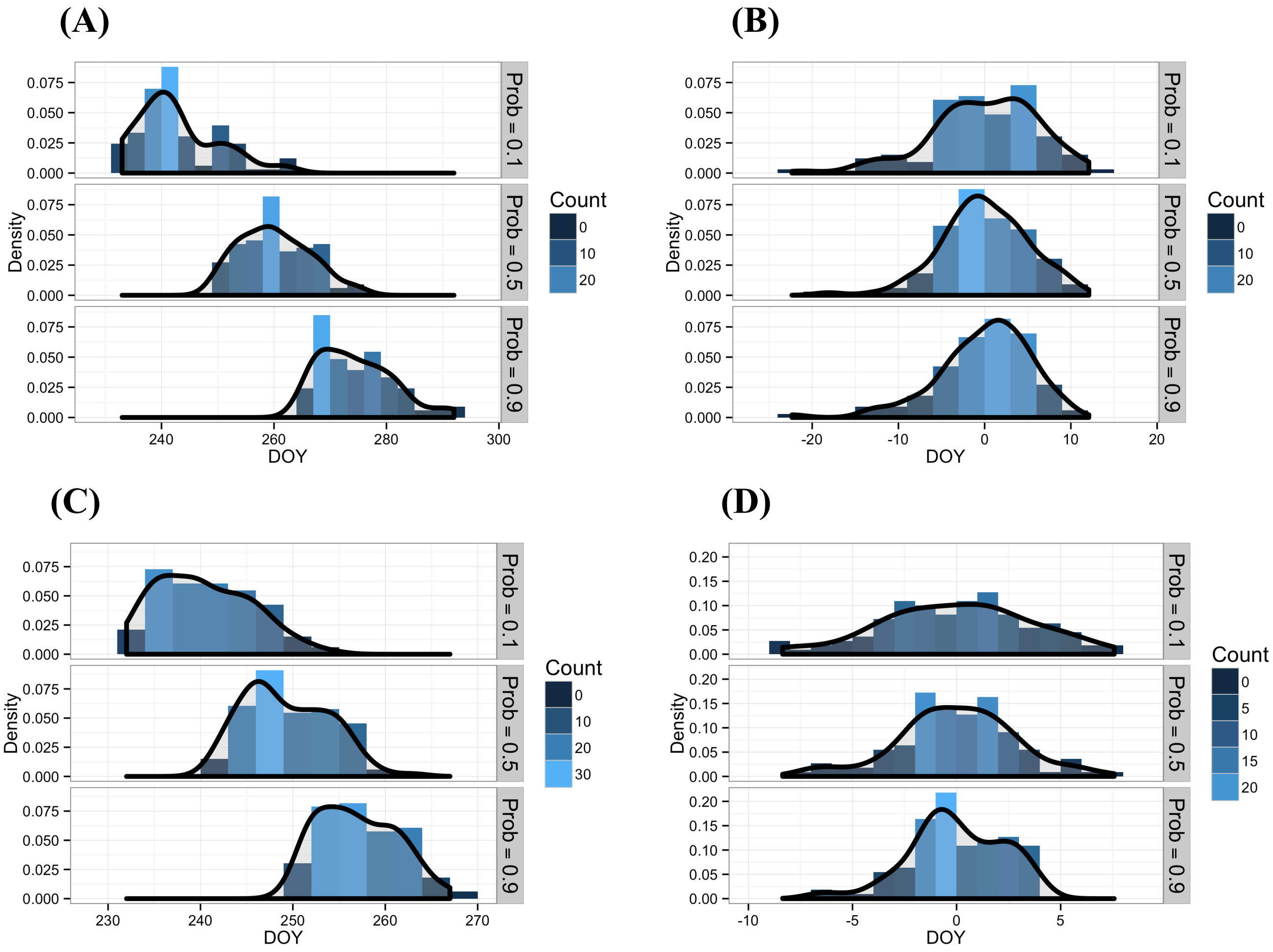


Figure 4.6 *Distribution of latest reliable seeding date (LRSD) values calculated with the conventional method before (A) and after (B) detrending. Distribution of LRSD values calculated with the proposed method before (C) and after (D) detrending.*

Table 4.2 *Method summaries of the ordinary kriging interpolations of datasets of latest reliable seeding dates (LRSD) calculated by the conventional and proposed methods.*

LRSD calculation method	***Conventional***			***Proposed***		
Probability level	***0.1***	***0.5***	***0.9***	***0.1***	***0.5***	***0.9***
Interpolation Method	OK	OK	OK	OK	OK	OK
Trend						
Order of trend	1st	2nd	2nd	2nd	2nd	2nd
Trend type	Global	Global	Global	Global	Global	Global
Trend Removal	Yes	Yes	Yes	Yes	Yes	Yes
Transformation	None	None	None	None	None	None
Searching Neighborhood						
Neighbors to include	15	15	15	15	15	15
Include at least	10	10	10	10	10	10
Sector type	Four	Four and 45°	Four and 45°	Four and 45°	Four and 45°	Four and 45°
Semiaxis (m)	110,744	70,633	79,531	67,445	67,445	67,445
Semivariogram						
Number of lags	12	12	12	8	12	12
Lag size (m)	13,843	9,565	9,062	14,000	8,431	8,431
Nugget	26.64	17.17	22.06	9.04	4.95	2.80
Model Type	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian
Range (m)	110,744	70,633	79,531	67,445	67,445	67,445
Anisotropy	No	No	No	No	No	No
Partial sill	7.09	6.40	5.17	2.67	2.65	2.38

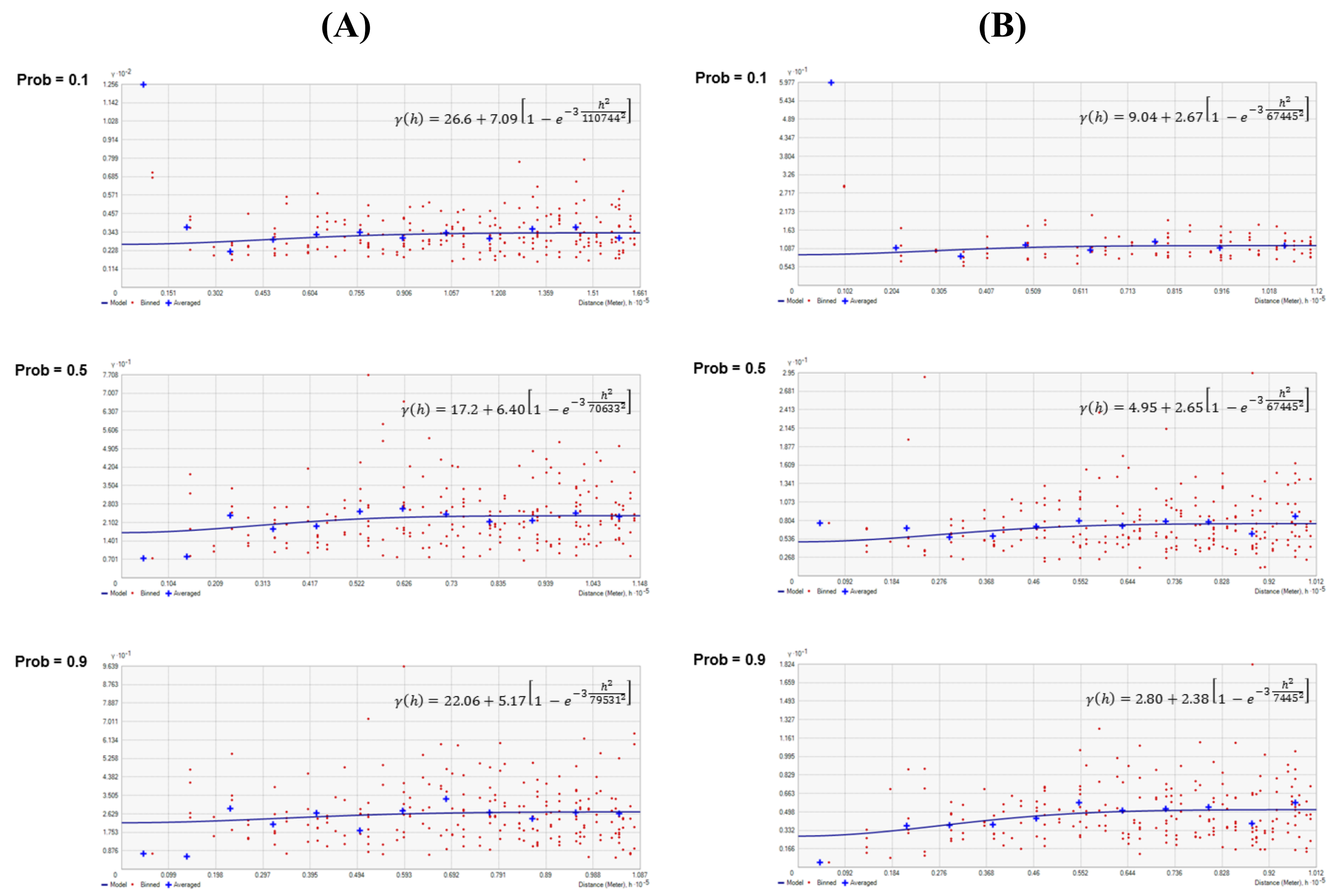


Figure 4.7 *Fitted semivariograms models on the GP residuals for the LRSD values calculated with the conventional (A) and proposed (B) methods at three probability levels.*

Table 4.3 *Distribution of the differences of latest reliable seeding date (LRSD) values calculated with the conventional and proposed methods at three probability levels.*

LRSD calculation method	***Conventional***			***Proposed***		
Probability level	***0.1***	***0.5***	***0.9***	***0.1***	***0.5***	***0.9***
Prediction Errors						
RMSE	5.71	4.80	5.21	3.39	2.67	2.13
MSE	-0.014	-0.004	-0.002	-0.001	-0.002	-0.001
RMSSE	1.016	1.006	1.007	1.000	1.000	0.991
ASE	5.60	4.76	5.17	3.40	2.67	2.14
Predicted vs Measured Regression Equation						
Slope	0.30	0.43	0.42	0.59	0.73	0.79
Intercept	168.9	150.6	160.0	97.8	68.2	51.9

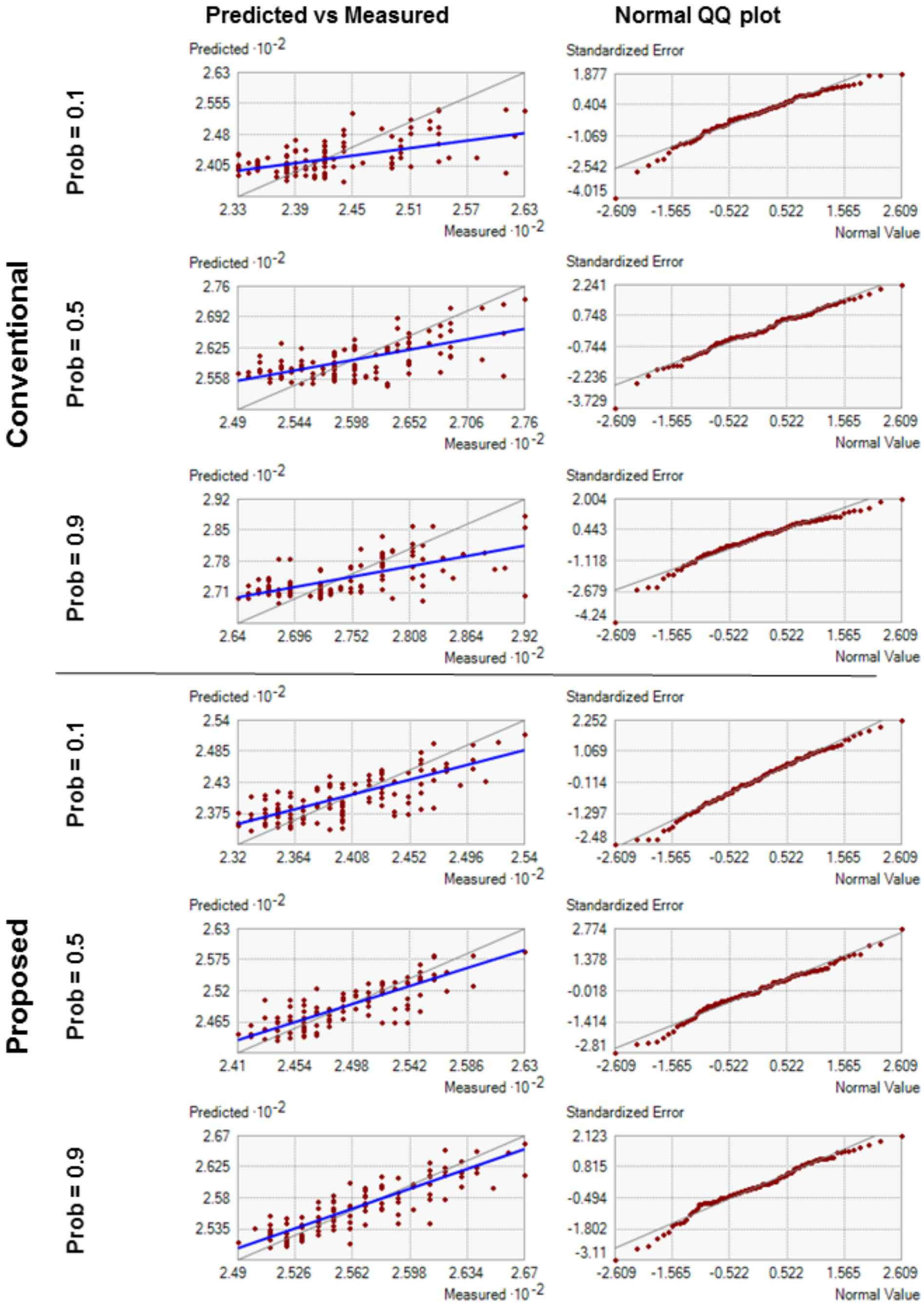


Figure 4.8 *Model error plots for the ordinary kriging interpolations the latest reliable seeding date values calculated with the conventional and proposed methods at three probability levels.*

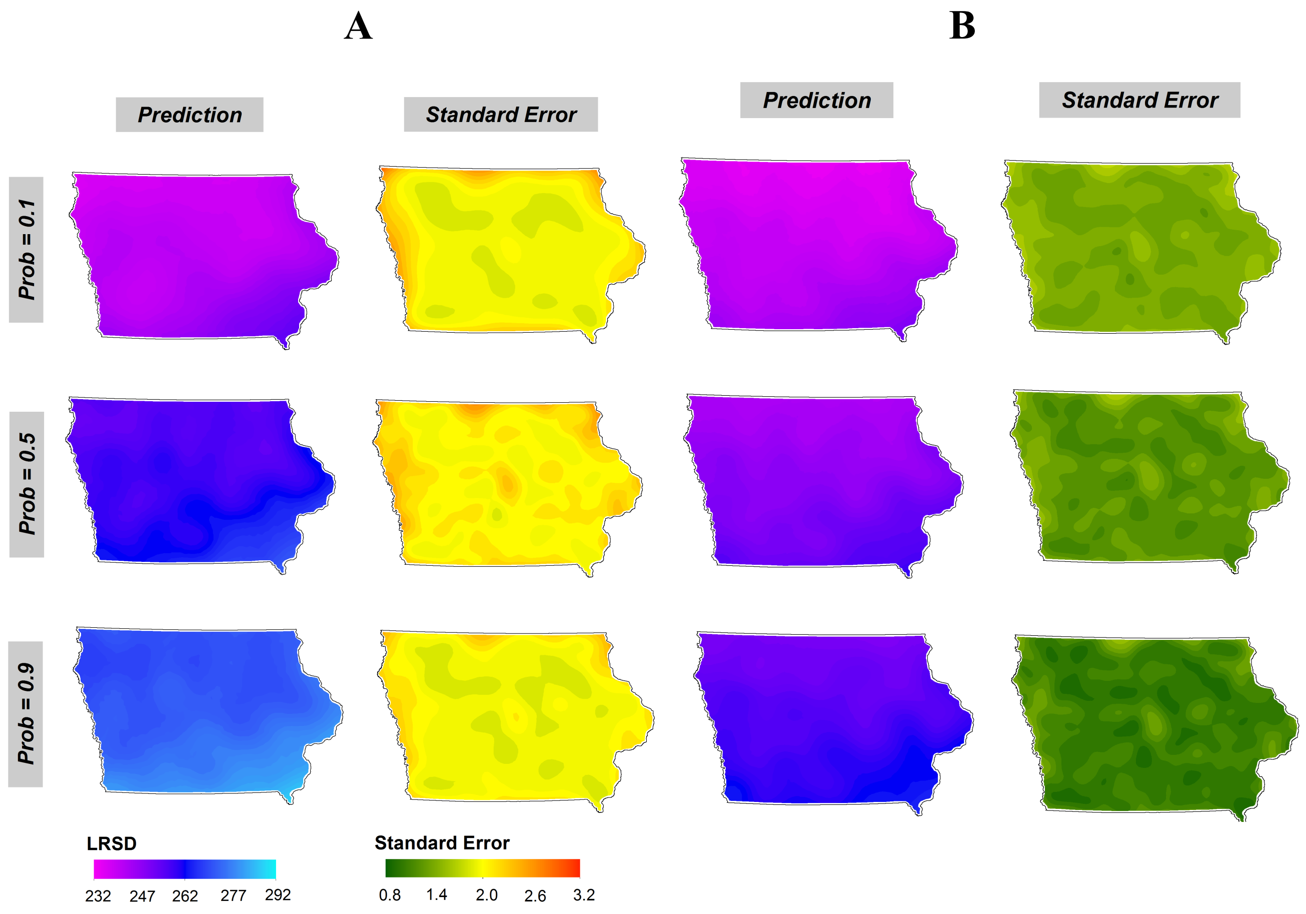
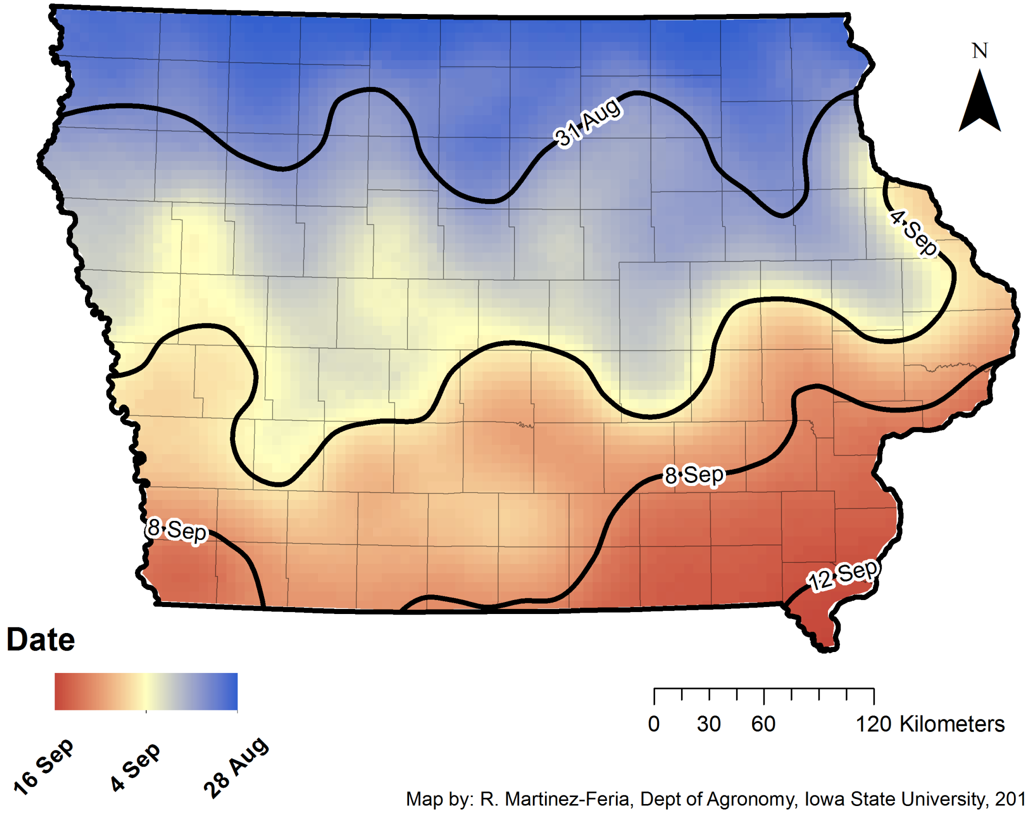


Figure 4.9 *Ordinary kriging raster outputs for the conventional (A) and proposed (B) calculation methods.*



Map by: R. Martinez-Feria, Dept of Agronomy, Iowa State University, 2015

Figure 4.10 *Latest reliable seeding date atlas for winter canola in Iowa.*

CHAPTER 5.

INTEGRATING WINTER CANOLA INTO SUMMER ANNUAL CROP ROTATIONS IN IOWA

A manuscript to be submitted to Renewable Agriculture and Food Systems

Abstract

Diversification of conventional cropping systems with winter annuals and perennial forage crops can be an effective strategy to reduce nutrient exports into water bodies. Winter canola (*Brassica napus*) frost-seeded with red clover (*Trifolium pretense*) could serve to diversify corn (*Zea mays* L.)-soybean (*Glycine max* (L) Merr.) rotations. This strategy can provide ground cover to reduce erosion and living roots to uptake nitrates, while having the potential to produce a marketable crop. Because winter canola is ideally seeded by early September to survive the winter in Iowa, adjustments to rotation schemes including corn and soybeans are needed. These adjustments change the economic profile of the cropping system. In this study we examine how including winter canola frost-seeded with red clover into summer annual rotations may affect profitability of Iowa cropping systems. Two cropping system alternatives, a short relative maturity (SRM) soybean–winter canola/red clover–corn (system A) rotation and a corn silage–winter canola/red clover–corn (system B) rotation, are proposed and compared to a corn–soybean (system C) baseline rotation. Enterprise budgets are constructed based on published estimates of costs of production, and system net returns are calculated based on expected commodity prices and crop yields. Sensitivity analyses are also performed by varying selected factors of production while holding all other parameters constant. The proposed systems are compared with the alternative of establishing winter canola or cereal rye (*Secale cereale*) as cover crops in system C. Results indicate that returns from the proposed systems may be comparable to the baseline rotation when relatively higher winter canola yields (3.4 to 4.6 Mg ha^{-1}) are achieved. Relatively high corn and soybean prices do not necessarily lead to economic advantages of the proposed alternatives over system C. A low nitrogen fertilizer price tends to improve the returns from System B relatively more to the other systems. The analyses and findings will be useful in guiding future research on the development of winter canola in Iowa.

Introduction

Nitrate (NO_3) and phosphorus (P) are essential nutrients for plant growth. Every season agricultural producers consider the availability of these nutrients in the soil and application needs of crops with the goal of optimizing production. In Iowa, substantial amounts of these nutrients may make it to water bodies (1–3) following heavy rainfall events, which may impact water quality for consumption and recreational use. However, not all of the nutrient pollution of waterways can be attributed to fertilizer use (4). In fact, much of the NO_3 from fields is lost even before summer annual crops, namely corn (*Zea mayz* L.) and soybean (*Glycine max* (L) Merr.), start growing vigorously (5,6). This is because during warm and wet periods in the fall and spring, microbial activity produces NO_3 from the soil organic matter, and without living plants to utilize it, NO_3 is readily transported to waterways by rain. Similarly, without the presence of a living canopy and roots to hold the soil in place, P can be transported along with soil particles into superficial water bodies through erosion and runoff (7). These are classic examples of negative externalities; unintended negative consequences of agricultural production of a system using only summer annual crops. Because of the constraints associated with growing summer annual crops and also the inherent uncertainty about environmental conditions and existing soil nutrients, producers have limited options and incentives to economically control nutrient flows within their fields and beyond.

Strategies to ameliorate nutrient pollution exist, but some of them come at substantial cost to the farming enterprise, and thus their adoption has generally remained low. For instance, built infrastructures such as controlled drainage, woodchip bioreactors and wetlands (8) have been identified as cost-effective edge-of-field NO_3 removal strategies, in terms of NO_3 removed per dollar invested (9). However, their establishment involves large up-front investments that producers and their lenders would unlikely make without the existence of cost-share and incentive programming because the cost of removing NO_3 is not recoverable at the farm – it is a societal or public benefit. Only 72 wetlands (treating in total roughly 505 ha) had been installed with the assistance of cost-share programs by 2011 in Iowa (9). Planting cover crops between the harvest and planting of summer annual crops can also be an effective strategy to reduce erosion and nutrient pollution (7,10–13). However, this practice will introduce additional production costs and uncertainties, and the agronomic benefits may not reliably translate into short-term economic returns to justify their use (14–16). Replacing annual crops with perennial bioenergy crops, such as *Miscanthus x giganteus* or switchgrass (*Panicum virgatum*) (17), or with native prairie (18), on strategic field areas (e.g. on riparian zones or on field edges) may also provide an alternative for curving nutrient exports. Ongoing research of the effectiveness and economic viability of these perennial biomass crops is identifying pathways for this technology (17,19); however, without functioning markets and the supply chain infrastructure for bioenergy, broad adoption by producers remains uncertain. Practices that have seen wider adoption thus far are no-tillage (20) and optimization of fertilizer application timing, source and rate (3). Although no-tillage is effective in reducing soil erosion and P runoff (3), this practice does not reduce NO_3 losses (21). Likewise, optimizing fertilizer rate, source and timing seems to be effective in reducing P transport to water bodies, but its potential to decreasing NO_3 emissions is limited (3).

Diversification of conventional cropping systems with winter annuals (22,23) and perennial forage crops (18,24–26) has also been identified as an effective strategy to reduce nutrient exports (6,27). In Iowa, plot-scale and model-based research has shown that cropping system diversification can have positive impacts on water quality while also having the potential to maintain productivity and profitability of cropping systems (18,23–25,28,29). The majority of these cropping system diversification studies have focused on rotations incorporating alfalfa hay (*Medicago sativa*) along with small-grain nurse crops, namely oat (*Avena sativa*), into crop rotations. As pointed out by Christianson et al. (9), while current prices of alfalfa hay could sustain profitability of these alternative cropping systems (24), the potential for large scale market effects if these rotations were widely adopted in a limited area could result in a decline of alfalfa prices, causing these systems to no longer be profitable. Moreover, adoption of these systems would require substantial investments in additional machinery for field and harvest operations, storage and transportation systems. Perhaps, these large investments may not be justified based on the expected returns to adopting these diversified cropping systems.

Diversifying Iowa cropping systems with winter canola

Canola is a productive oilseed crop grown for its high quality edible oil, with a viable and expanding market (30). As opposed to alfalfa hay, canola seed is traded in global commodity markets that depend little on regional production trends. Furthermore, canola seed prices have seen significant rises during the last decade, predominantly due to a steady domestic demand for vegetable oil and a strengthening international demand for Canadian canola (31,32). Winter varieties of canola (*Brassica napus* L.) could be particularly good candidates for diversifying cropping systems in Iowa because of their potential for mitigating NO_3 and P exports. As a winter annual crop, winter canola provides ground cover to reduce erosion and living roots to uptake NO_3 during the winter fallow period (Chapter 2). Winter canola is able to scavenge NO_3 during fall growth and spring regrowth (10), reducing leaching as much as 80% in some cases (33). In addition, Iowa-grown canola has the potential to survive the winter and produce a marketable crop (Chapter 2) (34) compatible with existing grain production and distribution schemes, thus limiting the need for additional machinery and infrastructure (35,36).

Winter canola has been adopted into crop rotations in the southern and central plains in recent years, predominantly in short rotation with winter wheat (*Triticum aestivum* L). This has arguably been stimulated by canola's high yield potential and profitability, and because it allows for more flexible weed control strategies than continuous winter wheat (35,37,38). Canola can be seeded and harvested using small-grains equipment (36), or conventional row crop planters with row spacing 38-76 cm, although decreases in yield from 0-10% have been observed for wide row spacing (39). Furthermore, winter canola could be intercropped with frost-seeded forage legumes (e.g. red clover [*Trifolium pretense* L.]) (34)

as it has already been done with small grains (40–42). In these systems, the cash crop stand serves as a companion crop for the forage legumes during establishment, while the intercrop can provide weed suppression, erosion control, forage for grazing and N for the following crop (41). This approach would serve to strategically increase the diversity of the proposed cropping systems, which could have similar benefits to the ones observed with small grains. Indeed, some research suggests that intercropping canola with legumes, specifically field peas (*Pisum sativum L.*), can increase seed yields and seed N yield efficiency of canola (43), while effectively suppressing weeds (44).

The main caveat of including this crop in rotation with corn and soybeans is that winter canola needs substantial time in the fall for realizing sufficient growth to survive the winter. Research suggests that the latest reliable seeding dates for winter canola in Iowa range from about 31 Aug in the north to about 12 Sep in the southeast (Chapter 3 and 4). Because the harvest of full maturity corn and soybean often occurs well into October, seeding winter canola may conflict with standing corn and soybeans. From an agronomic perspective, to successfully integrate this crop into conventional summer annual rotations in Iowa, adjustments to the rotation schemes are needed. Specifically, the inclusion of soybean cultivars with short relative maturity (SRM) that can be harvested early or the use of corn for other purposes (i.e. corn silage), has to be considered in order to allow enough time for canola seeding. These adjustments change the economic profile of the cropping system.

The objective of this research is to examine how including winter canola frost-seeded with red clover into these adjusted summer annual rotations affects the expected net returns of Iowa cropping systems. Enterprise budgets for winter canola production in Iowa are used to compare the economic costs and returns of two proposed rotation systems. Sensitivity analyses based on canola seed yields, commodity prices and N fertilizer input costs are performed to determine the conditions under which integration of canola is economically feasible. These systems are also compared against the alternative of establishing winter canola or cereal rye (*Secale cereale* L.) as cover crops in a baseline system under two methods: broadcasting and direct seeding. These analyses will be useful in guiding future research on the development of this crop in Iowa.

Materials and Methods

The primary goal of this study is to assess the economic feasibility of integrating winter canola into Iowa cropping systems assuming functioning marketing and distribution channels for canola seed in Iowa. To do so, two cropping system alternatives are proposed and compared to a conventional corn-soybean system. As in similar studies (24,29,38,45–48), the analysis of whole-farm net returns is conducted on a rotated hectare basis so that the analysis may be easily scaled up. The cash rent equivalent of land is included as a fixed cost throughout the analysis to account for the opportunity cost of land. We consider three qualities of land: low, medium and high productivity with \$560, \$675 and \$770 ha^{-1} yr^{-1} annual cash rental rates, respectively. Likewise, labor costs are fixed at a rate of \$13 hr^{-1} to account for the opportunity costs of labor. Federal subsidy payments are excluded from the analysis.

The cropping systems analyzed are:

System C: corn–soybean (2 yr rotation)
System A: soybean (SRM)–winter canola/red clover–corn (3 yr rotation)
System B: corn silage–winter canola/red clover–corn (3 yr rotation)

System C is the baseline scenario that represents a conventional Iowa corn-soybean system. In this system, corn plantings are expected in mid-April and harvest is expected in mid-October. Similarly, we expect soybeans are planted in early May and harvested in late September. For purposes herein, one half of the land is planted to each crop annually. System A is a rotation that includes winter canola planted in early September and harvested in mid-July. To allow sufficient time for establishment of canola, SRM soybeans are planted in mid-May and harvested in late August. A 20% yield loss of SRM (Relative Maturity= 0.5) is assumed compared to the full maturity varieties (Relative Maturity = 2.5), as indicated by Iowa State University (ISU) Extension's Soybean Planting Decision Tool (49). Red clover is frost-seeded into the canola stand in early spring, left as cover crop after canola harvest, and terminated with herbicides and tillage the following spring before corn planting. System B is a rotation in which corn is harvested for silage in late August, and then followed by winter canola. In this alternative, red clover is also frost-seeded as described above and terminated before corn planting. Red clover growth during the fall and regrowth in the spring in systems A and B may add value as forage for grazing or N fertilizer to the succeeding corn crop, but these potential benefits are not incorporated into the analysis. In both A and B systems, one third of the land is allocated to each crop annually.

Enterprise budgets for each crop are developed based on estimated costs of production published by ISU Extension's Ag Decision Maker (AgDM) (50). Default AgDM values are used for corn following soybeans, soybeans following corn, and corn silage following corn. A winter canola/red clover enterprise budget is constructed using available cost-return budget information for south central Kansas (51) updated with AgDM Iowa cost estimates, where they exist. The N requirement of canola is assumed to be 135 Kg ha^{-1}(52), with 35 Kg ha^{-1} applied at planting in the fall, and the balance top-dressed in the spring at frost seeding. Corn, soybean and corn silage yields considered for each grade of land in Mg ha^{-1} are displayed on Table 5.1.

Winter canola/red clover labor requirements are calculated at 6.1 hours ha^{-1} based on published estimates on machinery field capacities (53). In addition, winter canola crop insurance premium cost is assessed to be \$30.2 ha^{-1}, based on a determination from an insurer in the private sector. Variable costs of direct combining winter canola are assumed at \$26.9 ha^{-1} because it is expected that harvest time is approximately 30% higher than those of soybeans. Haul and handling machinery costs are computed based on canola seed yields. For corn following winter canola/red clover, the same cost estimates as for a corn following soybeans are used except that N requirements are assumed to be equal to those of corn following corn (i.e. no red clover N credit). Costs of production for all of the considered crops are shown in Tables 5.2-5.6.

The reference net returns for each system are computed using forecasted commodity prices. These are estimated using market information (i.e. future contracts, bases and \$US/\$CAN) collected on 6 March 2015. Based on these forecast analyses, canola prices are considered \$370 Mg^{-1} at sale in July 2015, corn prices are \$150 Mg^{-1} at sale in December 2015, and soybean prices are \$330 Mg^{-1} at sale in November 2015. Thus, a reference soybean-corn price ratio of 2.2, and a reference canola-soybean price ratio of 1.12 are considered. A reference yield of 2.0 Mg ha^{-1} for canola seed is expected, based on the average yield from the 2003 to 2012 National Winter Canola Variety Trials (54). Corn silage prices are computed using the AgDM corn silage pricer tool (55), assuming 8.69, 9.94 and 11.20 Mg ha^{-1} expected corn grain yields, and 8.96, 9.86 and 10.8 Mg ha^{-1} expected stover yields for low, medium and high productivity land, respectively. Silage is priced in the field (i.e. no storage cost) at the value of silage as feed (i.e. substitution price of grass hay plus corn grain), assuming the market price of grass hay substitute is \$128.9 Mg^{-1}. This estimate is determined based on the averages from 2010 to 2014 of large round bale hay auction prices in early September at the Rock Valley, Iowa market (56).

Sensitivity analysis

The economic feasibility of the studied cropping rotations is of primary interest, so sensitivity analyses are performed for each cropping system by varying individually key factors of production while holding all other parameters constant. The factors used to perform the sensitivity analysis are canola seed yield, commodity prices, soybean-corn price ratio, canola-soybean price ratio and nitrogen fertilizer price. The ranges of values used for the sensitivity analyses are displayed on Table 5.7. Response curves of the effect of these factors on system net returns across the studied range are calculated at each land grade. Also computed are curves of the differences in net returns between the alternatives and the baseline systems, which represent the value of adopting the proposed alternatives at different levels of the studied factor.

Comparison to using cover crops

To assess the economic performance of these systems compared to the option of establishing winter canola or cereal rye cover crops in a corn-soybean rotations, a partial budgeting analysis (Table 5.8) is performed using two seeding methods: direct seeding and aerial broadcasting. Cost of canola seed is assumed to be \$12.10 Kg^{-1} (51) while cost of cereal rye seed is considered at \$0.68 Kg^{-1}(57). For direct seeding, 6.0 and 60 Kg ha^{-1} seeding rates are assumed for winter canola and cereal rye, respectively. Winter canola and cereal rye aerial seeding rates are 11 and 116 Kg ha^{-1} respectively with aerial broadcasting. Application rates used are \$40.7 ha^{-1}(57) for cereal rye, whereas because of its lighter weight of seeds per hectare, cost of aerial broadcasting for winter canola is considered to be \$27.2 ha^{-1}(58). Yield decreases of 20% due to the inclusion of SRM soybeans when direct seeding winter canola are also considered. No yield decreases in system C due to potential negative rotation effects of cover crops on the subsequent corn crop are considered. Then, the cost of cover crop establishment under each method is added to the costs of the baseline rotation when comparing profitability to the proposed alternatives.

Results and Discussion

Table 5.9 provides the expected net returns for each of the three cropping systems, which are calculated based on estimated crop prices, yields and production costs. At the reference values used for the initial analysis, none of the systems produce positive net returns (Table 5.9); the baseline corn-soybean rotation generates the smallest net losses. Average across all land grades, system C loses \$206.3 ha^{-1}, which is about 56% and 47% less than systems A and B, respectively. The negative net returns are an artifact of the market conditions under which this analysis is performed, with historically high production costs and lower commodity prices. The high rental rates for land are especially burdensome for winter canola/red clover and soybean, in which budgeted land rent equivalents for these two crops represents roughly 45 to 50% of total production costs. Moreover, land rental rates seem to not accurately reflect the productivity potential of each land grade; the relation between expected yields and land rent equivalents is not constant across all land grades. Land rent rate divided by expected corn yield is 1.42, 1.52 and 1.56, for low, medium and high productivity land respectively, while land rent rate divided by expected soybean yield is 5.04, 5.46 and 5.67, for low, medium and high productivity land respectively. This helps explain the fact that system net returns are generally higher (i.e. smallest losses) in low productivity land and might indicate that high quality land may be overvalued.

Expensive land and input costs in Iowa may be linked to relatively high commodity prices during the past few years. These peaked in 2013 at about \$280 Mg^{-1} for corn and in 2012 at \$645 Mg^{-1} for soybean (59,60), but current forecasts set commodity prices at roughly 55 to 65% of these peak levels for the foreseeable future (59). It can be expected that farmland values and input costs will adjust accordingly, but the level at which they will stabilize, and when this will occur is still uncertain.

It is perhaps most useful to examine the relative returns of the alternative cropping systems compared with the standard rotation. This can be done by subtracting the expected net returns of the alternative cropping systems minus the expected net returns from the baseline system. The result represents the dollar value of adoption of these alternatives. Negative value of adoption may be considered as the additional losses incurred by adopting the system, while positive value of adoption may be considered as the economic advantages over the baseline system. According to computed estimates of system profitability (Table 5.9), the expected cost of adopting system A is \$219.9, \$266.7, and \$313.0 ha^{-1} for low, medium and high productivity land, respectively. Similarly, the cost of adopting system B instead of system C is \$165.2, \$187.6 and \$210.5 ha^{-1} for low, medium and high productivity land, respectively. A previous study also estimated the costs of adopting a diversified rotation as an nitrate mitigation strategy (9). In that study, adopting a rotation than included two years of corn followed by three years of alfalfa incurred in deficits that ranged from \$224 to \$408 ha^{-1} yr^{-1}, which is relatively higher than what is being estimated for the alternatives herein.

In general, corn seems to be the crop that achieves the highest net returns in all systems. Averaged by system, corn losses are 46% less than soybean in system A and B, and 65% less than winter canola/red clover in system A. Profitability seems to be more balanced among crops in system C, where losses of corn are only about 25% less than soybean. In system B, corn losses are greater when harvested for grain than for silage when grown on medium and high productivity land. Soybean is the second most profitable crop, with average losses across all land grades of \$235.3 ha^{-1} in system C. Because of the assumed 20% yield penalty for SRM soybeans, losses for this crop are increased to an average of \$454.5 ha^{-1} in system A. Winter canola/red clover is by far the least profitable crop with average losses of \$720.3 ha^{-1} in systems A and B.

It is important to note the fact that total production costs of winter canola/red clover and soybean seem to be comparable, as shown in Tables 5.3 and 5.4. In these enterprise budgets, total production costs of winter canola are about 9% higher than for soybeans. The main differences between these two crops are observed in the variable costs, with the added cost of N fertilizer for canola, and the relatively lower cost of canola seed. However, commodity prices tend to favor canola, typically being 1.07 to 1.36 times greater than soybeans (60,61). Thus, the primary difference in profitability between these two crops is given by their yield potential. This exemplifies the need for sensitivity analyses of this and other key factors to provide insights of their roll on the overall profitability of the production systems.

Sensitivity analyses

For farmers currently producing under the baseline corn-soybean system, adopting either of the proposed cropping systems changes the expected net returns from crop production. However, the expected value of adoption of these diversified systems is dependent on the specific production constrains and market conditions that they face. Therefore, it is valuable to analyze the sensitivity of key factors and quantify their effects on the net returns of each of the studied systems, to obtain a complete picture of the potential economic viability of integrating winter canola into summer annual rotations in Iowa.

Winter canola yield

Producers have little control over commodity prices and input costs, so a common strategy to manage risk and maintain profitability is to optimize the choice and levels of inputs to achieve a yield that maximizes expected profits. Currently no published data is available about the potential yield of winter canola in Iowa when integrated into a summer annual rotation. Therefore, the influence of various levels of winter canola's yield on the expected net returns of the proposed alternatives is analyzed here. For this, seed yield is varied from 1.0 to 4.0 Mg ha^{-1} and the response curves of its effect on system net returns are calculated. The slope of these response curves represents the expected change in net returns when the magnitude of the factor is increased by 1.0 Mg ha^{-1}. Then, the response curve is used to calculate the yield levels at which the net returns of the proposed system equal the net returns of the baseline rotation with all other factors set at the reference levels

(Table 5.7.) The results from these calculations are displayed on Table 5.10, while the response curves of winter canola yield are displayed on Figure 5.1.

Winter canola seed yield seems to have an important role in the net returns of the proposed systems. To increase returns by \$100 ha^{-1}, an increase of 0.82 Mg ha^{-1} in the yield of canola is needed. Because total revenue is computed as yield times the sales price, and net returns are total costs minus total revenue, a linear relationship between yield and net returns (i.e. constant slope) is expected. Moreover, because costs associated with a particular land grade remain constant while varying yield, then response curves across all land grades and systems have identical slopes. However, the changes in production cost associated with varying yield level (e.g. changes in the amount of inputs) are not included in this analysis, because at this moment, no information is available on this regard for Iowa-grown canola. However, if the relationship of yield and changes in production cost were modeled, changes in the magnitude of the slopes (i.e. non linear) across the studied range would be observed.

The canola yield required for achieving net returns equal to those of system C are presented in Table 5.10. For system B, winter canola yields between 3.4 and 3.7 Mg ha^{-1} are needed to be equally as profitable as the baseline rotation. This is comparable to full-maturity soybean yields typically achieved in Iowa. On the other hand, yield levels between 3.8 and 4.6 are needed in system A. A recent study (54) estimated that winter canola's yield potential with optimal weather conditions, best management practices, and the best available genetics is 7.0 Mg ha^{-1}, although real yields usually range between 0.0 to 4.0 Mg^{-1} ha. Moreover, this study found that winter canola yields tend to be greater in cooler environments with relatively stable amounts of precipitation throughout the year, and that yields tend to be higher in northern and Midwest regions. However, whether consistently achieving these relatively high yields in Iowa is possible is still questionable.

Commodity prices

It is expected that adoption of the proposed systems would also be influenced by the market conditions which individual producers face. Hence, the net returns of the proposed system alternatives are calculated at different levels of commodity prices to evaluate the conditions under which they are economically feasible. To do this, corn prices are varied within a range of \$75 to \$300 Mg^{-1} while holding all other factors constant, and response curves are computed. Because it is unreasonable to expect that corn prices will change independently from the prices of other commodities, soybean-corn price ratio and canola-soybean price ratio are maintained at the reference values. Furthermore, to model how changes in commodity prices affect returns at different levels of winter canola yield, two scenarios are selected: 1) a conservative scenario where canola yield is maintained constant at 2.0 Mg ha^{-1} across all three land productivity levels (i.e. the initial assumption), and 2) a high yielding winter canola scenario where the yield achieved is equal to the yield of soybeans at each land grade (i.e. 3.0, 3.4 and 3.7 Mg ha^{-1} at low, medium and high productivity land, respectively).

Changes in commodity prices seem to affect the economic profile of the proposed alternatives differently. While in all cases increasing commodity prices results in greater returns (Figure 5.2A), their effect on the difference in expected net returns caused by adopting these alternatives is dependent on the specific scenario of canola yield and land grade (Figure 5.2B). Under the conservative scenario, increasing commodity prices mean that system C has an increasing economic advantage over the proposed alternatives, as indicated by the negative slope of their response curves. Increasing prices seem to have a lesser effect on system B than system A, but none of these alternatives reaches the same returns as system C under the studied range. If a high yielding winter canola scenario is considered, then the value of adoption of system B decreases as commodity prices increase. This alternative is equally profitable than System C (i.e. value of adoption equal to zero) when corn prices reach \$155, \$193 and \$254 Mg^{-1} for low, medium and high productivity lands respectively (maintaining a soybean-corn price ratio at 2.2 and a canola-soybean price ratio of 1.12). Under this scenario, however, system A's response is still negative, with an increasing economic disadvantage as commodity prices increase.

Nonetheless, it is unlikely that commodity price ratios will remain constant as prices change, so exploring their effect is also beneficial. From 2005 to 2014, soybean prices remained usually between 2.11 to 2.91 times greater in relation to corn, while canola prices remained typically between 2.60 to 3.47 times greater than corn (60,61). However, canola seem to be more closely tied to soybean than to corn, with prices being typically 1.07 to 1.36 times greater for canola than for soybeans. For this analysis, soybean-corn price ratio is varied from 2.0 to 3.0, while maintaining corn prices constant at 150 Mg ha^{-1} and a canola-soybean price ratio of 1.12. Additionally, canola-soybean price ratio is varied from 1.0 to 1.4, maintaining corn prices constant at 150 Mg ha^{-1} and a soybean-corn price ratio of 2.2.

Under the conservative scenario, changing soybean-corn price ratio seems almost to have no effect on the value of adoption of system A. This is seen as relatively similar slopes of the response curves of net returns of systems A and C across all three land grades (Figure 5.3A), or as the nearly constant response on the value of adoption (Figure 5.3B). On the other hand, increasing soybean-corn price ratios has a positive effect on the value of adoption of system A under the high yielding canola scenario. Yet, the point where adopting system A can be done at no cost is not achieved under the studied range.

Varying canola-soybean price ratio has also a weak effect on net returns of the proposed alternatives. Because system C does not include winter canola, then changes in canola-soybean do not affect the economic profile of this system, such that the slopes of system net returns and value of adoption of the proposed alternatives are identical (Figure 5.4). Moreover, because the same yield is considered across land grades on the conservative scenario, the effect of the canola-soybean price ratio is not seen to differ across land productivity levels: an increase of 1 ratio point results in a increase of $220 in system net returns. Under the high yielding canola scenario, an economic advantage of adopting system B is detected as the canola-soybean price ratio increases. Price ratioes above 1.24, 1.18 and 1.13 on low, medium and high productivity land, respectively, tend to favor system B over the baseline rotation, if soybean-corn price ratio remains stable. For system A, this point is achieved when the canola-soybean price ratio is around 1.4.

Nitrogen fertilizer price

From all the inputs included in the production budgets, Nitrogen fertilizer cost is seen to have a significant influence across the studied production systems. This is because all three systems are heavy users of N, with 114, 170 and 74 kg of N ha^{-1} applied in systems A, B and C, respectively. Moreover, costs of N fertilizer represents about 20-25% of all variable costs in most crop budgets. To assess the impact of the price of N fertilizer, its price is varied from $0.52 to $2.08 kg^{-1} and response curves are calculated. As done in sensitivity analyses above, the value of adoption of the proposed systems is also computed by subtracting the net returns of systems A and B from the net returns from the baseline system C. Additionally, a conservative and a high yielding winter canola scenarios are also considered.

Results from the analysis indicate that response of system net return to changes in fertilizer cost is proportional to the amount of N fertilizer used in each system (Figure 5.5). Under the high yielding winter canola scenario, system B appears to produce higher returns than the baseline rotation, if N cost falls below \$0.64, \$0.83 and \$1.01 kg^{-1} in low, medium and high productivity land, respectively. Under the conservative scenario, the baseline rotation seems to be the most profitable system across all land grades. System C is the least sensitive to changes in N fertilizer prices due to its lower total N use; the inclusion of full maturity soybeans avoids the use of N fertilizer during the soybean phase of the rotation and reduces the amount of N applied to the following corn crop. System B is the most sensitive to changes in N fertilizer prices, because all cash crops included (winter canola, corn grain and silage) are strongly dependent on N applied for fertility. Nonetheless, the actual N fertilizer requirement of rotations that include winter canola/red clover may be less than considered here. This is because the inclusion of SRM soybean will likely reduce the N fertilizer needed for the following winter canola crop, although quantifying the magnitude of this benefit is still needed. Additionally, the N fixed by red clover may contribute to the overall needs of the subsequent corn crop (41,62). Yet, the N fixation potential of red clover in the proposed cropping systems needs to be determined to more adequately characterize the impact of this crop on system profitability.

Comparison to cover crop alternatives

Partial budgeting analysis reveals that direct seeding is a lower cost alternative for establishing both winter canola and cereal rye; direct seeding is, on average, 34% less costly than aerial broadcasting. The analysis also suggests that cereal rye cover crops possess an economic advantage over winter canola. Establishing a winter canola cover crop is, on average, approximately 35% more expensive than cereal rye, with increased cost of 30% and 41% under aerial and direct seeding methods, respectively (Table 9). It appears that the greatest disadvantage for using winter canola as a cover crop stems from its relatively higher seed cost when compared to cereal rye and most other species (57). Perhaps, substituting winter canola with brassica alternatives with lower seed cost such as winter rape (*B. rapa*) would be suitable for situations in which only the cover crop benefits are sought.

Nevertheless, when a 2.0 Mg ha^{-1} winter canola yield is considered, the costs of including any of these two cover crop alternatives in System C is typically lower than the cost of adopting both system A and B (Figure 5.6). This is with the exception of an aerially broadcasted winter canola cover crop and system B in low and medium productivity land, and direct seeding a winter canola cover crop and system A across all land grades. In the former case, the costs of aerially establishing canola exceed the net returns given up by adopting system B (Tables 5.8 and 5.9). In the latter case, direct seeding winter canola in early September requires the inclusion of SRM soybeans, which results in a yield decrease compared to relative full maturity varieties. These yield decreases are transtalated into additional costs of \$199.9, \$222.1 and \$244.3 ha^{-1} for low, medium and high productivity land, respectively. Thus, adopting system A is a more competitive alternative than establishing a winter canola cover crop under these conditions. Moreover, Figure 5.6 also shows that the advantage of systems A and C against establishing these cover crops is improved with increasing winter canola yield. This seems to indicate that planting these cover crops may be a less costly nutrient mitigation strategy than adopting these diversified rotations in situations when expected yields of winter canola are low. The opposite may be true if higher yields of winter canola are achieved.

Implications and further research

In this study, inclusion of winter canola into summer annual rotations is explored as a strategy for diversifying Iowa cropping systems. Results from the analyses suggest that the proposed alternatives are expected to produce substantially lower net returns when compared with the conventional corn-soybean system. This holds across varied yields and market conditions. Growing winter canola/red clover in rotation with corn silage and corn grain (system B) may have a greater economic advantage than if grown in rotation with SRM soybeans and corn grain (system A). Nonetheless, to be a competitive alternative to the baseline rotation (system C), or even against other NO_3 reduction practices including planting a cereal rye or winter canola cover crop, these systems require relatively high winter canola yields, perhaps to levels in which the would be comparable to those of full maturity soybeans. It is uncertain, however, whether consistently achieving these yield levels is agronomically feasible in Iowa, or if this would require increased amounts of inputs, which could change the economic profile of these systems. Therefore, research is needed to determine the yield potential of winter canola established after corn silage or SRM soybeans in Iowa, and the optimum requirements of N fertilization and other inputs.

The question of whether the inclusion of red clover in these systems would decrease N fertilizer use and/or affect the yield of the subsequent corn crop is not characterized in this analysis. In the Midwest, full-season overwintered red clover has seen to contain as much as 78 kg ha^{-1} of N at termination in May (63), while at least half of this N is estimated to be available to the following crop (64,65). Field research in Iowa showed that a corn soybean rotation extended with a year of small grains interseeded with red clover required up to 80% less synthetic N fertilizer inputs than a conventional rotation, although this research did not parse the amount of the N provided by manure applications and N fixed by the legume (19). Yet, inclusion of legume cover crops can offer agronomic rotation benefits to the succeeding corn crop in terms of increased yield (66), which are suspected to be due to factors beyond those related to the N supplied by legumes (62). Moreover, the rotation benefit of perennial legumes may increase over time, with changes in soil organic carbon and soil N mineralization potential (67), which could render these proposed systems more profitable in the long run. Therefore, research is also needed to quantify the short-term and long-term agronomic rotation benefits of the inclusion of red clover in these systems, to better characterize their feasibility.

Furthermore, work is needed to address the challenges posed by the lack of infrastructure and marketing avenues for Iowa-grown canola. To our knowledge, one canola-processing facility exists in the state of Iowa, which has capacity to custom process up to 36,200 Mg $year^{-1}$ of food-grade, organic and non-genetically modified oilseeds (68). However, other avenues for marketing Iowa-grown canola are currently limited, with the closest major canola seed processors being in North Dakota, Oklahoma and northern Minnesota (69). To be able to reach these markets, substantial losses due to transportation costs would need to be considered. Additionally, because global canola seed prices are set by trades performed in Canadian currency ($CAN), this means that expected net returns of these systems are also influenced by the $CAN/$US exchange rate. A strong $US could render Iowa-grown canola less competitive in the international markets, perhaps more than it would affect other commodities.

In this analysis, the value of adoption of these diversified systems is calculated without regard to the cost of the negative environmental externalities that these strategies are aiming to ameliorate. If the reduction in nutrient emissions achieved by adopting these strategies were compensated, then positive value of adoption could be attained at lower canola seed yields, making the alternatives more competitive. These incentives could be integrated as part of soil and water conservation plans or other environmental quality incentive programing. Yet, assigning a monetary value to the reduction of these environmental externalities to determine the size of the incentive is a complex task, and is not within the scope of this analysis. Nonetheless, this analysis is able to identify that the size of this financial incentive to make the alternatives competitive through a number of different yield and market scenarios could be approximated as the cost of adoption of the systems.

In summary, the most important finding identified by this study is that the inclusion of winter canola into summer annual rotations may be feasible only if higher winter canola yields are achieved. Reaching these yield levels will demand investments in research and technology to ensure that these productivity levels can be met. Alternatively, financial incentives approximately equal to the cost of adoption could be put in place to improve the competitiveness of these alternatives. Whatever the case, it is necessary to determine the true productivity potential of these systems. Perhaps a next step could be the establishment of long-term cropping system studies at various sites across the state to provide evidence of the true productivity potential of these systems under Iowa conditions, as well as their ability for effectively mitigating P and NO_3 losses. Only then could it be determined if the strategies proposed here would serve well to potentially mitigate some of the impacts of agriculture on water quality, while maintaining economic feasibility of Iowa cropping systems.

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Tables and Figures

Table 5.1 *Assumed yields (Mg ha^{-1}) for corn, soybeans and corn silage at three land productivity levels.*

Crop	***Land Productivity***		
	Low	***Medium***	***High***
Corn	10.1	11.3	12.6
Soybean	3.0	3.4	3.7
Corn Silage	47.0	53.8	58.2

Table 5.2 *Assumed costs of production per hectare for corn following soybean at three land productivity levels used in calculating returns for systems A and C. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

Cost of Production for Corn following Soybean									**Systems A and C**
				Land grade					
Item Description		***Low Productivity***			***Medium Productivity***			***High Productivity***	
			Costs			***Costs***			***Costs***
			Fixed	***Variable***		***Fixed***	***Variable***		***Fixed*** / ***Variable***
Preharvest Machinery									
Tandem Disk			$8.9	$7.7		$8.9	$7.7		$8.9 / $7.7
Field Cultivate			$6.2	$7.4		$6.2	$7.4		$6.2 / $7.4
Apply N			$12.1	$13.8		$12.1	$13.8		$12.1 / $13.8
Plant			$14.6	$13.6		$14.6	$13.6		$14.6 / $13.6
Spray			$5.4	$5.4		$5.4	$5.4		$5.4 / $5.4
Total			$47.2	$47.9		$47.2	$47.9		$47.2 / $47.9
Seed, Chemical	**Cost per unit**	**Units**			**Units**			**Units**	
Seed	$3.86 per 1000	61789 seeds		$238.5	74147 seeds		$286.2	86505 seeds	$333.9
Fertilizer									
Nitrogen	$1.04 per Kg	147 Kg		$152.6	147 Kg		$152.6	147 Kg	$152.6
Phosphate	$1.06 per Kg	67 Kg		$71.0	76 Kg		$80.5	84 Kg	$88.8
Potash	$0.90 per Kg	54 Kg		$48.5	60 Kg		$54.6	67 Kg	$60.7
Lime	yearly cost			$24.7			$24.7		$24.7
Herbicide				$87.7			$87.7		$87.7
Crop Insurance				$30.2			$33.6		$36.1
Miscelaneous				$22.2			$24.7		$27.2
Interest	5% annual rate for 8 months			$22.6			$24.9		$27.2
Total				$698.2			$769.7		$838.9
Harvest Machinery									
Combine			$47.0	$26.9		$47.0	$26.9		$47.0 / $26.9
Grain Cart			$14.6	$7.9		$14.6	$7.9		$14.6 / $7.9
Haul			$16.1	$15.1		$18.1	$17.0		$20.2 / $18.9
Dry	$1.60 per gal LP gas		$19.8	$75.9		$22.2	$85.4		$24.7 / $94.9
Handle (auger)			$6.5	$8.7		$7.3	$9.8		$8.1 / $10.9
Total			$103.9	$134.6		$109.2	$147.0		$114.5 / $159.5
Labor									
Wages	$13.00 per hour	6.4 hours	$83.5		6.4 hours	$83.5		6.4 hours	$83.5 /
Land									
Cash rent equivalent	per ha		$560			$675			$770 /
Total Costs	per ha		$794.5	$880.7		$914.7	$964.6		$1,015.2 / $1,046.3

Table 5.3 *Assumed costs of production per hectare for soybean following corn at three land productivity levels used in calculating returns for systems A and C. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

Cost of Production for Soybean following Corn **Systems A and C**

						Land grade				
Item Description		*Low Productivity*			*Medium Productivity*			*High Productivity*		
			Costs			*Costs*			*Costs*	
			Fixed	*Variable*		*Fixed*	*Variable*		*Fixed*	*Variable*
Preharvest Machinery										
Chisel plow			$8.9	$11.4		$8.9	$11.4		$8.9	$11.4
Tandem Disk			$8.9	$7.7		$8.9	$7.7		$8.9	$7.7
Field Cultivate			$6.2	$7.4		$6.2	$7.4		$6.2	$7.4
Plant			$14.6	$13.6		$14.6	$13.6		$14.6	$13.6
Spray (2 times)			$10.9	$10.9		$10.9	$10.9		$10.9	$10.9
Total			$49.4	$50.9		$49.4	$50.9		$49.4	$50.9
Seed, Chemical	**Cost per unit**	**Units**			**Units**			**Units**		
Seed	$55.00 per 140 K	346021 seeds		$135.9	346021 seeds		$135.9	346021 seeds		$135.9
Fertilizer										
Phosphate	$1.06 per Kg	40 Kg		$42.6	45 Kg		$47.4	49 Kg		$52.1
Potash	$0.90 per Kg	76 Kg		$68.8	84 Kg		$75.9	93 Kg		$84.0
Lime	yearly cost			$24.7			$24.7			$24.7
Herbicide				$65.5			$65.5			$65.5
Crop Insurance				$19.5			$22.0			$24.5
Miscelaneous				$22.2			$24.7			$27.2
Interest	5% annual rate for 8 months			$12.7			$13.3			$13.9
Total				$392.0			$409.4			$427.7
Harvest Machinery										
Combine			$37.6	$20.8		$37.6	$20.8		$37.6	$20.8
Grain Cart			$14.6	$7.9		$14.6	$7.9		$14.6	$7.9
Haul			$4.6	$4.2		$5.1	$4.7		$5.6	$5.2
Handle (auger)			$1.8	$2.5		$2.0	$2.7		$2.2	$3.0
Total			$58.5	$35.4		$59.2	$36.1		$59.9	$36.8
Labor										
Wages	$13.0 per hour	5.6 hours	$72.3		5.6 hours	$72.3		5.6 hours	$72.3	
Land										
Cash rent equivalent	per ha		$560			$675			$770	
Total Costs	per ha		$740.0	$478.3		$855.7	$496.4		$951.5	$515.5

Table 5.4 *Assumed costs of production per hectare for winter canola/red clover following soybean at three land productivity levels used in calculating returns for systems A and B. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn.*

Cost of Production for Winter Canola/Red Clover following Soybean or Corn Silage — **System A and B**

					Land grade				
Item Description		***Low Productivity***			***Medium Productivity***			***High Productivity***		
			Costs			***Costs***			***Costs***	
			Fixed	***Variable***		***Fixed***	***Variable***		***Fixed***	***Variable***
Preharvest Machinery										
Tandem Disk			$8.9	$7.7		$8.9	$7.7		$8.9	$7.7
Apply bulk fertilizer			$4.4	$4.2		$4.4	$4.2		$4.4	$4.2
Field Cultivate			$6.2	$7.4		$6.2	$7.4		$6.2	$7.4
Drill			$10.4	$10.6		$10.4	$10.6		$10.4	$10.6
Broadcast seeder (Red clover)			$6.7	$4.4		$6.7	$4.4		$6.7	$4.4
Apply spring N fertilizer			$4.4	$4.2		$4.4	$4.2		$4.4	$4.2
Spray			$5.4	$5.4		$5.4	$5.4		$5.4	$5.4
Total			$46.5	$44.0		$46.5	$44.0		$46.5	$44.0
Seed, Chemical	**Cost per unit**	**Units**			**Units**			**Units**		
Canola Seed	$12.11 per Kg	6 Kg		$72.7	6 Kg		$72.7	6 Kg		$72.7
Red Clover Seed	$4.41 per Kg	17 Kg		$74.9	17 Kg		$74.9	17 Kg		$74.9
Fertilizer										
Nitrogen	$1.04 per Kg	135 Kg		$140.4	135 Kg		$140.4	135 Kg		$140.4
Phosphate	$1.06 per Kg	18 Kg		$19.0	27 Kg		$28.4	34 Kg		$35.5
Potash	$0.90 per Kg	45 Kg		$40.5	56 Kg		$50.6	67 Kg		$60.7
Lime	yearly cost			$24.7			$24.7			$24.7
Herbicide				$40.4			$40.4			$40.4
Crop Insurance				$50.2			$50.2			$50.2
Miscelaneous				$22.2			$24.7			$27.2
Interest	5% annual rate for 10 months			$20.2			$21.1			$21.9
Total				$505.3			$528.2			$548.7
Harvest Machinery										
Combine			$37.6	$26.9		$37.6	$26.9		$37.6	$26.9
Grain Cart			$14.6	$7.9		$14.6	$7.9		$14.6	$7.9
Haul			$3.0	$2.8		$3.0	$2.8		$3.0	$2.8
Handle (auger)			$1.2	$1.6		$1.2	$1.6		$1.2	$1.6
Total			$56.3	$39.3		$56.3	$39.3		$56.3	$39.3
Labor										
Wages	$13.00 per hour	6.1 hours	$78.7		6.1 hours	$78.7		6.1 hours	$80.3	
Land										
Cash rent equivalent	per ha		$560			$675			$770	
Total Costs	per ha		$741.34	$588.6		$856.27	$611.4		$953.00	$632.0

Table 5.5 *Assumed costs of production per hectare for Corn following Winter Canola/Red Clover at three land productivity levels used in calculating returns for systems A and B. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn.*

Costs of Production of Corn following Winter Canola/Red Clover **Systems A and B**

Item Description			*Low Productivity*			*Land grade* *Medium Productivity*			*High Productivity*		
				Costs			*Costs*			*Costs*	
				Fixed	*Variable*		*Fixed*	*Variable*		*Fixed*	*Variable*
Preharvest Machinery											
Tandem Disk				$8.9	$7.7		$8.9	$7.7		$8.9	$7.7
Field Cultivate				$6.2	$7.4		$6.2	$7.4		$6.2	$7.4
Apply N				$12.1	$13.8		$12.1	$13.8		$12.1	$13.8
Plant				$14.6	$13.6		$14.6	$13.6		$14.6	$13.6
Spray				$5.4	$5.4		$5.4	$5.4		$5.4	$5.4
Total				$47.2	$47.9		$47.2	$47.9		$47.2	$47.9
Seed, Chemical	**Cost per unit**		**Units**			**Units**			**Units**		
Seed	$3.86	per 1000	61789 seeds		$238.5	74147 seeds		$286.2	86505 seeds		$333.9
Fertilizer											
Nitrogen	$1.04	per Kg	208 Kg		$216.7	208 Kg		$216.7	208 Kg		$216.7
Phosphate	$1.06	per Kg	67 Kg		$71.1	76 Kg		$80.6	84 Kg		$88.9
Potash	$0.90	per Kg	54 Kg		$48.6	60 Kg		$54.7	67 Kg		$60.7
Lime		yearly cost			$24.7			$24.7			$24.7
Herbicide					$87.7			$87.7			$87.7
Crop Insurance					$30.2			$33.6			$36.1
Miscelaneous					$22.2			$24.7			$27.2
Interest	5%	annual rate for 8 months			$24.8			$27.1			$29.3
Total					$764.5			$836.0			$905.3
Harvest Machinery											
Combine				$47.0	$26.9		$47.0	$26.9		$47.0	$26.9
Grain Cart				$14.6	$7.9		$14.6	$7.9		$14.6	$7.9
Haul				$16.1	$15.1		$18.1	$17.0		$20.2	$18.9
Dry	$1.60	per gal of LP ga		$19.8	$75.9		$22.2	$85.4		$24.7	$94.9
Handle (auger)				$6.5	$8.7		$7.3	$9.8		$8.1	$10.9
Total				103.93	134.55		109.22	147.01		114.53	$159.5
Labor											
Wages	$13.00	per hour	6.4 hours	83.5		6.4 hours	83.5		6.4 hours	83.54	
Land											
Cash rent equivalent		per ha		$560			$675			$770	
Total Costs		per ha		$794.5	$947.0		$914.7	$1,031.0		$1,015.2	$1,112.7

Table 5.6 *Assumed costs of production per hectare for Corn Silage following Corn at three land productivity levels used in calculating returns for system A. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn.*

Costs of Production of Corn Silage following Corn **System A**

Item Description			*Low Productivity*			*Medium Productivity*			*High Productivity*		
				Costs			*Costs*			*Costs*	
				Fixed	*Variable*		*Fixed*	*Variable*		*Fixed*	*Variable*
Preharvest Machinery											
Chisel Plow				$8.9	$11.4		$8.9	$11.4		$8.9	$11.4
Tandem Disk				$8.9	$7.7		$8.9	$7.7		$8.9	$7.7
Apply N				$12.1	$13.8		$12.1	$13.8		$12.1	$13.8
Field Cultivate				$6.2	$7.4		$6.2	$7.4		$6.2	$7.4
Plant				$14.6	$13.6		$14.6	$13.6		$14.6	$13.6
Spray				$5.4	$5.4		$5.4	$5.4		$5.4	$5.4
Total				$56.1	$59.3		$47.2	$47.9		$47.2	$47.9
Seed, Chemical	**Cost per unit**		**Units**			**Units**			**Units**		
Seed	$3.86	per 1000	71058 seeds		$274.3	85269 seeds		$329.1	99481 seeds		$384.0
Fertilizer											
Nitrogen	$1.04	per Kg	168 Kg		$174.7	168 Kg		$174.7	168 Kg		$174.7
Phosphate	$1.06	per Kg	83 Kg		$87.6	94 Kg		$99.5	102 Kg		$107.8
Potash	$0.90	per Kg	188 Kg		$169.9	215 Kg		$194.2	233 Kg		$210.4
Lime		yearly cost			$24.7			$24.7			$24.7
Herbicide					$87.7			$87.7			$87.7
Insecticide					$56.8			$56.8			$56.8
Crop Insurance					$30.2			$33.6			$36.1
Miscelaneous					$22.2			$24.7			$27.2
Interest on	5%	annual rate for 8 months			$31.1			$34.3			$37.2
Total					$959.4			$1,059.5			$1,146.6
Harvest Machinery											
Silage Harvester				$73.7	$52.9		$73.7	$52.9		$73.7	$52.9
Haul				$65.2	$73.9		$74.5	$84.4		$80.7	$91.5
Handle (silage unloader)				$20.6	$6.8		$23.5	$7.7		$25.5	$8.4
Total				$159.4	$133.5		$171.7	$145.1		$179.9	$152.7
Labor											
Wages	$13.00	per hour	12.4 hours	$160.7		12.4 hours	$160.7		12.4 hours	$160.7	
Land											
Cash rent equivalent		per ha		$560			$675			$770	
Total Costs		per ha		$936.01	$1,152.2		$1,054.3	$1,252.5		$1,157.6	$1,347.3

Table 5.7 *Ranges of values used for sensitivity analyses.*

Factor	*Units*	*Reference*	*Minimum*	*Maximum*	*Increments*
Canola yield	Mg/ha	2	1.0	4.0	0.6
Comodity Prices					
Corn	$/Mg	150	75	300	45
Soybean-Corn Price Ratio		2.2	2	3	0.2
Canola-Soybean Price Ratio		1.12	1	1.4	0.08
N fertilizer cost	$/Kg	1.04	0.52	2.08	0.312

Table 5.8 *Assumed partial cost structure of winter canola and cereal rye and winter canola cover crops seeded using two methods.*

Cover Crop Partial Budget

		Aerial Seeding		*Direct Seeding*	
		Cereal Rye	*Winter Canola*	*Cereal Rye*	*Winter Canola*
Seed					
Seeding Rate (Kg per ha)		116	11	60	6
Seed Cost (per Kg)		$0.68	$12.11	$0.68	$12.11
Total		$79.21	$133.26	$40.97	$72.69
Seeding					
Grain drill (fixed + variable)		$0.00	$0.00	$21.01	$21.01
Custom aerial broadcast		$44.49	$27.19	$0.00	$0.00
Termination					
Sprayer (fixed + variable)		$10.87	$10.87	$10.87	$10.87
Chemical		$12.36	$19.77	$12.36	$19.77
Labor	**hours**				
Drilling	0.5	$0.00	$0.00	$6.50	$6.50
Spraying	0.2	$2.60	$2.60	$2.60	$2.60
Total		$149.53	$193.69	$94.31	$133.44

Table 5.9 *Net return of crop the studied cropping systems at the reference levels of factors. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

		System								
	System	***A***			***B***			***C***		
	Land Productivity	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***
	Crop									
Net Return ($/ha)	Corn	-235.0	-250.9	-244.8	-235.0	-250.9	-244.8	-168.7	-184.5	-178.4
	Corn Silage				-252.2	-223.3	-179.2			
	Soybean	-416.2	-460.8	-486.6				-218.9	-241.6	-245.5
	Winter Canola / Red clover	-589.9	-727.7	-843.4	-589.9	-727.7	-843.4			
	System Net Return	-413.7	-479.8	-524.9	-359.0	-400.6	-422.4	-193.8	-213.1	-212.0

Table 5.10 *Effect of canola yield on system returns and calculated yield needed to equalize system C net returns. System C is a conventional corn and soybean rotation.*

		Net returns response to winter canola seed yield		***Point where marginal value of adoption equal to zero***	
System	***Land grade***	***slope***	***intercept***	***Net Returns ($/ha)***	***Yield (Mg/ha)***
A	Low	121.9	-657.5	-193.8	3.80
	Medium		-723.6	-213.1	4.19
	High		-768.7	-212.0	4.57
B	Low	121.9	-602.8	-193.8	3.36
	Medium		-644.4	-213.1	3.54
	High		-666.2	-212.0	3.73

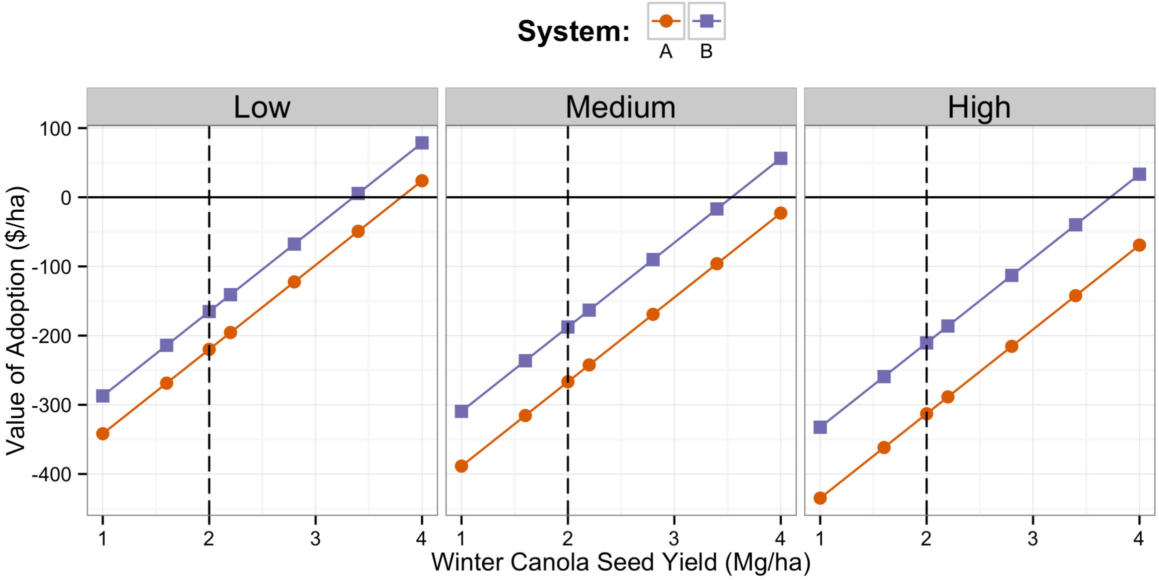

Figure 5.1 *Effect of varying winter canola seed yield on the value of adoption of the alternative systems across three land productivity levels. The value of adoption represents the change in returns associated with adopting the either A or B system compared with the baseline system C. The solid horizontal line represents the level in which system net returns are identical to the baseline system. The dashed vertical line represents the reference value of $150 Mg^{-1}. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

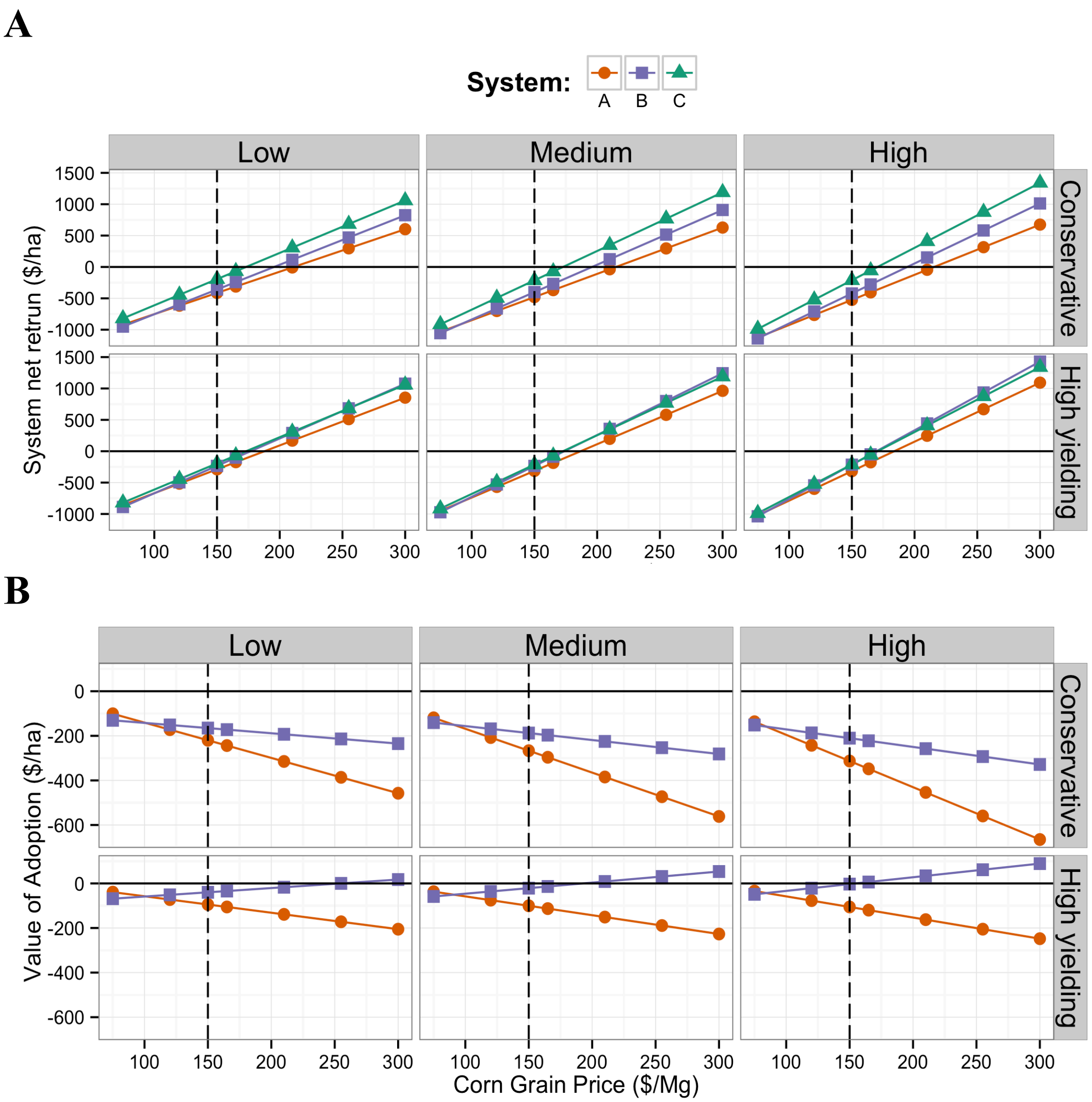

Figure 5.2 *Effect of varying commodity prices on net returns (A) and value of adoption (B) of the proposed systems under two canola yield scenarios and three land grades. The conservative scenario assumes a winter canola seed yield of 2.0 Mg ha^{-1}, while the high yielding canola scenario assumes yields equal to soybean (3.0, 3.4 and 3.7 Mg ha^{-1}). Soybean price is maintained at 2.2 times the price of corn, while canola price is maintained at 1.12 times the price of soybeans. Dashed line represents the value of the initial assumption of corn price at $150 Mg^{-1}. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

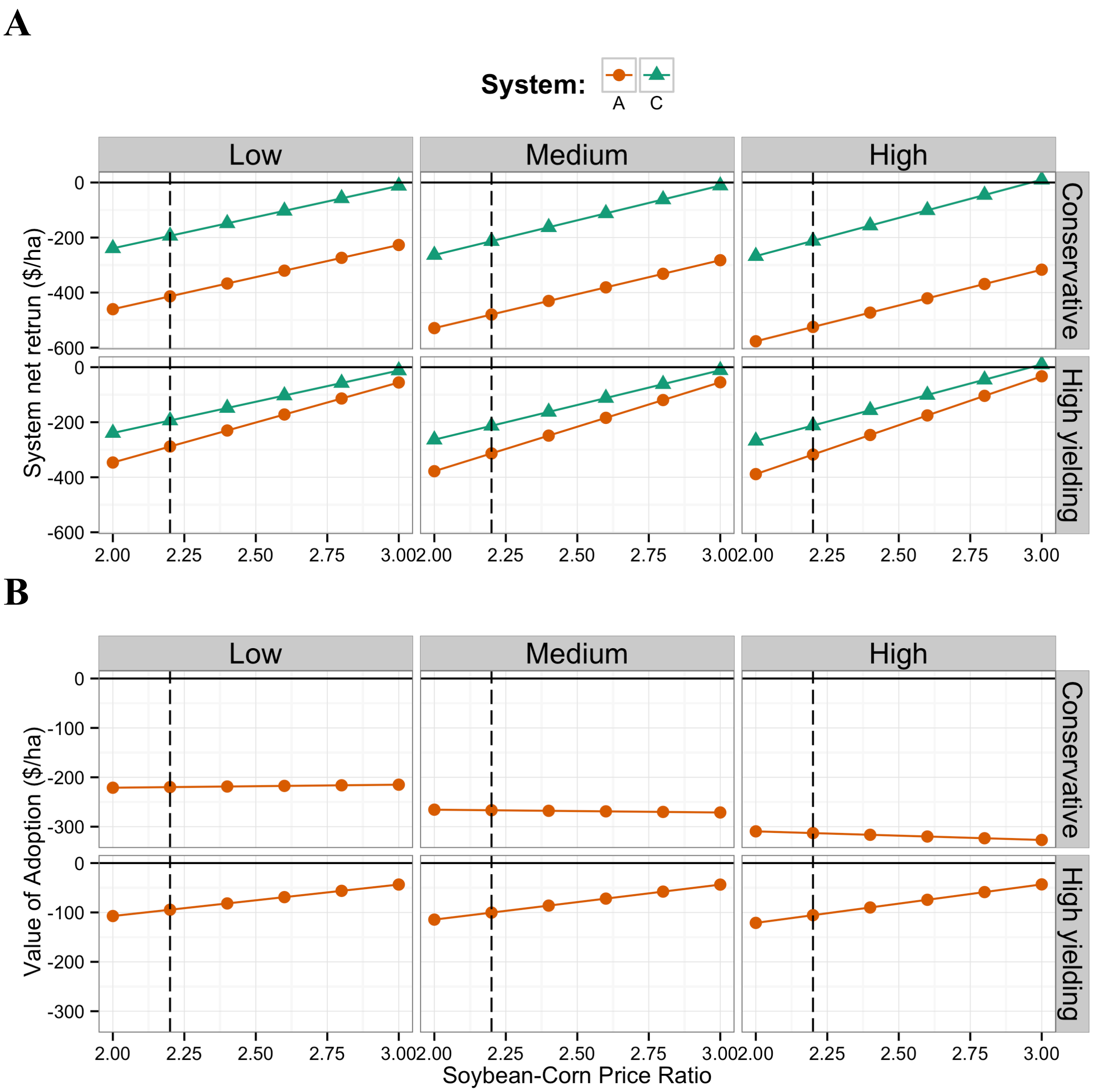

Figure 5.3 *Effect of varying soybean-corn price ratio on net returns (A) and value of adoption (B) of the system A under two canola yield scenarios and three land grades. The conservative scenario assumes a winter canola seed yield of 2.0 Mg ha^{-1}, while the high yielding canola scenario assumes yields equal to soybean (3.0, 3.4 and 3.7 Mg ha^{-1}). Canola price is maintained at 1.12 times the price of soybeans. Dashed line represents the value of the initial assumption of 2.2. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

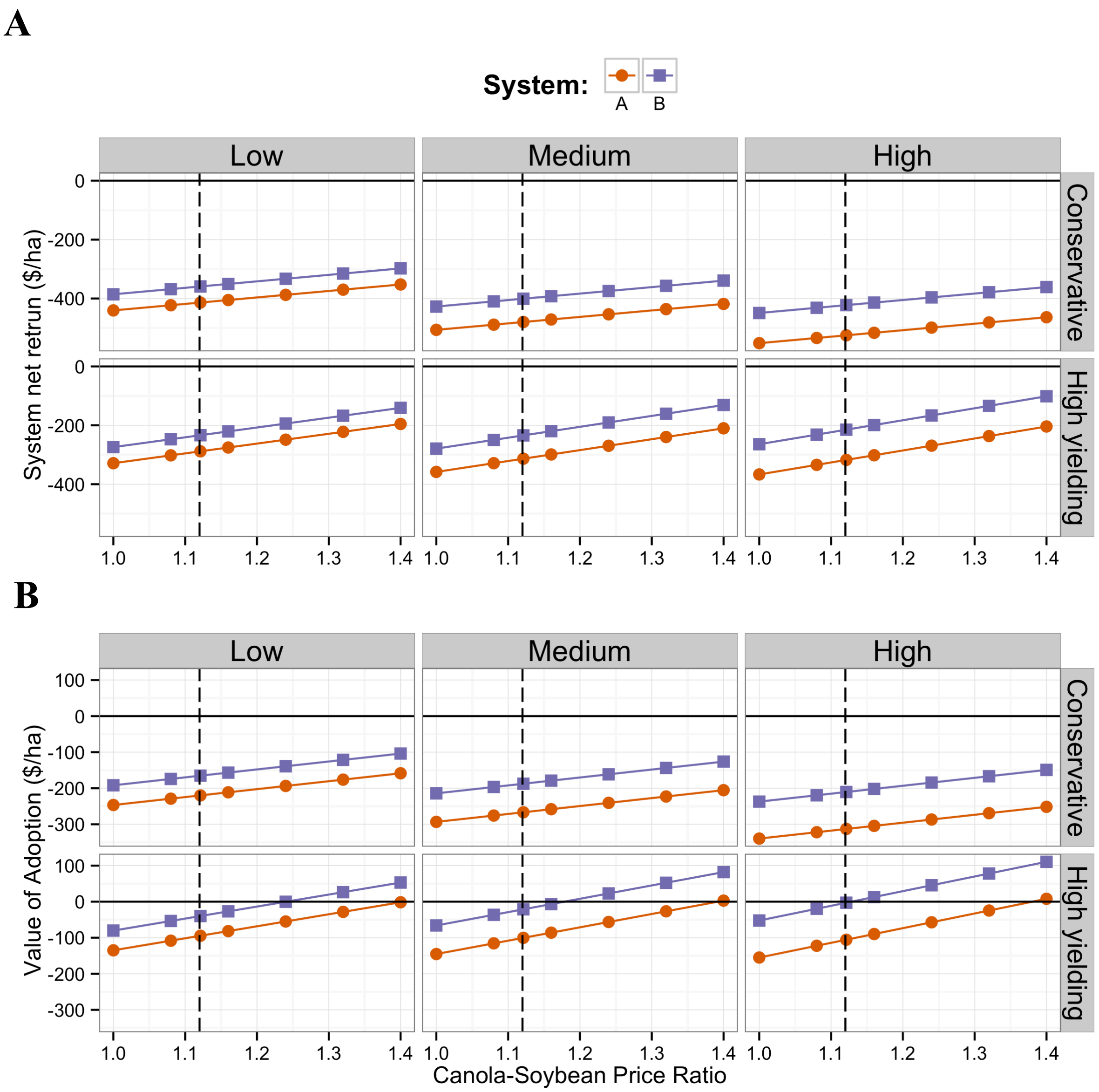

Figure 5.4 *Effect of varying canola-soybean price ratio on net returns (A) and value of adoption (B) of the proposed systems under two canola yield scenarios and three land grades. The conservative scenario assumes a winter canola seed yield of 2.0 Mg ha^{-1}, while the high yielding canola scenario assumes yields equal to soybean (3.0, 3.4 and 3.7 Mg ha^{-1}). Soybean price is maintained at 2.2 times the price of corn, and corn price is maintained constant at \$150 Mg^{-1}. Dashed line represents the value of the initial assumption of 1.12. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn.*

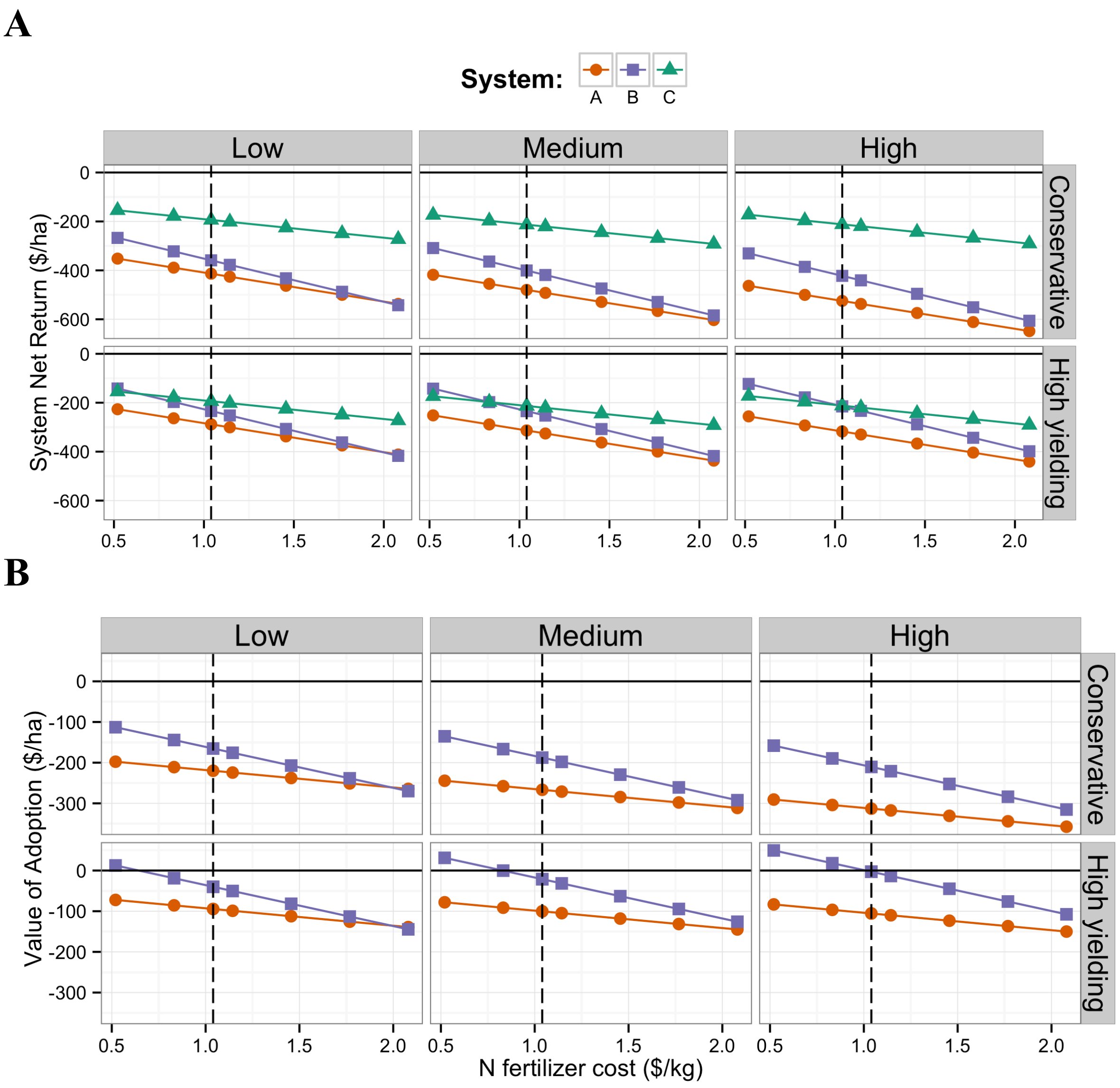

Figure 5.5 *Effect of varying N fertilizer on net returns (A) and value of adoption (B) of the proposed systems under two canola yield scenarios and three land grades. The conservative scenario assumes a winter canola seed yield of 2.0 Mg ha^{-1}, while the high yielding canola scenario assumes yields equal to soybean (3.0, 3.4 and 3.7 Mg ha^{-1}). Dashed line represents the value of the initial assumption at \$1.04 kg^{-1}. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn.*

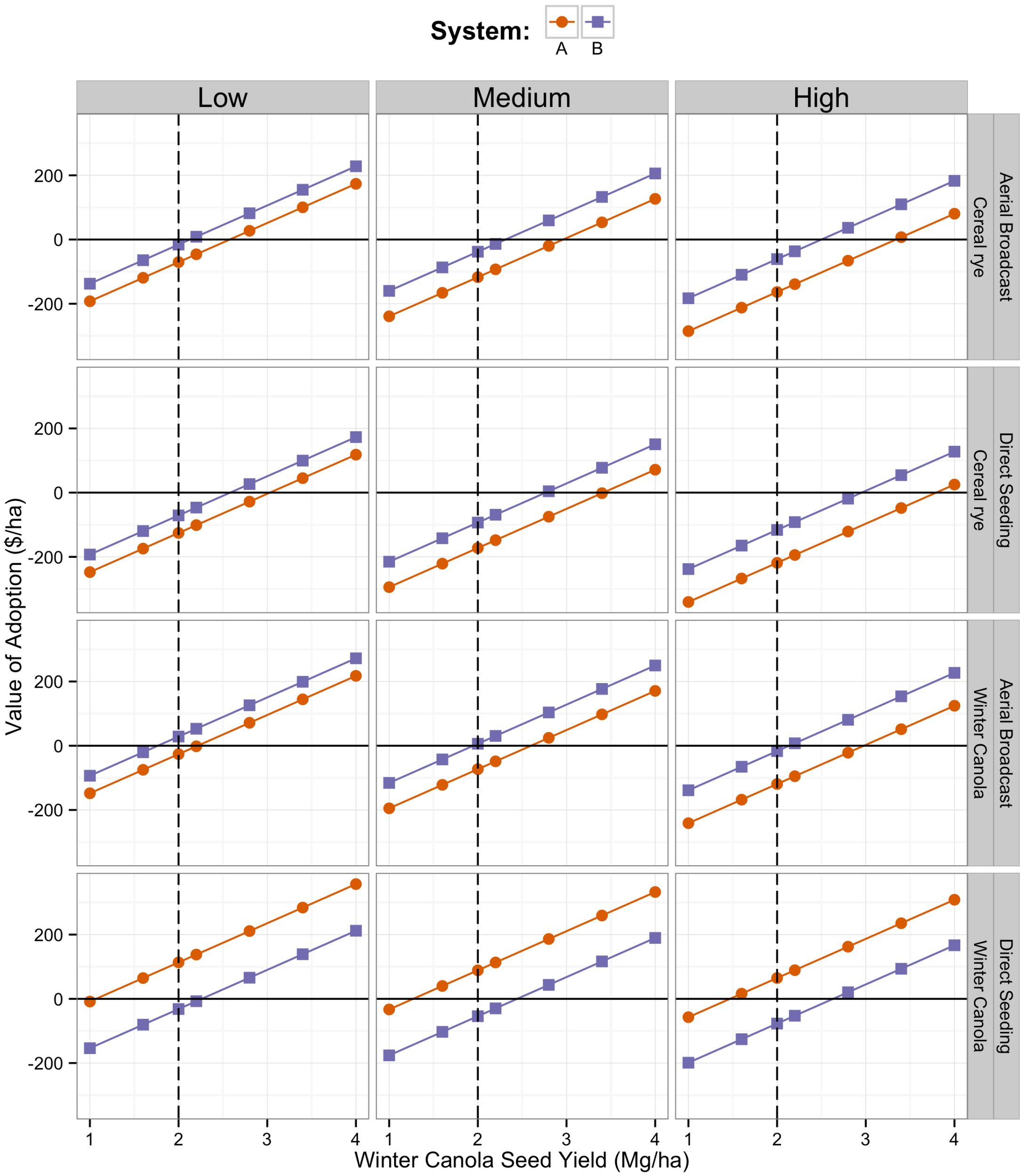

Figure 5.6 *Value of adoption of the proposed systems compared to establishing a cereal rye and winter canola cover crops under areal broadcasting and direct seeding methods at various levels of winter canola yield. Value of zero (solid line) indicates winter canola yield level in which the cost of establishing a cover crop and adopting the proposed systems are equal. Dashed line represents the value of the initial yield assumption at \$2.0 Mg*$^{-1}$*. System A is a rotation that includes short relative maturity soybeans, winter canola frost seeded with red clover and corn. System B is a rotation that includes corn silage, winter canola frost seeded with red clover and corn. System C is a conventional corn and soybean rotation.*

CHAPTER 6.

SUMMARY AND CONCLUSIONS

The general objective of the work presented in this thesis is to provide an assessment of the suitability of winter canola for delivering environmental and economic enhancements to conventional summer annual crop rotations in Iowa. We sought to determine whether establishing this crop in the fall provides sufficient winter cover benefits and the potential to produce an oilseed crop, while fitting within the logistic and economic constrains of current cropping systems. Because winter canola needs substantial time in the fall to achieve and optimal growth stage for overwintering, and corn and soybean typically are not harvested until mid October, a central question of interest in this research was to establish how late could this crop be seeded in this area without compromising its performance.

Summary of Findings

In Chapter 2, it is demonstrated that winter canola seeded in early September in central Iowa can produce as much as 3.1 Mg ha^{-1}of above ground biomass, provide up to 70% ground cover, and accumulate up to 60 kg ha^{-1} of N in the biomass during spring regrowth. It was also observed that seeding in mid September or beyond has the potential to cause poor establishment and insufficient growth, which can result in severe or complete winterkill. Nonetheless, this study is inconclusive about the effect of seeding date on winter survival across different environments, because of the winterkill of all treatments during the second year of the experiment due to extreme weather conditions during the winter of 2013-

2014. This seems to indicate the looming risk of winterkill for Iowa-grown winter canola, regardless of the amount of growth achieved in the fall. However, based on the results from these experiments, it is concluded that winter canola can be successfully established in the fall, survive the winter, and regrow in the spring in at least some years, but adequate conditions during fall growth are crucial.

Given this, further investigation was conducted in field plots and laboratory experiments to characterize the fall growing conditions that are optimal for maximizing canola's potential winter survival. According to the literature reviewed in Chapter 3, winter canola plants need to develop into a healthy, robust rosette of between 5 to 8 leaves before overwintering to achieve this optimal growth stage. Using this information as well as our own experimental data, we quantified the thermal time requirements for the development of at least five leaves for canola grown under field conditions in Iowa. Because most of the variation observed was due to delay in the emergence and establishment of the crop, we also characterized the effect of soil moisture and seeding depth on the thermal time requirement for emergence of canola seedlings. Based on the results from these experiments, which are highlighted in Chapter 3, it is estimated that winter canola plants require between 491 to 542 growing degree days (GDD) °C (Base = 4.5; Max = 30) after seeding. We also observed that dry conditions tended to increase the thermal time requirement for emergence by as much as 30% GDD°C, especially if seeds are placed on the top of the soil. This implies that broadcasting methods such as aerial seeding may be a risky method for establishing this crop if dry conditions are encountered.

In Chapter 4, this thermal time requirement was translated into estimates of the latest reliable seeding date for winter canola in Iowa, using historical weather observations during a

40-year range in locations across the state. As highlighted in this study, this proposed method for calculating a reliable seeding time frame produces more accurate estimates with less degree of error than the conventional recommendation when compared through spatial and geostatistical modeling procedures. It is concluded from this analysis that winter canola seeded by 31 Aug in the north to 12 Sep in the southeast will be exposed to enough thermal time to develop at least five leaves under typical growing conditions during at least half of the years in Iowa. Therefore, seeding beyond these dates in Iowa may not be advisable.

This seeding time frame implies that establishing winter canola in Iowa may conflict with standing corn and soybeans, because the harvest of these crops often occurs well into October. Therefore, from an agronomic perspective, adjustments to the rotation schemes of summer annuals are needed to successfully integrate this crop into conventional summer annual rotations. In Chapter 5, we considered rotating winter canola frost-seeded with red clover with short-relative-maturity (SRM) soybean cultivars that can be harvested early or the use of corn for other purposes (i.e. corn silage), and studied the economic profile of these systems comparing them to a conventional system. With carefully constructed enterprise budgets and by performing sensitivity analyses of key factors of production, it was revealed that both of the proposed alternatives tend to produce substantially less net returns than the conventional corn-soybean system, across various levels of canola yield potential and market conditions. Growing winter canola/red clover in rotation with corn silage and corn grain may have a greater economic advantage than if grown in rotation with SRM soybeans and corn grain. It was also identified that achieving relatively high winter canola yields (3.4 to 4.6 Mg ha^{-1}) is needed in these systems to be competitive alternatives against the conventional system. Additionally, the analysis indicated that planting cereal rye or winter canola cover crops may be a less costly nutrient pollution mitigation strategies that adopting these diversified rotations in situations when expected yields of winter canola are low.

Implications and Future Research

Based on the findings from the performed agronomic and economic studies, it is determined that winter canola has the potential to provide some environmental and economic enhancements to summer annual crop rotations in Iowa, although the specific situations in which canola can fit these rotations are limited. Winter canola may be effectively used as to provide ground cover benefits, but because it requires a late-August or early-September seeding date, direct seeding may not be a feasible method unless summer annual crops have been removed early (e.g. silage or SRM soybean varieties). Aerial broadcasting into standing crops could then be considered as an alternative for establishing canola under these circumstances, but as suggested by our findings, this method may result in delayed and poor establishment if dry conditions are encountered. It is still unknown whether canola is well adapted for growing under a senescing crop canopy, or if harvest operations and crop residues would affect the crop's ability to develop properly. Moreover, seeding rates and pre-plant N fertilizer application methods would likely have to be adjusted, if an oilseed harvest is sought. Thus, further investigation in this area is needed.

Another important aspect in need of more examination is canola's ability to provide erosion control. Here we assumed that the canola canopy provides the same relative erosion protection as surface residue or grass cover crops. But preliminary research (not described in this thesis) during the second year of our field experiment indicated that soil movement was greater in the cover crop plots than on untilled control plots. This may not be a completely fair comparison, but it should be noted that in contrast to the fibrous roots and dense vegetative structures of grasses, the architecture of the canola rosette, with wide, limp leaves and deep but thin taproot, might not be entirely favorable to protect the soil. Perhaps, canola's erosion mitigation potential could be improved by increasing plant populations or painting in binary mixes. On the other hand, winter canola's potential for scavenging NO_3 is well documented in the literature, but comparison to other cover crops grown under Iowa conditions would be useful to highlight its value as a tool for nitrate pollution mitigation tool. Thus, quantification of canola's environmental benefits is necessary.

At this moment, the economic incentives for incorporating a winter canola cash crop frost-seeded with red clover into Iowa rotations seem to be limited. Until winter canola's yield potential and optimum N use in these systems is fully understood, it may be premature to count this alternative as being financially competitive to conventional systems. We could speculate, however, other reasons that might drive adoption of diversified rotations such as an increase pressure from the public in the issue of water quality, or producers looking for ways to diversify their crop portfolio. Yet, it is most likely that adoption will be driven by their financial feasibility, thus research that is aimed to study these systems in more detail is needed. Perhaps, a first step could be the establishment of long-term cropping system studies at various sites across the state to provide evidence of the true productivity potential of these systems under Iowa conditions, as well as their ability for effectively mitigating P and NO_3 losses. This information would be valuable in determining if the strategies proposed here would serve well to potentially mitigate some of the impacts of agriculture on water quality, while maintaining economic feasibility of Iowa cropping systems.