FACTORS AFFECTING THE SUCCESSFUL ESTABLISHMENT OF AN OVERSEEDED WINTER RYE COVER CROP IN NORTHERN CLIMATES

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Abstract

Incorporating cover crops in the corn-soybean rotation is one way to improve soil quality over time and reduce nitrogen and erosion losses. In the Upper Midwest, however, cover crops can be difficult to establish after harvest of the main crop due to the short growing season. Overseeding prior to harvest may allow more time for growth. Three experiments were conducted to determine what factors are most likely to affect successful establishment of overseeded winter rye into standing corn and soybeans. The first experiment field tested aerial seeding at multiple locations in southeastern Minnesota to characterize the physical and chemical properties that affect fall biomass production. Precipitation within a week of seeding was found to be the most important factor in establishing a successful cover crop. The second experiment further elaborated on this by testing soil water potential and temperature on germination of rye seeds under laboratory conditions. Total germination was significantly decreased by decreasing water potential in the sandy loam, but not the clay or silt loam, suggesting that moisture content may be more important than water potential at the soil surface. Increasing temperature decreased total germination, most likely due to the increased incidence of mold at higher temperatures. The third experiment evaluated three overseeding techniques for standing soybeans: aerial seeding (AS), tractor-mounted air-flow spreader (TAF), and tractor-mounted fertilizer broadcast spreader (TBS). The AS treatment resulted in the lowest seeding density overall while the TBS treatment resulted in the highest density and was the most variable across plots. The differences in seeding density led to significant above-ground rye biomass differences in fall, although by spring, biomass was not different across seeding treatments. Soybean yields were not different across seeding techniques, suggesting that any of these practices are viable for on-farm use. Finally, the potential for overseeding cover crops, aerial seeding in particular, as a practice in the Upper Midwest was evaluated. Some of the current limitations include unpredictable weather, lack of aerial applicators, inconsistent stands due to pilot error and seed predation, and high costs.

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Introduction

During the last quarter of the 20th century, the two-year corn-soybean rotation became the dominant agricultural land use in the Upper Midwest (Randall 2003; Karlen 2004). However, research has shown that the corn-soybean rotation can degrade soil quality over time (Karlen et al. 2006), leads to topsoil losses from erosion (Randall 2003), and can contribute to significant losses of nitrate (NO_3) to ground and surface waters (Dinnes et al. 2002; Oquist et al. 2007). One solution for ameliorating these effects is the use of cover crops during the nongrowing-season, which can increase the amount of time the land is covered in vegetation. While many crops have been studied for potential use as a cover crop, cereal rye (*Secale cereale* L.) in particular has been shown to reduce nitrate leaching (Ditsch et al. 1993; McCracken et al. 1994; Strock et al. 2004; Fisher et al. 2011). Further advantages of rye include an increase in soil organic matter (Kuo and Jellum 2002), reduction of soil erosion (Langdale et al. 1991; Kaspar et al. 2001) and suppression of weeds (Barnes and Putnam 1983; Leibl et al. 1992; De Bruin et al. 2005).

Although the benefits of cover crop utilization on soil quality have been known for many years (Odland and Knoblauch 1938; Beale et al. 1955), the adoption of this practice has been minimal. One survey found that only approximately 18% of farmers in the U.S. Corn Belt had used cover crops in the past (Singer et al. 2007). One reason cited was the lack of knowledge about the practice, and it is true that uncertainties exist. For instance, there have been mixed reports of rye negatively affecting subsequent crops (Johnson et al. 1998; Tollenaar et al. 1993, Leibl et al. 1992), although other studies have shown that corn yields were actually improved with cover cropping compared with yields without a previous rye cover crop (Ball-Coehlo and Roy 1997; Ball-Coelho et al. 2005).

In addition to the reservations about yield suppression with rye, it is sometimes difficult to establish winter cover crops in the Upper Midwest due to cool temperatures and unpredictable rainfall. Cereal rye is considered a good cover crop for cooler climates because it is cold tolerant and easy to establish (Dabney et al. 2001), but a winter cover crop meta-analysis found that grass cover crops in the north-central U.S. would only have marginal benefits due to the short growing season (Miguez and Bollero 2005). There is some evidence that broadcasting seed into a standing crop, or overseeding, can result in earlier crop growth than drilling the seed after harvest (Frye et al. 1988). Current research is focused on this concept by overseeding rye during the early fall into a standing corn or soybean crop. Preliminary data have shown promising results, but field management of this practice needs to be optimized. The overall objectives of this research as addressed in the three following chapters were to: 1.) determine what factors are most likely to affect successful germination and establishment of overseeded winter rye; 2.) evaluate methods for overseeding rye into standing corn and soybeans; and 3.) assess the potential for this practice to be adopted in the Upper Midwest.

Chapter 1 - This chapter focuses on the factors most likely to affect establishment of winter rye into standing corn and soybeans. Beyond anecdotal evidence, factors that affect germination and survival of seed broadcast onto the soil surface have not been characterized. We conducted a field study to characterize the physical and chemical properties that affect successful rye growth in the fall, and conducted a germination experiment to determine optimal temperature and surface soil moisture contents needed for successful germination. It has been well documented that adequate soil moisture is required for optimal seed germination (Bewely and Black 1994; Nielson 2000), and although many studies have examined the relationship between germination and soil moisture content (Parker and Taylor 1965; Wright et al. 1978; Bouaziz and Hicks 1990; Blackshaw 1991; Mian and Nafziger 1994), most have used seed that was buried in the soil. Overseeded rye, however, is typically broadcast onto the soil surface and does not necessarily have good seed-soil contact. Surface soil moisture in the top few millimeters is highly variable compared with soil moisture at depth due to evaporation driven by direct interaction with the atmosphere (Hillel 1998).

Chapter 1 attempts to: 1.) determine the physical and chemical properties that affect aerially seeded rye establishment in corn and soybeans; 2.) characterize the amount of N removed from the soil by winter rye following corn and soybeans; 3.) under laboratory conditions, determine the effect of varying temperature and surface soil moisture contents and water potentials on germination of surface-broadcasted rye; and 4.) develop a simple model to predict germination percentages based on soil moisture content.

Chapter 2 – This chapter characterizes different methods of overseeding into standing soybeans. Cover cropping is particularly important in this crop due to the minimal residue left on the ground over winter. Two main broadcast methods are currently in use: aerial seeding via helicopter or fixed-wing aircraft and a spreader mounted to a high-clearance vehicle or tractor. Both have advantages and disadvantages. Aerial seeding keeps heavy machinery out of the field and is typically faster. Robison (2011) reported that aerial applicators can seed up to 81 ha per hour in Indiana, while using a highboy to broadcast seed can seed only 4-5 ha per hour. On the other hand, aerial seeding is not consistently uniform and costs of application can vary greatly (Wilson 2012). Broadcasting seed via high-clearance vehicle may provide more consistency across the field and may be done with equipment already on hand or through rentals from a local cooperative. However, it tends to be slower, requires the use of heavy equipment in the field, and may damage the standing crop. These seeding techniques have not been evaluated relative to one another. The objectives of this chapter were to: 1.) compare the seeding consistency and rye biomass yields of aerial seeding versus a tractor-mounted airflow spreader and a tractor-mounted fertilizer bucket spreader; 2.) determine if soybean yields were decreased due to damage from the tractor; and 3.) characterize the amount of soil nitrogen removed by the rye.

Chapter 3 – The final chapter explores the potential for overseeding a rye cover crop in the Upper Midwest, with a focus on aerial seeding. This method has increased in areas that have incentivized the use of cover crops. In Maryland, where there are concerns about agricultural pollution in the Chesapeake Bay, approximately 82,150 ha of cover crops were planted in 2007, with 12%, or 9,850 ha, applied aerially (Powell 2008). The areal extent nearly doubled during the subsequent three years with 161,900 ha planted in

2010 (Maryland Department of Agriculture 2012). This increase is likely related to the corresponding increase in dedicated funding for the Maryland Department of Agriculture's cover crop cost-share program from a maximum cost-share payment of \$124 ha^{-1} in 2007 to \$235 ha^{-1} in 2010 (Maryland Department of Agriculture 2010). Other areas that have seen an increase in aerial seeding are Indiana and Iowa, both important in corn and soybean production. In the fall of 2011, approximately 28,300 ha in northeast Indiana (Dave Robison, personal communication, 2012) and 8,100 ha in Iowa (Sarah Carlson, personal communication, 2012) were aerially seeded.

However, in spite of the benefits and success stories, aerial seeding is still considered a risky practice, and farmers in the northern Corn Belt are particularly hesitant, feeling that the practice is too unreliable and that the risks outweigh the benefits (Dave Linn, Daniel Gillespie, Tony Thompson, Dean Thomas, personal communications, 2012). The objective of this chapter is to review some of the limitations of aerial seeding and concludes by discussing future research directions and potential alternatives.

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Chapter 1 - Factors affecting successful establishment of aerially seeded winter rye in the northern U.S. Corn Belt

Cover crops can improve soil quality, decrease erosion, and reduce nitrate (N) leaching to groundwater. Establishing cover crops in the corn-soybean rotation in the northern U.S. Corn Belt can be difficult, however, due to the short time-frame between harvest and freezing temperatures. Aerial seeding into standing crops is one way to give cover crops more time to establish. Field studies were conducted to characterize the physical and chemical properties that affect successful winter rye establishment in corn and soybeans and total N uptake of rye in the fall, while a germination experiment was designed to determine optimal temperature and surface soil moisture content needed for successful germination. In the field study, 31 field-scale sites (22 in corn and 9 in soybeans) were aerially seeded in southeastern MN during late-August to early-September of 2009, 2010 and 2011. Above-ground rye biomass was collected prior to ground-freeze and multiple regression analysis was used to relate biomass to multiple soil and weather conditions. Total N uptake was determined, calculated as a percentage of inorganic soil N at the time of seeding, and then compared with biomass. Overall, precipitation the week after seeding was the most important factor in determining rye establishment, although our model accounted for only 43% of the variation in biomass. For this set of research sites, over 400 kg ha^{-1} of rye biomass was needed to take up half of the residual soil inorganic N. The germination study characterized winter rye germination on the surface of three different soils equilibrated to -50, -200, and -500 kPa water potential placed in three different low-temperature incubators at 10°C, 18°C and 25°C. Total germination was significantly decreased by decreasing water potential in the sandy loam, but not the clay or silt loam, suggesting that moisture content may be more important than water potential at the soil surface. Increasing temperature decreased total germination, but this was probably due to the increased incidence of mold at higher temperatures, which is not likely a concern in field settings.

Introduction

During the last quarter of the 20th century, the two-year corn-soybean rotation became the dominant agricultural land use in the Upper Midwest (Randall 2003; Karlen 2004). Recent research has shown that this agronomic practice can degrade soil quality over time (Karlen et al. 2006) and can contribute to significant losses of nitrate (NO_3) to ground and surface waters (Dinnes et al. 2002; Oquist et al. 2007). One mitigation strategy for reducing NO_3 loss is to incorporate cover crops into the rotation, which can increase the amount of time the land is covered in growing vegetation. While many crops have been studied for potential use as a cover crop, cereal rye (*Secale cereale* L.) in particular has been shown to reduce nitrate leaching (Ditsch et al. 1993; McCracken et al. 1994; Strock et al. 2004; Fisher et al. 2011). Further advantages of rye include an increase in soil organic matter (Kuo and Jellum 2002), reduction of soil erosion (Langdale et al. 1991; Kaspar et al. 2001) and suppression of weeds (Barnes and Putnam 1983; Leibl et al. 1992; De Bruin et al. 2005).

Although the benefits of cover crop utilization for soil quality have been known for many years (Odland and Knoblauch 1938; Beale et al. 1955), the adoption of this practice has been minimal. Singer et al. (2007) found that only about 18% of farmers in the U.S. Corn Belt had used cover crops in the past. One reason cited for minimal adoption is the lack of knowledge about the practice, and it is true that there are many risks. For instance, there have been mixed reports of rye negatively affecting subsequent crops. Johnson et al. (1998) reported that, in Iowa, corn yields were reduced following winter rye but not after oat. Tollenaar et al. (1993) suggested that winter rye caused a delay in corn development and a yield loss in the subsequent harvest. In both studies the authors mentioned that allelopathy from the rye may have played a role in yield reductions. A study in Illinois found that soybean yields were reduced when rye was killed immediately before planting due to low soybean stand (Leibl et al. 1992).

In contrast, some studies have shown that corn yields were actually improved with cover cropping compared with yields without a previous rye cover crop (Ball-

Coelho and Roy 1997; Ball-Coelho et al. 2005). It has also been reported that certain management practices can reduce the yield losses of corn and soybeans following winter rye. Ritter et al. (1998) and Andraski and Bundy (2005) concluded that rye cover crops grown on loamy sand will not reduce subsequent corn yields if irrigation is used. A number of studies have found that soybean and corn yields after winter rye were not reduced when the rye was killed one or more weeks before planting (Leibl et al. 1992; Strock et al. 2004; Ball-Coelho et al. 2005; Duiker and Curran 2005; Krueger et al. 2011).

There are also uncertainties about the costs associated with planting and killing a secondary crop without gaining a secondary monetary income. Studies in Minnesota and Missouri found that soybean yields following a rye cover crop were comparable to yields following winter fallow, but overall economic returns were usually reduced with the cover crop (Reddy 2001; De Bruin et al. 2005). One way to overcome the additional costs of planting a cover crop is through cost-sharing programs. In a survey conducted by Singer et al. (2007), 56% of respondents said they would use cover crops if cost-sharing was available, which is much higher than the 18% that claimed to have actually used the practice.

In addition to concerns about yield suppression and planting costs, winter cover crops can be difficult to establish in the Upper Midwest due to cool temperatures and unpredictable rainfall. Cereal rye is considered a good cover crop for cooler climates because it is cold tolerant and easy to establish (Dabney et al. 2001), but a winter cover crop meta-analysis found that grass cover crops in the north-central U.S. would have only marginal benefits due to the short growing season (Miguez and Bollero 2005). Strock et al. (2004) suggested that based on average weather patterns in southwestern Minnesota, rye would be a successful cover crop only in one out of four years. In these studies, however, rye was planted after the preceding crop was harvested, when temperatures were already cool. There is some evidence that broadcasting seed into a standing crop can result in earlier crop growth than drilling the seed after harvest (Frye et al. 1988), and Feyereisen et al. (2006) predicted a seeding date prior to 15 September in southwestern MN would minimize NO_3 losses. Recent research has tested these strategies by aerially seeding rye during the early fall into a standing corn or soybean crop. Preliminary data have shown promising results, but field management of this practice needs to be refined. For instance, beyond anecdotal evidence, factors that affect germination and survival of seed broadcast onto the soil surface have not been characterized.

Additionally, it has been well documented that adequate soil moisture is required for optimal seed germination (Bewely and Black 1994; Nielson 2000). While many studies have examined the relationship between germination and soil moisture content (Parker and Taylor 1965; Wright et al. 1978; Bouaziz and Hicks 1990; Blackshaw 1991; Mian and Nafziger 1994), most have used seed that was buried in the soil. Aerially seeded rye, however, is broadcast onto the surface of the soil and does not necessarily have good seed-soil contact. Surface soil moisture in the top few centimeters is highly variable compared with soil moisture at depth due to the evaporation driven by direct interaction with the atmosphere (Hillel 1998). Rapid changes in moisture content mainly affect the matric potential (Ψ_m) component of the total soil water potential (Ψ_t), which drives imbibition of ungerminated seeds (Hunter and Erickson 1952; Evans and Etherington 1990).

The objectives of this study were to: 1.) determine the physical and chemical properties that affect aerially seeded rye establishment in corn and soybeans; 2.) characterize the amount of N removed from the soil by winter rye following corn and soybeans; 3.) under laboratory conditions, determine the effect of varying temperature and surface soil moisture contents and water potentials on germination of surface-broadcasted rye; and 4.) develop a simple model to predict germination percentages based on soil moisture content.

Methods and Materials

Field Study

This study was conducted during three fall seasons (2009-2011) at multiple locations in Dakota, Fillmore, Goodhue, Olmsted, and Winona counties in southeastern

Minnesota (Figure 1-1). This area has a typical interior continental climate with cold winters (-9°C mean temperature) and moderately hot summers (20°C mean temperature). Sites were located on cooperator farms which were maintained according to the owner's discretion. Uncertified 'Rymin' rye was aerially seeded via helicopter at approximately 112 kg ha^{-1} into standing silage or grain corn in 2009 and 2010 (22 sites) and into standing soybeans in 2010 and 2011 (9 sites) (Table 1-1). Field sizes ranged from 2 to 20 ha. On the day of seeding, subsamples of seed were collected. Wet towel germination tests (Quarberg and Jahns 2000) found rye germination to exceed 90% each year.

In order to determine which factors affect rye germination and establishment, we measured a variety of soil and weather characteristics. On the day of seeding, a sample area was selected in each of the 31 fields at least 15 m from the field edge or head rows and mapped with a global positioning system (GPS) unit. Nine subsamples for soil characteristics were taken from a 3 by 3 grid, with each subsample being approximately 7.5 m apart. Soil moisture in the top 4 cm was determined with a TH_2O Soil Moisture Meter (Dynamax, Houston, TX) and values were averaged. Next, soil samples were collected from 0-15 cm and combined at each site for a range of soil tests. Soils were air-dried and ground to pass through a 2-mm sieve. Tests included organic matter, pH, Bray-phosphorus (P) or Olsen-P (depending on pH), and potassium (K) (Brown 1998). Total nitrogen (N) and carbon (C) were measured via combustion analysis (vario Max CN Analyzer, Elementar Analysensysteme, GmbH, Haunau, Germany), and 2 N KCl extractable nitrate-N (NO_3-N) and ammonium-N (NH_4-N) were determined conductimetrically (Carlson et al. 1990). Approximately 5-7 d after seeding, sites were resampled for soil moisture and then the actual seeding rate was estimated by counting the seeds in a known area (0.1 or 0.25 m^2) at each of the 9 subsample sites in each field and averaged. These data were not collected for soybeans in 2010, however.

Weather conditions that were considered to potentially affect rye establishment were precipitation and temperature. Daily precipitation from the Cooperative Observer Network and temperature data from the National Weather Service were retrieved from the Minnesota Climatology Working Group (2012) for the closest available location per site. Total precipitation for 2 d prior to seeding and 7 d after seeding was calculated.

These time ranges were chosen as indicators of moist or dry soil conditions before and after seeding. Additionally, growing degree days (GDD; base 4.4°C) were determined from the day of seeding until rye biomass was collected.

Other factors considered were harvest date of the main cash crop and residue cover on the soil surface. Harvest date of corn or soybeans for each field was given as an estimated date by each cooperator, and then converted to the number of days after seeding for the analysis. Residue on the soil surface was characterized by digital image analysis in standing corn only. Digital images were taken at a height of 1.5 m with a camera stand and analyzed with software (SamplePoint, version 1.54; Booth et al. 2006).

Rye biomass was collected from the same sites sampled earlier in the fall on approximately 105, 79, and 67 d after seeding in 2009, 2010, and 2011, respectively, prior to ground-freeze (Table 1-1). Six to nine 0.25 m^2 subsamples of above-ground biomass were removed and combined in a single paper bag. Plant matter was dried at 60°C, weighed to determine dry matter yields, and then ground with a Wiley mill to pass though a 2-mm screen. Total N in ground samples was determined with a combustion analyzer (Variomax CN Analyzer, Elementar Analysensysteme, GmbH, Haunau, Germany) following the methods of Horneck and Miller (1998). Total N uptake was calculated as the product of dry matter yields and percent N in plant matter.

Rye biomass yield data were analyzed using multiple regression analysis following the procedures of Beal (2005). First, the predictor variables were checked for multicollinearity using PROC CORR (SAS Institute Inc. 2010). Predictor variables included: soil moisture on the day of and one week after seeding; soil inorganic N (NO_3-N + NH_4-N), P, K, organic matter, pH, total N, and total C; total precipitation 2 d before seeding (DBS) and 7 d after seeding (DAS); harvest date of the main crop; estimated seeding rate; GDD; and estimated residue on the soil surface. Additionally, total N uptake and biomass yields were related using PROC REG (SAS Institute Inc. 2009). Interactions and main effects were considered significant at $p \leq 0.05$.

Germination Study

Winter rye seeds were germinated on various soil types and at different water potentials and temperatures at the University of Minnesota, Saint Paul, MN. Three soil types were chosen to represent a range of water holding capacities and soil textures across the state: a sandy loam (Coarse-loamy, mixed, superactive, mesic Mollic Hapludalf) from near Marion, MN; a silt loam (Fine-silty, mixed, superactive, mesic Mollic Hapludalfs) from near Elgin, MN; and a clay loam (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls) from near Morris, MN. Soils were collected in bulk from the top 15 cm of the Ap horizon during Oct 2009, air-dried, and ground to pass through a 2-mm sieve. Routine soil tests (Table 1-3) included organic matter, pH, Bray-phosphorus (Bray-P), and ammonium acetate extractable potassium (K) (Brown 1998). Total nitrogen (N) and carbon (C) were measured via combustion analysis (Variomax CN Analyzer, Elementar Analysensysteme, GmbH, Haunau, Germany).

For each soil type, the amount of air-dried soil needed to reach a bulk density of 1.0 g/cm^3 or greater was weighed out and mixed with enough deionized water to make a slurry. The slurry was poured into empty soil sample rings on top of pre-saturated ceramic plates and the water potential was adjusted to -50, -200, and -500 kPa with a high-range pressure plate system (Klute 1986). Once equilibrated, the soils were removed from the pressure system, and subsamples were taken to determine gravimetric soil moisture content.

Experimental units were soils packed into individual, labeled petri dishes (100 mm diameter x 10 mm high) so that the soil depth was 0.7 cm. This was equivalent to approximately 29 g of oven-dried soil. Uncertified ‘Rymin’ rye seed, which is typically available to farmers in the region, was used in this study. A wet-towel germination test (Quarberg and Jahns 2000) with several replicates verified the 80% germination rate stated on the label by the supplier. Thirty seeds were randomly placed on the soil surface in each petri dish. Lids were placed on each dish then placed and sealed in plastic bags to reduce moisture loss.

The experimental design was a 3 x 3 x 3 factorial in randomized complete blocks (RCBD) with four replications. Three low-temperature incubators were set at 10°C, 18°C, and 25°C, respectively. These temperatures were chosen to represent below-average, average and above-average temperature scenarios in mid-September, when aerially seeding is likely to occur. Within each incubator, replicates were placed at the same approximate location. For instance, replicates one and two were always placed above replicates three and four in the center of the incubator.

Germination, or radicle emergence >2 mm (Bewely and Black 1994; Raven et al. 2005), was counted daily for up to 12 d. A preliminary study suggested that germination did not occur after this time. The bags were briefly opened during the counting process to prevent accumulation of CO_2 or other gases. Germinated seeds were removed as they were counted. Total germination (a percentage) was calculated as the number of germinated seeds divided by 30 (the total number of seeds) and then multiplied by 100. After day 5 of the study, ungerminated seeds that were covered in mold were counted and removed, as they were considered unviable. Time until 50% germination (TG_{50}) was calculated as the number of days until 50% germination was reached.

Proportional data from this study were analyzed with PROC GLIMMIX (SAS Institute Inc. 2010) using a gamma distribution. The remaining data were analyzed using PROC MIXED (SAS Institute Inc. 2010). In all cases, replicates were considered to be random variables. Treatment means or interactions were compared using least-square means (SAS Institute Inc. 2010). Germination percentage was related to water potential with PROC REG and soil moisture content with PROC NLIM (SAS Institute Inc. 2010). The latter method does not calculate R^2 values, so the following equation was used:

$$R^2 = (CTSS - SSE) / CTSS$$

where R^2 is the fraction of the variation in the dependent variable as explained by the model, CTSS is the corrected total sums of squares, and SSE is the sums of squares of the error found in the PROC NLIM output (Robbins et al. 2006).

Results and Discussion

Field Study

Biomass predictors

Weather – Mean temperature and precipitation for each fall (2009-2011) are compared to 30-yr means in Table 1-2. The three counties listed contained most of the seeding sites. Precipitation was generally above average in 2009 and 2010, especially early in the season, while 2011 was drier than normal. In all three years, temperatures tended to be cooler than average.

Precipitation for 2 d prior and up to 7 d after seeding is shown in Figure 1-2. In 2009, there was adequate moisture prior to seeding in Fillmore County, but the more northern counties were considerably drier (Olmsted and Dakota). Precipitation in 2010 was ideal, as there was rain before and after seeding. In 2011, the northern counties were drier again, but Fillmore County received approximately 2 cm of rain after seeding.

Growing degree days (GDD) from the time of seeding until biomass harvest averaged 549, 539 and 341 GDD in 2009, 2010, and 2011, respectively. The lower value in 2011, mostly due to a later seeding date, may have limited establishment, although 'Aroostook' rye, which, like 'Rymin,' was developed for northern climates, can establish with 260-350 GDD (USDA-NRCS 2002).

Soil Characteristics – Mean soil moisture content, nutrient concentrations, pH, organic matter content, and surface residue cover are displayed in Table 1-3. Soil moisture tended to decrease from the day of seeding to 5-7 d after seeding in 2009 and 2010 while it increased in 2011. Soil moisture content was highest in 2010 due to the recent rainfall while conditions were drier in 2009 and 2011. Residual soil inorganic N in the top 15 cm was generally higher and more variable in corn than in soybeans, most likely a result of variability in fertilizer N applied at each corn site. Average P levels were considered very high (>21 ppm) at most sites while K levels ranged from low (41-80 ppm) to very high (>160 ppm) (Rehm et al. 2006). The high variability may be a result of previous manure use in some fields and not others. Organic matter content and pH were relatively stable across years and sites, as were total N and C. Surface residue cover in corn averaged around 25% in both 2009 and 2010, although the standard deviation was high most likely due to the variety of tillage types used by the farmers in this study.

Multicollinearity – As expected, multicollinearity was found among several of the predictor variables, including: soil moisture content and precipitation; P and K; and organic matter, total N and total C. Potassium was dropped from the analysis as levels were correlated with soil P levels. Since precipitation is easier for a farmer to measure than soil moisture, the latter variable was dropped. We also chose to keep precipitation 7 DAS instead of 2 DBS because several anecdotal reports state that rain is needed shortly after seeding to ensure germination (MDA 2008; Mutch and Martin 2010; USDA-NRCS 2010). Finally, since farmers are likely to know the organic matter content of their soils, total N and C were also dropped from the analysis.

Biomass Production

Biomass – Above-ground rye biomass averaged 26.4 kg ha^{-1} (range: 0 – 117 kg ha^{-1}) in 2009, 411.6 kg ha^{-1} (range: 0 - 1570 kg ha^{-1}) in 2010, and 66.3 kg ha^{-1} (range: 3 – 156 kg ha^{-1}) in 2011. Altogether, however, most sites (60%) had less than 50 kg ha^{-1} (Figure 1-3). Biomass tended to be lower in 2009 and 2011 compared with fall rye biomass reported in Ontario, Canada, where rye biomass ranged from 91 – 884 kg ha^{-1} after being broadcast into standing corn in August (Ball-Coelho and Roy 1997). In Iowa, which has a longer growing season, the average biomass for rye overseeded into soybeans was 410 kg ha^{-1} (Johnson et al. 1998). The difference was most likely due to the dry conditions before and after seeding in our study. In 2010, when conditions were wetter, biomass yields were similar to those reported in Ontario and Iowa.

Biomass Prediction – The multiple regression analysis was run twice. The first analysis included 13 of 31 sites due to missing data, and none of these sites were soybean fields. The three variables with missing data (harvest date, seeding rate, and % residue cover) were not significant in the model and therefore were dropped from the analysis.

The second analysis included all 31 sites and the following variables: inorganic N, pH, P, organic matter, precipitation 7 DAS, and GDD. The best model, as selected by the lowest Akaike's Information Criteria (AIC) value, suggested a significant relationship between fall biomass and total precipitation 7 DAS (R^2=0.4333; F=22.94; $p<0.001$):

$$Biomass = 78.1 * Precipitation\ 7\ DAS$$

where Biomass is fall above-ground rye dry matter in kg ha^{-1} and Precipitation 7 DAS is the total amount of precipitation (cm) for the 7 days following seeding. This particular model did not include an intercept, since biomass cannot be produced without precipitation. Adding additional variables did not significantly increase R^2 values.

Several reports have reached similar conclusions about the need for precipitation events close to the seeding date (Clark 2007; MDA 2008; Mutch and Martin 2010). The USDA-NRCS in Iowa suggests that precipitation is needed within 10 d if soil moisture on the day of seeding is not sufficient for germination (2010). Fisher et al. (2011) found that rye seedling emergence was more rapid when broadcast closer to rainfall events. One consideration is that precipitation 7 DAS was highly correlated with soil moisture content on the day of and one week after seeding, indicating that the latter variables may be important predictors of fall biomass production, as well.

Our model accounts for only approximately 43% of the variation in biomass production, however, despite having taken into account multiple possible variables. This indicates that there are additional factors that affect germination and establishment. For instance, Ball-Coelho and Roy (1997) suggest that light interception played an important role in increased rye biomass since the previous low-yielding corn crop in their study provided less light competition than in other years. Baker and Griffis (2009) also reported that rye biomass was reduced in their model if seeded too early into corn due to the low irradiance environment beneath the corn canopy. Several other successful models of rye growth take into consideration solar radiation interception, as well (Feyereisen et al. 2006, Whitmore and Shroder 2007), so it is likely an important variable.

Another possible factor is seed predation by insects and animals. Davis and Leibman (2003) found that predation of Giant Foxtail (*Setaria faberi*), a weed often found in corn and soybeans, peaked in September with 5-18% of seeds being eaten per day. Since most of our seeding happened in September and we noticed unexplained losses of seed at some sites, it is likely that predation occurred. In fact, a motion-sensitive camera that we placed in the soybean canopy provided visual evidence of predation by a rodent (Figure 1-4). Barnett and Comeau (1980) reported that much of the exposed seed in their study was eaten by birds. At several of our sites, we also noticed that the emerging coleoptiles of germinating rye seed were eaten. Similarly, in another study, ground beetles damaged the endosperm of germinating perennial ryegrass (Luff 1980).

Nitrogen Uptake – Average N concentration of the rye was 37.9 ± 6.6 g kg^{-1} across all sites and previous crops. Fall total N uptake values ranged from 0.1 to 44.7 kg ha^{-1}, similar to those reported by Ball-Coelho and Roy (1997), which were 2.6 – 40.7 kg ha^{-1}. They concluded that rye was a good N scavenger because N uptake increased with increasing N fertilizer rates for the previous corn crop.

In the current study, a strong relationship ($F = 6159.5$, $p<0.0001$) was found between biomass production and total N uptake (Figure 1-5), suggesting that higher amounts of biomass are needed in order to remove significant amounts of N in the fall. For instance, we found that approximately 300 kg of biomass per ha were needed to take up 10 kg N ha^{-1}. Only 16% of our 31 sites produced biomass greater than 300 kg ha^{-1} during the fall. In Ontario, broadcasted rye biomass also failed to accumulate this much dry matter in two out of three years (Ball-Coelho and Roy 1997). In Iowa, however, overseeded rye biomass averaged 410 kg ha^{-1} over three falls (Johnson et al. 1998), most likely due to a more favorable climate.

Germination Study

Water Potential vs. Moisture Content

At each water potential, the clay loam had the highest moisture content, and the sandy loam had the lowest (Figure 1-6). Fine-textured soils have more surface area and smaller pore-sizes, which allows water to bind more strongly to soil particles than a coarse-textured soil with larger pore-sizes and less surface area. Thus, it takes very little pressure to remove water from initially wet, coarse-textured soils, while greater pressure is needed to remove the same amount of water from wet, fine-textured soils (Campbell and Norman 1998). The reverse is true when the soils are dry.

Total Germination

The soil by moisture interaction was significant for total germination ($p<0.05$). Water potential did not affect germination for the clay or silt loam, but at -500 kPa, the sandy loam had less germination than the other treatments (Figure 1-7). This suggests that water potential may not be the main factor affecting germination of seeds broadcast on the soil surface, but that moisture content may play a larger role. Figure 1-8 shows total germination plotted against water potential (A.) and moisture content (B.) with their respective best-fit trend lines. Water potential only accounted for 13% of the variability ($R^2 = 0.13$) in the germination data, however, whereas moisture content accounted for 46% of the variability ($R^2=0.46$) indicating that the latter may have a stronger relationship with germination of seeds placed on the soil surface.

These findings are contrary to a well-documented theory that germination is driven by water potential (Hunter and Erickson 1952; Hadas and Russo 1974; Benech-Arnold and Sanchez 2004). Most of these studies, however, used seed that was buried in the soil with good seed to soil (and hence soil water-seed) contact. On the other hand, one study that germinated seeds on the surface of slate dust determined that in drier substrates moisture content appeared to be the limiting factor rather than water tension (Harper and

Benton 1966). Dasberg and Mendel (1971) found that the rate of water supply to the seed was a function of contact between the seed and soil while Hadas and Russo (1974) reported that seeds in coarse-textured soils have smaller relative wetted areas. These factors may help to explain our results. With the limited amount of soil contact the surface-applied seed had in the current study, it was more likely to be in contact with water in the clay than in the sand, regardless of the tension at which the water was held. Collis-George and Sands (1959) and Dasberg and Mendel (1971) argued that hydraulic conductivity may also play a large role in controlling germination rate since drier soils have less ability to transmit water to the seed. This is especially true of sandy soils which transmit water more slowly than clay soils under unsaturated conditions (Bouma and Denning 1972).

In this laboratory study, total germination was also significantly affected by temperature ($p<0.05$). As temperature increased, germination decreased with 90.4%, 82.6%, and 71.8% germination at 10°C, 18°C and 25°C, respectively. This was most likely due to a higher incidence of mold as temperatures increased (8.3%, 15.9%, and 23.4% of seeds became moldy on average at 10°C, 18°C and 25°C, respectively). Blackshaw (1991) reported a slight decrease in rye emergence as temperatures increased from 5-30°C, although germination did not decrease below 83%. The author did not report mold, suggesting that surface applications of seed are more likely to be compromised in this manner under laboratory conditions. Under field conditions, however, mold is not likely to be a concern.

Total Germination Model

A quadratic plateau model was used to describe the relationship between germination and moisture content ($R^2 = 0.46$) (Figure 1-8). The critical value (C.V.) was found at a moisture content of 0.083 g g^{-1} and is defined as the point above which germination is not affected by moisture content. Below this threshold, germination was drastically reduced following a quadratic decline:

$$G = -496.8 + 14046.1W - 84823.2W^2$$

where G is the total germination (%) and W is gravimetric moisture content. Below 0.051 g g^{-1} (5%) moisture content, germination will not occur.

One of the drawbacks of this model is that it only takes into account static soil moisture content at the soil surface. Most germination occurred within 2 d (data not shown) which under field conditions could be a small amount of time for the moisture status of the soil to change. However, the moisture at the soil surface is highly variable due to evaporation and precipitation (Hillel 1998). Future research should attempt to take into account changing soil moisture content over time in order for these simulations to apply to typical field conditions.

Germination Timing

The soil type by water potential interaction was significant ($p<0.05$) for the amount of time until 50% germination (TG_{50}) (Figure 1-9). At -50 kPa, TG_{50} was approximately 2 d in all soils. This was maintained at all moisture levels in the clay loam. A delay of 1.3 d in germination was found in the silt loam between -50 and -500 kPa tension, although these differences were not significant. In the sandy loam, decreasing water potential delayed germination by 1.9 and 6 d at -200 and -500 kPa, respectively. The differences across soil types at similar water potentials further demonstrates that moisture content and hydraulic conductivity may play a larger role in germination than water potentials, particularly when the seed has limited soil contact. When comparing fine sand to a “black earth” soil, Collis-George and Sands (1959) similarly found that the rate of seedling germination was reduced as soil tension increased.

Temperature also significantly affected TG_{50} ($p<0.05$), with values of 4.6, 2.8, and 3.1 d at 10°C, 18°C, and 25°C, respectively. Germination was delayed by 1.8 d when decreasing the temperature from 18°C to 10°C. A slight delay (0.3 d) was seen between 18°C and 25°C, but the difference was not significant. Wright et al. (1978) found that increasing the temperature from 21°C to 28°C generally decreased seedling emergence in a clayey soil, particularly at drier water potentials.

Some studies have documented that that emergence rate of seedlings was more influenced by temperature than soil moisture (Cutforth et al. 1985; Blackshaw 1991). In the current study, the opposite appeared to be true in the sandy loam, although the range of temperatures was not as large as in previous studies. Furthermore, Cutforth et al. (1985) found that soil moisture content influenced germination rate at high temperatures (30.5°C) but not at low temperatures (15°C). We did not find this to be the case since temperature effects were independent of the soil type by water potential interaction.

Conclusions

Under the conditions of this research, we found that precipitation within a week of aerial seeding is the most important factor in determining successful establishment of rye. However, since precipitation and soil moisture content were highly correlated, the latter variable may be important, as well. Additional factors such as light interception through the canopy and seed predators were not considered in the analysis, and may also play a role in establishment. A priority for research should be the characterization of cover crop seed predators and the testing of strategies to reduce seed losses.

Germination of rye on the soil surface under laboratory conditions was found to be driven by moisture content rather than water potential. A quadratic plateau model suggested that germination will decline rapidly below a moisture content of 0.083 g g^{-1} and will cease below 0.051 g g^{-1}. Germination timing was delayed only in the sandy loam at the lowest water potential, indicating that hydraulic conductivity may also play a role in germination of seeds on the soil surface. These findings suggest that overseeding onto coarse-textured soils should be avoided if there has not been a recent rainfall as these soils will dry out more rapidly and potentially delay or reduce germination.

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Table 1-1. Dates for aerial seeding and biomass sampling at 31 on-farm locations in southeastern MN.

	Aerial Seeding			**Rye Biomass Collection**		
County	**2009**	**2010**	**2011**	**2009**	**2010**	**2011**
Dakota	9-Sep	--	15-Sep	4-Dec	--	21-Nov
Fillmore	17-Aug	1-Sep	15-Sep	1-Dec	19-Nov	21-Nov
Goodhue	28-Aug	1-Sep	--	4-Dec	19-Nov	--
Olmsted	28-Aug	1-Sep	15-Sep	4-Dec	19-Nov	21-Nov
Winona	--	1-Sep	--	--	19-Nov	--

Table 1-2. Average monthly weather conditions in southeastern MN compared with the 30-yr mean[1].

	Precipitation, cm				Temperatures, °C			
	2009	2010	2011	30-yr Normals	2009	2010	2011	30-yr Normals
Dakota Co.								
Sep	1.5	16.1	1.5	8.9	17.6	14.8	16.0	21.4
Oct	15.5	4.7	1.5	6.4	5.6	11.1	11.8	15.1
Nov	1.4	6.0	1.1	5.9	4.9	0.8	3.0	4.2
Dec	5.8	6.2	2.3	2.9	-8.9	-10.4	-3.7	-4.1
Olmsted Co.								
Sep	2.7	27.1	5.6	7.9	17.0	15.3	15.2	20.7
Oct	16.4	1.6	0.7	5.6	5.9	11.4	11.7	13.8
Nov	1.3	6.9	0.7	5.1	6.0	1.8	3.6	3.7
Dec	5.6	4.1	1.7	2.6	-8.5	-9.6	-3.3	-4.2
Fillmore Co.								
Sep	4.1	23.1	6.7	9.1	16.8	15.3	15.2	22.4
Oct	17.2	2.6	1.4	5.9	6.1	10.3	11.0	15.8
Nov	1.1	6.7	1.6	5.4	5.0	1.7	3.1	5.7
Dec	6.9	8.4	3.2	3.3	-8.3	-9.4	-3.5	-2.2

[1] Average for the 30-year period from 1971 - 2000.

Table 1-3. Characterization of soil sampled from multiple sites in southeastern MN. Samples were collected in standing corn or soybeans.

	Soil Moisture (0-4 cm)		**Soil (0-15 cm)**							**Surface**
	0 d	**5-7 d**	**NH_4+NO_3**	**pH**	**P**	**K**	**Organic Matter**	**Total N**	**Total C**	**Residue Cover**
Field Study	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(ppm)		(ppm)	(ppm)	(%)	(%)	(%)	(%)
2009										
Corn	22.0 ± 5.4	19.3 ± 5.6	32.9 ± 32.4	6.8 ± 0.6	72.7 ± 73.0	191.2 ± 197.8	3.7 ± 1.0	0.18 ± 0.05	2.0 ± 0.6	26.8 ± 16.6
2010										
Corn	28.7 ± 5.9	26.1 ± 5.6	19.7 ± 15.3	7.4 ± 0.2	39.0 ± 13.7	126.2 ± 64.5	3.5 ± 0.4	0.17 ± 0.02	1.9 ± 0.4	25.6 ± 8.5
Soybean	34.8 ± 1.8	29.3 ± 3.7	7.9 ± 2.1	6.9 ± 0.4	38.0 ± 34.1	122.8 ± 40.7	3.3 ± 0.8	0.15 ± 0.04	1.5 ± 0.5	--
2011										
Soybean	14.3 ± 5.7	22.4 ± 9.6	7.7 ± 2.5	6.7 ± 0.4	41.8 ± 59.7	79.4 ± 15.5	3.0 ± 0.9	0.14 ± 0.05	1.5 ± 0.4	--
Germination Study										
Sandy Loam	--	--	30.3	6.3	58.5	155.0	2.1	0.11	1.3	--
Silt Loam	--	--	5.6	7.6	45.0	126.0	3.9	0.16	2.1	--
Clay Loam	--	--	12.2	7.9	18.5	300.0	4.6	0.19	2.8	--

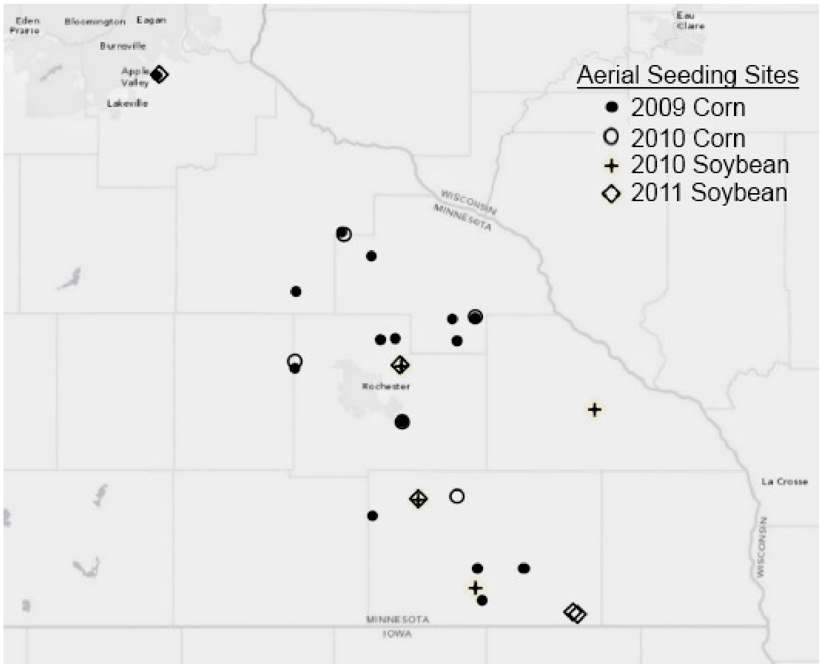

Figure 1-1. Aerial seeding site locations in southeastern Minnesota in 2009, 2010, and 2011. Winter rye was aerially seeded into standing corn or soybean fields.

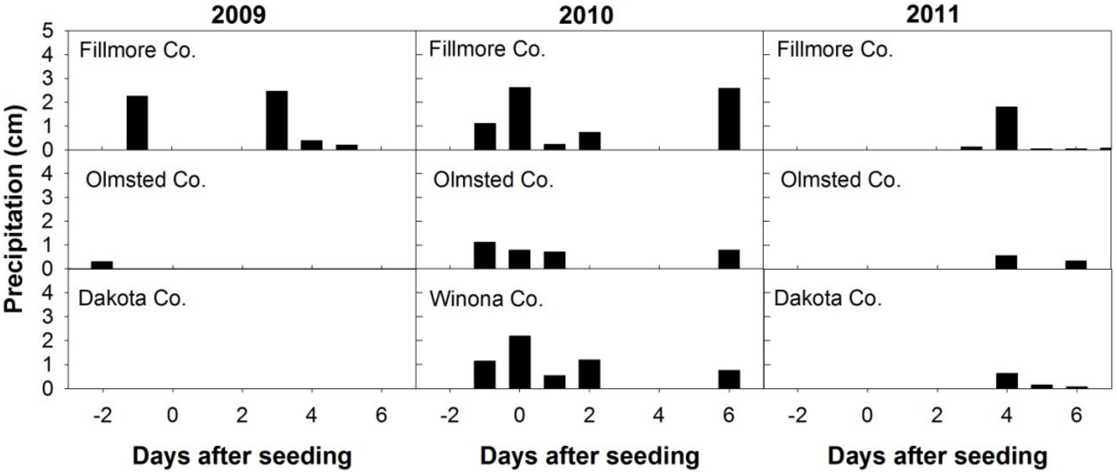

Figure 1-2. Daily precipitation 2 d prior to and 7 d after aerially seeding winter rye during the early fall in 2009, 2010, and 2011. The majority of sites were located in the southeastern MN counties shown each year.

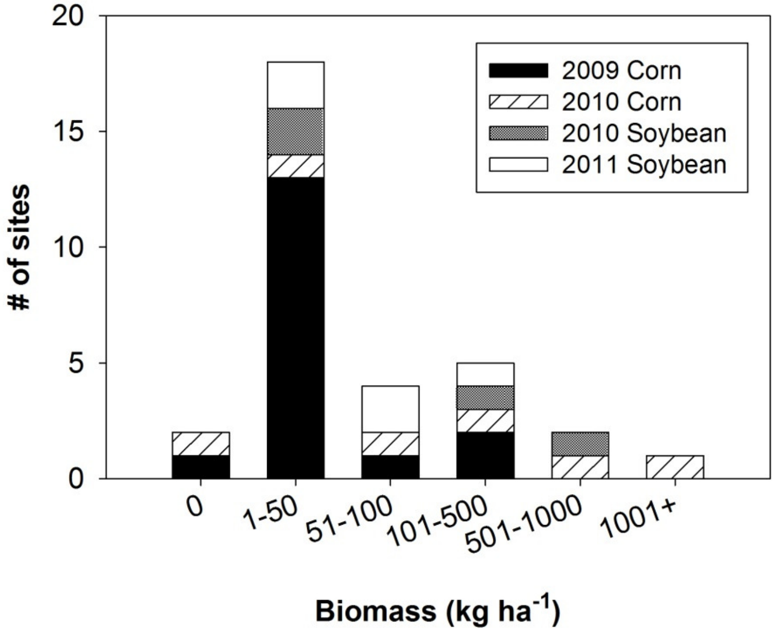

Figure 1-3. The number of sites with specified amounts of above-ground winter rye biomass collected in fall after corn in 2009 and 2010 and soybeans in 2010 and 2011.

Figure 1-4. Visual evidence of seed predation under a standing soybean canopy.

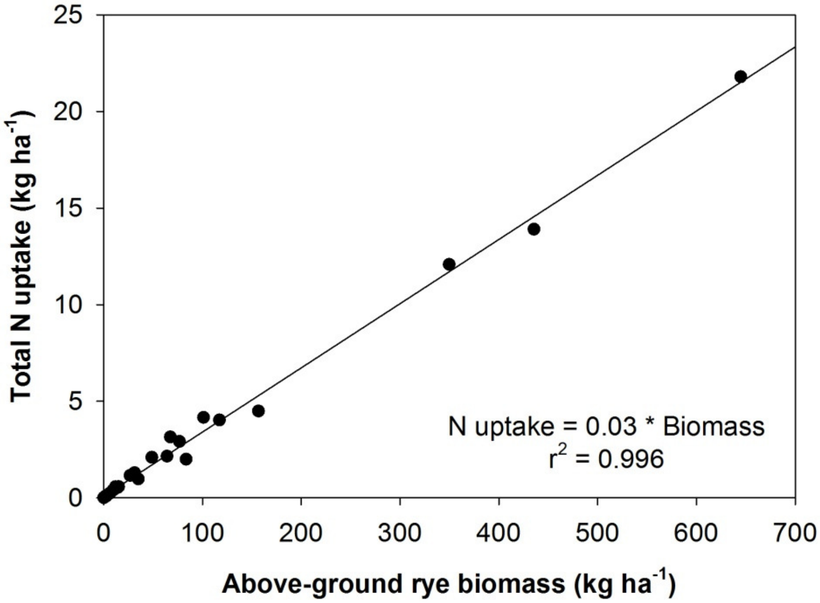

Figure 1-5. Above-ground winter rye biomass as related to total N uptake. Rye biomass was collected in the fall.

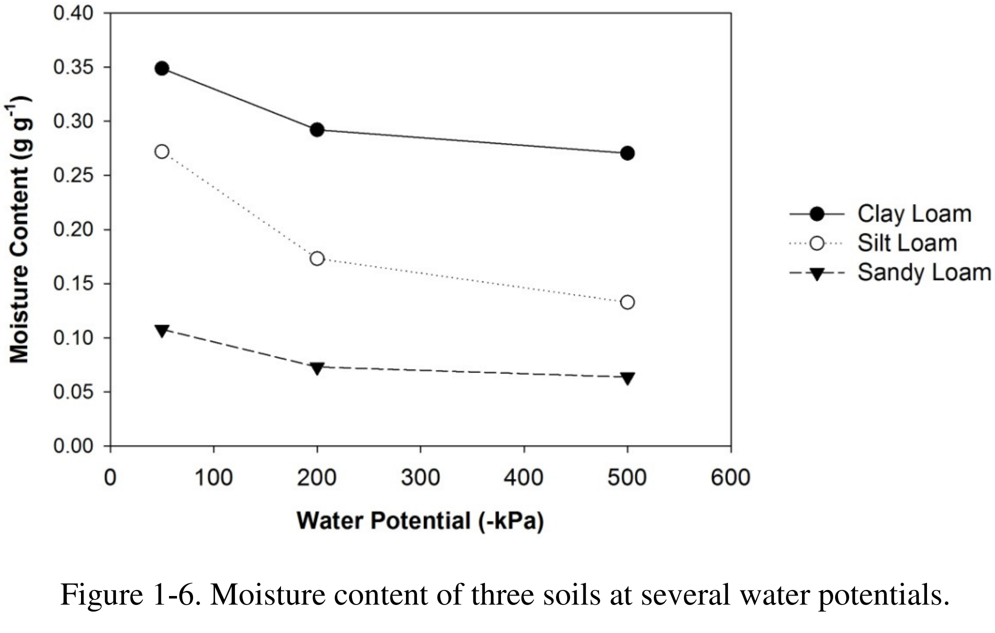

Figure 1-6. Moisture content of three soils at several water potentials.

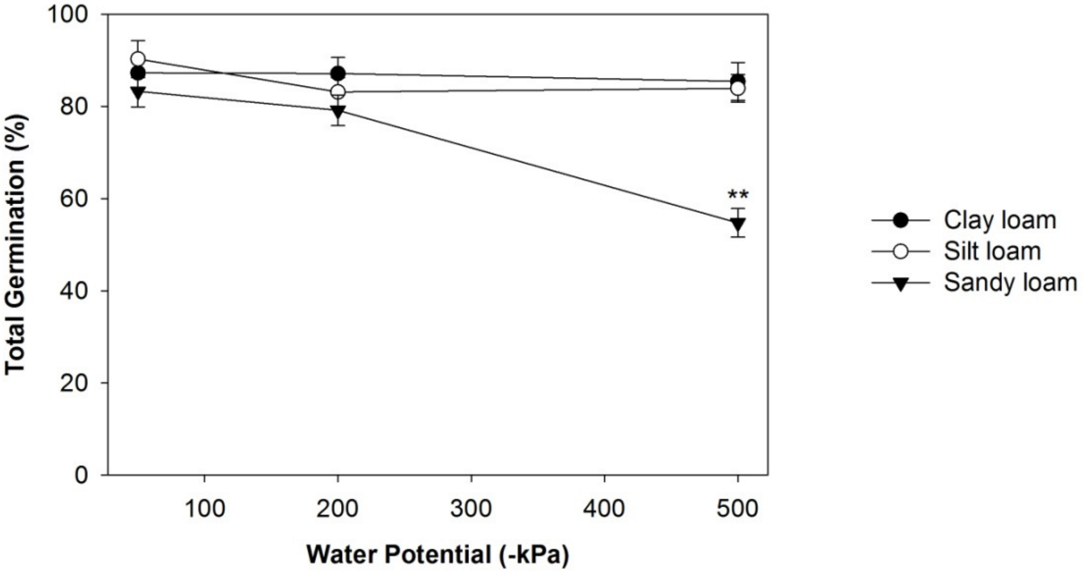

Figure 1-7. Average total germination (and standard errors) as affected by water potential on the surface of three soils. The ** represents a significant difference ($p<0.05$) from all other points.

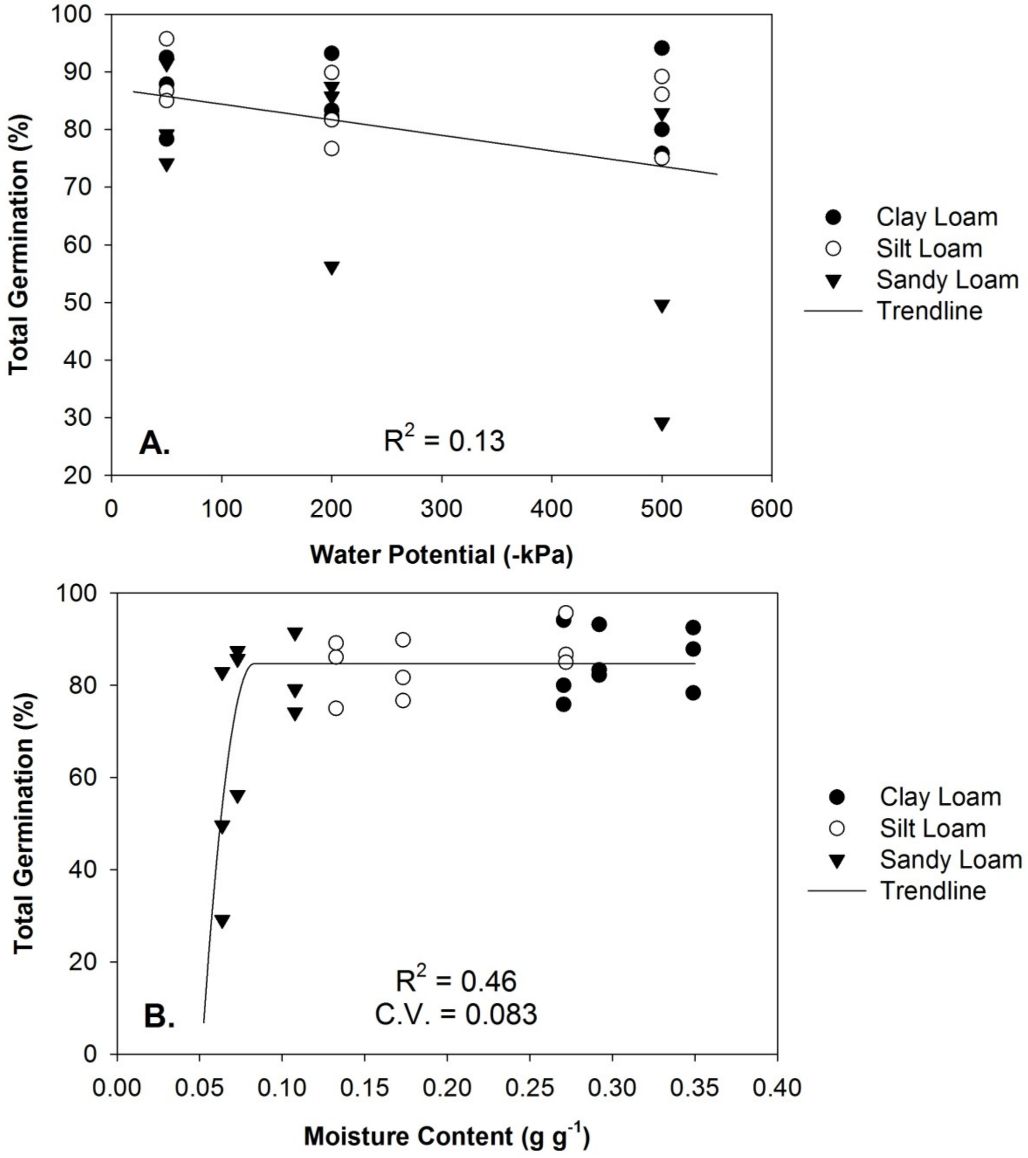

Figure 1-8. Total germination on the surface of three different soils as a function of (A.) water potential and (B.) moisture content with their respective trendlines. The C.V. in part B is the critical moisture value below which germination is affected.

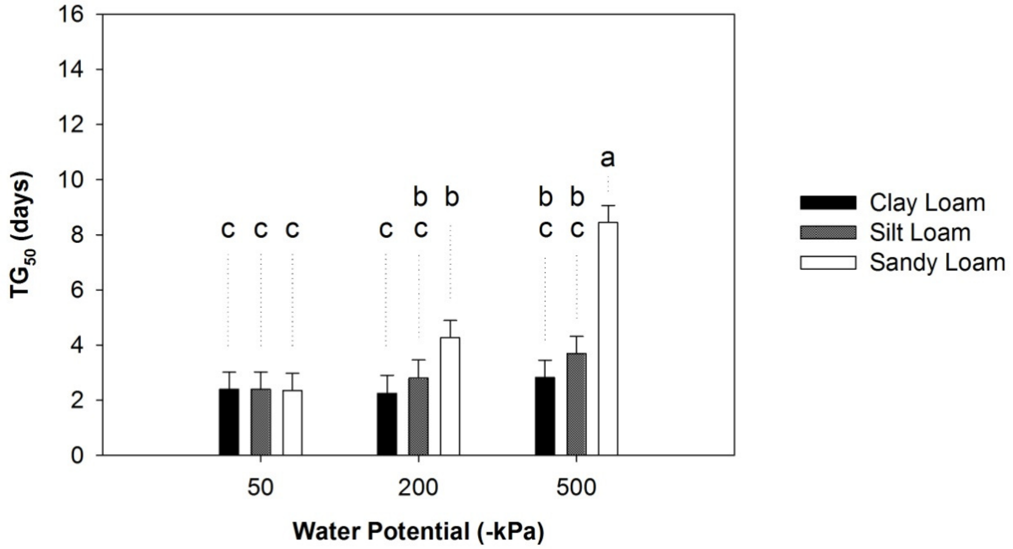

Figure 1-9. The time until 50% germination (TG50) as affected by water potential and soil type. Bars with the same letter above are not considered significantly different ($p>0.05$).

Chapter 2 - A comparison of methods for overseeding winter rye into standing soybeans in the Upper Midwest

Incorporating cover crops in the corn-soybean rotation is one way to improve soil quality over time and reduce nitrogen and erosion losses. In the Upper Midwest, however, establishing cover crops after harvest of the main crop can be difficult due to the short growing season. Overseeding prior to harvest may allow more time for growth. This study was conducted in 2010 and 2011 to evaluate three winter rye overseeding techniques for standing soybeans: aerial seeding (AS), tractor-mounted air-flow spreader (TAF), and tractor-mounted fertilizer broadcast spreader (TBS). The experimental design was randomized complete blocks with treatments applied in early to mid-September at Rosemount Research and Outreach Center in Rosemount, MN. Seeding density, soybean yields, spring above-ground biomass, nitrogen uptake, and soil moisture were characterized each year. Fall biomass production was only evaluated in 2011 due to an early snowfall in 2010. Seeding density in the AS treatment was the lowest and was the least variable across rows while the TBS treatment was the most variable but tended to have the highest density. This led to significant ($p<0.05$) above-ground rye biomass differences in the fall of 2011 with 2.6, 12.3, and 17.5 kg ha^{-1} produced for the AS, TAF and TBS treatments, respectively. Spring biomass totals, averaged over both years, were not different with values ranging from 226 to 319 kg ha^{-1}. Nitrogen uptake followed a similar pattern, with differences in the fall (0.1, 0.4, and 0.6 kg N ha^{-1} for the AS, TAF, and TBS treatments, respectively) but not in the spring (ranges from 8.6 - 11.7 kg N ha^{-1}). Soybean yields after seeding and soil moisture in the fall and spring were not different across application methods. Although not part of the experimental design, rye drilled after harvest in the same fields, by comparison, tended to have lower biomass accumulation in spring.

Introduction

During the last few decades, the two-year corn-soybean rotation has become the dominant agricultural land use in the Upper Midwest (Randall 2003; Karlen 2004). This occurred mainly to keep up with demand as acreage in the southern United States declined, but also because of increased food and industrial uses for the two crops (Hart 2006; Karlen et al. 2006). Currently, the United States exports 20% of its corn (*Zea mays* L.) and 54% of its soybean (*Glycine max* L.) crops each year, making the country important in the world trade market (USDA 2010a,b). While it is clear that this particular cropping system has many societal and economic benefits, recent research has found that this practice may degrade soil quality over time (Karlen et al. 2006) and will potentially contribute to the significant loss of nitrate-nitrogen (NO_3-N) to ground and surface waters (Dinnes et al. 2002; Oquist et al. 2007). It has been reported that the Upper Mississippi River Basin contributes almost 40% of the total nitrogen (N) flux to the Mississippi River which in turn contributes to hypoxia in the Gulf of Mexico (Aulenbach 2007). With the increased demand for bio-fuels, millions of acres of retired farmland are likely to return to crop production (Collins 2006), thereby increasing the negative effects of such an intensive cropping system. If the nation intends to meet these growing demands while safeguarding its natural resources, alternative management practices must be incorporated into the farming system to reduce NO_3 leaching while maintaining productivity.

One solution for reducing NO_3 loss is the use of cover crops during the off-season, which can increase the amount of time the land is covered in growing vegetation. Cover crops function as catch crops by removing inorganic N from the soil profile, including residual N fertilizer from the previous crop, and holding it in organic form (Dinnes et al. 2002). The following spring the bound N is slowly released to the subsequent crop as the cover crop residue decomposes (Ruffo and Bollero 2003). After long-term use of this practice, corn yields have been shown to increase (Ball-Coelho and Roy 1997; Ball-Coelho et al. 2005) while soybean yields have been maintained or increased with proper management techniques (Moore et al. 1994; Ruffo et al. 2004; Strock et al. 2004).

Although many crops have been studied for potential use as a cover crop, cereal rye (*Secale cereale* L.) particularly has been shown to reduce nitrate leaching (Ditsch et al. 1993; McCracken et al. 1994; Strock et al. 2004; Fisher et al. 2011). Meisinger et al. (1990) reported that legumes such as hairy vetch and crimson clover also have the ability to take up residual N fertilizer but cereals were superior. Further advantages of rye include an increase in soil organic matter, reduction of soil erosion, improved soil structure (Snapp et al. 2005) and suppression of weeds (Barnes and Putnam 1983; Leibl et al. 1992; De Bruin et al. 2005). In addition, rye is especially useful for northern climates because it is cold tolerant and easy to establish (Dabney et al. 2001).

Even though cover crop benefits have been long known (Odland and Knoblauch 1938; Beale et al. 1955), implementation of this practice has been minimal, particularly in the Upper Midwest. In Minnesota, only 4% of farmers reported currently using cover crops, while participation ranged from 7% to 26% in Illinois, Iowa, Nebraska, and Ohio (CTIC 2010). The main barrier to cover crop use in Minnesota was listed as the short growing season (CTIC 2010). In their winter cover crop meta-analysis, Miguez and Bollero (2005) also concluded that grass cover crops in the north-central U.S. would have only marginal benefits. Based on average weather patterns in southwestern Minnesota, Strock et al. (2004) suggested that rye would be a successful cover crop in 25% of years. In these studies, however, temperatures were already cool when rye was planted after harvest of the preceding crop.

One solution is to extend the growing season by broadcasting cover crops into the standing cash crop. This has been shown to result in earlier crop growth than drilling the seed after harvest (Frye et al. 1988) and is especially useful in soybeans, which leave minimal residue on the ground over winter. Two main broadcast methods are currently in use: aerial seeding via helicopter or fixed-wing aircraft and a spreader mounted to a high-clearance vehicle or tractor. Both have advantages and disadvantages. Aerial seeding keeps heavy machinery out of the field and is typically faster. Robison (2011) reported that, in Indiana, aerial applicators can seed up to 81 ha per hour, while a highboy can only seed 4-5 ha per hour. On the other hand, aerial seeding is not consistently uniform and cost of application can vary greatly (Wilson 2012). Broadcasting seed via high-clearance vehicle may provide more consistency across the field and may be done with equipment already on hand or through rentals from a local cooperative. However, this method tends to be slower, requires the use of heavy equipment in the field, and may damage the standing crop. These seeding techniques have not been evaluated against one another. The objectives of this study were to: 1.) compare the seeding consistency and rye biomass yields when using aerial seeding versus a tractor-mounted airflow spreader and a tractor-mounted fertilizer bucket spreader; 2.) determine whether soybean yields would decrease due to damage from the tractor; and 3.) characterize the amount of soil nitrogen removed by the rye.

Methods and Materials

This study was initiated during two fall seasons (2010 and 2011) in two soybean fields at the University of Minnesota's Rosemount Research and Outreach Center near Rosemount, MN. The soil at both sites is predominantly Waukegan silt loam (fine-silty over sandy, mixed mesic Typic Hapludoll) with 0-1% slopes. Both fields are farmed in a conventionally tilled corn and soybean rotation, and were planted in 'Northrup King' soybeans the year of seeding with 0.76 m row spacing. Representative soil samples from 0-15 cm were collected on the day of seeding for routine soil tests (Brown 1998), and KCl extractable NO_3-N and ammonium-N (NH_4-N) were also determined (Table 2-1). Precipitation and temperature were measured continuously at a weather station located within 3 km.

Seeding treatments were replicated three times in 2010 and four times in 2011 in a randomized complete block design. The treatments were: aerial seeding (AS), tractor-mounted air-flow spreader (TAF), and tractor-mounted bucket spreader (TBS). Each method was calibrated to seed 112 kg ha^{-1} (341 seeds m^{-2}) of uncertified 'Rymin' winter rye. For the AS treatment, seed was applied on 9 Sep 2010 and 15 Sep 2011 with a modified bucket spreader attached to a helicopter. For the TAF and TBS treatments, seed was applied on 14 Sep 2010 and 19 Sep 2011 when the soybeans had dropped approximately 50% of their leaves. We used a tractor modified for a row-crop system with narrow tires and 0.6 m clearance. A Gandy Orbit-Air applicator (Owatonna, MN) spread seeds over 12 rows (9.1 m) with separate spreaders in each row for the TAF treatment while a bucket fertilizer spreader with spinning plate was used in the TBS treatment to broadcast seed to approximately 9.8 m width. Seeded plots were 9.1 m by 402 m (0.37 ha) in 2010 and 9.1 m by 487 m (0.44 ha) in 2011. All samples, except the soybean yields, were collected from a 9.1 m by 21 m (0.19 ha) area within the larger plots. Additionally, four replicates of rye were drilled at 90 kg ha^{-1} with a grain drill on 14 Oct 2010 and 18 Oct 2011 after soybean harvest. These plots were not originally part of the experimental design and were not considered in the statistical analyses but were used as a general comparison to overseeding.

Measurements throughout the fall and following spring in both years included soil moisture, seed density, and soybean grain yield. Soil moisture from 0-6 cm was measured with a Dynamax TH_2O Soil Moisture Meter (Houston, TX) within 3 d of soybean harvest in the fall. In the spring, soil moisture was determined on 29 Apr 2010 and 5 Apr 2011. The earlier date in 2011 was due to an earlier than normal planting date of the following crop. Additionally, we measured soil moisture of non-seeded areas during both falls and in spring 2011 to determine whether surface soil moisture was depleted or conserved. Rye seed density was characterized by counting the number of seeds in a known area (0.25 m^2) on 16 Sep 2010 and 21 Sep 2011. In each plot, seeds were counted twice, approximately 12.7 m apart, and averaged. This was done once between every other soybean row for six counts per plot in 2010 and five counts per plot in 2011 to determine the variability of each seeding method. Soybean grain yields were harvested from each larger plot on 12 Oct 2010 and 17 Oct 2011 to determine the extent of damage, if any, during overseeding with a tractor. This assumes the helicopter, which flew approximately 15m above the canopy, did not also damage the standing soybeans.

In order to estimate cumulative rye growth in the fall and spring, rye biomass was collected on 5 Apr 2011, 21 Nov 2011, and 5 Apr 2012. Fall biomass samples were not collected in 2010 due to an early heavy snowfall that covered the plants. Rye was clipped at the soil surface in three 0.25 m^2 quadrats and combined into one sample in the fall. For the spring biomass determination, subsamples were collected at one quarter (1Q), one half (2Q) and three quarters (3Q) of the plot width to characterize variability across the application pathway. Two quadrats approximately 12.7 m apart were collected and combined for each subsample. Plant biomass was dried at 60°C, weighed to determine dry matter yields, and then ground with a Wiley mill to pass through a 2-mm screen. Total N in ground samples was determined with a combustion analyzer (Vario EL CNS Analyzer or vario Max CN Analyzer, Elementar Analysensysteme, GmbH, Haunau, Germany) following the methods of Horneck and Miller (1998). Total N uptake was calculated as the product of dry matter yields and percent N in plant biomass, and then averaged for each plot.

Data from the study were analyzed using PROC MIXED (SAS Institute Inc. 2010) with replications and years considered as random variables. Subsamples were considered as repeated measures for the seeding density and spring above-ground rye biomass analyses. All interactions that included "year" were assessed by year-specific inference using best linear unbiased predictors (BLUPs) as described by Littell et al. (2006). When appropriate, treatment means were compared using the least-square means (SAS Institute Inc. 2010). Interactions and main effects were considered significant at $p \leq 0.05$.

Results and Discussion

Weather – Average precipitation and temperature for each cover crop season are compared with the 30-year normal in Table 2-2. During the 2010/2011 season, fall (Sep – Nov) and winter (Dec – Feb) temperatures were near average, while the spring tended to be cooler. Fall and spring were wetter than average, especially in Sep and Apr. The 2011/2012 season was warmer than normal, especially between Nov and Mar. The fall was particularly dry with a deficit of 14.7 cm below the 30-yr normal from Sep – Nov. The winter and spring received average precipitation.

A precipitation event near the seeding date is essential for establishing an overseeded cover crop. Wilson (2012) reported that rainfall within a week of seeding was the most important factor in predicting fall biomass production of winter rye in southeastern MN. In fall 2010, there was 2.1 cm of rain within 7 d of the AS treatment and 4.7 cm of rain within 7 d of the TAF and TBS treatments. Conditions were drier in 2011 with all three treatments receiving only 0.75 cm of rain.

Seeding Densities – Statistical analysis of seeding density revealed a significant three-way interaction between rows sampled, treatments and years (Figure 2-1). The TAF treatment tended to have more seeds per square meter than the AS treatment, although differences were not significant in either year with the exception of row 6 in 2011. The TBS treatment tended to have more seeds than the TAF treatment, but differences were only significant in rows 3, 5, and 9 in 2010. In 2011, differences were more complicated. Row 6 in the TAF treatment was not different from any TBS row while rows 2, 4, 8, and 10 in the TBS treatment were higher in seed count than rows 8 and 10 in the TAF treatment. In 2010, the seeding density in the TBS treatment was higher than with the AS treatment in all rows. A similar pattern was seen in 2011 except row 6 in the TBS treatment was not different than the rows in AS treatment.

The AS treatment resulted in the least variability (no differences) across rows in both 2010 and 2011 while the TAF treatment was more variable in 2011 compared with 2010 due to row 6 having more seeds per square meter than rows 8 and 10. This suggests that the TAF spreader seeded more heavily down the center of the plot in 2011 compared with 2010. It is unclear why this happened in one year and not the other. The TBS treatment was the most variable in both years. In 2010, rows 3 and 9 had more seeds than rows 7 and 11. In 2011, the TBS treatment spread seeds more heavily to the left and right of the plot compared with the center, which had fewer seeds per unit area. Contrary to these findings, Barnett and Comeau (1980) reported that oat, wheat, and barley seeds were spread more unevenly with an aerial applicator than a fertilizer spreader. The authors suggested that airplane drag and wind may have caused the high degree of variability. In another study, Wilson (2012) found that aerial seeding was highly variable across multiple field sites with seeding rates of 77.9 ± 44.0 kg ha^{-1} (the goal was to seed at 112 kg ha^{-1}). In the present study, we characterized the seeding density variability of a single pass of a helicopter, although most agricultural fields are large enough to require multiple passes. In Indiana, one aerial applicator left 24 m gaps in seeding across multiple fields as a result of not knowing the width of the spread pattern (Robison 2010) which can be affected by aircraft height, wind, and weight of the seed. Broadcasting from a tractor-mounted spreader may be more precise across a whole field because seeds are less affected by these characteristics, but more research is needed to characterize whole-field applications.

While the AS and TAF treatments were the least variable, they also tended to have the lowest seeding densities. All three treatments were calibrated to distribute 341 seeds m^{-2}, yet only the TBS treatment averaged this value in both years. Seeds were observed beyond the plot boundaries in the AS treatment, which suggests the spread pattern was wider than expected. The pilot typically accounts for overlap when seeding, but our experimental units required only one pass of the helicopter which may account for the lower seeding density than expected. It is unclear why the TAF treatment seeded rye at a lower rate than expected. Higher seeding densities are important for increased biomass production (Boyd et al. 2009), although increased tillering and individual plant growth may occur when lower seeding densities result in reduced competition with other plants (Ball 1986).

Soybean Yield - The treatment by year interaction was not significant, though soybean yields in 2010 (3.33 ± 0.07 Mg ha^{-1}) were significantly higher than yields in 2011 (1.88 ± 0.07 Mg ha^{-1}). This was most likely due to drier than average conditions in August (data not shown) and September 2011. The winter rye application method did not affect soybean yields (Figure 2-2). Assuming that the helicopter did not damage the soybeans in the AS treatment, driving the tractor through the plots in the TAF and TBS treatments did no appreciable damage to the standing crop. Similarly, Johnson et al. (1998) and Smith and Kallenbach (2006) reported no soybean yield losses using a modified drop seeder for overseeding cereal rye and annual ryegrass. These authors, as well as Hively and Cox

(2001), concluded that overseeded rye did not compete with the soybeans for moisture and nutrients and did not interfere with the main crop harvest. In this study, rye plants were not tall enough to be cut by the combine and thus did not interfere with soybean harvest.

Rye Biomass – Rye biomass production was affected by application method in Fall 2011 (Table 2-3). The AS treatment resulted in the lowest fall growth and was less than with the TBS treatment. The TAF treatment produced an intermediate amount of rye biomass and was not different than the other treatments. This pattern directly corresponds with seeding densities found earlier in the fall, illustrating the importance of seed coverage for sufficient biomass production. The amounts of biomass accumulated were within the ranges reported by Wilson (2012) for helicopter seeding of rye into corn and soybeans during the fall of 2011 in southeastern Minnesota. The biomass values in both studies were lower than those reported in Iowa, however, where the average biomass for rye overseeded into soybeans was 410 kg ha^{-1} (Johnson et al. 1998). Iowa has a warmer climate and longer fall growing season than Minnesota, the likely cause of the higher amount of biomass.

Spring rye biomass was not affected by treatments or subsample location (Table 2-3), nor were there any significant interactions. There were differences between years, however, with 2010 having more biomass than 2011. This was likely due to the more favorable moisture conditions during fall 2010 and spring 2011. In New York, Hively and Cox (2001) reported 200 kg ha^{-1} of rye biomass in one of two years of their study. Rye in that study was broadcast after soybean harvest and failed to establish in the second year. In Iowa, rye biomass accumulated 1870 kg ha^{-1} by early May (Johnson et al. 1998). Even though that study had an additional month of growth, our spring biomass was well below their reported fall biomass.

Application method affected fall biomass production, but not spring accumulation (Table 2-3). This suggests that rye in the AS and TAF treatments, which had the lowest biomass in the fall, were able to increase spring production, possibly due to lack of competition from other rye plants. Boyd et al. (2009) reported that spring rye biomass was unaffected by seeding rate and attributed it to compensatory growth through increased tillering. Other studies have also found that cereal tillering is typically reduced by increased seeding rate (Peltonen-Sainio et al. 2002; Venuto et al. 2004). Although this aspect was not characterized in this experiment, it may explain the trend seen in the data.

Overseeded rye tended to produce more biomass than rye that was drilled after soybean harvest (Table 2-3), but the lack of a statistical comparison makes it difficult to make any definitive conclusions about the two planting methods. Other studies have presented similar findings. Feyereisen et al. (2006) predicted through modeling that rye planted in mid-September would produce two times the amount of biomass compared with rye planted one month later. Under the conditions of this study, the overseeded treatments appeared to produce over 20 times the amount of drilled biomass. Frye et al. (1988) also concluded that broadcasting seed into a standing crop allows more time for growth than waiting until harvest to drill the seed. However, if overseeding is not possible until nearly harvest, it may not be as beneficial. Fisher et al. (2011) reported seedling emergence was more reliable with drilled rye than with broadcast rye when planted on the same day. During a drier than normal year in that study, seedlings in the drilled treatments appeared within 7 d of seeding while it took a significant rain event 28 d later to germinate the surface-broadcast seed. This illustrates the importance of timely precipitation after overseeding for successful establishment. Seeding earlier in the fall increases the chances of receiving adequate rainfall while temperatures are still warm.

N Uptake – The N concentration of rye tissue was not affected by application method in the fall of 2011, but differences in total N uptake were significant (Table 2-3). Both biomass production and N uptake showed a similar trend, with the AS treatment having the lowest biomass and N uptake while the TBS treatment had the highest, suggesting that N uptake was mostly determined by biomass production in the fall. Similarly, a Canadian study found that N uptake was highest in years with the most biomass production of rye overseeded into corn (Ball-Coelho and Roy 1997).

Nitrogen concentration of spring biomass was also not different across treatments, nor were there any significant interactions. In 2010, biomass N concentration was significantly lower than in 2011 (Table 2-3). Seeding densities were similar across years for each treatment, but biomass production was lower in the second year, suggesting the C:N ratio increased as total biomass increased. Wagger (1989) and Clark et al. (1994) also found the C:N ratio of rye to increase as biomass production increased.

Application treatments did not affect total N uptake in the spring, and there were no significant interactions. Total N uptake varied between years, with rye in 2010 taking up more N than in 2011 as a result of increased biomass production. These values were similar to the ranges found in other studies. In Maryland, N uptake from overseeded rye ranged from 3.4 to 39.5 kg ha^{-1} (Fisher et al. 2011), while rye broadcast after soybean harvest in New York took up approximately 4 kg N ha^{-1} (Hively and Cox 2001). These values were similar to N uptake from rye drilled after harvest. Kessavalou and Walters (1999) reported N accumulations ranging from 9 to 60 kg ha^{-1} after soybeans in Nebraska. Nitrogen uptake from drilled rye in the current study was much lower than these values (Table 2-3). This suggests that at more northern locations in the corn/soybean belt, overseeded rye has the potential to scavenge more N than rye drilled after harvest, providing an important environmental service.

Soil Moisture – There were no treatment or year differences in surface soil moisture post-soybean harvest in the fall and no significant treatment by year interaction (Table 2-4). Soil moisture was generally low in both years. Observationally, the areas without overseeded rye had similar average moisture contents, suggesting that neither moisture depletion nor conservation had occurred by this date. Apparently the minimal fall rye growth was insufficient to influence soil moisture conditions.

Spring soil moisture contents for each year were analyzed separately because of the difference in sampling dates. There were no treatment differences in either year (Table 2-4), consistent with the similar amounts of biomass production across application methods. In 2011, we observed that moisture content was similar between rye seeding treatments and areas with no rye, which indicates that soil moisture depletion would not have been an issue for the following crop. Johnson et al. (1998) reported corn yield reductions following rye, but concluded that soil moisture depletion was not the cause.

However, rye killed in late May influenced soil moisture at 30-60 cm depth in one dry year of a two-year study in Minnesota (De Bruin et al. 2005), and it is generally accepted that timely methods for controlling rye are necessary to minimize impacts on the following crop.

Conclusions

In this study, winter rye was successfully overseeded into standing soybeans using three different techniques. Aerial application tended to seed at a lower density than tractor-mounted methods of broadcasting which lowered fall rye biomass production. By the spring sampling date, however, above-ground biomass accumulation was unaffected by application method, suggesting that compensatory growth had occurred. Similarly, N uptake was lower in the AS treatment than with the TBS treatment in the fall, but was not different from the other treatments by the spring. This may indicate that a lower seeding rate could be used to produce similar amounts of rye biomass in spring. Our findings in a concurrent study suggest that seed predation may limit rye establishment in some fields, however (Wilson 2012), so a higher seeding rate is still suggested.

Rye that was drilled after soybean harvest was not included in the statistical analyses, but tended to have lower biomass and less N uptake than overseeded rye. Under the conditions of this study, overseeding rye into a standing crop may have allowed more time for fall growth and potentially provided an important environmental service by taking up excess nitrogen although some studies have suggested that drilling rye after harvest may be more reliable (Hively and Cox 2001; Fisher et al. 2011). These observations along with mixed results in the literature suggest that further research is needed.

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Table 2-1. Soil properties before seeding at Rosemount Research and Outreach Center, near Rosemount, MN.

	0-15 cm					
Year	pH	Bray-P	Organic Matter	K†	NO_3^--N†	NH_4^+-N†
		mg kg^{-1}	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
2010	5.5	9.0	4.5	89.0	4.6	3.4
2011	7.3	147.0	3.9	98.0	3.8	2.3

†Extractable

Table 2-2. Average monthly weather conditions at Rosemount Research and Outreach Center, near Rosemount, MN compared with the 30-yr mean[†].

	Precipitation (cm)			Temperature (°C)		
	2010 - 2011	2011 - 2012	30-yr Normals	2010 - 2011	2011 - 2012	30-yr Normals
Sep	14.4	1.4	7.7	14.8	16.0	15.5
Oct	2.8	1.4	5.5	11.1	11.8	9.0
Nov	6.0	1.0	5.1	0.8	3.0	-0.6
Dec	3.5	2.1	2.5	-10.4	-3.7	-8.9
Jan	1.1	0.8	2.7	-12.8	-6.1	-12.2
Feb	3.2	4.2	1.9	-9.1	-3.3	-8.3
Mar	5.1	4.3	5.0	-3.4	8.1	-0.9
Apr	18.9	8.0	6.3	6.7	8.9	7.4
Fall (Sep - Nov)	23.3	3.7	18.4	8.9	10.3	8.0
Winter (Dec - Feb)	7.8	7.1	7.1	-10.8	-4.4	-9.8
Spring (Mar - Apr)	24.0	12.3	11.3	1.6	8.5	3.2

†Average for the 30-year period from 1971 - 2000.

Table 2-3. Above-ground biomass production, N concentration, and total N uptake of winter rye overseeded into soybeans near Rosemount, MN.

Effect	Above-ground Rye Biomass†		N Concentration†		Total N Uptake†	
	kg ha^{-1}		g kg^{-1}		kg ha^{-1}	
Fall 2011						
Treatment‡						
AS	2.6 ± 3.2	b	40.7 ± 1.8	a	0.1 ± 0.1	b
TAF	12.3 ± 3.2	ab	35.6 ± 1.8	a	0.4 ± 0.1	ab
TBS	17.5 ± 3.2	a	34.7 ± 1.8	a	0.6 ± 0.1	a
Spring §						
Treatment						
AS	226.2 ± 154.1	a	44.7 ± 7.9	a	8.6 ± 4.8	a
TAF	270.4 ± 154.1	a	41.3 ± 7.9	a	11.0 ± 4.8	a
TBS	319.7 ± 154.0	a	40.5 ± 7.9	a	11.7 ± 4.8	a
Drilled¶	10.1 ± 7.1		50.0 ± 4.7		0.5 ± 0.4	
Subsample#						
1Q	281.4 ± 151.4	a	--		--	
2Q	264.6 ± 151.5	a	--		--	
3Q	270.2 ± 151.5	a	--		--	
Year						
2010	416.8 ± 47.9	a	34.5 ± 1.4	b	14.7 ± 1.9	a
2011	127.3 ± 42.6	b	49.9 ± 1.3	a	6.2 ± 1.7	b

†Means with the same letter within columns and effect-sampling-date are not significantly different ($p > 0.05$)

‡AS, TAF, and TBS are aerial seeding, tractor-mounted airflow spreader, and tractor-mounted bucket spreader, respectively

§Data averaged over 2010 and 2011

¶Not included in the statistical analysis

#Subsamples collected at 1/4 plot width (1Q), 1/2 width (2Q), and 3/4 width (3Q)

Table 2-4. Surface soil moisture as affected by overseeded application methods and years.

	Soil moisture 0-6cm[†]		
Effect	Fall[‡]	Spring 2011	Spring 2012
	---------------- % ----------------		
Treatment[§]			
AS	15.5 ± 3.3 a	29.1 ± 4.3 a	20.0 ± 1.0 a
TAF	13.9 ± 3.3 a	27.5 ± 4.3 a	21.4 ± 1.0 a
TBS	13.1 ± 3.3 a	27.5 ± 4.3 a	21.5 ± 1.0 a
No rye[¶]	15.8 ± 2.5	--	20.0 ± 1.6
Year			
2010	11.8 ± 2.4 a	--	--
2011	16.6 ± 2.0 a	--	--

[†] Means with the same letter within columns and effect-sampling-date are not significantly different (p>0.05)

[‡] Data averaged over 2010 and 2011

[§] AS, TAF, and TBS are aerial seeding, tractor-mounted airflow spreader, and tractor-mounted bucket spreader, respectively

[¶] Not included in the statistical analysis

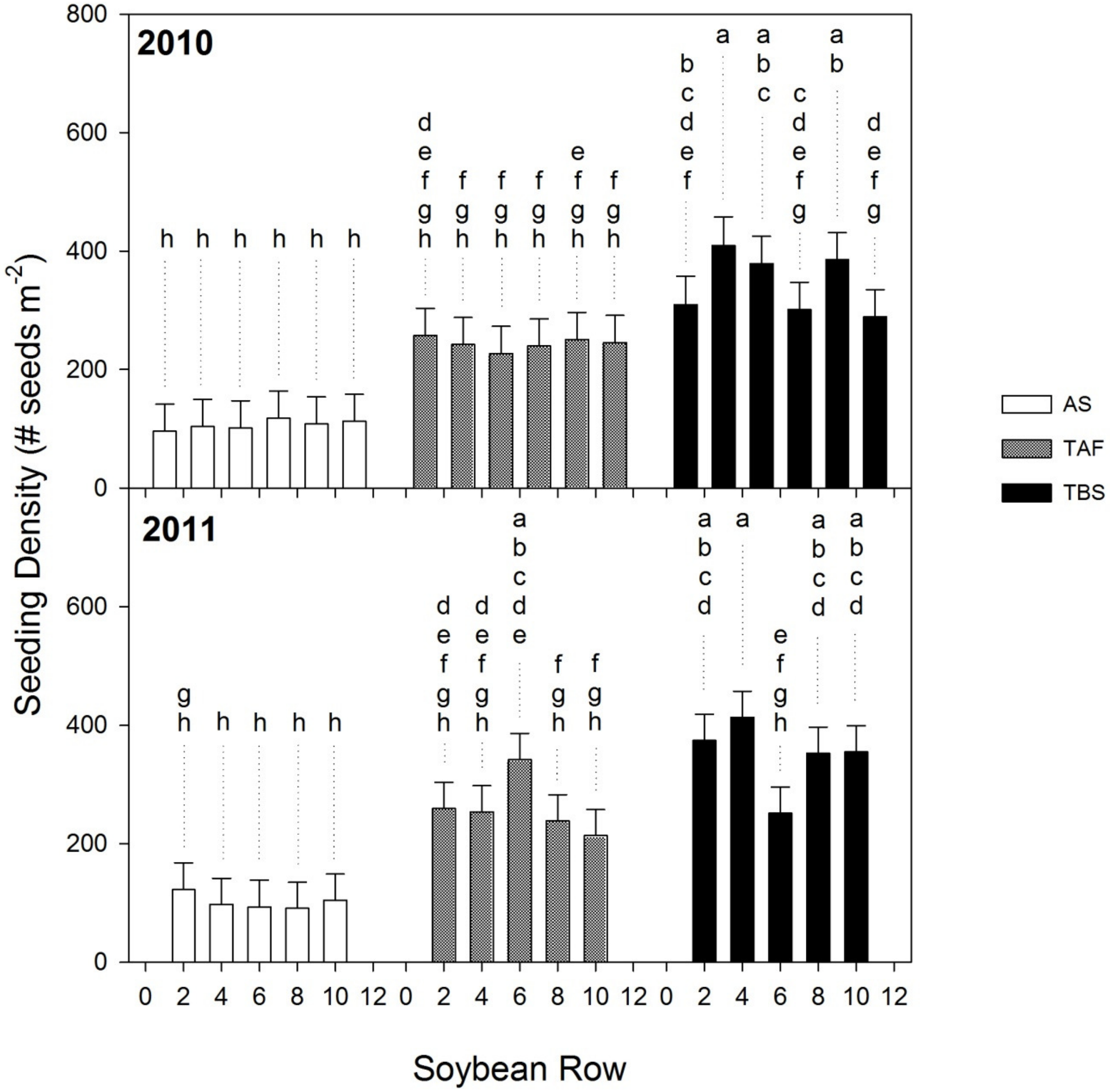

Figure 2-1. Seeding density of three methods to overseed winter rye into standing soybeans. Application treatments were aerial seeding (AS), tractor-mounted air-flow spreader (TAF), and tractor-mounted fertilizer broadcast spreader (TBS). Bars with the same letter above are not significantly different ($p > 0.05$).

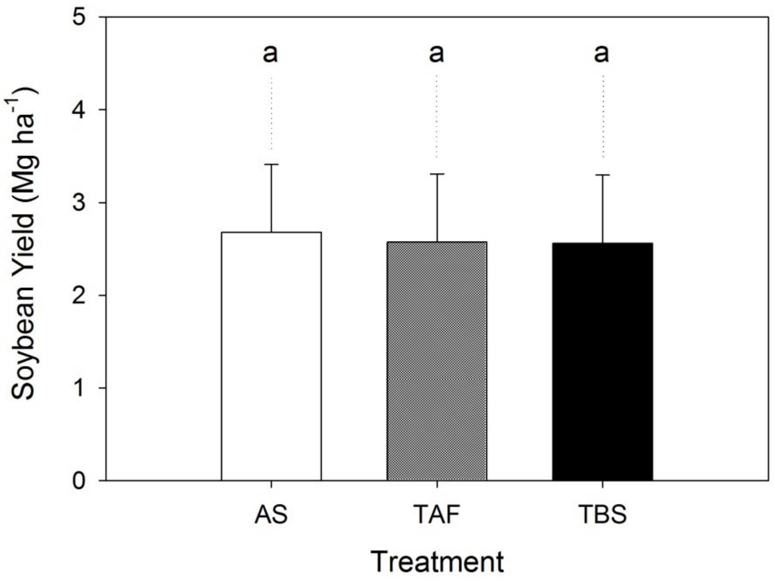

Figure 2-2. Soybean yields averaged over two years following overseeding of winter rye. Application treatments were aerial seeding (AS), tractor-mounted air-flow spreader (TAF), and tractor-mounted fertilizer broadcast spreader (TBS). Bars with the same letter above are not significantly different ($p > 0.05$).

Chapter 3 - Aerially seeding cover crops in the northern U.S. Corn Belt: Limitations, future research needs, and alternative practices

Introducing cover crops into the corn-soybean rotation is one way to improve soil quality and reduce soil and nutrient losses. However, successful establishment after harvest of the main crop is highly unpredictable as a result of the short growing season in the northern U.S. Corn Belt. Aerial application into standing corn or soybeans may allow more time for fall growth, but the practice is considered risky and adoption is low. Some of the current limitations include unpredictable weather, lack of aerial applicators, inconsistent stands due to pilot error and seed predation, and high costs. To encourage implementation in this region, future research should focus on characterizing the mechanics of aerial application and finding cover crop cultivars appropriate for the northern climate and low soil moisture conditions. Since we cannot control the weather, this practice may not be appropriate every year but is one way to increase adoption throughout the region. Alternative methods to aerial seeding include self-seeding, manure slurry seeding, and using seed coatings, but these have not been well researched, especially for northern climates.

Introduction

It has been well documented that the two-year corn-soybean rotation, a prominent agricultural practice in the midwestern U.S., can lead to reduced soil quality (Odell et al. 1984; Karlen et al. 2006) and significant losses of nitrate to the environment (Dinnes et al. 2002; Oquist et al. 2007). By incorporating cover crops into this short rotation, farmers can reduce soil erosion, increase soil organic matter, and improve soil structure

(Snapp et al. 2005). Certain crops, cereals in particular, can also reduce nitrate leaching (Ditsch et al. 1993; McCracken et al. 1994; Strock et al. 2004; Fisher et al. 2011).

Despite the many benefits, however, regional adoption of this practice is low (Singer et al. 2007) because of a number of uncertainties. For instance, farmers have reported that yield reductions in corn and soybeans occur 18% of the time, mostly following grasses such as annual ryegrass, winter wheat and winter rye (Singer 2008). Research has found that yield losses may be due to nitrogen (N) immobilization (Wagger 1989b; Tollenaar 1993), poor seed-soil contact due to thick residues (Leibl et al. 1992), early-season soil moisture competition (Munawar et al. 1990; Warnes et al. 1991), or allelopathic effects (Tollenaar 1993; Johnson et al. 1998).

On the other hand, there are management practices that can reduce these issues, and 46% of surveyed Corn Belt farmers reported that cover crops actually increase corn and soybean yields (Singer 2008). One practice is to kill grass cover crops one or more weeks before planting (Leibl et al. 1992; Strock et al. 2004; Crandall et al. 2005; Duiker and Curran 2005; Krueger et al. 2011). Killing the cover crop early allows more time for decomposition and N release (Wagger 1989a). Using cover crop mixtures, such as cereals and legumes, has also been reported to decrease yield losses (Mitchell and Teel 1977; Clark et al. 1994; Clark et al. 1995; Miguez and Bollero 2005), mainly by increasing N content of residues (Ranells and Wagger 1996). Another management option is to use irrigation when available to reduce potential moisture competition (Mitchell and Teel 1977; Ritter et al. 1998; Andraski and Bundy 2005). Under dryland conditions, Wortman (2012) concluded that managing cover crop residues as a mulch instead of incorporating them into the soil increased soil moisture availability for the following cash crop. Additionally, Clark et al. (1995) found that soil moisture conservation in the summer when rye and hairy vetch residues were present was more important than spring moisture depletion in determining corn yield.

In addition to the reservations about yield suppression, establishing winter cover crops in cooler climates can be difficult due to the short growing season. Miguez and Bollero (2005) reported that grass cover crops in the north-central U.S. would only have marginal benefits due to low biomass production. Through growth simulations, Baker and Griffis (2009) found that the main limitations were degree days and photosynthetically active radiation (PAR). Strock et al. (2004) suggested that based on average weather patterns in southwestern Minnesota, winter rye would only be a successful cover crop in one out of four years. In the above studies, however, temperatures were already cool when the cover crop was planted following harvest of the preceding crop. As another option, Frye et al. (1988) suggested that broadcasting seed into a standing crop can result in earlier crop growth than drilling the seed after harvest. Through growth simulations based on field experiments in northern climates, Feyereisen et al. (2006) recommended planting by 15 Sep to maximize biomass production, although studies in southwestern Minnesota reported that earlier planting (15 Aug) resulted in higher biomass production than waiting until 15 Sep (Moncada and Sheaffer 2010). Some farmers and researchers are testing these concepts by aerially seeding cover crops during the early fall into a standing cash crop. Results have been mixed. A study in Saskatchewan, Canada, found that winter wheat drilled post-harvest resulted in higher plant density and grain yield than wheat broadcast prior to harvest (Collins and Fowler 1992). On the other hand, in 2010, a farmer in Iowa found that biomass of aerially seeded hairy vetch, rapeseed, and tillage radish was much greater than when drilled after harvest (Carlson 2012). Because of mixed results, some areas of the country have seen more adoption of the practice than others.

Aerial seeding of cover crops has particularly increased in areas that have incentivized the use of cover crops. In Maryland, where there are concerns about agricultural pollution in the Chesapeake Bay, approximately 82,150 ha of cover crops were planted in 2007, with 12%, or 9,850 ha, applied aerially (Powell 2008). The hectarage nearly doubled during the subsequent three years with 161,900 ha planted in 2010 (Maryland Department of Agriculture 2012). This increase is likely related to the corresponding increase in dedicated funding for the Maryland Department of Agriculture's cover crop cost-share program from a maximum cost-share payment of \$124 ha^{-1} in 2007 to \$235 ha^{-1} in 2010 (Maryland Department of Agriculture 2010). Other areas that have seen an increase in aerial seeding are Indiana and Iowa, both important in corn and soybean production. In the fall of 2011, approximately 28,300 ha in northeast Indiana (Dave Robison, personal communication, 2012) and 8,100 ha in Iowa (Sarah Carlson, personal communication, 2012) were seeded aerially. In Iowa, this method was used for about half of the reported cover crop acreage.

In addition to extending the fall season for cover crops, aerial seeding has other benefits, as well. Using a plane or helicopter reduces trips through the field with heavy machinery, reducing wheel traffic and compaction. This is particularly important when conditions do not allow for entering a field. Aerial seeding also takes less time than drilling or broadcasting, thus freeing up farm labor (Mintz 2012). Robison (2011) reported that aerial applicators can seed up to 81 ha per hour in Indiana, while a highboy can only seed 4 to 5 ha per hour.

However, in spite of the benefits and successes, aerial seeding is still considered a risky practice, and farmers in the northern Corn Belt are particularly hesitant, feeling that the practice is too unreliable (Dave Linn, Daniel Gillespie, Tony Thompson, Dean Thomas, personal communications, 2012). Collins and Fowler (1992) concluded that the high risk of failure offsets the advantages of overseeding compared with drilling. The objective of this paper is to discuss some of the limitations of aerial seeding, future research that is needed to overcome barriers, and alternative cover cropping practices.

Limitations

Weather – Autumn weather conditions, mainly precipitation and temperature, are unpredictable in the northern portion of the Corn Belt. Strock et al. (2004) found that the probability of favorable weather for cover crop establishment was 25% in southwestern Minnesota. Using the methods outlined in their paper, we compared the weather conditions of other areas in the Corn Belt to those of fall 2010, which was identified as a successful cover crop year in southeastern Minnesota. Weather conditions for Sep – Nov in each reported region were retrieved from the National Climactic Data Center (NCDC 2012). For each year between 1981 and 2010, precipitation data for the three-month period were totaled and then subtracted from the southeastern Minnesota 30-year average (1981-2010). The same procedure was used for average temperature. The resulting coordinate pairs were plotted (Figure 3-1). The likelihood of having conditions favorable for fall establishment in each region was calculated by totaling the number of years with weather conditions similar to the successful fall of 2010 in southeastern Minnesota and dividing each total by 30 years. The fall of 2010 in southeastern Minnesota had with the highest amount of rye biomass reported by Wilson (2012). Conditions that fall were wetter and warmer than the 30-yr average.

By this analysis, southern Minnesota and Wisconsin have the lowest chance for successful establishment of aerially seeded cover crops (Figure 3-1). These two areas are the farthest north and thus the coldest. Southwestern Michigan has the highest chance for establishment with warmer temperatures and more precipitation, most likely because of its close proximity to Lake Michigan and the resulting increased moisture in the atmosphere. In central Iowa there is just under a 50% chance, while in central Indiana and Illinois cover crops would be successful in 2 out of 3 years. Precipitation tends to increase from west to east, which is apparent in the increasing chance of successful establishment from west to east. Correspondingly, Collins and Fowler (1992) concluded that broadcast seeding relied heavily on post-seeding rainfall, and Wilson (2012) reported that precipitation within one week of seeding was the most important factor in determining fall rye cover crop establishment and growth.

Aerial Applicators – At this point, aerial seeding is more art than science. Multiple factors must be considered when applying seed, including: wind speed/direction, weight of seed, broadcast width, height of flight, and shape of field. Pilots decide how high above the canopy they need to fly for a specific broadcast width, depending on seed weight. Lighter seeds tend be blown off-target and may be more affected by the wind than heavier seeds. For these reasons, seed mixes present their own difficulties for aerial applicators. The shape of the field also determines how the applicator will fly. Large square or rectangular fields are easier to navigate than fields with contours.

With all of these factors to consider, it is not surprising that aerial applications do not always provide the cover that farmers want in their fields. In southeastern Minnesota, 100% coverage with helicopter application down to approximately 20% coverage due to skips has been observed. In Indiana, one applicator left 24 m gaps across multiple fields (Robison 2010). With the need to improve application and a growing interest in cover cropping, there was a training session held for aerial applicators in Aug 2011 (Gardisser 2011). This training was mostly focused on fixed-wing aircraft applicators, however, so more education may be needed for helicopter pilots. Some have speculated that turbulence from the helicopter blades may make seeding even more unpredictable (Buckley 2011).

Potentially increasing the chance of poor application is a shortage of applicators willing to aerially seed cover crops in the northern part of the Corn Belt. The Allegan Conservation District surveyed aerial applicators throughout the Midwest and found that Wisconsin had 2 applicators for cover crops, while the states with more favorable weather had more: Michigan had 25 and Indiana had 7 aerial applicators (Mark Ludwig, personal communication, 2012). Gruver (2012) reported 7 cover crop applicators in Illinois. The Iowa Cover Crop Business Directory, listed are 14 aerial applicators in Iowa compared with 2 in Minnesota (Ogawa and Burke 2011). Since aircraft operators do exist in Minnesota (45 Minnesota-based pilots are registered members of the Minnesota Agricultural Aircraft Association), is the lack of specialized aerial applicators must be due to a lack of demand for aerial seeding. With an increase in hectarage in the state, it is possible that more pilots will become interested in seeding cover crops, potentially lowering the costs of aerial application.

Seed Predation – Aerially applied seed remains on the soil surface and becomes vulnerable to predation by insects, rodents, and birds. Farmers have reported significant losses (Lessiter 2009), and this was observed at our research sites, as well. In Aug 2010, we aerially seeded three corn fields in southeastern Minnesota and conducted seed counts (9 replicates in 0.25 m^2 area) on the day of seeding and one week later. Initial seeding rates were 77.9 ± 44.0 kg ha^{-1}. One week later, the count was 15.2 ± 12.5 kg ha^{-1}, or a 48% to 98% loss. Davis and Leibman (2003) found that predation of weed seeds often found in corn and soybeans peaked in September with 5% to 18% of seeds being eaten per day. Similarly, in Iowa, 80% to 90% of weed seeds in corn and soybeans were eaten in late August and September compared with only 30% in July, early August, and October (O'Rourke et al. 2005). This time period coincides with aerial seeding and may be one cause of the missing seed. Those studies mainly focused on invertebrates, but there are other seed predators, as well. Barnett and Comeau (1980) reported that a large proportion of aerially applied seed was eaten by birds as it lay exposed on the soil surface while in other studies mice were observed consuming weed seeds located on the soil surface (Brust and House 1988; Cardina et al. 1996; Cromar et al. 1999).

Besides disappearing seed, we have also found damage in seed that was applied to corn and soybean fields. It appeared that the coleoptiles were eaten. In other studies, ground beetles damaged the endosperm of germinating perennial ryegrass and weeds such as common chickweed and redroot pigweed (Lund and Turpin 1977; Luff 1980), but we also observed slugs and millipedes with their heads inside the seed. Lund and Turpin (1977) found that once seeds were damaged in this manner, they did not germinate. Seed predation of surface-applied cover crops may be an important limiting factor, but available data are scarce.

Economics – One of the main drawbacks to using cover crops is the cost (CTIC 2010), which includes buying seed, planting it, and in the case of winter rye, killing the crop in the spring. In Minnesota, it was reported that costs may be offset by an increase in cash crop yield the following year, but at other times economic returns are reduced (De Bruin et al. 2005). Estimating the cost of aerially seeding a cover crop is problematic but some data are available (Table 3-1). Seed costs are highly variable, depending on type of cover crop used and the available supply. For example, in 2010, cereal rye varied from $0.32 to

\$0.41 kg^{-1}, annual ryegrass from \$1.04 to \$1.21 kg^{-1}, and hairy vetch from \$3.13 to \$4.63 kg^{-1} across Wisconsin, Minnesota, and Illinois (Gruver 2012). Aerial application costs can also be inconsistent and depend on the number of trips per field (depending on seed weight), proximity of fields to a runway or landing site, fuel prices, and total acreage being seeded (Carlson 2010).

Generally, the costs of aerial seeding are competitive or slightly higher than drilling after harvest of the main crop. The Iowa Farm Custom Rate Survey estimated that drilling small grains would cost \$38 ha^{-1} on average with diesel priced at \$0.99 l^{-1} (Edwards et al. 2012). Broadcasting the seed with a tractor was less expensive, costing \$29 ha^{-1}. In Minnesota, planting rye with a no-till drill was estimated to be \$53 ha^{-1} assuming the price of diesel at \$0.95 l^{-1} (Lazarus 2012). The fee for aerial seeding in the fall of 2011 was approximately \$40 and \$62 ha^{-1} in parts of Iowa and Minnesota, respectively (Table 3-1). One of the benefits of aerial seeding is that it does not require existing farm labor so that other tasks on the farm may be completed in a timely manner. This is hard to monetize but should be taken into account when comparing the slightly higher fees with those of drilling the seed.

One way to reduce the cost of aerial seeding is through participation in a cost-share program. These programs are a primary reason that cover crop hectarage in Maryland and Iowa has dramatically increased over the last few years. For the fall of 2011, the Maryland Department of Agriculture (2011) offered up to \$210 ha^{-1} (\$124 base pay plus \$86 in additional incentives) to farmers who aerially seeded. In Iowa, the Natural Resources Conservation Service (NRCS) paid approximately \$124 ha^{-1} for cover crops (NRCS-IA 2010). These amounts typically cover the cost of seed and application with enough left over to manage the crop in the spring.

In the Midwestern U.S., only 11% of farmers reported using cover crops in the previous five years (only 10% in Minnesota), yet 56% said they would plant cover crops if cost-sharing were available (Singer et al. 2007). Interestingly, there are cost-share programs available through the NRCS in most states in the region (Table 3-2), so it seems that more advertising may be needed. Also of note is that payments are typically lower in the northern states (approximately \$59 ha^{-1} on average) compared with those farther south (\$84 ha^{-1}). Increased cost-sharing may be necessary to further promote cover cropping in the northern part of the region.

Future Research

While a recent study has characterized the factors that affect successful establishment of aerially seeded winter rye (Wilson 2012), more research is needed to improve success rates. For instance, the mechanics of aerial application need to be refined. Farmers are less likely to adopt the practice if applicators are doing a poor job of seeding fields. Researchers and pilots should focus on determining the optimal speed and height above the canopy to seed a variety of cover crops with enough overlap to avoid gaps. While some of this information has been disseminated for fixed-wing aircraft pilots, helicopter applicators will benefit from this knowledge, as well.

Researchers should also focus on finding appropriate cultivars for aerially seeded winter cover crops. Because aerial application places seed on the soil surface, appropriate cultivars must germinate with less moisture and be resistant to potential seed predators. Some work has been done to find a rye cultivar that reaches maturity earlier than the standard variety used in Minnesota (‘Rymin’), but results have been mixed (Kantar 2009). Currently, there are only a few species suitable for cover cropping that do not winterkill in the northern Corn Belt, with cereal grains such as winter wheat and winter rye being the hardiest. Some legumes such as clovers and hairy vetch may overwinter, but more cold-tolerant varieties would be useful to increase nitrogen production for the following cash crop. Additional efforts should focus on maximizing stand establishment of these cover crops in existing corn and soybeans.

Alternative Practices

Several alternative practices for establishing cover crops have been suggested, although few have been studied in the Upper Midwest. One method, broadcasting with high-clearance vehicles, is comparable to aerial seeding but has the same drawbacks because seed does not have good contact with the soil. Other methods include applying a coating to the seed, self-seeding, or applying the cover crop with manure (manure slurry seeding).

Broadcasting with high-clearance vehicles – As a result of poorly distributed aerial applications, some farmers and researchers have looked for alternative means for broadcasting seed. These options can include highboy seeders, tractors modified for higher clearance, and modified sprayers. Robison (2011) and Mintz (2012) reported that the positive aspect of this type of application is improved seed placement with very few skips. Wilson (2012) concluded that on-the-ground broadcast spreaders resulted in more uniform seeding density for cereal rye than aerial seeding, although fall biomass production was similar on average.

When compared with aerial seeding, the negatives of highboys and modified tractors include more time and labor and the cost to retrofit equipment if it cannot be rented locally (Robison 2011; Mintz 2012). There is also concern that these methods can damage the standing crop, but Wilson (2012), Johnson et al. (1998), and Smith and Kallenbach (2006) reported no soybean yield losses using modified drop seeders for overseeding cereal rye and annual ryegrass. As with aerial applications, however, seeding without incorporation is still highly dependent on weather, and precipitation is needed soon after seeding. Both types of application also generally require higher seeding rates due to higher seed mortality.

Seed Coatings – A variety of seed coating technologies have recently become available. The first is a polymer that prevents fall germination by absorbing moisture but not allowing the moisture to pass to the seed. Once the ground and seed freezes over winter, the polymer matrix becomes cracked and moisture is allowed to pass to the seed for spring germination. One use for this technology is to fall plant canola for a spring crop, but if conditions are dry in the fall, spring germination can be greatly decreased (Willenborg et al. 2004). The second type of coating is a temperature-activated polymer. Formulations have been developed that allow germination to occur only above certain atmospheric or soil temperatures (Greene and Balachander 1999). This has been used successfully to increase early-planted corn and soybean emergence in multiple locations across the Midwest (Johnson et al. 1999; Gesch et al. 2012). A third coating option from Smith Seed Services is specifically targeted for aerial seed applications. The manufacturer states that the coating adds density to the product making it more accurate to apply from the air. The coating is also said to increase seed-to-soil contact and wick water to provide a consistent level of moisture around the seed (Smith Seed Services 2012). However, at this time field research using this product is limited.

The first two types of polymers may be useful to fall-apply cover crops for spring growth, but they are not likely to provide the benefits of fall ground cover. The third product may increase the probability of successful establishment of aerially applied seed, but research is needed. One consideration for all three, however, is the additional cost of the seed with a coating. Cover cropping is already an additional expense that may not result in monetary gain, making coated seeds an unattractive option.

Self-seeding – One way to reduce the cost of seed and labor for planting a cover crop each year is to allow the cover crop to self-seed. In other words, the cover crop is only managed in soybean or corn planting rows and is allowed to produce seed in the interrow where it disperses and produces the cover crop for the following fall. In Iowa, McDonald et al. (2008a) found that wheat exhibited the most promising capability of self-seeding compared with rye and triticale, although all three cereals reduced corn yields due to competition (McDonald et al. 2008b). The authors suggest that more research is needed to determine management techniques to reduce competition and improve seed dispersion.

Manure Slurry Seeding – Mixing cover crop seed with manure slurry and applying it after harvest of the cash crop is one approach that has been developed by researchers at Michigan State University. Harrigan et al. (2006) reported that plant density with this method was lower in Michigan than when the cover crops were drilled, but fall total biomass was similar to or greater than drilled biomass due to larger individual plants. This practice minimizes trips across the field while the manure provides moisture and nutrients to the developing crop. In return, cover crops coupled with manure minimize nutrient losses from the field (Parkin et al. 2006; Singer et al. 2008; Kovar et al. 2011).

One drawback is that the equipment used in Michigan is not necessarily standard in other areas of the Corn Belt. For instance, the drop tubes for applying the slurry and seed in the Michigan study were spaced approximately 19 cm apart (Harrigan et al 2006), which is similar to the spacing of a grain drill. In south-central Minnesota, many farmers use manure injection sweeps that are spaced 50 to 76 cm apart and may place seed deeper into the soil (Jill Sacket, personal communication, 2012). Since planting density was already lowered in the manure slurry seeded plots in the Michigan study, it is unclear whether this practice would be beneficial with the use of different equipment. Furthermore, this practice can only be used after harvest of the cash crop, suggesting that, like drilling, it may not fit into the corn-soybean rotation in cooler climates.

Conclusions

Aerial seeding has allowed farmers in the Upper Midwest to fit cover crops into the corn-soybean rotation. The practice has grown over the past few years in other areas, but in the northern Corn Belt, adoption has been limited because of unpredictable weather, lack of aerial applicators, poor stands due to pilot errors and seed predation, and high costs. By improving application methods and the cultivars used for cover crops, we can potentially increase adoption of the practice. This will in turn increase the demand for pilots willing to aerially seed in the region, thus bringing down the cost. However, we still cannot control the weather, so this practice may not be appropriate for every year. It is just one tool to be used to increase cover crop hectarage in the northern Corn Belt. Alternative practices for establishing cover crops have been suggested but more research is needed to determine whether these practices can succeed in northern climates.

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Table 3-1. Costs for aerially seeding winter cover crops at several locations during fall 2011.

Location	Seed	Seeding Rate	Costs Seed	 Aerial Application	 Total	Reference
Wilmington, OH	Organic Winter Rye	94 kg ha^{-1}	\$0.66 kg^{-1}	\$25 - \$40 ha^{-1}	\$87 - \$102 ha^{-1}	(Ryan Alexander, personal communication, 2012)
Iowa	--	84 kg ha^{-1}	--	\$40 ha^{-1}	\$79 - \$86 ha^{-1}	(Sarah Carlson, Steve Berger, personal communications, 2012)
SE Minnesota	Winter Rye	112 kg ha^{-1}	\$0.52 kg^{-1}	\$62 ha^{-1}	\$120 ha^{-1}	(Melissa Wilson, personal communication, 2012)

Table 3-2. U.S. Natural Resources Conservation Service cost-share programs for FY 2012.

State	Cover Crop	Payment Rate	Reference
		(per ha)	
IA	Non-legumes	\$66.92	(NRCS-IA 2012)
	Legumes	\$63.85	
IL	Non-legumes	\$87.62	(NRCS-IL 2012)
	Legumes	\$95.78	
IN	Species Mix	\$103.78	(NRCS-IN 2012)
MI	Non-legumes	\$48.16	(NRCS-MI 2011)
	Legumes	\$69.86	
MN	Non-legumes	\$48.16	(NRCS-MN 2012)
	Legumes	\$69.86	
WI	Non-legumes	\$48.16	(NRCS-WI 2012)
	Legumes	\$69.86	

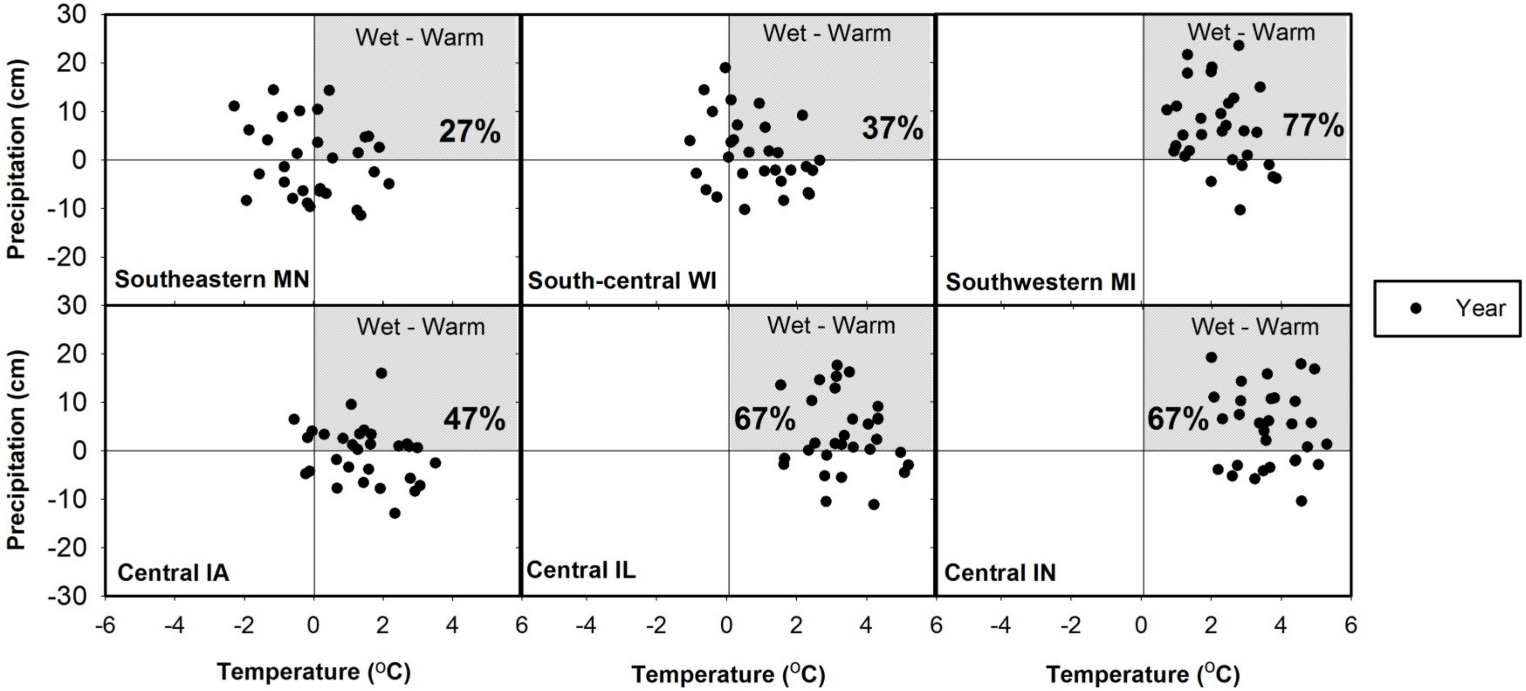

Figure 3-1. Yearly departure of temperature and precipitation in several areas of the U.S. Corn Belt from the southeastern Minnesota (MN) 30-yr (1981-2010) average temperature and precipitation during Sep – Nov. Shaded areas highlight the years with favorable weather conditions (wetter and warmer than the MN average) and percentages indicate the probability of favorable weather conditions for establishment of aerially seeded cover crops.

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