INCREASING SUSTAINABILITY OF AGRICULTURAL SYSTEMS THROUGH ADAPTIVE CROP MANAGEMENT PRACTICES AND TECHNOLOGIES

A Dissertation
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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June 2017

Acknowledgements

I would like to thank the Minnesota Department of Agriculture – Clean Water Research Fund, the Minnesota Agricultural Experiment Station funds, and the Hueg-Harrison Fellowship for supporting this research and my graduate degree program. This work and my education have benefitted tremendously from the guidance of my advisory committee. I am extremely grateful to my advisor Dr. M. Scott Wells for his mentorship, motivation, and friendship, and for providing me the tools and experience to prepare for my career. I am also especially thankful to my co-advisor, Dr. Jeffrey Coulter, for his thorough revisions, insight, and motivation to publish my work. Drs. Craig Sheaffer, Krishona Martinson, and John Baker have also supported various aspects of my research and served fundamental roles in my education.

The tremendous amount of field work required by these projects would not have been possible without the experience and dedication of Eric “Rocket” Ristau. Thank you for showing me around Minnesota, and for providing the finest company, stories, and lessons over many miles on the road and days in the field. Alex Hard and Joshua Larson were also extremely helpful in coordinating tasks in the field and lab. I also appreciate the excellent technical and logistical support from Steve Quiring, Tom Hoverstad, and Wade Ihlenfeld, statistical support from Drs. Jacob Jungers and Tyler Tiede, and help in the field and lab from many fellow graduate students. I am particularly grateful to the Applied Plant Sciences graduate student community for the camaraderie throughout my program.

Above all, I am thankful to my family, my parents, grandparents, sisters, in-laws, nieces and nephews, and to many friends (you know who you are) who have all motivated me and carried me through, and for the love and support of my wife Stefani.

Dedication

To Stefani, my wife and greatest friend, for your patience, faith, and inspiration.

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CHAPTER 1: ESTABLISHMENT AND FUNCTION OF COVER CROPS INTERSEEDED INTO CORN

1.1 Summary. Cover crops can provide ecological services and improve the resiliency of annual cropping systems; however, cover crop use is low in corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotations in the upper Midwest due to challenges with establishment. Our objective was to compare three methods to establish cover crops (winter rye [*Secale cereale* L. 'Rymin'], red clover [*Trifolium pretense* L. 'Medium'], hairy vetch [*Vicia villosa* Roth], field pennycress [*Thlaspi arvense* L. 'MN-106'], and a mixture (MIX) of oat [*Avena sativa* L.], pea [*Pisum sativum* L.], and tillage radish [*Raphanus sativus* L.] in corn at the seven leaf collar stage. Establishment methods included directed broadcast of seed into the inter-row (DBC), directed broadcast with light incorporation (DBC+INC), and a high-clearance drill (DRILL).

Fall cover crop biomass was greater with the DRILL method than DBC for all cover crops except pennycress, and the DRILL and DBC+INC methods resulted in greater spring biomass for red clover and hairy vetch than DBC. Cover crop biomass and N uptake in the spring was among the greatest with winter rye (means = 971 kg DM ha^{-1} and 25 kg N ha^{-1}, respectively). Cover crop treatments did not affect corn grain or silage yield, and reduced seed yield of the subsequent soybean crop by 0.4 Mg ha^{-1} (10%) only when poor termination of hairy vetch occurred at Lamberton. Soil nitrate N was reduced by winter rye at both locations and by hairy vetch, red clover, and pennycress at Waseca, compared to the no cover control. These results demonstrate that cover crops can be interseeded into corn at the seven leaf collar stage in the upper Midwest to reduce residual soil nitrate N while maintaining corn and subsequent soybean yields; however; appropriate timing and method of cover crop termination is critical to avoid competition with the subsequent soybean crop.

1.2 Introduction. Effective cover cropping practices can mitigate negative environmental impacts and enhance the resiliency of annual cropping systems. Corn and soybean were planted on 18.2 million hectares (85% of cropland) in the upper Midwest in 2016 (USDA-NASS CDL, 2016), and corn-soybean rotations in the upper Midwest are susceptible to nutrient loss via surface runoff, leaching, and subsurface tile drainage (Randall et al., 2003; Strock et al., 2004). This offsite movement of nutrients has negative environmental and economic repercussions, including contributions to nitrate loading in municipal water supplies and hypoxia in the Gulf of Mexico (Gilliam and Skaggs, 1986; Mitsch et al., 2011). The greatest risk of N loss in annual cropping systems in the upper Midwest occurs during the spring prior to establishment of the primary crop. Randall et al. (2003) reported that 69% of annual nitrate N loss via drainage occurs in April through June in corn-soybean rotations in the upper Midwest. Winter annual cover crops can be integrated into annual-based cropping systems to sequester N and reduce losses (Feyereisen et al., 2006; Qi and Helmers, 2010; Blanco-Canqui et al., 2015). In the mid-Atlantic, winter cereal cover crops reduced nitrate N leaching by 50 to 95% from a simulated corn-soybean crop rotation (Meisinger and Ricigliano, 2017). Cover crops can also protect soil from erosion, contribute to soil organic matter, and improve soil aggregate stability and soil water retention (Reicosky and Forcella, 1998; Dabney et al., 2001). Despite these demonstrated benefits, cover crops are uncommon in corn-soybean rotations in the upper Midwest (Singer et al., 2007).

The difficulty of establishing cover crops following corn is a primary factor limiting adoption in the upper Midwest (Singer, 2008, SARE-CTIC, 2016), where relatively short growing seasons create an adverse environment for successful post-harvest establishment (Singer et al., 2007). For example, Feyereisen et al. (2006) modeled cover crop growth in the upper Midwest and found that winter rye should be planted on or before 15 September to achieve the greatest reductions in N loss. To bypass this issue, cover crops can be interseeded into standing corn, allowing sufficient time to establish before winter (Wilson et al., 2013; Belfry and Van Eerd, 2016). Previous research on interseeding cover crops in the upper Midwest has assessed only aerial broadcast planting. Wilson et al. (2013) reported that the success of winter rye establishment when aerial broadcast planted into mature corn (late-August to mid-September) was correlated with the occurrence and quantity of precipitation within 1 wk of planting. Reliable methods of cover crop establishment need to be identified to facilitate adoption of cover cropping practices in the upper Midwest.

Successful establishment of cover crops depends on both the timing and method of planting. Competition for solar radiation is often a primary limiting factor in the establishment and survival of interseeded cover crops (Humphreys et al., 2003). Cover crops interseeded prior to closure of the primary crop canopy must be planted early enough to establish roots while sufficient solar radiation is reaching the soil surface, yet late enough to avoid direct competition with the primary crop for water, nutrients, and solar radiation (Abdin et al., 1997). Cover crop establishment can also be improved by planting methods that increase seed-to-soil contact (Boyd and Van Acker, 2003; Wilson et al., 2013). New planting methods have been adapted to place seed directly in the inter-row and increase seed-to-soil contact when interseeding cover crops. These include high-clearance drills (Roth et al., 2015) and other high-clearance implements that broadcast cover crop seed directly into inter-rows beneath the canopy of the primary crop. Suitable methods of interseeding cover crops, however, likely vary with cover crop species, field conditions, planting timeframe, and area to plant.

Suitable cover crop species and reliable establishment methods need to be assessed to identify viable cover cropping strategies that provide environmental benefits while maintaining productivity in corn-soybean rotations in the upper Midwest. Several species have been identified with potential for use as winter annual cover crops (SARE-CTIC, 2016). Winter rye is an extremely cold-tolerant and efficient scavenger of excess N (Wilson et al., 2013). Field pennycress is a winter-annual brassica that has been adapted as an oilseed crop for relay- and double-cropping systems in the upper Midwest (Johnson et al., 2015). Red clover and hairy vetch are legume cover crops that have both shown potential in previous interseeding research (Belfry and Van Eerd, 2016). A non-winter-hardy mixture consisting of oat (grass), tillage radish (brassica), and field pea (legume) is also of interest as a cover cropping option capable of providing ecological services in the fall, and not requiring termination in the spring. The objectives were to 1) gauge establishment success of a range of cover crop species and planting methods, 2) identify planting methods and species that optimize cost, feasibility, and benefit of interseeding cover crops, and 3) determine whether successfully interseeding cover crops into corn can provide ecological benefits through utilization of excess N and water without reducing corn and subsequent soybean yields.

1.3. Materials and Methods.

1.3.1 Field Experiments. Field experiments were established in 2014 and 2015 at the University of Minnesota Southern Research and Outreach Center at Waseca, MN (44°03’41.77”N 93°30’47.53” W) on a Webster clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and at the University of Minnesota Southwest Research and Outreach Center at Lamberton, MN (44°10’04.35”N 95°18’02.80” W) on an Amiret loam (Fine-loamy, mixed, superactive, mesic Calcic Hapludolls). Air temperature and precipitation data were obtained from weather stations located within 1 km of the experiments (Table 1-1). Fertilizers were applied in the spring prior to seedbed preparation and corn planting according to University of Minnesota guidelines for corn and soybean production (Kaiser et al., 2011). In all experiments, ammonium sulfate $[(NH_4)_2SO_4]$ was applied to supply 17 kg S ha^{-1}. A total of 224 kg N ha^{-1} was applied in both years at Waseca, with 15 kg N ha^{-1} from ammonium sulfate and 209 kg N ha^{-1} as urea $[CO(NH_2)_2]$ in 2014, and 15 kg N ha^{-1} from ammonium sulfate, 196 kg N ha^{-1} as anhydrous NH_3, and 12 kg N ha^{-1} as urea in 2015. Totals of 183 and 252 kg N ha^{-1} were applied at Lamberton in 2014 and 2015, respectively, with 15 kg N ha^{-1} from ammonium sulfate and the remainder as urea (168 and 237 kg N ha^{-1} in 2014 and 2015, respectively). Fertilizer P and K were also applied at Lamberton in 2015 at rates of 112 kg P ha^{-1} as calcium dihydrogen phosphate [$Ca(H_2PO_4)_2 \bullet H_2O$] and 67 kg K ha^{-1} as potassium chloride (KCl). Corn ('Pioneer P0193AM') was planted in rows spaced 76 cm apart at both locations between 28 April and 5 May at 86,500 seeds ha^{-1}. Weeds were controlled with glyphosate [N-(phosphonomethyl) glycine] (0.84 kg a.e. ha^{-1}) prior to corn planting, and immediately prior to cover crop interseeding.

The experimental design was a randomized complete block with six replications. Plots were 3 × 15 m (four corn rows wide).Treatments were a factorial arrangement of five cover crop options (four species and one mixture) planted with three interseeding methods and a experimental control with no cover crop planted (CHK). Cover crops were interseeded into corn at the seven leaf collar stage between 23 and 26 June. Cover crop species were rye, pennycress, red clover, hairy vetch, and MIX planted at 168, 9.9, 13.4, 35.1, and 140 kg pure live seed ha^{-1}, respectively. All legumes were inoculated with appropriate rhizobia species by thoroughly mixing fresh inoculant and seed at planting, using N-Dure True Clover Inoculant for the red clover, and Pea/Vetch Inoculant (INTX Microbials, LLC, Kentland, IN) for the hairy vetch and MIX. Cover crop planting methods included direct broadcast of seed into the inter-row (DBC), and directed broadcast into the inter-row with light soil incorporation (DBC+INC), and a high-clearance no-till drill (DRILL; 3-in-1 InterSeeder^{TM}, InterSeeder Technologies, Woodward, PA). Cover crops planted with the DBC method were broadcast directly by hand into the three inter-rows of each plot with no soil disturbance. The DBC+INC planting method was performed with modifications to the high-clearance no-till drill that involved raising drill units so that the seed fell onto the soil surface and incorporation of broadcast seed with custom-made units installed on the drill that consisted of a light closing chain followed by a harrow-tine rake to achieve light soil disturbance (Fig 1-1). The DRILL treatment had three drill units spaced 19 cm apart and centered within each of three inter-rows per plot, leaving a 38-cm-wide gap for each corn row.

Following cover crop emergence, time-domain transmittance soil moisture sensors (Acclima Digital TDT®, Acclima, Inc., Meridian, ID) were installed between 3 and 16 July in each experiment. Sensors were placed at depths of 30 and 60 cm in DRILL-planted winter rye and MIX plots and in the CHK plots. Data loggers (DataSnap SDI-12, Acclima, Inc., Meridian, ID) were installed in each replication and configured to record volumetric water content on 1-hr intervals. In each experiment, soil volumetric water content was recorded through the duration of the corn-soybean cropping cycle and ended just prior to soybean harvest.

Cover crop and corn biomass and subsequently N content was measured at corn physiological maturity (between 25 and 29 September), and cover crop biomass was also measured in the spring prior to termination (between 6 and 17 May). All aboveground cover crop biomass within a 91 × 76 cm sample area was hand-harvested between the center two corn rows in each plot. Corn biomass was measured by hand-harvesting all plants from 3 m of row in each plot at corn maturity. Ears were removed from plants, after which stalks were cut 15 cm above the soil surface and weighed fresh. Seven stalks were randomly subsampled and ground. Ground stover samples were mixed thoroughly subsampled (~1 kg), and subsamples were immediately weighed in the field. All cover crop biomass samples and stover subsamples and ears were dried at 60°C in a forced-air oven until constant mass, after which cover crop biomass samples and stover subsamples were weighed. Dried ears were shelled using a single-ear electric sheller and grain and cob weights were recorded. Corn stover, cob, and grain weights were then summed to compute corn aboveground biomass and adjusted to 650 g kg^{-1} moisture to report as silage yield. Corn stover, cob, and grain samples from the DRILL and CHK treatments, and all cover crop biomass samples were ground to pass through a 1-mm screen using a Cyclotec Sample Mill (FOSS North America, Eden Prairie, MN), and total N concentration was measured by combustion using an Elementar VarioMAX (Elementar Analysensysteme, Mt. Laurel, NJ). Cover crop and corn N concentrations were then converted to N content (kg N ha^{-1}) according to corresponding biomass measurements.

Corn grain yield was measured by harvesting the central 13 m of the center two rows of each plot with a plot combine, and yields were adjusted to 155 g kg^{-1} moisture. The combine header was kept directly below the height of the ears to minimize the quantity of stover deposited on cover crops and serve as a snow catchment to enhance winter survival of cover crops. In each experiment, cover crops were terminated with glyphosate [N-(phosphonomethyl) glycine] (0.84 kg a.e. ha^{-1}) between 12 and 20 May and soybean (ASGROW ‘AG1733’) was no-till planted in all plots at 395,000 seeds ha^{-1} between 19 and 28 May. In each experiment, red clover and hairy vetch cover crops were not completely terminated with the first application of glyphosate so a second application of glyphosate at the same rate and formulation was applied following soybean emergence between 10 and 20 June; however, some of the hairy vetch survived at Lamberton in both years and remained under the soybean canopy where it was protected from subsequent applications of herbicide. Soybean grain yield was measured by harvesting the central 13 m of the center two rows of each plot with a plot combine between 6 and 20 October and yield was adjusted to 130 g kg^{-1} moisture.

Soil nitrate N was measured in the DRILL and CHK plots immediately following corn grain harvest, and the following spring prior to cover crop termination. Soil was sampled to a depth of 1.2 m using a hydraulically-driven soil probe (3.8 cm i.d.). Three cores from each plot were divided into 30-cm increments, composited by depth, mixed, subsampled (~300 g), and dried at 35°C. Dried soil samples were ground to pass through a 2-mm screen and analyzed for soil nitrate N concentration by Cd reduction using a flow injection analyzer (Technicon AutoAnalyzer, Technicon Systems, Inc., Oakland, CA). An additional core was taken from each plot, divided into the same increments, and retained for determination of soil bulk density by drying at 105°C until constant mass and weighing. Soil bulk density was used to convert soil nitrate N concentration to content, and soil nitrate N content for the 0- to 1.2-m depth was calculated as the sum of the 30-cm increments.

1.3.1 Efficiency Analyses. Analyses were conducted to evaluate the cost and efficiency of cover cropping practices relative to potential benefit. Cover crop seed costs for winter rye, medium red clover, hairy vetch, and MIX were set at $0.48, 5.50, 4.36, 3.41, and 1.10 kg^{-1}, respectively, based on quotes from regional suppliers. Currently, there is no established market for pennycress seed, so the assumed value of pennycress was conservatively set at \$5.50 kg^{-1}. Planting costs were based on regional custom rates for interseeding cover crops, and were considered to be \$37 ha^{-1} for the DRILL and \$35 ha^{-1} for the DBC and DBC+INC planting methods (B. Brunk, personal communication, 2017). Planting speeds were assumed to be 9, 17, and 25 ha hr^{-1}, based on a 9.1-, 18.3-, and 27.4-m wide planter traveling at 12, 11.2, and 11.2 km hr^{-1} for the DRILL, DBC+INC, and DBC, respectively. Spring cover crop biomass was used to characterize benefit since this response was recorded across all cover crop species and planting methods, and is directly correlated with ecological services, including N uptake (Wilson et al., 2013) and increases in soil organic matter (Reicosky and Forcella, 1998) and surface residue. To account for cost, speed, and benefit in a single index, each indicator was scaled such that the maximum for each indicator was equal to 1, with cost scaled as the inverse such that greater values indicate lower costs. A radar graph was used, with the value for each scaled indicator extending from a common origin outward at equal angles. An overall efficiency index was caluclated as the area of the triangle formed by the resulting three vertices.

1.3.2. Statistical Analyses. Statistical analyses were performed using the MIXED procedure of SAS 9.4 (SAS, Inst. Inc., Cary, NC). Fixed effects were location, cover crop species, cover crop planting method, and their interactions for cover crop biomass in the fall and spring, cover crop tissue N content in the fall and spring, corn grain yield, corn silage yield, soybean seed yield, and the efficiency index. Since total aboveground corn N uptake, corn grain N uptake, and fall- and spring-soil nitrate N content were measured only from DRILL and CHK plots, fixed effects for these response variables were location, cover crop species, and their interaction. Random effects were year, block nested within year by location, and corresponding interactions with fixed effects. Individual analyses by day were conducted for soil volumetric water content throughout the cropping cycle, with separate analyses for each experiment to enable comparison of specific environmental and cover crop factors in relation to soil water. To meet the requirements of normality and common variance, power transformations were applied to cover crop biomass and N content response variables according to the Box-Cox method (Box and Cox, 1964). Means for all response variables were separated using Fisher's LSD at $P \leq 0.05$.

1.4. Results and Discussion.

1.4.1. Environmental Conditions. Mean Monthly-average air temperature was within 2°C of 30-yr averages throughout the growing season (April–September) in all experiments except September 2015 when mean air temperatures were 4°C greater than normal at both locations. From the time of cover crop planting to fall biomass sampling, cumulative growing degree units (GDUs) with a base temperature of 0°C were within 1810 to 1950 GDUs in all experiments, and from 1 March to the time of spring biomass sampling, cumulative GDUs ranged 496 to 614 GDUs. Precipitation totals (April–September) were above average in all experiments (Table 1-1) and exceeded the 30-yr average at Waseca by 247 and 539 mm in 2015 and 2016, respectively. In all experiments, 5 to 23 mm of precipitation occurred within 7 d of cover crop planting and 10 to 38 mm occurred within 10 d.

1.4.2. Cover Crop Biomass and Nitrogen Content. Cover crop planting method and the interaction between planting method and cover crop species affected fall cover crop biomass (Table 1-2). The DRILL resulted in greater fall biomass than the other two planting methods for hairy vetch, MIX, and rye (Fig. 1-2). Red clover fall biomass was greater with the DRILL and DBC+INC than DBC, and planting method did not affect fall biomass in pennycress. These findings support that increased seed-to-soil contact improves cover crop establishment (Boyd and Van Acker, 2003; Wilson et al., 2013), and that optimum planting depth is correlated to seed size, such that species with larger seeds require greater planting depths than species with smaller seeds (Hakansson et al., 2011). The DRILL planting method, achieving the greatest planting depth and seed-to-soil contact, showed the greatest benefit for the large-seeded cover crops in this study (winter rye, MIX, and hairy vetch), whereas red clover, a smaller-seeded species, showed similar increases in fall biomass with DBC+INC and the DRILL, and pennycress, the smallest-seeded species in this study, showed no response to planting method (Fig 1-2). Averaged by cover crop species, fall biomass ranged from 9 to 84 kg DM ha^{-1} with an overall average of 41 kg DM ha^{-1}. Wilson et al. (2013) report winter rye biomass ranging 26 to 506 kg DM ha^{-1} in southeastern Minnesota, yet most sites averaged <50 kg DM ha^{-1}. This aligns with winter rye biomass in this study, which averaged 21 kg DM ha^{-1} with DBC and DBC+INC planting methods and 61 with DRILL; although Wilson et al. planted with aerial broadcast later in the corn growing season (late-August to mid-September) and measured cover crop biomass later in the fall (mid-November to early-December). Belfry and Van Eerd (2016) report much greater cover crop biomass at corn harvest (725 and

1352 kg DM ha^{-1} for winter rye and hairy vetch, respectively) in seed corn that was de-tasseled prior to pollination and had male rows (1 to 3 of every 4 to 8 rows) removed after pollination, which likely increased solar radiation reaching cover crops beneath the corn.

Cover crop biomass in the spring was affected by location, planting method, and the interaction between planting method and cover crop species (Table 1-2). Overall, spring biomass was greater at Waseca (968 kg DM ha^{-1}) than at Lamberton (233 kg DM ha^{-1}). The DBC method resulted in less spring biomass than other planting methods for hairy vetch and red clover; however, planting method did not affect winter rye or pennycress biomass in the spring (Fig 1-2), indicating that compensatory spring growth made up for initial differences in winter rye biomass (Boyd et al., 2009). Wilson et al. (2013) concluded that precipitation within 7 d following broadcast planting of cover crops improved establishment and biomass accumulation. All experiments received precipitation within 7 d of planting, and greater-than-normal precipitation throughout the growing season (Table 1-1), so caution is advisable with respect to conclusions about efficacy of broadcast planting.

Cover crop N content in the fall was not affected by location, cover crop species, or planting method (Table 1-2), and average N content ranged from only 0.3 to 2.6 kg N ha^{-1}, compared to reports of 0.1 to 45 (Wilson et al., 2013) and 15 to 57 kg N ha^{-1} (Belfry and Van Eerd, 2016). However, fall N uptake is not as critical as cover crop establishment, winter survival and spring N uptake, since the greatest risk of N loss occurs in the spring (Randall et al., 2003). Spring N content was affected by location, planting method, and the interaction between cover crop species and planting method (Table 1-2). Cover crop N content in the spring was greater at Waseca (26.0 kg N ha^{-1}) than Lamberton (7.1 kg N ha^{-1}). The DRILL and DBC+INC planting methods resulted in greater spring cover crop N content than DBC for hairy vetch and red clover, but planting method did not affect spring N for pennycress and winter rye (Table 1-3). These effects coincide with differences in biomass between species and across locations, as cover crop N content was strongly correlated ($R = 0.99$; $P < 0.001$) with aboveground cover crop biomass. Averaged by species, spring cover crop N content ranged from 11 to 24 kg N ha^{-1} with an overall average of 17 kg N ha^{-1}, indicating that some interseeded cover crops have potential to sequester excess N that may otherwise be vulnerable to off-site movement.

1.4.3 Soil Nitrate N and Water Content. Fall soil nitrate N to a depth of 1.2 m was not affected by location or cover crop species (Table 1-2). This is explained by minimal cover crop N uptake in the fall (mean = 1.3 kg N ha^{-1}). Across locations, fall soil nitrate N content averaged 117 kg NO_3-N ha^{-1}. Spring soil nitrate N was affected by the interaction of location and cover crop. At Lamberton, rye resulted in less soil nitrate N than all other cover crops and the no cover check (Table 1-4). The lack of significant nitrate N reductions by other species at Lamberton coincides with lower spring biomass production (<350 kg DM ha^{-1}). At Waseca, rye, hairy vetch, red clover, and pennycress all resulted in less soil nitrate N than MIX and the no cover check (Table 1-4). A negative correlation ($R = -0.70$; $P = 0.003$) between spring cover crop biomass and departures in soil nitrate N from the no cover CHK occurred, supporting that cover crop biomass can serve as a valid indicator for ecological services in the reduction of excess soil nitrate N. Strock et al. (2004) report losses up to 54 kg NO_3-N ha^{-1} through leaching and runoff during years of high precipitation in corn-soybean rotations. In this study, interseeded rye cover crops reduced spring soil nitrate N compared to the no cover crop check by 53 kg NO_3-N ha^{-1} at Waseca and by 39 kg NO_3-N ha^{-1} at Lamberton. These findings agree with reports of cover crops reducing potential for nitrate leaching (Meisinger and Ricigliano, 2017) and imply that interseeded cover crops can provide a direct benefit to water quality in the upper Midwest.

At the time of cover crop termination, rye treatments reduced volumetric soil water (0.25 cm^3 cm^{-3}) compared to the no cover crop control (0.29 cm^3 cm^{-3}) at Waseca in 2014 (Fig. 1-3). Volumetric water content was not different between treatments in other experiments throughout the study. The effect observed at Waseca in 2014 aligns with differences in rye biomass and spring precipitation between experiments. Rye biomass averaged 1.6 Mg DM ha^{-1} in the spring of 2015 at Waseca, but only 0.4 Mg DM ha^{-1} at Lamberton. Cumulative precipitation from 3 wk prior to cover crop termination was greater at Waseca in 2016 (74 mm) than in 2015 (32). Therefore, the Waseca 2014 site-year had both sufficient rye growing and low enough precipitation to result in measureable differences in soil water. Aside from water use, cover crops have been reported to increase infiltration and water holding capacity (Reicosky and Forcella, 1998; Dabney et al., 2001), which may have contributed to the lack of differences observed, particularly in periods of greater-than-normal precipitation.

1.4.4. Corn Yield and Nitrogen Uptake. Corn grain and silage yields were not affected by location, cover crop species, or planting method (Table 1-2), and averaged 9.9 Mg ha^{-1} and 48.4 Mg ha^{-1}, respectively. These results are consistent with reports for cover crops interseeded into corn at the four and seven leaf collar stages in Michigan, USA and in southwestern Ontario, Canada (Baributsa et al. 2008; Belfry and Van Eerd, 2016). The critical period of weed control in corn can to extend to the 14-leaf stage (Hall et al., 1992); however, the yield response to weed control has been optimized at the 10-leaf-tip stage (Page et al., 2012), which coincides with the seven leaf collar stage and aligns with the lack of cover crop effects on corn yield in this study. Earlier planting of cover crops may enable direct competition and yield reductions (Jones et al., 1998). Considering that precipitation during the growing season was above average in all experiments in this study (Table 1-1), more experiments with a range of precipitation and soil water status will be necessary to inform farm practices.

Corn grain and silage N uptake were influenced by the main effects of location and cover crop species (Table 1-2). Silage and grain N uptake were greater at Lamberton (184 kg N ha^{-1} and 128 kg N ha^{-1}, respectively) than at Waseca (150 kg N ha^{-1} and 109 kg N ha^{-1}). Winter rye resulted in less corn N uptake (160 kg N ha^{-1}) than hairy vetch and CHK (mean = 174 kg N ha^{-1}), and less grain N uptake (112 kg N ha^{-1}) than CHK, MIX, and hairy vetch (mean = 121 kg N ha^{-1}), providing evidence that assimilation of N by rye may have reduced N availability for corn. Similarly, Belfry and Van Eerd (2016) found that interseeded cover crops sequestered 42 kg N ha^{-1} at corn harvest without affecting corn yield, although they did not report corn N uptake. The observed differences in corn

N uptake without differences in corn yield suggest that N was not limiting in this study and excess uptake can be attributed to luxury consumption (Macy, 1936). These results support that interseeding cover crops into corn at the seven leaf collar stage introduces little to no risk of corn yield reduction, at least in years with above normal precipitation (Table 1-1).

1.4.5. Soybean Grain Yield. Soybean yield was influenced by the interaction between location and cover crop species (Table 1-2). Hairy vetch resulted in lower soybean yield (3.8 Mg ha^{-1}) than pennycress and MIX (mean = 4.2 Mg ha^{-1}) at Lamberton, but similar yield to that with the other cover crop species and the no cover CHK (mean = 4.1 Mg ha^{-1}). Soybean yield at Waseca was not affected by cover crop species (mean=4.3 Mg ha^{-1}). Despite planting 9 to 18 days late for optimum yield in this region (Severson, 2013), all soybean yields were greater than the corresponding county averages during the study (3.7 and 4.1 Mg ha^{-1} for Lamberton and Waseca, respectively) (USDA-NASS, 2017a). Lower soybean yields following hairy vetch at Lamberton were likely due to poor termination of hairy vetch prior to soybean planting and subsequent competition with the soybean crop. Inadequate termination of hairy vetch with glyphosate has also been reported by Palhano et al. (2015). With the exception of hairy vetch at Lamberton, the lack of cover crop effects on subsequent soybean yield is consistent with previous reports (Reddy, 2003; Wells et al., 2014). These findings highlight the importance of complete cover crop termination, and support that soybean can be no-till planted into terminated cover crops without a yield penalty.

1.4.6. Management Efficiency. Cover crop species and planting method both affected management efficiency (Table 1-2). Directed broadcast was most efficient and DRILL was the least efficient (Fig. 1-4). This efficiency is largely influenced by speed of planting when there are no differences in cover crop biomass in the spring (benefit) and planting costs with planting method. The values used in this analysis were selected to represent the optimum planting speed for each method. Environmental conditions often necessitate speed when interseeding into corn at the seven leaf collar stage, as this is a narrow timeframe to plant all land area targeted. On average, only 3.3 days in the last week of June are suitable for in-field farm operations (USDA-NASS, 2017b). Precipitation generally occurred shortly before and after planting in this study. Therefore, the requirement for ample time with suitable field conditions may limit the potential acreage to be interseeded, and speed of planting will determine the most efficient interseeding option. With the current capacity of these planting methods, DBC was the most efficient in this study. Under wet conditions, aerial broadcast planting may be a more appropriate method while the corn canopy is still open. This method is not limited by field-workability, and can be successful if the soil is wet or rain occurs shortly after planting (Wilson et al., 2013). Planting methods that achieve greater seed-soil contact may be more successful under drier conditions (Boyd and Van Acker, 2003; Hakansson et al., 2013), although environmental conditions in this study did not serve to demonstrate this potential. A national survey of farmers (SARE-CTIC, 2016) identified cover crop establishment and time/labor required for planting and management as the top perceived challenges to integrating cover crops. This study and efficiency analysis provide a frame of reference for comparing both the speed and benefit of different establishment methods.

1.5 Conclusions. Cover crops were successfully established via interseeding into corn at the seven leaf collar stage without affecting corn yield. Subsequent soybean yield was also not affected by the previous cover crop species or planting methods, with the exception of hairy vetch at Lamberton. Winter rye was consistently among the highest in cover crop biomass and N uptake, which consequently resulted in generally lower spring soil nitrate N. The DRILL planting method, which achieved the greatest seed-soil contact, resulted in greater cover crop biomass in the fall compared to DBC for all species except pennycress, and spring cover crop biomass was increased with DRILL and DBC+INC for hairy vetch and red clover. Spring soil water content was reduced by the interseeded rye cover crop in only one of four site-years, when sufficient rye biomass was present and spring precipitation was less. Cover crops that produced >350 kg DM ha^{-1} in the spring reduced soil nitrate N compared to the no cover crop check, providing a direct improvement to water quality downstream. These findings support that 1) cover crops can be interseeded into corn at the seven leaf collar stage in the upper Midwest without risk of reducing corn yield, 2) interseeded cover crops can potentially provide ecological benefit, and 3) cover crops should be completely terminated prior to no-till planting soybean to avoid potential yield reductions.

Table 1-1. Monthly total precipitation in 2014, 2015, and 2016 and departures from the 30-yr (1984-2013) averages at Lamberton, MN and at Waseca, MN.

Month	Lamberton			Waseca		
	2014	2015	2016	2014	2015	2016
	------------------------------------- mm -------------------------------------					
January	17.5 (3)	11 (-4)	8 (-7)	36 (4)	19 (-13)	11 (-20)
February	13.0 (0)	5 (-8)	18 (5)	40 (15)	19 (-6)	22 (-4)
March	25 (-16)	10 (-31)	51 (10)	35 (-29)	29 (-35)	56 (-7)
April	87 (11)	31 (-44)	85 (9)	141 (60)	70 (-12)	50 (-31)
May	46 (-37)	139 (57)	141 (59)	73(-27)	121 (21)	95 (-5)
June	188 (82)	128 (23)	66 (-40)	328 (210)	194 (74)	121 (2)
July	30 (-65)	96 (1)	176 (81)	30 (-82)	188 (76)	227 (115)
August	94 (1)	113 (20)	135 (41)	81 (-40)	152 (32)	297 (177)
September	154 (70)	87 (3)	134 (49)	59 (-34)	149 (56)	376 (283)
October	12 (-40)	41 (-11)	72 (19)	35 (-33)	31 (-37)	79 (11)
November	13 (-21)	84 (50)	47 (13)	28 (-27)	101 (46)	41 (-13)
December	25 (6)	34 (15)	29 (10)	18 (-20)	88 (50)	54 (16)

Table 1-2. Significance of fixed effects for cover crop biomass and N uptake, soil nitrate N content, corn yield and N uptake, soybean yield, and cropping practice efficiency in response to five cover crop species planted using three methods at Waseca, MN and Lamberton MN in 2014 and 2015.

	Source of variation[†]						
Dependent variable	L	M	L × M	S	L × S	M × S	L × M × S
	------------------------------- *P* > *F* ---------------------------------						
Fall cover crop biomass	0.321	0.04	0.496	0.383	0.458	0.006	0.424
Spring cover crop biomass	0.001	0.004	0.147	0.079	0.197	0.015	0.677
Fall cover crop N content	0.325	0.198	0.71	0.206	0.115	0.058	0.188
Spring cover crop N content	<0.001	0.001	0.141	0.159	0.082	0.002	0.522
Fall soil NO_3-N content	0.75	-	-	0.75	0.356	-	-
Spring soil NO_3-N content	0.548	-	-	0.048	0.019	-	-
Corn grain yield	0.499	0.561	0.224	0.465	0.816	0.667	0.095
Corn silage yield	0.228	0.119	0.063	0.252	0.183	0.173	0.466
Corn grain N uptake	0.005	-	-	0.049	0.955	-	-
Corn silage N uptake	<0.001	-	-	0.044	0.658	-	-
Soybean grain yield	0.53	0.715	0.296	0.366	0.018	0.913	0.919
Efficiency Index	0.072	<0.001	0.054	<0.001	0.190	0.472	0.393

† L, location; M, planting method; S, cover crop species.

Table 1-3. Cover crop species effects on tissue N content in spring at Lamberton, MN and Waseca, MN.

	Tissue N Content[†]			
Planting Method	Hairy Vetch	Pennycress	Red Clover	Winter Rye
	------------------ kg N ha^{-1} ------------------			
DBC[‡]	6.7b[§]	11.7a	11.7b	21.7a
DBC+INC	14.9a	11.6a	19.4a	25.8a
DRILL	18.9a	10.8a	21.1a	26.0a

[†] Means presented for biomass and tissue N content are back-transformed from log-transformed model estimates.

[‡] DBC, direct broadcast; DBC+INC, direct broadcast with light incorporation; DRILL, high-clearance no-till drill.

[§] Within a column, means with the same letter are not significantly different at $P \leq 0.05$ according to Fisher's LSD.

Table 1-4. Effects of interseeded cover crops on spring soil NO_3-N at Waseca, MN and Lamberton, MN.

Cover crop species	Soil NO_3-N content	
	Lamberton	Waseca
	----------- kg NO_3-N ha^{-1} -----------	
No cover crop	75.2a[†]	108.9a
Winter rye	36.7b	56.3b
Pennycress	70.0a	74.4b
Red clover	79.0a	69.4b
Hairy vetch	75.3a	64.3b
MIX[‡]	67.3a	102.2a

† Within columns, means with the same letter are not significantly different at $P \leq 0.05$ according to Fisher's LSD.

‡ MIX, mixture of oat [*Avena sativa* L.], pea [*Pisum sativum* L.], and tillage radish [*Raphanus sativus* L.].

Fig. 1-1. Incorporation units consisting of a light chain and harrow-tine rake, installed with drill units lifted above the soil surface to simulate directed broadcast interseeding with light incorporation. Incorporation units were removed and drill was lowered to achieve the high-clearance drill planting method.

Fig. 1-2. Cover crop species and planting method effects on cover crop biomass in fall and spring at Lamberton, MN and Waseca, MN. DBC, direct broadcast; DBC+INC, direct broadcast with light incorporation; DRILL, high-clearance no-till drill. MIX, mixture of oat [*Avena sativa* L.], pea [*Pisum sativum* L.], and tillage radish [*Raphanus sativus* L.]. Means presented are back-transformed from log-transformed model estimates. Within cover crops, means with the same letter are not significantly different at $P \leq 0.05$ according to Fisher's LSD.

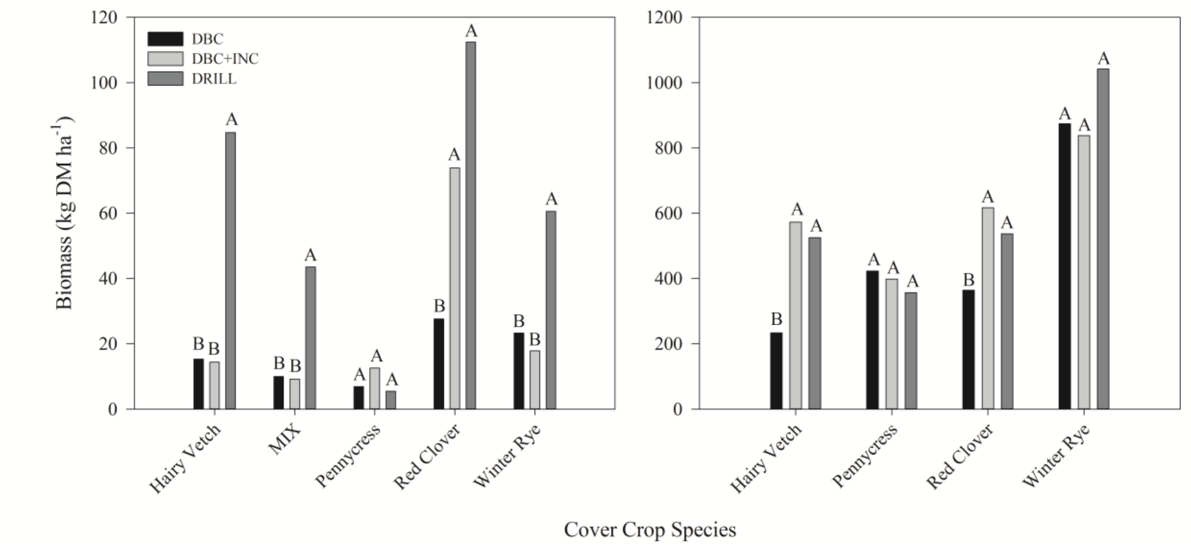


Fig. 1-3. Volumetric soil moisture at 30-cm under a rye cover crop and a no-cover crop check, shown with precipitation and cumulative Growing Degree Units (GDUs) in spring 2015 and 2016 at Lamberton, MN and Waseca, MN. Units not shown for GDUs. Vertical dashed lines indicate the day cover crops were terminated in each experiment. Within panels, means with the same letter are not significantly different according to Fisher's LSD at $P \leq 0.05$.

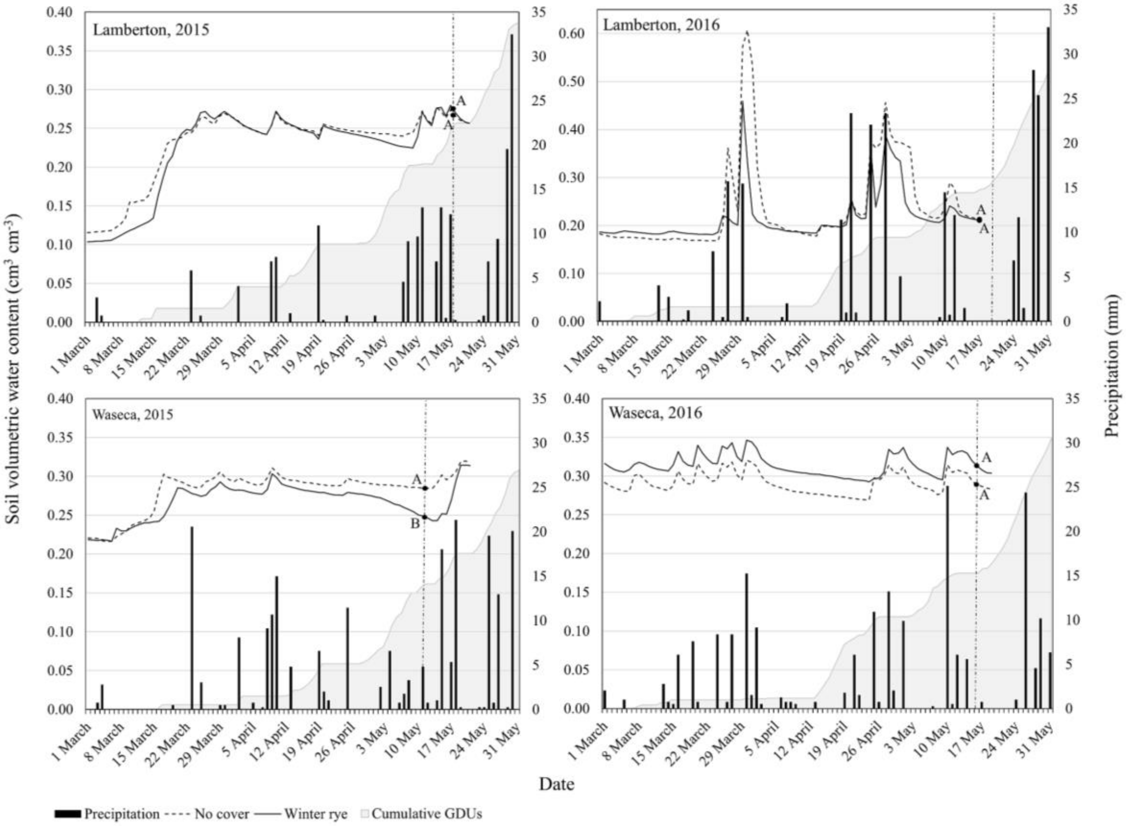
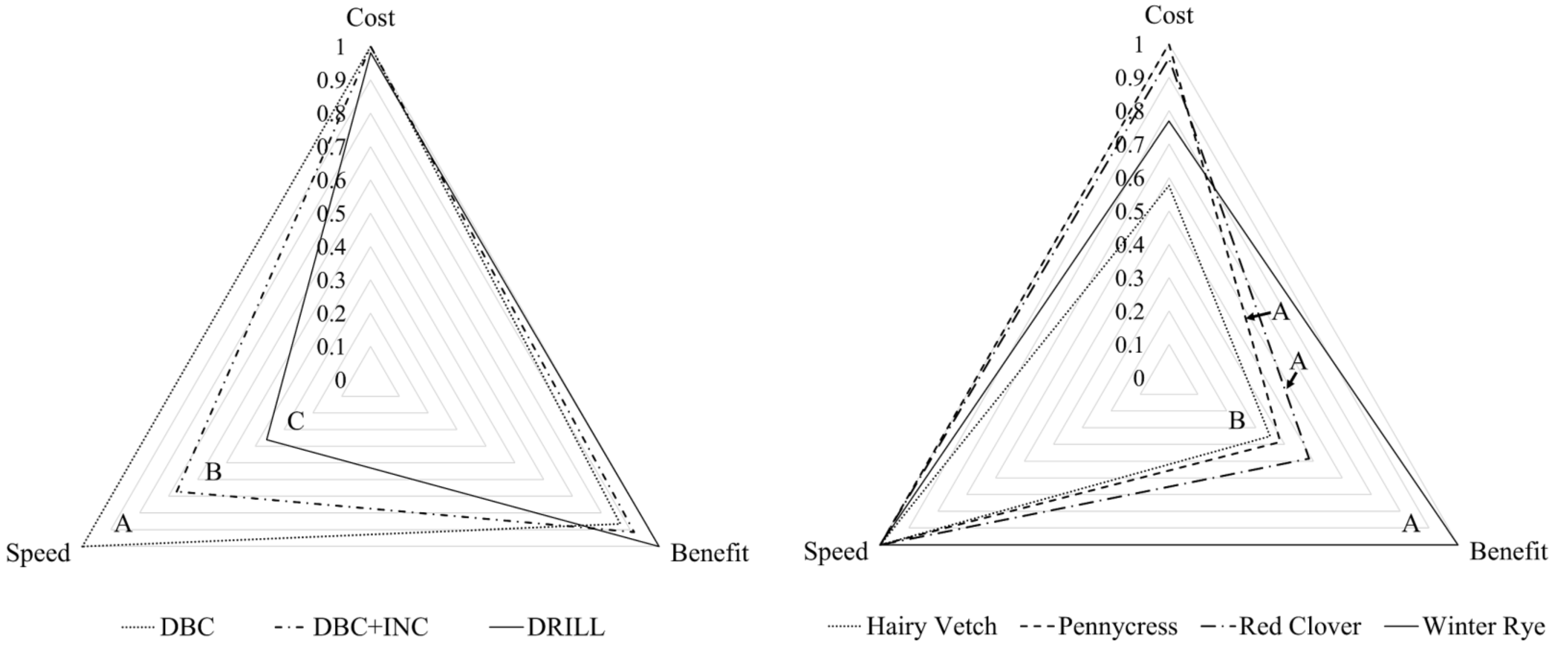


Fig. 1-4. Comparison of cost, speed, and benefit (spring cover crop biomass) of three cover crop planting methods (left) and four cover crop species (right). Means are normalized on a 0 to 1 scale, . Management efficiency is scored as the area of the triangle. Within panels, triangles with the same letter are not significantly different according to Fisher’s LSD at $P \leq 0.05$.



CHAPTER 2: DIRECT-SEEDED ANNUAL FORAGES FOLLOWING SPRING-TERMINATED ALFALFA

2.1 Summary. Winterkill of alfalfa (*Medicago sativa* L.) causes substantial yield losses in northern environments, requiring alternative forages to meet livestock needs. This study explores the forage crop yield, nutritive value and N response of seven annual forage species and one grass-legume biculture, no-till planted into spring-terminated alfalfa. Forages were planted in late-May at Rosemount, MN in 2014 and 2015 and at Waseca, MN in 2015 with split-plot factors of three N fertilizer rates (0, 56, and 112 kg N ha^{-1}) and were harvested on approximately 30-d intervals. When successfully established, teff [*Eragrotis tef* (Zuccagni) 'Summer Lovegrass'] and sudangrass [*Sorghum bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) 'PCS 3010'] were among the highest-yielding species, with yields ranging from 4.2 to 9.9 Mg DM ha^{-1} and 6.8 to 8.9 Mg DM ha^{-1}, respectively. Fertilizer N increased yields of all species at Rosemount in 2014; however, N needs were met by terminated alfalfa at both locations in 2015. Weed biomass increased with the addition of fertilizer N in site-years when weeds were present. Nitrogen fertilization did improve forage nutritive value through decreased neutral detergent fiber concentration and increased crude protein concentration and neutral detergent fiber digestibility (48-hr in-vitro) in all site-years. However, N fertilization had no effect on economic net return in two of three site-years. Annual ryegrass [*Lolium multiflorum* (Lam.) 'Jumbo'] most consistently resulted in the greatest net return. No-till

planting annual forages into terminated alfalfa can provide forage to offset losses and utilize alfalfa N in situations of alfalfa winterkill.

2.2 Introduction. Alfalfa winterkill and winter injury can have negative impacts on forage production in the northern United States (McKenzie et al. 1988; Wells et al., 2014), Canada (Bélanger et al., 2006), and northern Europe (Liatukienė et al., 2008). For example, in 2013, alfalfa winter injury and winterkill were reported by 93% of alfalfa producers surveyed across Minnesota and Wisconsin, and approximately 40% reported greater than 60% loss of alfalfa stands (Wells et al., 2014). Such losses bear major economic consequences, as alfalfa contributed an average of $10.8 billion to the U.S. economy in 2014 and 2015 (USDA-ERS, 2016). In these years, the north central United States (Michigan, Minnesota, North Dakota, South Dakota, and Wisconsin) accounted for an average 44% of the nation’s alfalfa hectarage and 38% of national production (USDA-ERS, 2016; USDA-NASS, 2016).

Effective management strategies in response to alfalfa winterkill are not well understood, as winterkill events often coincide with cold and wet spring conditions that delay planting. Additionally, the extent of damage may not be apparent with initial regrowth (Anderson and Watkins, 1991). Therefore, winterkill assessment often is too late or field conditions often are unfavorable for planting a full-season annual crop. Replanting alfalfa immediately following established alfalfa is not advised due to residual autotoxicity (Chung and Miller, 1995a; Chon et al., 2004). Delayed autotoxicity has also been reported to reduce alfalfa yields the second year after replanting (Seguin et al. 2002). Reliable alternative crops to replace the lost alfalfa need to be identified and tested.

No-till planting annual forages into winterkilled alfalfa may be a suitable low-input strategy to provide supplemental forage following alfalfa winterkill and to utilize residual N from alfalfa. Warm- and cool-season annual forage grasses can be planted in northern environments to provide supplemental forage (Peterson et al., 2007), and species have been identified with high potential for yield and forage quality (Berti et al., 2011). Additionally, many of these annual forages can tolerate intensive cutting schedules (Redfearn and Nelson, 2003; Roseberg et al., 2005) to provide a forage yield distribution meeting the needs of producers otherwise expecting a typical production year of alfalfa. Current university recommendations for supplemental forage include full-tillage and either early planting of small grains such as oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), and triticale (X *Triticosecale* Wittmack) or later planting of either silage corn (*Zea mays* L.), forage sorghum (*Sorghum bicolor* L.), sorghum-sudangrass hybrids [*Sorghum bicolor* (L.) X *S. bicolor* (L.) subsp. *drummondii* (Nees ex Steud.)], or sudangrass (Undersander, 2003; Peterson et al, 2007; Leep and Min, 2009). In partially damaged stands, Undersander (2013) recommends a mixture of Italian ryegrass (*Lolium multiflorum* Lam.) and perennial ryegrass (*Lolium perenne* L.). However, annual forages have not been assessed when no-till planted into terminated alfalfa.

Warm-season alternative forages include sorghum, sudangrass, sorghum-sudangrass hybrids, Japanese millet (*Echinochloa esculenta* A. Braun), and teff. Forage varieties of sorghum, sudangrass, and hybrids with the 'brown midrib' gene mutation have reduced lignin content and greater digestibility (Fritz et al., 1981; Collins and Fritz, 2003). As a group, these forage grasses are characterized as having high yield potential (Dial, 2012) and tolerance to low soil fertility (Moore, 2003). Japanese millet and teff are gaining interest as forage grasses in the U.S. (Roseberg et al., 2005; Lauriault, 2013; Sheahan, 2014) but have not been extensively studied as forages in the upper Midwest. Japanese millet is capable of rapidly producing forage biomass with favorable nutritive value (Yabuno, 1987; Sheahan, 2014) and can tolerate multiple harvests, with reported yields of 6.8 to 10.5 Mg DM ha^{-1} yr^{-1} (Berti et al., 2011). Teff is known for heat and drought tolerance (Girma et al., 2012), as well as tolerance of multiple harvests (Roseberg et al., 2005). Annual total yields of 8.3 to 12.0 Mg DM ha^{-1} have been reported for teff in North Dakota (Berti et al., 2011).

Cool-season options include annual ryegrass, Italian ryegrass and red clover (*Trifolium pratense* L.). Annual ryegrasses are noted as efficient scavengers of nutrients (Graber et al., 1927; Evers, 2002), and exhibit quick establishment, high nutritive value and yield potential, and excellent grazing tolerance (Moore, 2003; Redfearn and Nelson, 2003), but are less tolerant of low fertility (Redfearn et al., 2002; Barker and Collins, 2003). Yields of annual ryegrass and Italian ryegrass in Minnesota range from 6.0 to 6.5 Mg ha^{-1} under intensive cutting management (Peterson, 2004). Considering nutrient use efficiency and forage potential, ryegrasses could maximize utilization of available N from alfalfa residues. To maintain a N contribution and improve forage quality, red clover can be combined with annual ryegrass as a biculture forage option. The low fertility tolerance and taproots of red clover improve its suitability as a grass companion crop (Moore, 2003).

Nitrogen fertility and availability are important considerations following terminated alfalfa. Establishing N-demanding grass crops such as corn following established stands of alfalfa in rotation often require little or no N fertilization, as decomposing alfalfa roots and residues can provide ample N (Yost et al., 2014b). Yost et al. (2013) found no response of grain or silage yield to fertilizer N in no-till corn following alfalfa terminated either in the previous fall or in the early spring. Winterkill situations may result in less time and unfavorable (cold and wet) conditions for mineralization of alfalfa N. Additionally, N mineralization rates can be delayed in no-till systems compared to conventional tillage (Phillips et al., 1980). In the upper Midwest, no-till planting of corn, a warm season annual grass, is often less successful due to depression of soil temperatures (Smith et al, 1992). No-till planting annual forages may be a viable option to recuperate forage losses in situations of winterkilled alfalfa, yet the response to added N fertilizer also needs to be assessed.

Although alfalfa winterkill and resulting forage shortages are a common occurrence in northern environments, no-till establishment of annual forage grasses to provide supplemental forage has not been reported. Forage species of interest are brown-midrib sorghum (SORG) [*Sorghum bicolor* (L.) ‘BMR6’], sudangrass (SUDAN) [*Sorghum bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) ‘PCS 3010’], hybrid sorghum-sudangrass (SSG) (‘PCS 2020’), annual ryegrass (ARG) [*Lolium multiflorum* (Lam.) ‘Jumbo’], Japanese millet (JMIL) [*Echinochloa esculenta* (A. Braun)], Italian ryegrass (IRG) [*Lolium multiflorum* (Lam.) ‘Green Spirit’], teff (TEFF) [*Eragrotis tef* (Zuccagni) ‘Summer Lovegrass’] } and one grass-legume biculture {ARG with red clover (RC+RG) [*Trifolium pratense* (L.)]. Our objectives were to 1) quantify the forage yield and nutritive value of these seven annual forage species and one grass-legume biculture no-till planted into spring-terminated alfalfa, 2) assess the responses of these forage species to fertilizer N, and 3) gauge the economic viability of these practices according to current markets.

2.3 Materials and Methods

2.3.1 Field Experiments. Field experiments were established in 2014 and 2015 at the University of Minnesota Rosemount Research and Outreach Center near Rosemount, MN (44°42’37.34”N 93°06’10.61”W) on a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) and at the University of Minnesota Southern Research and Outreach Center near Waseca, MN (44°03’41.77”N 93°30’47.53” W) on Glencoe clay loam (fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls). Air temperature and precipitation data were obtained from weather stations located within < 2 km of the experiments (Fig. 2-1). All experiments were established in spring-terminated stands of alfalfa (‘Pioneer 55V12’ and ‘WL348AP’ at Rosemount and Waseca, respectively) that were established in 2012 at both locations. Alfalfa was in the second and third year of production in 2014 and 2015, respectively. Field sites with uniform alfalfa stands and plant densities (>20 plants m^{-2}) were selected to minimize heterogeneity within experiments. Each experiment had a split-plot arrangement of treatments in a randomized complete block design with four replications. Main plot (1.8 × 27.4 m) treatments were seven forage grasses and one grass-legume biculture that were no-till planted into terminated alfalfa and split-plot (1.8 × 9.1 m) treatments were three rates of N fertilizer (0, 56, and 112 kg N ha^{-1}) broadcast as urea ($CO(NH_2)_2$) immediately after planting. Forage species failed to establish successfully at Waseca in 2014 due to abnormally wet conditions following planting, particularly the occurrence of 33 cm of rainfall in June (Fig. 2-1); therefore, this site-year was excluded from the study.

In all experiments, alfalfa plant density, aboveground biomass, root biomass in the 0- to 15-cm depth, and soil nutritive status in the 0- to 30-cm depth were sampled 3 to 7 d before alfalfa termination (Table 2-1). All aboveground biomass was harvested by hand and roots were excavated from two representative areas (0.5 × 0.5 m) in each replication. Alfalfa roots were washed and trimmed to 15 cm before drying. Alfalfa aboveground biomass and root samples were dried at 60°C in a forced-air oven until constant mass. Composite samples of eight soil cores (2-cm diameter) were collected from each replication from the 0- to 30-cm depth and dried at 35°C in a forced-air oven. To simulate winterkill, all alfalfa in the experimental area was terminated with glyphosate [N-(phosphonomethyl) glycine] (1.74 kg a.e. ha^{-1}) when alfalfa was 0- to 15-cm tall on 16 May in 2014 at Rosemount and on 8 and 11 May in 2015 at Rosemount and Waseca, respectively.

Forages were no-till planted with a Truax Flex II-88 Grass Drill (Truax Company, Inc., New Hope, MN) into terminated alfalfa on 28 May in 2014 at Rosemount and 19 and 20 May in 2015 at Rosemount and Waseca, respectively, in rows spaced 20 cm apart. Planting rates are reported as mass of pure live seed (PLS). Brown-midrib sorghum, SUDAN, SSG, ARG, JMIL, IRG, and TEFF were planted at 39.0, 44.4, 39.0, 32.3, 33.0, 38.1, and 12.9 kg PLS ha^{-1}, respectively. In the ARG+RC grass-legume biculture, 'Jumbo' annual ryegrass and medium red clover were planted at 16.1 and 8.9 kg PLS ha^{-1}, respectively. Medium red clover seed was treated with N-Dure True Clover Inoculant (INTX Microbials, LLC, Kentland, IN) by thorough mixing fresh inoculant and seed at planting. To control weeds, experimental areas were sequentially treated immediately following planting with the identical formulation and rate of glyphosate applied prior to planting. However, some annual weeds (yellow foxtail [*Setaria pumila* (Poir.) Roem. and Schult.] and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]) emerged after crop emergence at both locations in 2015 and could not be controlled by herbicides or common cultural practices without damaging the forage crops. In each site-year, forage establishment was assessed by measuring plant density in representative plots for each species. Plant density was determined by counting plants within two 1-m sections of row for SORG, SUDAN, SSG, and JMIL, and by digging a representative 30-cm section of row to effectively separate and count plants for ARG, IRG, ARG+RC, and TEFF. Plants were counted prior to the first harvest at Rosemount in 2014 and prior to the final harvests at both locations in 2015. Visual estimates of forage crop percent ground cover were also recorded prior to the first harvest in all site-years.

Forages were harvested three times annually to emulate an intensive harvest regime for maximizing forage yield and nutritive value. In each experiment, the first harvest occurred between 7 and 18 July, the second harvest was between 6 and 20 August, and the third harvest was between 7 and 22 September. Brown-midrib sorghum, SUDAN, SSG, and JMIL were cut at 15 cm above the soil surface and TEFF, ARG, IRG, and ARG+RC were cut at 10 cm above the soil surface to allow for adequate regrowth (Moore, 2003; Redfearn and Nelson, 2003; Roseberg et al., 2005). A Carter forage harvester (Carter Manufacturing Co., Brookston, IN) was used for all harvests at Rosemount in 2014 and the second harvest at Rosemount in 2015. A swath of 0.45 m was trimmed from the borders and ends of the experimental units and the remaining 0.91 × 8.2 m within the center of the plot was harvested to measure yield. Bulk yield samples were weighed fresh and subsampled (~0.5 kg). Subsamples were weighed fresh, then dried at 60°C in a forced-air oven until constant mass to determine DM yield. Weeds contributed to total forage biomass in 2 of 3 site-years, the exception being Rosemount in 2014. Weeds were predominantly yellow foxtail and barnyardgrass. Crop and weed biomass were measured by hand harvesting three representative areas (0.4 x 0.5 m) per experimental unit at both locations in 2015. Crop and weed biomass were separated in the field at all hand harvests, then dried at 60°C in a forced-air oven until constant mass, and weighed to determine DM yield. Remaining biomass was cleared with a forage harvester after each harvest in all site-years.

2.3.2 Sample Analyses. Dried soil samples were ground to pass through a 2-mm sieve and analyzed for soil organic matter (loss on ignition), pH (1:1 soil/water), total N and organic C (combustion), NO_3-N (cd reduction), Bray-1 P, and ammonium acetate extractable K according to standard procedures described by Nathan and Gelderman (2015) (Table 2-1). Dry alfalfa biomass, alfalfa roots, and forage crop biomass samples were ground to pass through a 6-mm screen using a Thomas Wiley Mill (Thomas Scientific, Swedesboro, NJ). The coarse ground samples were mixed, subsampled (~30 g), and ground to pass through a 1-mm screen using a Cyclotec Sample Mill (FOSS North America, Eden Prairie, MN). Total N and C concentration in alfalfa roots were measured through combustion with an Elementar VarioMAX (Elementar Analysensysteme, Mt. Laurel, NJ) (Table 2-1). Alfalfa aboveground biomass and forage crop biomass subsamples were mixed thoroughly and scanned with a Perten NIRS (Model DA 7200) (Perten Instruments, Springfield, IL) using generalized hay equations developed from wet chemistry analysis on a diversity of warm- and cool-season grass species to estimate standard measures of forage nutritive value: crude protein (CP) concentration, neutral detergent fiber (NDF) concentration, and 48-hr in-vitro neutral detergent fiber digestibility (NDFd) (Oba and Allen, 1999, Satter and Roffler, 1975).

2.3.3. Economic Analyses. An assessment of partial net return was conducted in U.S. dollars based on market values and current rates for inputs and farm operations (Lazarus, 2015; Plastina and Johanns, 2016). Urea fertilizer costs averaged \$276 Mg^{-1} in May of both years according to market reports (IndexMundi, 2016). Seed costs were \$5.10, 4.36, 3.55, 2.02, 1.10 3.60, 6.14, and 8.25 kg PLS^{-1} for SORG, SUDAN, SSG, ARG, JMIL, IRG, TEFF, and ARG+RC, respectively, based on current rates from regional seed dealers (Albert Lea Seedhouse, Albert Lea, MN; and Prairie Creek Seed, Cascade, IA). Equipment and labor costs for planting, fertilizing, and harvesting were based on regional estimations of custom rates (Lazarus, 2015; Plastina and Johanns, 2016). Input costs did not account for transport and storage of the crop or costs associated with land ownership or rent. The value of the annual forages was based on regional hay market reports which associate the Relative Forage Quality index (RFQ) and current prices (UW-Extension Team Forage, 2016). Forage nutritive value of weed biomass was not measured, but was estimated to have an Relative Feed Value (RFV) of 100 based on previously reported measurements of NDF and acid detergent fiber (ADF) content of yellow foxtail (Temme et al., 1979) and barnyardgrass (Dongmeza et al., 2009). We assigned an economic value of \$60 Mg^{-1} to weed biomass based on prices paid according to RFV at a quality tested hay auction (Quality Tested Hay Auction, in Sauk Centre, MN).

2.3.4 Statistical Analyses. Statistical analyses were performed using the MIXED procedure of SAS (SAS Institute, 2012). Response variables were crop biomass, weed biomass, forage crop CP, NDF, and NDFd, and net return. Crop biomass and weed biomass were analyzed as total annual DM combined across harvests. Forage CP, NDF, and NDFd were analyzed as yield-weighted averages of annual totals (Eq. 1):

$$Yield\ weighted\ average = \sum_{i=1}^{n}\left(\frac{Yield_i}{Yield_{total}} \times FNV_i\right) \qquad [1]$$

where, for a given experimental unit, $Yield_i$ is crop biomass at the *i*th harvest, $Yield_{total}$ is the total annual biomass, and FNV_i is the corresponding forage nutritive value parameter at the *i*th harvest. To meet the requirements of normality and common variance, power transformations were applied to response variables according to the Box-Cox method (Box and Cox, 1964). Following analysis, means were back-transformed for presentation. Models for all response variables included site-year, forage species, fertilizer N rate, and their interactions as fixed effects. Random effects included block nested within site-year and the block by forage species interaction nested within site-year. A significant three-way interaction occurred between site-year, forage species, and N rate for net return; therefore, this response variable was analyzed and reported by site-year. Means were separated using Fisher's protected LSD at $P \leq 0.05$.

2.4 Results

2.4.1 Environmental Characteristics. Maximum and minimum air temperatures were cooler than the 30-yr (1984-2013) averages in April through July at Rosemount in 2014 and similar to the 30-yr averages during the remainder of the 2014 growing season and throughout 2015 at both locations (Fig. 2-1). Total precipitation from April through

October was above average in all site-years and excessive in June of 2014. Across site-years, soil pH at the 0- to 30-cm depth ranged from 5.8 to 6.2, soil P ranged from 23 to 77 mg kg^{-1}, and soil K ranged from 127 to 200 mg kg^{-1} at alfalfa stand termination (Table 2-1). Total N in alfalfa roots in the 0- to 15-cm depth ranged from 21 kg N ha^{-1} at Waseca in 2015 to 80 kg N ha^{-1} at Rosemount in 2014. Total N in aboveground alfalfa biomass ranged from 14 kg N ha^{-1} at Waseca in 2015 to 60 kg N ha^{-1} at Rosemount in 2014.

2.4.2 Forage Crop Establishment. Establishment was generally successful across forage species, although SORG, SSG, SUDAN, and TEFF each exhibited poor establishment in at least one site-year, and JMIL exhibited poor stand persistence in two site-years. In all site-years, ARG and IRG plant densities exceeded 600 plants m^{-2}, exhibiting >60% establishment of PLS planted, and annual ryegrass in the ARG+RC mixture exceeded 300 plants m^{-2} (>60% PLS established); however, red clover density was always lower than 70 plants m^{-2} (<15% PLS established). Brown-midrib sorghum and SSG had >30 plants m^{-2} (>30% PLS established) both years at Rosemount; however, at Waseca in 2015, plant densities averaged 2 and 1 plants m^{-2} for SORG and SSG, respectively (<2% PLS established). Plant densities for SUDAN were 205 and 46 plants m^{-2} at Rosemount in 2014 and 2015, respectively, but only 5 plants m^{-2} at Waseca in 2015. Initial establishment of JMIL was successful in all site-years with 422 plants m^{-2} at Rosemount in 2014 and >70% coverage (visually assessed) at both locations in 2015; however, JMIL plant densities were $\leq$ 30 plants m^{-2} (<3% PLS established) prior to the final harvest at both locations in 2015. Teff plant density was >900 plants m^{-2} (>20% PLS established) at

Rosemount in 2014 and at Waseca in 2015; however TEFF had only 47 plants m^{-2} at Rosemount in 2015 (<1% PLS established).

2.4.3 Crop and Weed Biomass. Total forage crop biomass was affected by the interaction between forage species and site-year, and by the interaction between fertilizer N rate and site-year (Table 2-2). Teff had greater yields than SORG, IRG, and SSG at Rosemount in 2014 (Fig. 2-2). In contrast, sudangrass was the highest-yielding species at Rosemount in 2015 but TEFF was the lowest-yielding. Annual ryegrass and TEFF had greater yields than ARG+RC, SUDAN, SORG, and SSG at Waseca in 2015. Fertilizer N increased forage yield of all crops with each increase in N rate at Rosemount in 2014; across forage species, crop biomass was 8.1, 8.8, and 9.5 Mg DM ha^{-1} with 0, 56, and 112 kg N ha^{-1}, respectively. Fertilizer N did not affect crop biomass at either location in 2015. Distribution of forage yield across harvests was relatively consistent between forage species and across site-years, with the second harvest frequently accounting for the greatest proportion of season total yield. Among species, the first harvest accounted for 20 to 31%, the second harvest accounted for 37 to 59%, and the third harvest accounted for 18 to 37% of total season yields.

Weed biomass (yellow foxtail and barnyardgrass) was affected by fertilizer N rate, and by the interaction between forage species and site-year (Table 2-2). Addition of 56 or 112 kg N ha^{-1} resulted in greater weed biomass (mean = 2.5 Mg DM ha^{-1}) than 0 kg N ha^{-1} (2.1 Mg DM ha^{-1}). Sudangrass had the least weed biomass, whereas weed biomass was greatest with JMIL, ARG+RC, and TEFF at Rosemount in 2015 (Fig. 2-2). In contrast, weed biomass at Waseca in 2015 was among the lowest with TEFF, ARG, IRG, and JMIL, while SORG, SSG, and SUDAN had the highest weed biomass.

2.4.4 Forage Crop Nutritive Value

2.4.4.1 Crude Protein. Forage crop CP concentration was affected by N rate, and by the interaction between forage species and site-year (Table 2-2). Averaged across all site-years and species, forage crop CP concentration was 105, 114, and 121 g kg^{-1} CP with 0, 56, and 112 kg N ha^{-1}, respectively. Italian ryegrass had greater CP concentration than that of all other forage species at Rosemount in both years. Teff, SUDAN, SORG, and JMIL were among species with the least CP concentration at Rosemount in 2014, and SUDAN and SORG were among the least in 2015 (Table 2-3). Similarly, forage CP concentration was greatest with IRG, ARG+RC, and SSG, and was least with TEFF, SUDAN, and JMIL at Waseca in 2015.

2.4.4.2. Neutral Detergent Fiber: Forage crop NDF concentrations were affected by the interaction between forage species and site-year, the interaction between fertilizer N rate and site-year, and the interaction between forage species and fertilizer N rate (Table 2-2). Averaged across all forage species, fertilizer N rate did not affect forage NDF concentration at Waseca in 2015. However, NDF concentration was greater with 0 kg N ha^{-1} (608 g kg^{-1} NDF) compared to 56 or 112 kg N ha^{-1} (mean = 592 g kg^{-1} NDF) at Rosemount in 2014, and with 0 kg N ha^{-1} (618 g kg^{-1} NDF) compared to 56 or 112 kg N ha^{-1} (mean = 600 g kg^{-1} NDF) at Rosemount in 2015. Among forage species, increasing N fertilizer rate did not affect NDF concentration for IRG, ARG+RC, SSG, or SUDAN.

Forage NDF concentration was greater with 0 kg N ha^{-1} (613; 621; and 633 g kg^{-1} NDF) compared to 56 and 112 kg N ha^{-1} (mean = 594; 596; and 605 g kg^{-1} NDF) in SORG, JMIL, and TEFF, respectively. Addition of 112 kg N ha^{-1} decreased NDF concentration (551 g kg^{-1} NDF) compared to 0 and 56 kg N ha^{-1} (mean = 570 g kg^{-1} NDF) in ARG. Forage NDF concentration was least with IRG at Rosemount in both years, (Table 2-3). Teff and SSG were among the greatest at Rosemount in 2014 and SORG, SSG, and SUDAN had the greatest NDF concentration at Rosemount in 2015. Teff also had the greatest NDF concentration at Waseca in 2015 and IRG and ARG+RC were among the least in NDF.

2.4.4.3 Neutral detergent fiber digestibility: Forage crop NDFd was affected by fertilizer N rate, and by the interaction between forage species and site-year (Table 2-2). Averaged across all species and site-years, forage NDFd increased with each rate increase in N fertilization; the 0, 56, and 112 kg N ha^{-1} resulted in 626, 645, and 659 g kg^{-1} NDFd, respectively. Forage NDFd was greater for IRG than all other species, and was the least for JMIL at Rosemount in both years (Table 2-3). Italian ryegrass, SORG, and SSG were among the greatest NDFd at Waseca in 2015, and JMIL and TEFF had the least NDFd.

2.4.5. Net Return. Economic net return was affected (*P* = 0.047) by the interaction between fertilizer N rate and forage species at Rosemount in 2014, and the forage species main effect influenced net return in all site-years (*P* < 0.001). Addition of fertilizer N did not affect economic net return at either location in 2015. Regarding the interaction, fertilizer N rate did not affect net return for SORG, JMIL, SSG, or TEFF at Rosemount in 2014; however, 112 kg N ha^{-1} resulted in higher net return ($1304 ha^{-1}) than 0 kg N ha^{-1} (942 $ ha^{-1}) for ARG. Addition of 112 kg N ha^{-1} resulted in higher net return ($1150 and 1250 ha^{-1}) than 0 and 56 kg N ha^{-1} (mean = $847 and 702 ha^{-1}) for IRG and SUDAN, respectively; and 56 and 112 kg N ha^{-1} resulted in higher net return (mean = $1273 ha^{-1}) than 0 kg N ha^{-1} ($959 ha^{-1}) for ARG+RC. The ARG+RC biculture and ARG were among the greatest net return, and JMIL, TEFF, and SSG were among the lowest at Rosemount in 2014 (Table 2-4). Italian ryegrass, ARG, SUDAN, and SSG were among the greatest in net return and TEFF resulted in the lowest net return at Rosemount in 2015. Annual ryegrass resulted in higher net return than all other forage species at Waseca in 2015, and SORG, SSG, and SUDAN were among the lowest.

2.5. Discussion. This work demonstrates that annual forage grasses can be no-till planted into terminated alfalfa as a viable source of supplemental forage; however, the findings of this study also highlight variability and risk associated with this cropping strategy. No-till planting likely resulted in cooler soil temperatures (Licht and Al-Kaisi, 2005), which probably affected forage crop establishment (Herbek et al., 1986) as well as N mineralization rate (Phillips et al., 1980; Agehara and Warncke, 2005). Establishment issues in the current study only occurred with warm-season grasses (TEFF at Rosemount and SORG, SSG, and SUDAN at Waseca in 2015). This aligns with previous reports of reduced sorghum establishment when no-till planted into high levels of surface residue

(Doran et al., 1984) and reduced corn establishment when no-till planted into cool wet soil (Herbek et al., 1986). Total N in alfalfa roots in the 0- to 15-cm depth plus aboveground biomass ranged from 35 kg N ha^{-1} at Waseca in 2015 to 139 kg N ha^{-1} at Rosemount in 2014 (Table 2-1). This is consistent with literature (Yost et al., 2014a, b) summarizing university guidelines that recommend reduced alfalfa N credits to corn for thinner alfalfa stands. However, the highest levels of measured alfalfa N did not always result in a reduced or eliminated response to N fertilization, as shown by the positive yield response to N fertilizer at Rosemount in 2014. Furthermore, terminating alfalfa in the spring rather than the fall to simulate winterkill may have delayed the onset of mineralization of alfalfa-derived organic N compared to actual winterkill situations. In light of the variability and risk inherent in alfalfa winterkill situations, this work demonstrates that management practices with the most consistent establishment, forage yield, and nutritive quality will be the most reliable in practice.

Annual forage crops generally exhibited a balanced distribution of yield across harvests under the intensive cutting schedule applied. This reflects a harvest frequency similar to alfalfa and implies that these annual species can provide forage coinciding with the time-sensitive needs of producers. Total crop biomass was similar to or greater than yields previously reported for all species (Sedivec and Schatz, 1991; Redfearn et al., 2002; Berti et al., 2011) at Rosemount in 2014, but generally lower at both locations in 2015 (Fig. 2-2). The previous studies planted forages into prepared seedbeds and did not report issues with weeds. Reduced crop biomass coincided with the occurrence and level of weed biomass at both locations in 2015. When all forage species established well, weeds were not an issue as evident at Rosemount in 2014. Across site-years, ARG and IRG were most consistent in acceptable stand establishment and crop biomass, while SSG was frequently among the lowest yielding. Teff and SUDAN showed the highest crop biomass potential when successfully established, however poor establishment was an issue with each of these species in at least one site-year. Fertilizer N only increased forage crop biomass at Rosemount in 2014. This was likely due to reduced mineralization of alfalfa residues under colder-than-normal air temperatures (Agehara and Warncke, 2005) throughout the first half of the 2014 growing season (Fig 2-1). This is consistent with reports of positive responses to N fertilizer in wheat no-till planted into terminated alfalfa (Westerman and Crothers, 1993), inferring that mineralization was not adequate early enough in the year to support the cool-season cereal crop. Crop biomass was not affected by added fertilizer N at either location in 2015, confirming the supply of adequate N following alfalfa within no-till systems (Yost et al., 2013), although only a total of 35 kg N ha^{-1} was measured in aboveground biomass and alfalfa roots to a depth of 15 cm (Table 2-1). This suggests that alfalfa-derived organic N beyond the range measured likely contributed to the N credit, or that other factors may have been limiting in this site-year.

Weeds were present and competitive with forage crops in 2 of 3 site-years in this study. This contrasts previous research reporting allelopathic weed suppression from alfalfa residue (Chung and Miller, 1995b). The only site-year where weeds were not an issue was Rosemount in 2014 which also had the highest previous alfalfa stand density (Table 2-1). This aligns with reports of increased weed populations with decreasing alfalfa stand density (Cummings et al., 2004) although the presence of weeds between locations in 2015 did not seem to be influenced by differences in plant density of the previous alfalfa stands. At each location in 2015, forage species with poor establishment consistently resulted in the highest in weed biomass (Fig 2-2). Among successfully established species, the annual ryegrass and red clover biculture commonly resulted in the greatest weed biomass, and was only among the highest yielding forage species when weed competition was not an issue at Rosemount in 2014. In all site-years, establishment of red clover ranged from only 7 to 13% of pure live seed planted, whereas 64 to 74% of annual ryegrass seed successfully established. This is consistent with the findings of Klebesadel and Smith (1959) who report reduced red clover establishment and vigor under companion crops that cause early and extended shading. Poor establishment of red clover, in addition to the reduced ryegrass seeding rate, may explain the increased weed biomass observed in this treatment. Alternatively, ARG and IRG seeded at full rates established successfully in all site-years and were consistently among the lowest in weed biomass. Other work has reported equal or greater fertilizer N uptake by weeds than by the intended crop (Blackshaw et al., 2003). This aligns with the current study, where weed biomass was increased with N fertilization in site-years with no crop yield N response, providing additional justification for withholding N fertilizer for annual forages when following alfalfa. With increasing alfalfa stand age, both the likelihood of winterkill (McKenzie et al., 1988) and the incidence of subsequent weed issues (Cummings et al., 2004) are expected to increase; therefore, management considerations should anticipate weeds issues in alfalfa winterkill situations. In this study, ARG and IRG demonstrated reliable establishment under no-till conditions and most consistently resulted in lower weed biomass.

Forage nutritive value parameters are discussed from the perspective of dairy feed quality, as this is the primary use of alfalfa in the northern United States and Canada. Sloan et al. (1988) and Roffler et al. (1978) reported greater milk yield as CP increased from 157 to 187 g kg^{-1} CP, and from 122 to 162 g kg^{-1} CP, respectively. Colmenero and Broderick (2006) reported that CP greater than 165 g kg^{-1} did not increase milk yield. In the current study, CP did not exceed 144 g kg^{-1}. Therefore, protein supplementation may be required to optimize milk yield with these forages. Reported average NDF for alfalfa ranges from 419 to 490 g kg^{-1} and NDFd ranges from 325 to 460 g kg^{-1} (Collins, 1988; Lamb et al., 2006). For the forage grasses in this study, NDF ranged from 507 to 645 g kg^{-1} and NDFd ranged from 571 to 765 g kg^{-1}. It is well understood that greater dry matter intake is achieved at lower NDF concentrations (Briceno et al., 1987; Kendall et al., 2009), and milk yield potential increases with increasing NDFd (Oba and Allen, 1999; Kendall et al., 2009). Compared to alfalfa, the forage species in this study had generally greater NDF, but also greater NDFd, indicating that these forages could serve as a partial replacement of alfalfa in dairy feeds. Forage nutritive values for all species were similar to previously reported values (Sedivec and Schatz, 1991; Redfearn et al., 2002; Berti et al., 2011), and Italian ryegrass most consistently produced the highest forage CP and NDFd and the lowest NDF concentration, followed by ARG+RC and ARG (Table 2-3). Teff, JMIL, SORG, SSG, and SUDAN frequently resulted in forage with lower CP, higher NDF, and lower NDFd compared with the ryegrass forages (Table 2-3), which aligns with literature reporting greater forage digestibility among C_3 grasses compared to C_4 grasses (Akin et al., 1983; Akin, 1989). Forage nutritive value was also generally improved with fertilizer N compared to the non-N-fertilized control. These findings are consistent with reports of luxury consumption of available N by annual forage grasses and corresponding increases in CP (Marino, et al., 2001; Beyaert and Roy, 2005; Roseberg et al., 2005). It should also be considered that in actual winterkill of alfalfa, there can be incomplete termination of the stand (Wells et al., 2014), and surviving alfalfa can contribute to the yield and nutritive value of the forage crop harvested. Overall, our findings suggest that IRG, ARG, and ARG+RC would be the most valuable dairy feed replacement to buffer lost alfalfa production.

Net return of the management options investigated was largely driven by the varying costs of seed and fertilizer N costs, in addition to forage yield and nutritive value. The added cost of N fertilizer was only justified with increased net return for ARG, IRG, ARG+RC, and SUDAN at Rosemount in 2014. This correlates to observed increases in both yield and forage quality in this site-year, and supports the efficient use of available N by the ryegrass forages reported in the literature (Graber et al., 1927; Evers, 2002). Fertilizer N had no effect on net return in all other site-years, consistent with the lack of a positive yield response to fertilizer N. Annual ryegrass was consistently among the greatest in net return, and SORG, JMIL, SSG, SUDAN, and TEFF generally resulted in lower net return (Table 2-4). Sheaffer et al. (2014) reported net return for an alfalfa establishment year with an annual ryegrass companion crop to range from \$283 to 2055 ha^{-1} with a mean \$1078 ha^{-1}. In the current study, net returns for ARG ranged from \$446 to 1110 ha^{-1}, indicating the economic viability was comparable to an establishment year of alfalfa with a companion crop in a similar environment. In some cases, net returns of higher-yielding forage species were lower due to higher seed cost. For example, SUDAN, SSG, and SORG averaged over 100% greater crop biomass than JMIL at Rosemount in 2015 (Fig. 2-2); however, economic net return was similar among these four species (Table 2-4) due to the lower cost of JMIL seed. Variation in forage nutritive value also contributed to differences in economic net return; TEFF and JMIL had similar biomass compared to ARG at Rosemount in 2014 and at Waseca in 2015 (Fig. 2-2), yet ARG had greater economic net return in both of these site-years (Table 2-4).

2.6. Conclusions. No-till planting annual forages into terminated alfalfa is an economically viable strategy in response to alfalfa winterkill. Teff and SUDAN were frequently among the highest-yielding species, although these species each established poorly in one of three site-years. Italian ryegrass, ARG, and ARG+RC consistently provided the greatest forage nutritive value, and SORG, JMIL, SSG, SUDAN, and TEFF generally the least. From a management perspective, ARG and IRG were most consistent to establish and were consistently among the highest yielding and the highest forage nutritive value. This work suggests that ARG is the most reliable and economically viable option to mitigate risk in a winterkill situation. Italian ryegrass is also a reliable option to achieve greater forage nutritive value, but at a greater seed cost. The selected forage species exhibited efficient utility of the alfalfa N credit, as the addition of fertilizer N was not justified economically in two of three site-years. Appropriate management practices depend on current market status and specific goals of the producer. This research establishes the potential for economically viable forage production from annual forage species no-till planted into terminated alfalfa. Future work is needed to assess factors affecting stand establishment and weed management strategies for annual forage grasses no-till planted into terminated alfalfa.

Table 2-1. Alfalfa and soil characteristics at Rosemount and Waseca, MN in the spring prior to alfalfa stand termination in 2014 and 2015.

	2014	2015	
Characteristic	Rosemount	Rosemount	Waseca
Alfalfa			
Height, cm	18	20	25
Plant density, plants m^{-2}	334	157	27
Root biomass (0-15 cm), Mg DM ha^{-1}	3.9	2.9	1.2
Aboveground biomass, Mg DM ha^{-1}	1.3	1.4	0.4
Root N (0-15 cm), kg N ha^{-1}	79.6	49.2	21.2
Root C:N	18.7	24.9	24.2
Aboveground biomass N, kg N ha^{-1}	59.7	49.4	14.1
Soil, 0-30 cm			
Soil organic matter, g kg^{-1}	3.9	4.0	3.9
pH	6.1	6.2	5.8
Total N, g kg^{-1}	1.5	2.0	2.0
Organic C, g kg^{-1}	20.5	22.3	22.7
NO_3-N, mg kg^{-1}	1.3	1.5	0.5
K, mg kg^{-1}	184	127	200
Bray-1 P, mg kg^{-1}	77	56	23

Table 2-2. Significance of fixed effects for annual total crop biomass, annual total weed biomass, forage crop crude protein (CP), neutral detergent fiber (NDF), neutral detergent fiber digestibility (48-hr in-vitro) (NDFd) of forages at Rosemount, MN in 2014 and 2015 and at Waseca, MN in 2015.

	Dependent Variable				
	Crop biomass	Weed biomass	Crude protein	NDF	NDFd
Sources of variation	------------------------------- $P > F$ ------------------------------- --				
Site-year	<0.001	0.099	<0.001	<0.001	0.127
Forage species (FS)	0.002	<0.001	<0.001	<0.001	<0.001
Site-year × FS	<0.001	<0.001	<0.001	<0.001	<0.001
N rate	0.022	0.025	<0.001	<0.001	<0.001
Site-year × N rate	0.001	0.737	0.060	0.022	0.082
FS × N rate	0.174	0.266	0.121	0.005	0.141
Site-year × FS × N rate	0.381	0.947	0.150	0.242	0.079

Table 2-3. Forage nutritive value of eight forage crops with three fertilizer N rates at Rosemount, MN in 2014 and 2015 and at Waseca, MN in 2015.

	CP	NDF	NDFd
	---------------------------- g kg^{-1} ------------------------		
Rosemount 2014			
ARG†	106 b§	577 d	641 cd
ARG+RC	107 b	572 d	644 b-d
IRG	139 a	513 e	765 a
JMIL	101 bc	604 c	511 f
SORG	100 bc	618 bc	658 bc
SSG	108 b	625 ab	668 b
SUDAN	93 c	620 b	626 d
TEFF	97 c	635 a	580 e
Rosemount 2015			
ARG	114 bc	579 c	652 bc
ARG+RC	112 c	580 c	639 bc
IRG	133 a	555 d	701 a
JMIL	98 d	615 b	571 e
SORG	91 de	634 a	640 bc
SSG	98 d	645 a	660 b
SUDAN	87 e	638 a	606 d
TEFF	124 ab	592 c	624 cd
Waseca 2015			
ARG	129 bc	532 ef	649 c
ARG+RC	143 a	522 fg	654 c
IRG	144 a	507 g	704 a
JMIL	116 d	594 b	571 d
SORG	127 c	544 de	695 a
SSG	139 ab	561 cd	684 ab
SUDAN	116 d	570 c	655 bc
TEFF	114 d	617 a	599 d

† ARG, *Lolium multiflorum* cv 'Jumbo;' ARG+RC, biculture of *Lolium multiflorum* cv 'Jumbo' and *Trifolium pratense* (L.); IRG, *Lolium multiflorum* (Lam.) 'Green Spirit;' JMIL, *Echinochloa esculenta* (A. Braun); SORG, *Sorghum bicolor* (L.) 'BMR6;' SSG, *Sorghum bicolor* (L.) X *S. bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) 'PCS 2020;' SUDAN, *Sorghum bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) 'PCS 3010;' TEFF, *Eragrotis tef* (Zuccagni) 'Summer Lovegrass.'

§ Within columns, means with the same letter are not significantly different at $P \leq 0.05$.

Table 2-4. Partial economic net return of eight annual forage crops at Rosemount, MN in 2014 and 2015 and at Waseca, MN in 2015.

Forage species	2014	2015	
	Rosemount	Rosemount	Waseca
	------------------------------	$\$$ ha^{-1}	------------------------------
ARG†	1110 ab§	529 ab	446 a
ARG+RC	1168 a	293 c	222 b
IRG	948 bc	600 a	232 b
JMIL	657 e	356 bc	135 b-d
SORG	889 cd	423 bc	-41 e‡
SSG	835 c-e	469 ab	-3 de‡
SUDAN	884 cd	469 ab	82 c-e‡
TEFF	745 de	96 d‡	234 b

† ARG, *Lolium multiflorum* cv ‘Jumbo;’ ARG+RC, biculture of *Lolium multiflorum* cv ‘Jumbo’ and *Trifolium pratense* (L.); IRG, *Lolium multiflorum* (Lam.) ‘Green Spirit;’ JMIL, *Echinochloa esculenta* (A. Braun); SORG, *Sorghum bicolor* (L.) ‘BMR6;’ SSG, *Sorghum bicolor* (L.) X *S. bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) ‘PCS 2020;’ SUDAN, *Sorghum bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) ‘PCS 3010;’ TEFF, *Eragrotis tef* (Zuccagni) ‘Summer Lovegrass.’

‡ Denotes poor forage species establishment (<10% coverage) in a given site-year.

§ Within columns, means with the same letter are not significantly different at $P \leq 0.05$.

Fig. 2-1. Monthly average minimum and maximum air temperatures and monthly total precipitation in 2014 and 2015 compared to the 30-yr (1984-2013) average at Rosemount, MN (top) and at Waseca, MN (bottom).

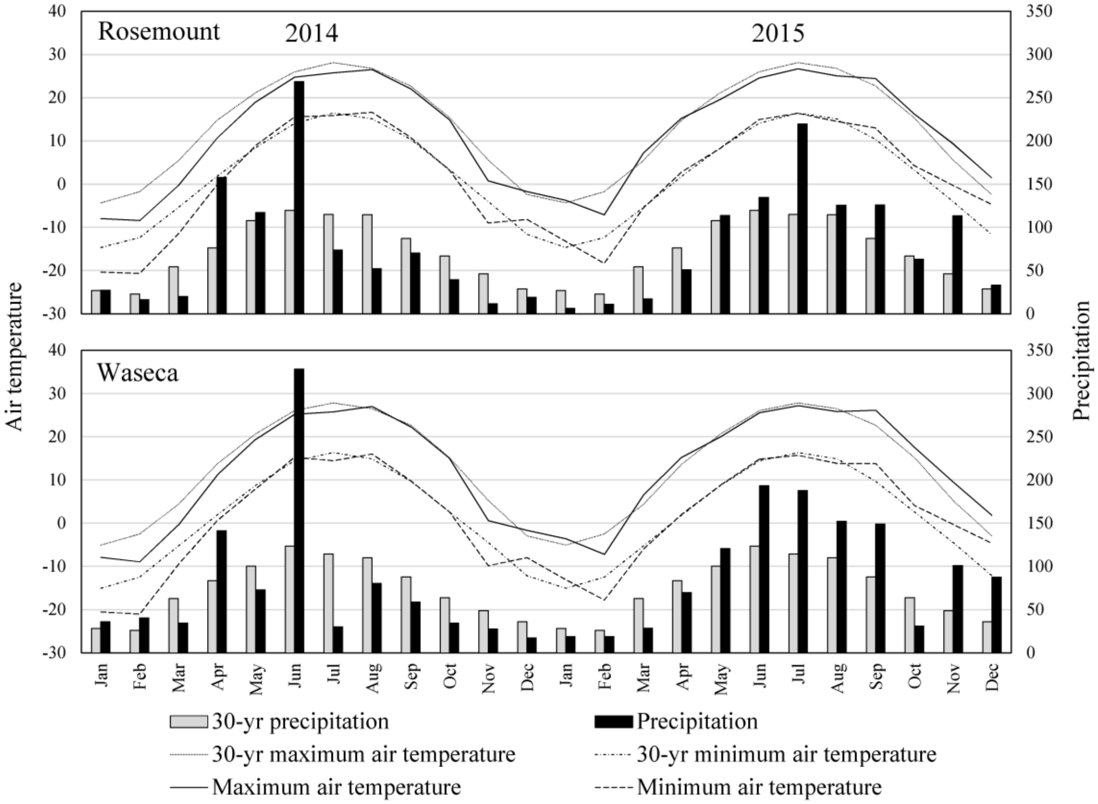
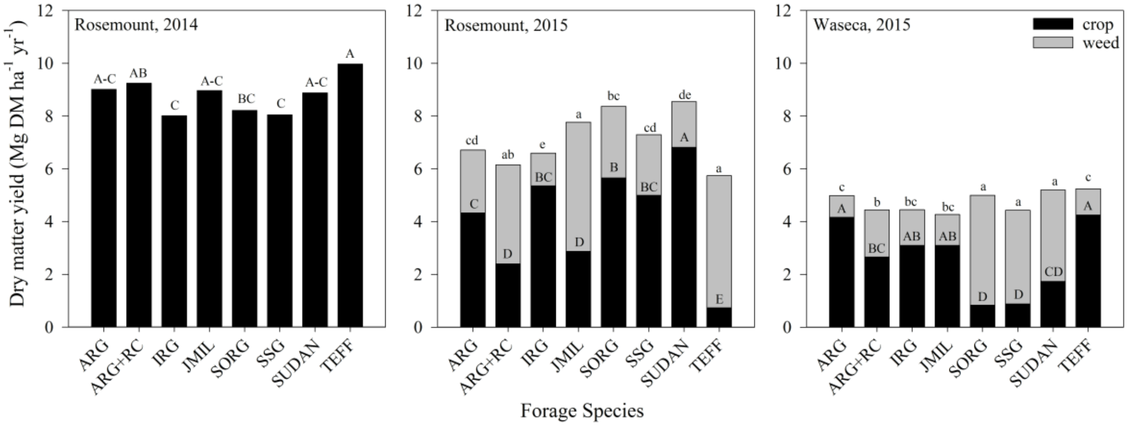


Fig. 2-2. Total annual crop and weed dry matter yields for eight warm-season annual forage crops at Rosemount, MN in 2014 (left) and 2015 (center) and at Waseca, MN in 2015 (right). Within a site-year, bars with the same uppercase letter did not differ in crop dry matter yield ($P \leq 0.05$) and bars with the same lowercase letter did not differ in weed dry matter yield ($P \leq 0.05$). ARG, *Lolium multiflorum* cv ‘Jumbo;’ ARG+RC, biculture of *Lolium multiflorum* cv ‘Jumbo’ and *Trifolium pratense* (L.); IRG, *Lolium multiflorum* (Lam.) ‘Green Spirit;’ JMIL, *Echinochloa esculenta* (A. Braun); SORG, *Sorghum bicolor* (L.) ‘BMR6;’ SSG, *Sorghum bicolor* (L.) X *S. bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) ‘PCS 2020;’ SUDAN, *Sorghum bicolor* (L.) subsp. *drummondii* (Nees ex Steud.) ‘PCS 3010;’ TEFF, *Eragrotis tef* (Zuccagni) ‘Summer Lovegrass.’ Forage species exhibiting poor establishment (<5% live seed planted) were TEFF at Rosemount in 2015 and SORG, SSG, and SUDAN at Waseca in 2015.



CHAPTER 3: ESTIMATING ALFALFA YIELD AND NUTRITIVE VALUE WITH REMOTE SENSING AND ENVIRONMENTAL FACTORS

3.1 Summary. In-field estimations of alfalfa yield and nutritive value can inform management decisions to optimize forage quality and production. However, acquisition of timely information at the field scale is limited using traditional measurements such as destructive sampling and assessment of plant maturity. Remote sensing technologies (e.g. measurement of canopy reflectance) have the potential to enable rapid measurements at the field scale. Canopy reflectance (350-2500 nm) and LiDAR-estimated canopy height were measured in conjunction with destructive sampling of alfalfa across a range of maturity at Rosemount, MN in 2014 and 2015. The full range of reflectance data was processed with stepwise regression using the Bayesian Information Criterion to identify individual wavebands most correlated with alfalfa nutritive value. Models were reduced by spectral range and number of wavebands to improve model utility., and cumulative Growing Degree Units (GDUs) and canopy height were added as predictors. Optimum predictions of R^2 = 0.89, 0.91, 0.89, 0.87 for yield, crude protein, neutral detergent fiber, and neutral detergent fiber digestibility (48-hr in-vitro). This research establishes potential for remote sensing measurements to be integrated with environmental information to achieve rapid and accurate predictions of alfalfa yield and nutritive value at the field scale for optimized harvest management.

3.2 Introduction. Alfalfa is the most valuable and intensively produced forage crop in the U.S, and precise management is critical to optimize profitability (Bouton, 2007). Accurate, in-situ estimations of alfalfa yield and nutritive value can could inform timing of harvest , although rapid methods capable of accurate predictions at the field-scale need to be developed. In-situ estimations of forage yield and nutritive value can be categorized into three general groups: 1) environment-based estimations, 2) contact measurement, and 3) non-contact measurement. These general classes vary in accuracy and utility, and are not commonly used in production.

Environment-based estimations use known weather data at a given location to predict stages of crop growth and development. Examples include predictions based on cumulative Growing Degree Units (GDUs), rainfall, or changes in day length. Environmental predictors have been used to estimate both alfalfa yield (Smeal et al. 1991) and quality (Sulc et al., 1999). Traditional GDU calculations for alfalfa use a static base temperature (5°C); however, Sharrat et al. (1998) report that the optimum GDU base temperature for alfalfa may change throughout the growing season, from 3.5°C early in the growing season to 10°C later in the summer. Predictions of nutritive value based only on cumulative GDUs have limited accuracy (Sulc et al., 1999), but the use of a modified GDU scale has not been investigated for predictions of alfalfa nutritive value. The two primary advantages of using environmental data are that generally it is free and easily accessible, and applications can be automated to use real-time information, requiring little to no cost or labor.

Contact measurement involves physical sampling and direct measurement of a parameter (i.e. crop maturity, height, or chemical analyses for nutritive value). Maturity assessments include averaging numerical growth stages weighted by number of stems [mean growth stage by count (MSC)] or plant mass within each group [mean growth stage by weight (MSW)] (Kalu and Fick, 1981). Maturity indices are reported to be highly predictive of alfalfa nutritive value; for example, MSW predicted alfalfa crude protein ($R^2 = 0.88$), neutral detergent fiber ($R^2 = 0.95$), acid detergent fiber ($R^2 = 0.90$) and lignin ($R^2 = 0.84$) (Kalu and Fick, 1983). Hintz and Albrecht (1991) report predictions based on node number and plant height can provide more rapid predictions with accuracy similar to or greater than MSC and MSW. Owens et al. (1995) report that using the PEAQ system based on the maturity of the most mature stem, and the height of the tallest stem provides accurate estimates of fiber composition ($R^2 = 0.72$ for NDF and ADF), but are less predictive for CP ($R^2 = 0.37$). As another contact measurement, Lyons et al. (2016) show potential for alfalfa height to predict yield ($R^2 = 0.66$). These methods are consistently demonstrated as valuable indicators, although it is difficult to accurately represent an entire field with contact measurement, considering time and labor requirements. Additionally, the accuracy of these methods may fluctuate across varying environmental conditions (Sanderson, 1992), and with new reduced-lignin alfalfa cultivars (Grev et al., 2017).

Non-contact measurement involves estimations based on remote sensing technologies such as measurement of canopy reflectance, infrared measurement of canopy temperature, and SONAR or LiDAR based estimates of height. Precision crop management tools (remote sensing and UAVs) are being developed and implemented in many crops as technology becomes more affordable and specific applications are developed (Mulla, 2013). Spectral vegetative indices (SVIs) are functions of canopy reflectance developed to assess ground cover, crop health, drought stress, and nutrient deficiencies in several major crops. These remote sensing tools can be integrated into UAV (Unmanned Aerial Vehicle) platforms to enable real-time assessments of crop nutritive value parameters at the field scale (Zhang and Kovacs, 2012). Recent research has demonstrated the potential for measurement of canopy reflectance to predict nutritive value in alfalfa monocultures (Starks et al., 2016) as well as perennial forage grasses (Starks et al., 2006). Starks et al. (2016) report predictions based on canopy reflectance to estimate CP (R^2 = 0.78), NDF (R^2 = 0.77), and ADF (R^2 = 0.83). In addition to measurement of canopy reflectance, ultra-sonic or LiDAR (Light Detection and Ranging) technology can enable remote measurement of crop height and facilitate improved estimations of crop biomass (Pittman et al., 2015). Crop height is also related to alfalfa nutritive value (Owens et al., 1995), and remote estimations of height may improve predictions. These tools, however, have not been developed for practical estimations of alfalfa nutritive value, and their efficacy has not been compared to traditional methods.

Remote measurements of canopy reflectance and crop height have potential to inform alfalfa management decisions at the field scale; however, the costs of these technologies are currently prohibitive in on-farm applications and these tools have not been tested in combination with environment-based estimations. The cost of spectral measurement technology increases with increasing spectral range and resolution of the instrument. Tools may be developed that use fewer wavebands, of lower resolution, achieving a more affordable application, and may be combined with free environmental data (GDDs or rainfall) to improve the utility of these technologies. The objectives of this research were 1) to develop a system of in-situ alfalfa assessment that, in contrast to previous systems, integrates environmental data with remote sensing data for improved predictability, and 2) to determine whether measurement of a reduced set of wavebands (fewer wavebands with lower resolution in easily measureable ranges of the spectrum) can be combined with environmental factors such as cumulative growing degree units to facilitate rapid and accurate predictions of alfalfa nutritive value.

3.3 Materials and Methods.

3.3.1 Field Experiments. Field experiments were conducted in 2014 and 2015 at the University of Minnesota Rosemount Research and Outreach Center near Rosemount, MN (44°42’37.34”N 93°06’10.61”W) on a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). Sites were fertilized with K and S according to soil requirements for alfalfa production, and irrigated to meet monthly average precipitation levels. Air temperature and precipitation data were obtained from weather stations located within < 1 km of the experiments (Table 3-1).

The experimental approach was to measure canopy reflectance from alfalfa stands of varying maturity established by delayed mowing. In 2014 data were collected from a stand of ‘Dekalb 4401-RR’ planted in 2013 (Site 1) and a stand of ‘Pioneer 55V12’ planted in 2012 (Site 2). Each stand had > 50 plants m^{-2}. All alfalfa was at the first flower stage when cut at a height of 5 cm from the entire plot area (30 × 38 m) and removed. Each site was divided into a complete randomized design with four replications. Plots (1.8 × 4.6 m) on 3-4 d intervals from the time of initial cutting of the alfalfa on 31 July, resulting a range of maturities of regrowth from 18 cutting dates. In 2015, experiments were re-established at Site 1 for the first cutting of the year, then moved to a different stand (same age and cultivar) for the 3rd cutting cycle of the year. Each experiment was a complete randomized design with 12 replications. Plots (1.8 × 1.8) were mowed on 3-4 d intervals for 10 mowing dates. Approximately one week following the final cut, all treatments in 6 of the 12 replications were scanned and sampled. The remaining 6 replications were scanned and sampled approximately 10 d later. This took place under sunny conditions for all sampling dates in 2015.

Canopy reflectance spectra (350-2500 nm) were collected using a backpack spectroradiometer (ASD FieldSpec 4, Analytical Spectral Devices, Inc., Boulder, CO) at each sampling date prior to destructive sampling. All reflectance data was collected between 10:00 a.m. and 2:00 p.m. Fifteen reflectance readings were collected from each plot with the fiber optic cable (12.5° viewing aperture) oriented at 90° (nadir) approximately 1 m above the canopy to sample a 0.2 m diameter viewing area with each reading. The instrument was calibrated using a barium sulfate white reference between replications to account for any fluctuations in ambient light conditions.

In 2015, a single-beam LiDAR instrument (Lidar Lite, Pulsed Light Inc.) was used to remotely predict alfalfa canopy height prior to sampling. The LiDAR unit was mounted on a horizontal swinging arm attached to a tripod. The tripod was leveled at the edge of each plot with the arm extending over the plot at a constant height to measure distance to the canopy. Measurements were collected as the unit was moved across the center of each plot, and predicted canopy height was calculated as the difference from sensor height above the ground surface. This gave a yield of 280-600 readings per plot. Three physical measurements of canopy height were also recorded to the nearest cm using a meter stick. Some plots with the greatest maturity had lodged at the time of sampling. Considering the intended application of this technology, these treatments exceeded the practical range for harvest; therefore, LiDAR measurements from lodged plots were excluded from the analysis.

To quantify alfalfa maturity (MSW and MSC), a strip (7.6 cm × 3 m) was harvested from the center of each plot at 5 cm height using handheld electric clippers. Maturity samples were sorted according to the growth staging scale described by Kalu and Fick (1981). All stems within each growth stage were counted to calculate MSC, dried at 60°C and weighed to calculate MSW. Bulk forage samples for measurement of yield and nutritive value were hand-harvested from 1 m^2 (four 0.25 m^2 areas) per plot, and dried at 60°C in a forced-air oven until constant mass. Dry alfalfa biomass samples were ground to pass through a 6-mm screen using a Thomas Wiley Mill (Thomas Scientific, Swedesboro, NJ). The coarse ground samples were mixed, subsampled (~30 g), and ground to pass through a 1-mm screen using a Cyclotec Sample Mill (FOSS North America, Eden Prairie, MN). Alfalfa subsamples were mixed thoroughly and scanned with a Perten NIRS (Model DA 7200) (Perten Instruments, Springfield, IL) to estimate forage crude protein (CP), neutral detergent fiber (NDF), and 48-hr in-vitro neutral detergent fiber digestibility (NDFd) according to predictive equations calibrated with wet chemistry analyses.

3.3.2. Statistical Analyses. Statistical analyses consisted of the construction, validation, and comparison of predictive models to estimate alfalfa yield (kg DM ha^{-1}), CP, NDF, and NDFd. Analyses were performed in the R statistical programming environment (R Development Core Team, 2017) using packages ‘zoo’ (Zeileis et al., 2017) and ‘alr4’ (Weisberg, 2014). In practice, readings from active spectral sensors would not be affected by ambient light conditions, therefore, only data from sunny days (n = 254) were used for construction and validation of models using canopy reflectance. The entire dataset (n = 301) was used for predictions based on maturity or environmental conditions (MSC, MSW, GDUYs). In both cases, the master dataset was randomly divided into calibration (75%) and validation (25%) subsets. All summary statistics represent the fit of the initial calibrated model to the validation subset.

Two different calculations were performed for cumulative GDUs. The first calculation ($GDU_{base\text{-}5}$) used a static base temperature (T_b) of 5°C. The second ($GDU_{scale\text{-}}$

$_{base}$) used a modified scale informed by Sharratt et al. (1989) with T_b graduating continuously from 3.5°C on 1 April to 10°C on 31 July, then remaining at 10°C throughout the remainder of the growing season. Cumulative GDUs were calculated for the specific growth period of each plot, from the time of initial mowing to the time of sampling and harvest. Models were fit via simple linear regression to test both GDU calculations, MSW and MSC as predictors of alfalfa biomass and nutritive value. The GDU calculations, as well as LiDAR-estimated canopy height (2015) were also tested as added predictors in models using canopy reflectance.

Predictive wavebands were identified from the canopy reflectance measurements and equations were developed using forward- and backward-stepwise regression, and all models were selected to minimize the Bayesian information criterion - BIC (Schwarz, 1978). Full models consisting of all selected wavebands were subsequently reduced to simplify the parameters required and improve utility (and affordability) of the application. Models were first reduced by spectral range, limiting predictors to only wavebands within the visible and near-infrared spectrum (VIS-NIR) (400-1100 nm), and reiterating the step-wise procedure for each response. In the final stage of model reduction, selected wavebands were scouted for collinearity. When two wavebands were strongly correlated ($R > 0.95$), the waveband least correlated to the response variable was removed. Coefficients of determination (R^2) and BIC values were calculated for each model to assess performance.

An alternative model selection approach was also tested to identify a set of common wavebands, hereafter referred to as the utility spectra, in the VIS-NIR region to predict all response variables. This process selected only wavebands with the greatest direct correlation to the response, and avoided the selection of neighboring wavebands (within 50 nm). Five correlated wavebands (4 VIS and 1 NIR) were common or similar among the response variables, and were used with the GDU predictor to fit linear models via multiple regression.

3.4 Results and Discussion.

3.4.1 Environmental Conditions. Monthly average air temperatures were similar to 30-yr averages during the alfalfa growth cycles used in this study (Table 3-1). During August 2014, the first month of the study, monthly total rainfall was below normal; however, irrigation was applied to supply total water similar to monthly average precipitation. Overall, environmental conditions were favorable and not limiting to alfalfa growth throughout the duration of the study.

3.4.2 Maturity-based Estimations. Maturity indices, MSC and MSW, were generally accurate predictors of alfalfa CP and NDF (Table 3-2); although, prediction accuracy was less than previously reported (R^2 = 0.88 and 0.95 for CP and NDF, respectively) by Kalu and Fick (1983). Previous work has not reported methods of estimating alfalfa NDFd in-situ, but maturity-based predictions of NDFd were less accurate than expected, considering Kalu and Fick (1983) found strong correlations with fiber fractions related to NDFd, such as acid detergent fiber and lignin.

3.4.3 Growing Degree Units. Cumulative Growing Degree Units since the last harvest provided more accurate predictions of CP and NDF than the maturity-based predictions, but less accurate predictions of yield and NDFd (Table 3-2). Prediction accuracy was greater than reported by Hakl et al. (2010) for CP and NDF (R^2 = 0.65 and 0.40, respectively). However, Hakl et al. compiled data across four years and only harvested from late-vegetative to early-bloom, likely resulting in a narrower range of responses with greater environmental variability than was measured in the current study. The poor prediction accuracy of NDFd supports that in-field estimations of alfalfa nutritive value should not be based on GDUs alone (Sulc et al., 1999). Prediction accuracy increased for all responses with the modified scale of GDU base temperatures compared to the traditionally accepted static T_b of 5°C (Table 3-2). This supports the findings of Sharratt et al. (1989), and warrants further investigation into the use of temporally graduating base temperatures in GDU calculations.

3.4.4 Canopy Reflectance. Models based on canopy reflectance alone were generally more predictive with the greater spectral range (350-2500 nm) before model reduction, and decreased in predication accuracy with each step of model reduction (Table 3-2). Predictions of CP and NDF based on 11 to 12 wavebands in the VIS-NIR spectral range were similar to those achieved by Starks et al. (2016), who used this range at higher resolution to estimate CP (R^2 = 0.78), NDF (R^2 = 0.77). Reduced models, using only 5 to

6 wavebands, resulted in slightly less predictive accuracy, but may provide improved utility of this technology. Predictions of yield based on canopy reflectance were greater than those reported by Pittman et al. (2015) ($R^2 = 0.38 – 0.56$), although we selected from a wider spectral range with greater resolution.

3.4.5 LiDAR-Estimated Canopy Height. In plots measured before lodging, LiDAR-estimated canopy height was strongly correlated with alfalfa biomass (Fig. 3-1). This agrees with other alfalfa yield predictions based on height (Pittman et al., 2015; Lyons et al., 2016), and adds value to potential remote sensing applications in alfalfa management. In a field application, structure-from-motion analyses from UAV imagery, before and after alfalfa growth, may be a more efficient way to remotely estimate canopy height (Matthews et al., 2013), as LiDAR-based estimations rely on a precise, known height above the ground surface.

3.4.6 Model Combinations. Models combining the reduced VIS-NIR wavebands and GDUs as predictors explained more variability in CP and NDF than any other method. The models using VIS-NIR, GDUs, and LIDAR resulted in the most accurate predictions of yield and NDFd (Table 3-2). Previous work has shown improved predictions of fiber composition with measurements of the tallest stem in a sample (Owens et al., 1995). Similarly, the addition of LiDAR measurements improved predictions of NDFd. Using only the five selected utility bands, GDU_{SB} and LiDAR-estimated canopy height, models resulted in R^2 = 0.81, 0.87, 0.73, and 0.83 for yield, CP, NDF, and NDFd respectively.

3.5 Conclusions. This work establishes the potential for integrating environmental data such as GDUs with canopy reflectance data and remote measurements of canopy height for improved estimations of alfalfa yield and nutritive value. Reduced sets of specific wavebands in the VIS-NIR range may provide greater utility at lower cost than measuring high resolution spectral data. Sensors measuring these selected wavebands may be integrated into UAV platforms along with a digital camera to generate estimations of crop yield and quality. A management system integrating this technology could use sensor readings and readily available environmental data for rapid measurements at the field scale.

Table 3-1. Mean air temperature and total monthly precipitation from April to October in 2014 and 2015 at Rosemount, MN.

Month	Air Temperature		Precipitation	
	2014	2015	2014	2015
	----------- °C -----------		----------- mm -----------	
April	5 (-3)[†]	9 (1)	158 (81)	51 (-25)
May	14 (-1)	14 (-1)	117 (9)	114 (6)
June	20 (0)	20 (0)	268 (149)	135 (15)
July	20 (-1)	22 (-1)	74 (-41)	220 (105)
August	22 (0)	20 (-1)	52 (-62)	126 (11)
September	16 (-0)	19 (2)	70 (-17)	126 (39)
October	9 (-0)	10 (1)	39 (-28)	63 (-4)

† Departures from 30-yr averages shown in parentheses.

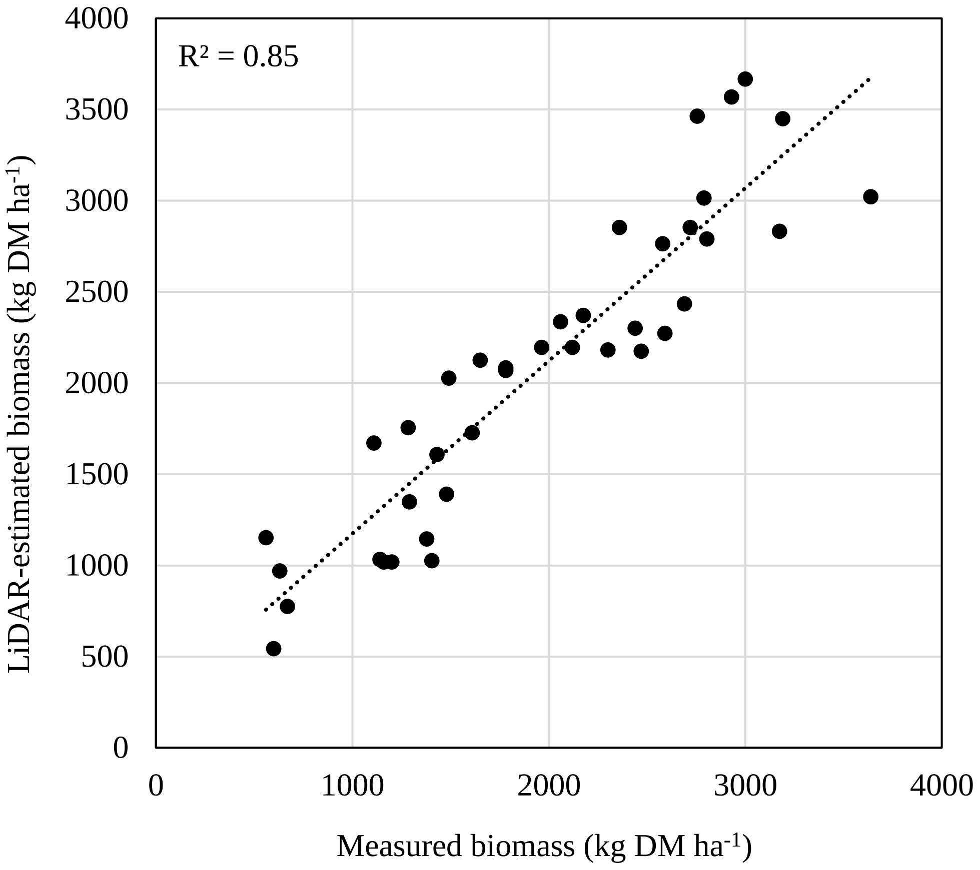
Table 3-2. Adjusted coefficients of determination (R^2), Bayesian Information Criterion (BIC), and number of wavebands used (λ) in models to predict alfalfa yield (kg DM ha-1), crude protein (CP), neutral detergent fiber (NDF), and neutral detergent fiber digestibility (48-hr in-vitro) (NDFd).

Model	Yield			CP			NDF			NDFd		
	R^2	BIC	λ	R^2	BIC	λ	R^2	BIC	λ	R^2	BIC	λ
MSC	0.70	3532	-	0.83	878	-	0.81	1112	-	0.67	1295	-
MSW	0.77	3184	-	0.80	759	-	0.86	996	-	0.69	1173	-
GDU $_{\text{base 5}}$	0.26	3893	-	0.76	1020	-	0.81	1277	-	0.31	1553	-
GDU $_{\text{base scaled}}$	0.47	3844	-	0.87	924	-	0.87	1201	-	0.48	1505	-
VIS + NIR + SWIR $_{\text{full}}$	0.80	3013	5	0.84	731	7	0.84	962	13	0.81	1122	11
VIS + NIR $_{\text{full}}$	0.73	3610	5	0.85	900	12	0.76	1210	11	0.79	1359	6
VIS + NIR $_{\text{reduced}}$	0.64	3674	3	0.72	1038	5	0.71	1292	6	0.70	1458	5
VIS + NIR + GDU $_{\text{base scaled}}$	0.66	3669	3	0.91	825	5	0.89	1154	6	0.76	1412	5
VIS + NIR + LIDAR‡	0.89	1281	3	0.66	314	5	0.67	412	6	0.70	453	5
VIS + NIR + LIDAR + GDU	0.89	1285	3	0.85	250	5	0.79	380	6	0.87	396	5

† MSC, mean alfalfa stem growth stage by count; MSW, mean alfalfa stem growth stage by weight; GDD $_{\text{base-5}}$, cumulative growing degree units since last alfalfa harvest (base temperature = 5°C); GDU $_{\text{scaled-base}}$, cumulative growing degree units since last alfalfa harvest, base temperature graduating from 3.5°C (1 April) to 10°C (31 July) and static at 10°C through the remainder of the year; VIS, wavebands within the visible region of the electromagnetic spectrum (350-750 nm); NIR, wavebands within the near-infrared region of the electromagnetic spectrum (751-1100 nm); SWIR, wavebands within the near-infrared region of the electromagnetic spectrum (1101-2500); LIDAR, lidar-estimated canopy height.

‡ Models including LIDAR were calibrated on smaller dataset (n = 127).

Figure 3-1. LiDAR-estimated alfalfa biomass compared to measured biomass at Rosemount, MN in 2015.



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