Potassium and Nitrogen Management during the Rotation from Alfalfa to Corn

A THESIS

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

OF THE UNIVERSITY OF MINNESOTA

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

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SEPTEMBER 2011

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ACKNOWLEDGEMENTS

I would like to sincerely thank my two excellent advisors, Drs. Jeff Coulter and Michael Russelle for their generous help and support in this research. I appreciate the support given by Drs. Craig Sheaffer and William Lazarus as committee members. I thank Ryan Maher, Eric Ristau, and the cooperating farmers for all their help with the trials and data collection. I thank my wife Natalie, son Bryan, and daughter Madilyn for their patience and support. This research was funded in part by the Minnesota Agricultural Fertilizer Research and Education Committee and the Minnesota Corn Research and Promotion Council.

ABSTRACT

High K and N fertilizer prices in recent years have made it imperative for growers to apply optimum fertilizer rates in alfalfa (*Medicago sativa* L.)–corn (*Zea mays* L.) rotations. Although adequate K is needed for both yield and persistence of alfalfa, current University K fertilizer guidelines in the Corn Belt do not change for the last production year, when alfalfa stand persistence is typically not a concern. Furthermore, little is known about carryover of K applied to alfalfa on first-year corn grain and silage yields. In 2008 to 2010, on-farm research was conducted on 10 fields with medium soil test K (STK) to determine response to K for alfalfa yield and quality in the last production year, and to estimate K carryover to first-year corn. Alfalfa yield and relative feed value (RFV) and quality (RFQ) did not improve with K fertilization. Herbage K concentration and K uptake increased with K fertilization across sites, indicating that applied K was available during the season of application. Regardless of K rate applied to alfalfa, additional K applied to corn increased corn stover and silage yields by 10 and 8%, respectively. However, when K was not applied to the corn, each 100 kg ha^{-1} increase in the index of available K increased corn grain yield by 0.5 Mg ha^{-1}, decreased stover yield by 0.4 Mg ha^{-1}, and did not affect silage yields. This suggests that carryover K was less available than K applied to corn. Therefore, on medium STK soils going into the last year of alfalfa, applying fertilizer K to first-year corn rather than alfalfa may enhance economic returns. Compared to corn following corn, N guidelines for corn following alfalfa in the

Corn Belt suggest that N rates for first-year corn after alfalfa be reduced by 168 kg N ha^{-1} when ≥43 to 53 alfalfa plants m^{-2} are present at termination, however, these guidelines have been questioned as corn grain yields have increased. In addition to the 10 N response trials in the K experiment, experiments were conducted at another six locations in Minnesota to address questions regarding N availability to first-year corn after alfalfa that relate to amount and timing of alfalfa regrowth incorporation. Corn yield and fertilizer N uptake were not affected by regrowth management, tillage timing at six locations, or carryover K at 10 locations. Corn grain yield ranged from 12.1 to 16.0 Mg ha^{-1} among 16 site-years, but responded to N fertilizer on just one location. At this location with above-average rainfall and inadequate soil drainage, the economic optimum N rate (EONR) was 85 kg N ha^{-1} (assuming prices of \$0.87 kg^{-1} N and \$132 Mg^{-1} grain) and grain yield was 15.8 Mg ha^{-1}. Assuming the same N price and \$39 Mg^{-1} silage, the EONR for silage yield across the additional six locations in 2010 was 31 kg N ha^{-1}. These results demonstrate that on highly productive medium- to fine-textured soils in the Upper Midwest with ≥43 alfalfa plants m^{-2} at termination, first-year corn grain yields are usually maximized without N fertilizer, regardless of alfalfa regrowth management or timing of incorporation, but that small N applications may be needed to maximize silage yields.

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CHAPTER 1

Potassium and Nitrogen Management during the Rotation from Alfalfa to Corn: A Literature Review

POTASSIUM MANAGEMENT

With 3.89 million hectares harvested each year in U.S. Corn Belt states (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin), alfalfa is the fourth most widely grown crop after corn, soybean [*Glycine max* L. (Merr.)], and wheat (*Triticum aestivum* L.) (USDA-NASS, 2009). Although alfalfa hay yields for the region average between 5 and 7 Mg dry matter (DM) ha^{-1} (USDA-NASS, 2009), growers in the upper twentieth percentile of profitability from Corn Belt states in the University of Minnesota Farm Financial Database (Minnesota, Nebraska, North Dakota, Ohio, and Wisconsin) produced an average of 13 Mg ha^{-1} from 2008 to 2010 (Center for Farm Financial Management, 2011). This disparity between average forage yield and attainable yield raises the question: How can producers improve their crop management practices to increase alfalfa yield? One possible answer is that nutrient application rates need to be increased.

Alfalfa is stressed by frequent harvests, field traffic, winter conditions, poor drainage, and drought. Potassium is crucial for tolerance to these stresses and maximum yield because it improves carbohydrate storage in alfalfa roots and helps increase the regrowth rate (Reid et al., 1965; Schnappinger et al., 1969). High levels of soil fertility and pest control have been required to maintain stands and maximize yields (Berg et al., 2005; 2007). Current K fertilizer guidelines for established alfalfa vary widely among Corn Belt states. For example, Minnesota recommends 80 kg K ha^{-1} to established alfalfa for a yield goal of 11 Mg DM ha^{-1} when STK is in the medium range (81-120 mg K kg^{-1} ammonium acetate-exchangeable K) (Rehm et al., 2000). However, the University of Nebraska recommends only 30 kg K ha^{-1} (ammonium acetate-exchangeable K; Tarkalson and Shapiro, 2005) while the University of Wisconsin recommends 250 kg K ha^{-1} (Bray 1-exchangeable K; Laboski et al., 2006) for medium STK levels. Furthermore, Wisconsin recommends increasing K rates for established alfalfa by 20% if a stand life longer than 3 yr is desired. In addition to the wide range of K fertilizer recommendations for alfalfa, none of the recommendations for the Corn Belt change for the last production year when stand persistence is not a major concern (Iowa, Sawyer et al., 2007; Illinois, Fernandez and Hoeft, 2009; Michigan, Ohio, and Indiana, Vitosh et al., 1995; Minnesota, Rehm et al., 2000; North Dakota, Franzen, 2010; Nebraska, Tarkalson and Shapiro, 2005; South Dakota, Gerwing and Gelderman, 2005; Wisconsin, Laboski et al., 2006). However, it may be important to maintain alfalfa stands $\geq$43 plants m^{-2} in the last production year in order to maximize the nitrogen (N) fertilizer replacement value (N credit) to the following corn crop (e.g., Rehm et al., 2006) and to avoid nitrate leaching losses during the alfalfa growing season (Entz et al., 2001).

At least two concerns about K supplementation face growers. The most important is fertilizer price. In the past three decades (1978 to 2007), commercial fertilizer prices for the most widely used K source averaged about \$176 Mg^{-1} KCl, but have been three to four times higher beginning in 2008 (USDA-ERS, 2011). This raises the risk of lower profits if crop response to the input is lower than expected. The second concern is due to luxury consumption of K by alfalfa, which poses the additional risk of high forage K concentration. High dietary K concentrations in periparturient cow rations may increase the risk of parturient paresis (milk fever) (Horst et al., 1997). Furthermore, luxury consumption increases K removal from the field, leaving less residual K for the following crop.

If carryover K increases corn yield, growers would have additional time and options for purchasing and applying K for corn. For example, if K price is expected to rise, extra K could be applied to the alfalfa rather than corn. However, there is little information on whether carryover K from alfalfa can increase grain and silage yields of the subsequent corn crop. Research is needed to determine the extent to which luxury K consumption by alfalfa in its final year of production reduces overall fertilizer K use efficiency in the cropping system, and how much extra K would be required to fertilize both crops in one application. Furthermore, we found no published reports on the effect of carryover K on alfalfa N credits to first-year corn.

NITROGEN MANAGEMENT

Each year, corn is grown after alfalfa on roughly 1.1 million ha in US Corn Belt states (USDA-NASS, 2009), assuming 28.6% of alfalfa is rotated to corn annually (Peterson and Russelle, 1991). This represents only about 5% of total field corn hectarage in the region (USDA-NASS, 2009), but this rotation may be the path to a more sustainable future. For example, during a 35-yr-long field trial in Wisconsin, grain yield of first-year corn following alfalfa increased by 100 kg ha^{-1} yr^{-1} compared to 28 kg ha^{-1} yr^{-1} for continuous corn that received 224 kg N ha^{-1} (Stanger and Lauer, 2008). Furthermore, a vast body of literature (125 site-years) indicates that 91% of the time first-year corn grown after a good stand ($\geq$43 plants m^{-2}) of alfalfa on medium or fine-textured soils requires no fertilizer N to maximize grain yield (Triplett et al., 1979; Fox and Piekielek, 1988; Bundy and Andraski, 1993; Morris et al., 1993; Schmitt and Randall, 1994; Lory et al., 1995; Rasse and Smucker, 1999; Andraski and Bundy, 2002; Basso and Ritchie, 2005; Stanger and Lauer, 2008). At the 11 sites in these studies where corn was responsive to N fertilizer, only 48 kg N ha^{-1} was needed to maximize corn grain yield. Most current university N fertilizer guidelines in Corn Belt states advise growers to reduce fertilizer N on first-year corn after alfalfa by 168 kg ha^{-1} when $\geq$43 to 53 alfalfa plants m^{-2} are present at the time of termination (Michigan, Ohio, Indiana, Vitosh et al., 1995; Iowa, Blackmer et al., 1997; Wisconsin, Laboski et al., 2006; Minnesota, O'Leary et al., 2008). When these recommendations are followed, growers save about \$145 ha^{-1} in

N fertilizer costs at \$0.87 kg^{-1} N. Nevertheless, growers and their advisors have questioned whether alfalfa provides sufficient N for contemporary, high yielding corn crops.

The reliability of the alfalfa N credit to first-year corn is well established, but studies addressing the effects of time of incorporation and alfalfa regrowth are relatively sparse. In Wisconsin, the timing of alfalfa incorporation (fall vs. spring) had minor impacts on first-year corn grain yields the following year (Smith et al., 1992). In comparison, corn in Michigan recovered more ^{15}N from labeled alfalfa plants when alfalfa was incorporated in the spring on a medium-textured soil, but tillage timing did not alter N recovery on a sandy loam soil (Harris and Hestermann, 1992). In New York, grain yield was reduced when alfalfa was incorporated in the spring on a clay loam soil (Karunatilake et al., 2000), whereas Lawrence et al. (2008) found similar corn silage yield with fall or spring incorporation in New York, although tillage timing was confounded with location in their study. The amount of alfalfa regrowth incorporated may alter the effect of incorporation time. On medium- and fine-textured soils, fertilizer N recommendations in Minnesota and Wisconsin suggest a supplementary 45 kg N ha^{-1} credit may be taken if >20 cm of alfalfa regrowth is present when the alfalfa stand is terminated (Laboski et al., 2006, O'Leary et al., 2008). No previous studies that we are aware of have determined how alfalfa N credits are affected by the interaction between alfalfa regrowth and tillage timing. Although the importance of regrowth in providing N to the following corn crop is likely greater with poor rather than good stands of alfalfa, even with the latter, a corn grower could save an additional \$39 ha^{-1} in N fertilizer expenses for first-year corn if moving tillage time from fall to spring or incorporating alfalfa regrowth increased the N credit by 45 kg N ha^{-1}, assuming \$0.87 kg $^{-1}$ N.

Several soil and plant tests have been developed to estimate the N requirements of corn. The BSN test was developed as a late-season tool for determining N status of predominately continuous corn and corn following soybean (*Glycine max* L.) (Binford et al., 1990, 1992), but also has been recommended for use in corn after alfalfa (Blackmer and Mallarino, 2000). However, limited information is available on the effectiveness of this test for corn following alfalfa (Bundy and Andraski, 1993).

Optimum rates of N fertilizer for corn yield can be influenced by the soil K fertility. When high amounts of N are available to corn, as is generally the case when corn follows alfalfa, adequate K fertility can reduce stalk lodging and increase ear and stover yield (Welch and Flannery, 1985; Heckman and Kamproth, 1992). Therefore, an additional consideration in determining alfalfa N credits to first-year corn may be the effects of residual K from the last alfalfa production year. Carryover K may impact the amount of N needed for optimum first-year corn yields, yet we found no published reports on the interaction of K fertility with alfalfa N credits, presumably because previous research on N credits was conducted on soils fertilized with adequate amounts of K.

In order to improve fertilizer K and N recommendations during the rotation from alfalfa to corn, two studies were conducted at 16 locations in Minnesota. The objectives of the first study were to determine the effects of spring K application on the yield and quality of last-year alfalfa and carryover K effects on first-year corn yield. We hypothesized that alfalfa yield and quality would increase on medium STK soils with K fertilizer topdressed in the last production year, but that current K recommendations are too high for optimum economic return due to high K prices. We also hypothesized that excess K applied to alfalfa would carry over to increase the subsequent corn grain and silage yield. To test these hypotheses, K fertilizer was applied to last-year alfalfa and to the following corn crop on soils in the medium range of STK at 10 locations in 2008 to 2010. In the second study across the existing 10 and additional six locations, the objectives were to determine how carryover K and alfalfa regrowth amount and incorporation time impact corn yield, fertilizer N uptake, residual NO_3-N, and the fertilizer N requirement of first-year corn, respectively.

CHAPTER 2

Potassium Management during the Rotation from Alfalfa to Corn

MATERIALS AND METHODS

On-farm experiments were established in alfalfa fields entering their second to fourth year after seeding, and which the cooperating growers intended to terminate and rotate to corn (Table 1). Dairy cow manure had been applied in the fall or spring before alfalfa seeding at all locations except Norwood-2, which had not received manure for >25 yr. Manure was not applied to any field after seeding. Topsoil (0-15 cm) pH at four locations was ≤6.5, which is below optimum (Rehm et al., 2000; Peters et al., 2005) (Table 1), and one location was irrigated (Fig. 1).

The experimental design was a randomized complete block with three or four replications at each location. Main plot treatments were K fertilizer rates applied to alfalfa as topdressed KCl at 0, 19, 46, 93, and 186 kg K ha^{-1}, and measured 18 m long by 14 m wide. Subplots were established in the subsequent corn crop (described below). Potassium fertilizer was applied 1 mo before the first harvest at three locations in 2009 and immediately after the first harvest at the remaining seven locations (Table 1).

Soils were sampled for STK by compositing six to eight cores (1.9 cm i.d. by 15 cm deep) collected from main plots prior to alfalfa K fertilization. Soil samples were dried in a forced-air oven at 35°C until constant mass and sent to a certified commercial soil testing laboratory to determine ammonium acetate-exchangeable K. At the conclusion of the alfalfa phase of the experiment, alfalfa stands were terminated according to the standard practice of cooperating growers in the fall or spring by moldboard or chisel plowing. Corn hybrids adapted to the local growing season length were selected, planted, and managed by cooperating growers. Corn was planted about 5 cm deep between late April and mid-May at seeding rates of 74,100 to 90,000 seeds ha^{-1} (Table 2). Six subplots measuring 9 m long by 5 m wide (six corn rows) consisted of five N fertilizer rates ranging from 0 to 180 kg N ha^{-1} and one treatment of 90 kg N ha^{-1} plus 186 kg K ha^{-1}. Fertilizer treatments were surface broadcast as NH_4NO_3 and KCl at 1 to 4 wk after corn planting (Table 2). The fertilizer N response of corn will be described in detail in a separate manuscript. When needed, P was surface broadcast to all alfalfa and corn at the time of K application according to University of Minnesota recommendations (Rehm et al., 2000, 2006). Topsoil K samples were collected from the 90 kg N ha^{-1} subplots prior to corn K fertilization at nine locations (excluding Pine Island due to missing data) following the sampling and analysis methods described for the initial soil samples collected during the alfalfa phase of the study. After corn harvest, topsoil K samples were collected at seven locations (Cannon Falls, Norwood-2, and Pine Island were not sampled due to time and weather constraints) from the 90 kg N ha^{-1} subplots with and without an additional 186 kg K ha^{-1} applied to corn. These topsoil samples were taken only from the nonfertilized alfalfa main plots, because tillage that occurred before corn planting differed among locations and mixed the topsoil to depths below the 15-cm soil sampling depth. Growing season precipitation and temperature were obtained from the nearest National Weather Service locations (Fig. 1).

Alfalfa and Corn Analysis

After K application, alfalfa yield and quality samples were taken at a typical harvest height (about 7.5 cm above the soil surface) three to five times, by hand clipping two 1-m^2 plots in each main plot before the cooperating grower harvested the experimental area with field-scale equipment. Alfalfa herbage samples were dried in a forced-air oven at 60°C until constant mass, weighed, and ground to pass a 1-mm sieve. Total annual alfalfa DM yield was calculated only from harvests that occurred after K fertilization, and was reduced by 11.5% to reflect the average mechanical harvest loss experienced by growers (Rotz and Muck, 1994). Before stand termination in the fall, alfalfa plants were dug, separated from soil, and counted by crowns in two 0.61-m^2 plots within each main plot to determine final plant population (FPP).

Alfalfa herbage samples from all harvests after K fertilization were scanned at 1100-2500 nm by near-infrared reflectance spectroscopy (NIRS) using a Foss model 6500 (Foss North America Inc., Eden Prairie, MN) to predict crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and *in vitro* 48-h NDF digestibility (NDFD) concentrations. Calibration samples (n = 58) were selected using Intrasoft Int.

software (ISI, Port Matilda, PA) and were analyzed with standard wet chemical analysis at the University of Wisconsin-Madison Soil and Forage Analysis Lab. The NIRS predictions were calibrated to the wet chemical analysis using regression (CP, $R^2 = 0.76$, $P < 0.001$; ADF, $R^2 = 0.89$, $P < 0.001$; NDF, $R^2 = 0.86$, $P < 0.001$; NDFD, $R^2 = 0.68$, $P < 0.001$). Neutral detergent fiber estimates were increased by 7.5% to reflect average alfalfa field curing and mechanical harvesting loss (Rotz and Muck, 1994). Standard equations were used to calculate RFV and RFQ (Undersander and Moore, 2002). Average annual CP, ADF, NDF, NDFD, RFV, RFQ, and herbage K concentration for each location were computed on a DM yield-proportional basis across harvests taken after K fertilization.

Potassium concentration was measured by extracting whole herbage tissue samples for 5 min with 0.5*M* HCl (Rao et al., 1998) and analyzing the extracts with atomic emission spectroscopy using a Perkin Elmer AAnalyst 400 (Perkin Elmer, Waltham, MA). To validate the 0.5*M* HCl extraction method for alfalfa, calibration samples from the first harvest after K fertilization in 2008 also were analyzed with inductively coupled plasma atomic emission spectroscopy after HCl extraction using a Perkin Elmer Optima model 3000 (Perkin Elmer, Waltham, MA) at the University of Minnesota Research Analytical Lab. Atomic emission spectroscopy data were increased by 15% to match the inductively coupled plasma atomic emission spectroscopy results ($R^2 = 0.99$, $P = <0.001$). Herbage K concentration and unadjusted DM yield averaged across harvests after K fertilization were multiplied to compute K uptake. Apparent K fertilizer uptake was calculated as the difference in K uptake of each rate of K fertilizer from the nonfertilized control plot within a given block. Fertilizer efficiency was calculated as apparent fertilizer K uptake divided by applied K. The index of available K was calculated as initial STK multiplied by assumed bulk density (1.3 g cm^{-3}), plus fertilizer K applied, and minus annual alfalfa K uptake. Initial STK was included in the index of available K to compensate for plot-to-plot variability in initial soil K supply.

Corn grain yield was measured by hand harvesting 3 m of row from one of the two center rows in each subplot. Harvested corn ears were dried in a forced-air oven at 60°C until constant mass, shelled using a single ear electric sheller, and weighed separately by cob and grain. Grain yield was adjusted to 155 g kg^{-1} moisture. Dried grain samples were ground to pass a 1-mm sieve. After ears were picked, stover was harvested by cutting eight stalks at typical harvest height (about 15 cm above the soil surface) within the 3 m of row where grain was harvested in each subplot. Harvested stover was weighed, ground with a Kajon chipper (Lindig Mfg. Corp., St. Paul, MN), and subsampled (about 1.5 kg) in the field. Stover subsamples were dried in a forced air oven at 60°C until constant mass and fine ground to pass a 1-mm sieve. Grain, cob, and stover yields were used to calculate silage yield at 650 g kg^{-1} moisture. Stover was not harvested at the Mantorville site due to severe stalk lodging. Harvest index was determined as the grain DM percentage of total aboveground DM. Ground corn grain, stover, and cob subsamples were combined on a DM yield-proportional basis, digested with 16*M* nitric acid and hydrogen peroxide, and analyzed for K concentration with inductively coupled plasma atomic emission spectroscopy at a certified commercial laboratory for four treatments (the nonfertilized alfalfa plots with and without an additional 186 kg K ha^{-1} applied to corn, and the 93 and 186 kg K ha^{-1} alfalfa plots with no additional K applied to corn) across all blocks and locations except Mantorville. Corn tissue K concentrations were multiplied by silage DM yield to compute whole plant K uptake.

Statistical Analysis

Alfalfa data were analyzed by K application timing using the MIXED procedure of SAS (SAS Institute, 2006) at $P \leq 0.05$. Location and block (nested within location) were considered random effects and K rate was considered a fixed effect. Residuals were examined for normality and common variance using the UNIVARIATE procedure of SAS (SAS Institute, 2006) and scatterplots of residuals vs. predicted values (Kutner et al., 2004). The seven locations with K applied after the first harvest all had three harvests after K application, and thus alfalfa data were subjected to repeated measures analysis with harvest as the repeated measure using the compound symmetry covariance structure. The compound symmetry structure was chosen out of several covariance structures tested based on the fit statistics. The interaction between harvest and K rate was not significant ($P \geq 0.18$) for yield and quality parameters (Table 3) and the significance of main effect of K rate on yield and quality was similar for the by-harvest and annual estimates (Table

4). Therefore, data from these seven locations were analyzed as total annual alfalfa DM yield and average annual quality (Table 4). Alfalfa data from three locations with K applied before regrowth in the early spring could not be analyzed using repeated measures due to the unequal number of harvests (3-5) across locations. Soil test K in the spring before K fertilization was significant ($P \leq 0.05$) as a covariate for annual alfalfa DM yield, K concentration, K uptake, ADF, and NDF when K treatments were applied after first harvest, and for CP when K treatments were applied before first harvest. However, we did not use STK as a covariate because the significance of the main effects of K and the mean separations were similar whether or not STK was included. The percentage of total random variation associated with the effects of location and interactions among location and fixed effects was calculated from covariance parameter estimates.

When K rate was significant, linear, quadratic, and logistic regression equations were developed to describe the response of the dependent variables using the MIXED and NLIN procedures of SAS (SAS Institute, 2006). Many regression models were evaluated, and we selected models that produced the smallest residuals and were significant ($P \leq 0.05$, linear and quadratic models; $P \leq 0.10$, logistic model) (Kutner et al., 2004). Fisher's protected LSD test ($P \leq 0.05$) was used to compare treatment means of dependent variables that were significantly affected by K rate for both alfalfa and corn, but did not fit regression models. Corn data from Norwood-1 were not included in this analysis because of an error in corn planting. Corn data from all other locations were combined because the index of available K accounted for differences in alfalfa K application timing across locations. These data were analyzed by regression using the MIXED procedure of SAS at $P \leq 0.05$.

RESULTS AND DISCUSSION

Growing season (April through September) precipitation totals during alfalfa production at all locations (5 in 2008 and 5 in 2009) were between 16 and 167 mm (4 and 49%) below the 30-yr average (1971-2000) (Fig. 1). In contrast, growing season precipitation totals during corn production were 23 to 31% below the 30-yr average in 2009 and 22 to 34% above the 30-yr average in 2010. The 2010 corn growing season had above average precipitation in September, but this likely had no effect on corn response to early-season K application or residual K remaining from fertilization of alfalfa since corn was at or near physiological maturity. The highest growing season precipitation departures during alfalfa production were 140 and 167 mm (39 and 49%) below the 30-yr average, and occurred at Mantorville and Pine Island in 2009, respectively (Fig. 1). These two locations also had the highest growing season precipitation departures during corn production, which were 255 and 264 mm (34 and 34%) above the 30-yr average in 2010, respectively. Average air temperatures were near the 30-yr average (1971-2000) for both the alfalfa and corn growing season (April through September) at all locations, with the highest departure being 2°C below average.

Alfalfa Yield and Potassium Uptake

Covariance parameter estimates indicated that location accounted for most of the total random variability in DM yield when K was applied before (90%) or after (82%) the first alfalfa harvest. In comparison, the interaction between location and K rate accounted for a relatively small amount of the total random variation (<1%) for both application timings. Total annual alfalfa DM yield was higher on average when K was applied in the early spring before the first harvest (7.9 Mg DM ha^{-1}) than after the first harvest (5.3 Mg DM ha^{-1}) because the former included the grower's first harvest. However, yield did not increase significantly with K fertilizer, whether K was applied before or after the first harvest (Table 4).

The lack of alfalfa yield response to K fertilizer in this study was unexpected, as similar studies have found increased yield as K fertilization rose to nearly 200 kg K ha^{-1} in 3- to 5-yr-old alfalfa stands on soils with STK near 81-120 mg kg^{-1} (Bailey, 1983; Berg et al., 2005; 2007; Peters et al., 2005; Lissbrant et al., 2009). Furthermore, the classification of 'medium' STK is that yield responses are likely. However, under irrigation in Nebraska and Colorado, there was no response of alfalfa yield to applied K fertilizer when STK was 118 and 126 mg kg^{-1} [Havlin et al. (1984) and Rehm (1989), respectively]. In addition, on soils with low STK, maximum K rates that increased alfalfa yield have varied widely from 37 kg K ha^{-1} in Minnesota (Hanson and McGregor, 1966), 200-224 kg K ha^{-1} in Manitoba and Wisconsin (Bailey, 1983; Walker et al., 1987), and >400 kg K ha^{-1} in Wisconsin (Smith 1975; Rominger et al., 1976), whereas others have found no yield response in Virginia and Minnesota [Lutz (1973) and Sheaffer et al. (1986), respectively]. Based on estimated annual alfalfa DM yields averaged over 10 locations in this study (8.2 Mg DM ha^{-1}), about 65 kg K ha^{-1} would have been recommended by the University of Minnesota (Rehm et al., 2000). At the average KCl prices from 2007 to 2011 (\$1.03 kg^{-1} K) (USDA-ERS, 2011), alfalfa growers following these guidelines would have spent about \$67 ha^{-1} on the K fertilizer alone. It appears that either a new STK range must be defined that gives more reliable crop response or that other factors need to be incorporated when interpreting exchangeable STK (e.g., potential release of nonexchangeable K, Markus and Battle, 1965; Bailey, 1983).

The lack of yield increase to applied K may have been due to poor fertilizer recovery by the alfalfa, but increasing herbage K concentrations indicated that fertilizer K was available. When K was applied before the first harvest, covariance parameter estimates indicated that location and the interaction between location and K rate accounted for <1 and 23% of the total random variability in herbage K concentration, respectively. The small percentage of random variation in K concentration associated with location and the high percentage associated with the interaction between location and K rate may have been due to diverse harvest schedules used at the three locations where K was applied before the first harvest (Table 1). In contrast, at the seven locations where K was applied after the first harvest, there were three harvests after fertilization at each location, and the main effect of location and the location by K rate interaction accounted for 66 and 6% of the total random variability in herbage K concentration, respectively.

Mean annual herbage K concentration was significantly increased by K application (Table 4) and was higher when K was applied after the first harvest (21.1 to 27.1 g kg^{-1}) than before (17.5 to 24.4 g kg^{-1}). However, the slopes for the response of herbage K concentration to K rate were similar for both application timings (Fig. 2A). With each 50 kg K ha^{-1} of applied fertilizer, herbage K concentration increased linearly by 1.8 and 1.6 g kg^{-1} for before and after first harvest application timing, respectively (Fig. 2A). This evaluation of early application timing included the grower’s first harvest, which typically yields more than other harvests and may have lower herbage K concentration due to dilution by structural DM. However, when the first harvest was excluded from the three locations where K fertilizer was applied before the first harvest, the linear response of herbage K concentration to K rate ($y = 16.9 + 0.0328x$, $R^2 = 0.77$, $P < 0.01$) was similar. The increase in herbage K concentration with K fertilization in this study was lower than that observed on similar soils with low STK in Minnesota (Sheaffer et al., 1986) and medium STK soils in Wisconsin (Smith, 1975), and greater than that on very high testing soils in Spain (Lloveras et al., 2001). Although published critical K concentrations for alfalfa herbage vary widely (9.0 to 24.1 g kg^{-1}) [Lissbrant et al. (2010) and references cited therein], average herbage K concentrations in the nonfertilized plots for before (17.5 g kg^{-1}) and after first harvest K application (21.1 g kg^{-1}) were within the published critical level range and were close to the critical level (21.5 g kg^{-1}) for the highest yields obtained with modern cultivars and management (Lissbrant et al., 2010). Based on these published studies and the high tissue K concentration in our work, it would have been surprising had a yield response to K occurred at these 10 locations.

Covariance parameter estimates indicated that location accounted for <1 and 14% of the total random variability in average annual apparent fertilizer K uptake when K was applied before or after the first harvest, respectively. The interaction between location and K rate accounted for 30 and 3% of the total random variability in apparent fertilizer K uptake for the early and late K applications, respectively. The high percentage of total random variability associated with the interaction of location and K rate for the early application timing may have been due to the differences in harvest schedules at the three locations (Table 1). Apparent K fertilizer uptake for the early application timing increased by 21 kg K ha^{-1} with each 50 kg K ha^{-1} of applied fertilizer (Fig. 2B). When the highest amount of K was applied, average apparent K uptake was 85% higher for the early application timing than the later timing ($P \leq 0.05$) (Fig. 2B). This was likely due to the greater number of harvests (>3) at two out of the three locations with K applied before the first harvest (Table 1).

Increases in herbage K concentration and K uptake with K fertilization, along with the lack of alfalfa yield response, provide evidence that K fertilizer was available for plant uptake across harvests and locations and that luxury consumption occurred. Excess K uptake can be problematic when alfalfa is fed at high inclusion rates in fresh cow rations because it increases the risk of milk fever when dietary K concentrations surpass 21 g kg^{-1} (Horst et al., 1997). Another drawback with luxury consumption is that the fertilized crop will leave less fertilizer K for the following crop, thereby reducing overall fertilizer use efficiency in the crop rotation and net return for growers. Alfalfa K fertilizer uptake efficiency was not affected by K fertilization rate for either application timing (Table 4) and averaged 39 and 25% when K was applied before and after the first harvest, respectively. Therefore, between 61 to 75% of the K fertilizer was not removed in alfalfa herbage and should have been available to the subsequent corn crop.

Forage Quality

According to the covariance parameters, location accounted for 65, 95, 96, and 85% of the total random variability in CP, ADF, NDF, and NDFD, respectively, when K fertilizer was applied in the early spring before the first harvest. In contrast, when K fertilizer was applied after the first harvest, location accounted for 91, 87, 87, and 79% of the total random variability in CP, ADF, NDF, and NDFD, respectively. The greatest difference in total random variability between K application timings was with CP, which may reflect differences in regrowth intervals among locations. In contrast, the interaction between location and K rate accounted for <1% of the total random variation for each quality parameter and both application timings , indicating that the effect of K fertilization rate on average annual CP, ADF, NDF, and NDFD concentrations was consistent across locations.

Crude protein concentrations averaged 230 g kg^{-1} across locations, harvests, and K timings. However, CP was not affected by K fertilizer rate, regardless of application timing (Table 4). This is consistent with results obtained by Burmester et al. (1991) and Lloveras et al. (2001) on medium to high K testing soils, but others on medium to low testing K soils reported lower CP concentrations with increased K application (Smith, 1975; Sheaffer et al., 1986; Lissbrant et al., 2009).

Neutral detergent fiber concentration was not affected by fertilizer K applied after the first harvest, but K rate affected NDF at the early application timing (Table 4). When K was applied before the first harvest, NDF averaged 3% lower with the 19 kg K ha^{-1} rate than the other rates (Table 5). These results are contrary to recent research in Indiana (Lissbrant et al., 2009), which reported higher NDF concentrations (reduced forage quality) as K fertilizer rates increased.

The only forage quality parameters that had a significant response to K fertilization for both K application timings were ADF and NDFD (Table 4). With each 50 kg K ha^{-1} increase in K rate, average ADF concentration increased by nearly 3 and 1 g kg^{-1} when K was applied before and after the first harvest, respectively (Fig. 3A). Lissbrant et al. (2009) found higher increases in average ADF concentrations as K rate increased to 400 kg K ha^{-1}, whereas Malhi et al. (2005) found no ADF response to applied K in timothy (*Phleum pratense* L.).

Neutral detergent fiber digestibility averaged over harvests and locations was higher when K was applied before the first harvest, but the response of NDFD to K fertilizer was similar for the application timings (Fig. 3B). Predicted NDFD increased in a curvilinear fashion by nearly 19 g kg^{-1} as K rate increased from 0 to 186 kg K ha^{-1}, regardless of K application timing (Fig. 3B). In a greenhouse study, Peoples and Koch (1979) found that K deficient alfalfa plants reached maturity more rapidly. Therefore, it is likely that K fertilizer additions may have delayed alfalfa maturity and thus increased NDFD. In contrast, Lissbrant et al. (2009) found decreased *in vitro* true DM digestibility as K fertilization increased on soils with similar taxonomy to the soils in this study. Small increases in NDFD may improve DM intake and milk production of dairy cows (Oba and Allen, 1999; Kendall et al., 2009), but it is doubtful that the change in magnitude we observed in this single component of the total mixed ration would improve overall lactation performance if alfalfa is fed as part of a total mixed ration (Raeth-Knight et al., 2005).

Even though K fertilization resulted in a small increase in average ADF concentrations and an improvement in NDFD, K fertilization had no effect on average RFV (182) or RFQ (180) over harvests and locations when K was applied after the first alfalfa harvest (Table 4). When K was applied before the first alfalfa harvest, RFQ averaged 178 and was not affected by applied K, whereas RFV ranged from 177 to 184 but did not differ among the 0, 93, and 186 kg K ha^{-1} rates (Table 5). These small differences in RFV values would not likely affect milk production when alfalfa hay is fed at 35 to 50% of the dietary DM (Turnbull et al., 1982; Alhadrami and Huber, 1992). The lack of large differences in RFV or RFQ with K fertilization for either application timing indicates that prices received for hay or the value of feed on the farm would not have been affected by K rate. Thus, from a forage yield and quality standpoint, there were no apparent biological or economic advantages to applying K at these 10 locations, even though they all had medium STK levels.

Final Plant Populations

Final plant populations were not affected by K fertilization (Table 4), averaged 72 plants m^{-2} (45-107 plants m^{-2}) across all locations, and supported above average alfalfa yields for the region. We did not measure initial plant population before K application and this may have reduced our ability to detect within-plot stand loss. We expected populations to decline on soils at the low end of the medium range for K in the nonfertilized plots (Sheaffer et al., 1986; Burmester et al., 1991), but other factors may have helped maintain plant populations, such as leniency of previous fall harvests (Kallenbach et. al, 2002), adequacy of soil pH (Peters et al., 2005), and improved stress tolerance of these modern alfalfa cultivars (Lamb et al., 2006).

Soil Test Potassium

Soil test K showed little change during this 2-yr-long experiment. Initial alfalfa STK across all main plots ranged from 79 to 111 mg K kg^{-1} among locations. Although initial STK varied within each location, only 11 of the 173 main plots had STK concentrations >120 mg K kg^{-1}. In the nonfertilized control plots, the average difference of initial alfalfa STK and initial corn STK across nine locations (excluding Pine Island) was not different from zero (P = 0.19) and ranged from -28 to 36 mg K kg^{-1} at the plot level.

Therefore average initial STK in the nonfertilized corn plots remained in the medium range at all locations except at Pierz (67 mg kg^{-1}) and Norwood-2 (77 mg kg^{-1}), which were in the low range. When no K was applied to the corn, STK did not change during the corn growing season (P = 0.25) over seven locations (excluding Cannon Falls, Norwood-2, and Pine Island). However, at these same locations, applications of 186 kg K ha^{-1} to corn planted into nonfertilized alfalfa plots increased average STK by about 17 mg kg^{-1} above the initial corn STK ($P = 0.02$). These data suggest that significant drawdown of STK did not occur during the last alfalfa production year or in the subsequent corn year, although ≥120 kg K ha^{-1} was removed in the harvested herbage of the control plots and corn K uptake was ≥99 kg K ha^{-1}.

Corn Yield and Potassium Uptake

According to covariance parameter estimates, location accounted for 38% of the total random variability in corn grain yield, whereas the interactions among location, index of available K, and K applied to corn accounted for ≤6%. The interaction between the index of available K and new K applied to corn was significant for corn grain yield (Table 6). Corn that received 186 kg K ha^{-1} at emergence was not affected by the index of available K, whereas grain yield increased 0.5 Mg ha^{-1} with each 100 kg K ha^{-1} increase in the index of available K for corn that was not independently fertilized (Fig. 4). Therefore, excess K applied to alfalfa was available to the next corn crop. According to the 95% confidence band, the index of available K needed to be nearly 250 kg K ha^{-1} before yield of nonfertilized corn equaled the yield of corn that received K fertilizer at emergence. However, the index of available K had poor predictive power for grain yield ($R^2 = 0.04$). On medium STK soils in Iowa, corn grain yield was increased with broadcast-applied K at only one of nine locations (Mallarino and Blackmer, 1994) and at two of three locations more recently (Kaiser et al., 2005).

Covariance parameter estimates indicated that location accounted for 14% of the total random variability in stover yield, whereas interactions among location, index of available K, and K applied to corn accounted for <1%. Similarly, the covariance parameter estimates for silage yield indicated that 25% of the random variation in silage yield was associated with location and <1% was associated with interactions among location, index of available K, and corn-applied K. Stover yields of the fertilized and nonfertilized corn declined by 0.4 Mg ha^{-1} with each 100 kg K ha^{-1} increase in the index of available K ($y = 8.85 – 0.0042x$, $R^2 = 0.19$, $P < 0.001$). New K applications of 186 kg K ha^{-1} to corn in each of the existing alfalfa K fertilizer treatments increased stover yield by 0.8 Mg ha^{-1}(10%) and silage yield by 2.7 Mg ha^{-1} (8%) compared to nonfertilized corn, regardless of the index of available K (Table 6). However, the application of 186 kg K ha^{-1} to corn did not improve economic returns when average KCl ($1.03 kg^{-1} K; USDA-ERS, 2011) and corn silage prices ($31 Mg^{-1}; Center for Farm Financial Management, 2011) for 2005 to 2010 were considered.

Covariance parameter estimates indicated that location accounted for 27% of the total random variability in harvest index, whereas interactions among location, index of available K, and K applied to corn accounted for ≤8%. Harvest index was also significantly affected by new K application of 186 kg K ha^{-1} to corn (Table 6). The average harvest index was slightly higher for nonfertilized corn (0.550) than fertilized corn (0.548), but this small difference was likely unimportant.

Averaged over eight site-years, whole-plant corn K uptake was similar (114 kg K ha^{-1}) for plots that received no K in the alfalfa year and 186 kg K ha^{-1} in the corn year (0 K alfalfa/186 K corn) and for those that received 186 K alfalfa/0 K corn. Corn in these two treatments contained significantly more K than 0 K alfalfa/0 K corn and 96 K alfalfa/0 K corn treatments, which averaged 99 kg K ha^{-1}. These data from eight locations provide evidence that the highest rate of K applied to alfalfa carried over and may have been available to corn in similar amounts as the K applied to corn in the nonfertilized alfalfa plots, however; we cannot estimate the optimum K rate to corn from this experiment.

CONCLUSIONS

In the last production year of alfalfa, we found no benefit to forage yield or quality from applying K fertilizer either before or after the first alfalfa harvest on soils with medium STK. Are the K requirements of alfalfa changing? Perhaps, and if so, we speculate that it could be due to improved stress tolerance in newer cultivars, but direct comparisons of K requirements among contrasting cultivars are lacking. Whatever the cause is, our results support the idea that K fertilizer recommendations may need to be reduced for good stands of alfalfa in the last production year when STK is in the medium range, or that the range of STK defined as ‘medium’, i.e., likely to respond to K addition, may need to be adjusted downward.

Grain yield increased with the index of available K when the corn was not directly fertilized with K. Only when the index reached approximately 250 kg K ha^{-1} were the yields of the fertilized and nonfertilized corn equal. Potassium fertilizer applied to corn increased corn stover and silage yields across all previous alfalfa K rates. Excess K fertilizer applied to alfalfa may provide enough carryover K for corn grain yield, but unless K fertilizer prices are considerably lower in the alfalfa year, it appears more risky to rely on carryover because of luxury consumption of applied K by alfalfa. Thus, applying recommended rates of K fertilizer directly to the following corn crop will likely be more profitable.

Table 1. Soil and alfalfa characteristics by location for on-farm experiments in Minnesota.

Year†	Location‡	Dominant soil series (classification)	Soil pH	STK§	Alfalfa cultivar	Stand age¶	Harvests#
				mg kg^{-1}		years	
2008	Albertville	Lester loam (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs)	5.9	111	Croplan ‘Trailblazer 7.0’	5	3
	Cannon Falls	Estherville sandy loam (sandy, mixed, mesic Typic Hapludolls)	7.1	98	Geerston Seed ‘Multi 5301’	3	3
	Pierz	Nokay loam (coarse-loamy, mixed, superactive, frigid Udollic Epiaqualfs)	6.9	89	Pioneer ‘54V46’	4	3
	Rochester-1	Port Byron silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls)	6.4	108	NK ‘Geneva’	4	3
	Rochester-2	Garwin silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls)	6.2	110	Pioneer ‘53Q60’	5	3
2009	Mantorville	Marquis silt loam (fine-loamy, mixed, superactive, mesic Oxyaquic Hapludolls)	7.4	101	Pioneer ‘54V46’	3	3
	Norwood-1	Le Sueur loam (fine-loamy, mixed, superactive, mesic Aquic Argiudolls)	6.7	85	NK ‘Genoa’	4	5
	Norwood-2	Sparta loamy sand (sandy, mixed, mesic Entic Hapludolls)	7.7	79	Mycogen ‘4A421’	4	3

Paynesville	Tara silt loam (fine-silty, mixed, superactive, frigid Aquic Hapludolls)	6.4	92	Grassland ‘Dynamic’	5	3
Pine Island	Downs-Hersey silt loam (fine-silty, mixed, superactive, mesic Mollic Hapludalfs)	6.5	95	Producers ‘A30-06’	4	4

† Experiments established in alfalfa fields that were rotated to corn the following year.

‡ Potassium applied before alfalfa regrowth in the spring at Norwood-1, Paynesville, and Pine Island. Potassium applied after the first alfalfa harvest at the other locations.

§ Average soil test K (STK) for the surface 0 to 15 cm for all main plots prior to K fertilization of alfalfa.

¶ Establishment year included.

Number of harvests after K fertilizer application.

Table 2. Corn seeding rate, hybrid, planting and fertilization date and initial soil test K (STK) of on-farm experiments in Minnesota.

Location†	Seeding rate	Hybrid	Planting date	K fertilization date	STK‡
	seeds ha^{-1}				mg kg^{-1}
Albertville	74,100	Pioneer ‘38P40’	25 Apr. 2009	7 May 2009	91
Cannon Falls	85,000	DeKalb ‘DKC52-59’	9 May 2009	23 May 2009	85
Pierz	75,000	Producers ‘5732’	2 May 2009	19 May 2009	67
Rochester-1	80,000	DeKalb ‘DKC52-62’	7 May 2009	1 June 2009	102
Rochester-2	75,000	Pioneer ‘37Y14’	5 May 2009	29 May 2009	109
Mantorville	90,000	Pioneer ‘34A85’	20 Apr. 2010	27 Apr. 2010	116
Norwood-1	82,500	Garst ‘86M39’	22 Apr. 2010	28 Apr. 2010	106
Norwood-2	77,500	Mycogen ‘2R430’	26 Apr. 2010	2 June 2010	77
Paynesville	74,800	Wolf River Valley ‘2987’	18 May 2010	4 June 2010	86
Pine Island	81,300	Producers ‘6372’	28 Apr. 2010	27 May 2010	-§

† Potassium applied before alfalfa regrowth in the spring at Norwood-1, Paynesville, and Pine Island. Potassium applied after the first alfalfa harvest at the other locations.

‡ Ammonium acetate-exchangeable K for the surface 0 to 15 cm of soil in the nonfertilized plots.

§ Data not available.

Table 3. Significance of the *F* tests for fixed effects of potassium (K), harvest (H), and their interaction from repeated measures statistical analysis for alfalfa yield and quality parameters averaged over seven locations where K was applied after the first alfalfa harvest.

Dependent variable†	Fixed source of variation		
	K	H	K x H
	----------- *P* > *F* -----------		
Yield	0.31	0.10	0.80
K conc.	<0.001	0.91	0.47
App. K uptake	<0.001	0.99	0.65
CP	<0.001	0.28	0.18
ADF	0.046	0.43	0.45
NDF	0.72	0.43	0.82
NDFD	<0.01	0.28	0.18
RFV	0.59	0.44	0.66
RFQ	0.69	0.82	0.73

† ADF, acid detergent fiber; App. K uptake, apparent fertilizer K uptake; CP, crude protein; K conc., herbage K concentration; NDF, neutral detergent fiber; NDFD, NDF digestibility; RFQ, relative feed quality; RFV, relative feed value.

Table 4. Significance of the *F* tests for the fixed effect of potassium (K) fertilization before and after first alfalfa harvest on total annual alfalfa dry matter yield and average annual quality.

Dependent variable†	Before first harvest‡	After first harvest§
	----------- *P* > *F*	-----------
Yield	0.20	0.25
K conc.	<0.001	<0.001
App. K uptake	<0.01	<0.001
KUE	0.98	0.34
CP	0.64	0.78
ADF	<0.001	0.01
NDF	<0.01	0.70
NDFD	<0.001	<0.001
RFV	<0.01	0.36
RFQ	0.056	0.54
FPP	0.60	0.54

† ADF, acid detergent fiber; App. K uptake, apparent fertilizer K uptake; CP, crude protein; FPP, final plant population; K conc., herbage K concentration; KUE, K fertilizer uptake efficiency; NDF, neutral detergent fiber; NDFD, NDF digestibility; RFQ, relative feed quality; RFV, relative feed value.

‡ Three locations in 2009.

§ Seven locations (five in 2008 and two in 2009).

Table 5. The effect of potassium (K) fertilization before and after first alfalfa harvest on observed annual means for neutral detergent fiber (NDF) and relative feed value (RFV).†

	Before first harvest‡		After first harvest§	
K rate	NDF	RFV	NDF	RFV
kg K ha^{-1}	g kg^{-1}		g kg^{-1}	
0	359a¶	180bc	352a	183a
19	350b	184a	352a	183a
46	357a	181ab	350a	184a
93	358a	180bc	354a	181a
186	362a	177c	353a	181a

† Weighted means over locations and alfalfa harvests following K fertilization.

‡ Three locations in 2009.

§ Seven locations (five in 2008 and two in 2009).

¶ Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$.

Table 6. Significance of the *F* tests for the fixed effects of potassium (K) applied to corn (CK), index of available K (IAK), and their interaction on corn yield and harvest index (HI).

Source	Grain†	Silage‡	Stover	HI
	-------------------	*P* > *F*	-----------------	
CK	<0.001	<0.001	<0.001	<0.001
IAK	0.66	0.10	0.048	0.52
IAK x CK	0.04	0.051	0.25	0.64

† Grain yield for nine locations.

‡ Silage yield, stover yield, and HI for eight locations.

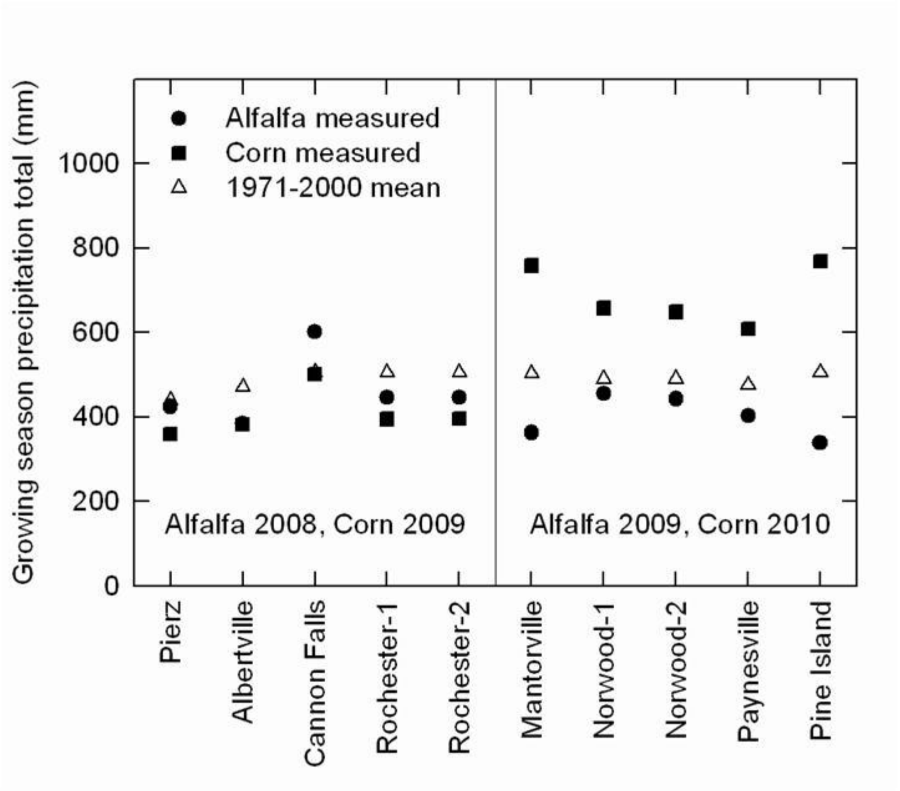


Fig. 1. Measured and 30-yr average (1971-2000) precipitation totals for alfalfa and corn growing seasons (April through August). Five locations in 2008 and five in 2009 were last production year alfalfa fields followed by corn the subsequent year. The Cannon Falls site received 191 and 114 mm irrigation water, which was added to measured precipitation in 2008 and 2009, respectively.

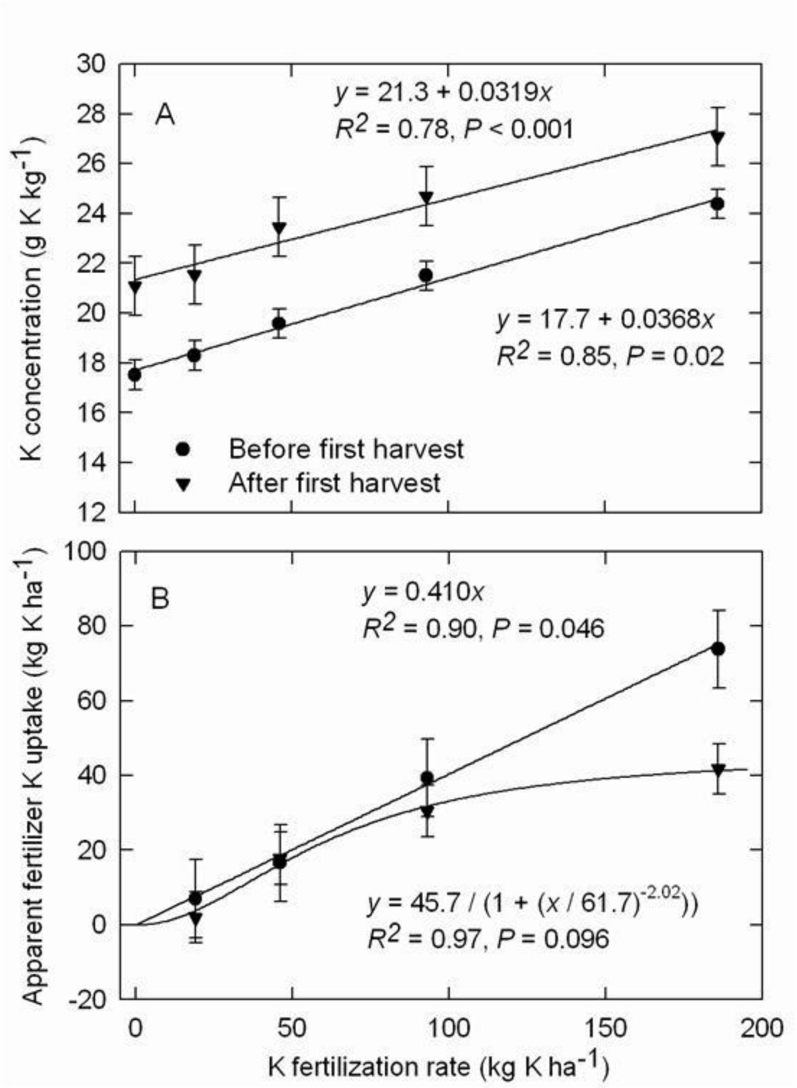


Fig. 2. Response of alfalfa (A) average annual herbage K concentration and (B) average apparent fertilizer K uptake to topdressed K fertilizer. Fertilizer K was applied before the first alfalfa harvest at three locations in 2009 (circles) and after

the first harvest at five locations in 2008 and two in 2009 (triangles). Error bars indicate standard error of the mean.

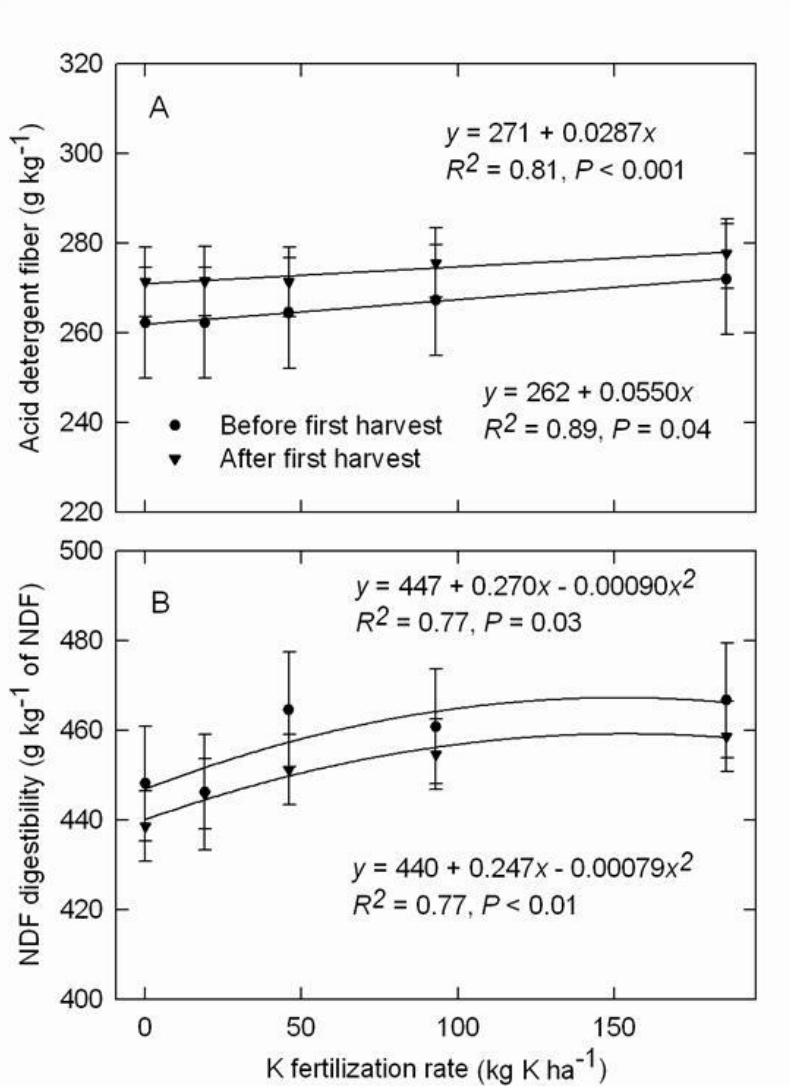


Fig. 3. Response of alfalfa average annual (A) acid detergent fiber (ADF) and (B) neutral detergent fiber digestibility (NDFD) concentrations to topdressed K fertilizer. Fertilizer K was applied before the first alfalfa harvest at three locations in 2009 (circles) and after the first harvest at five

locations in 2008 and two in 2009 (triangles). Error bars indicate standard error of the mean.

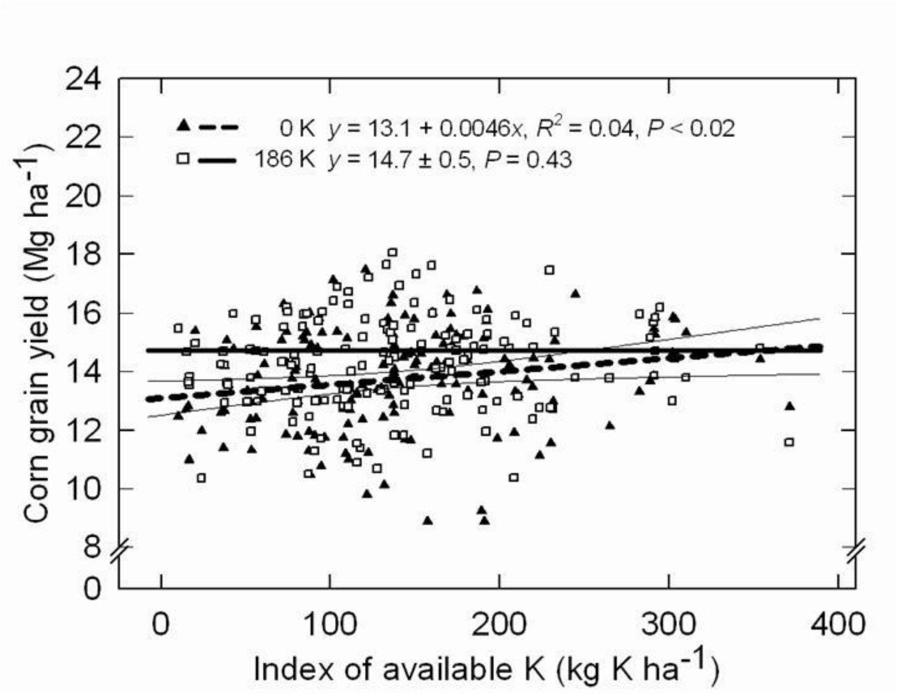


Fig. 4. Response of corn grain yield to index of available K with (open squares) or without (closed triangles) 186 kg K ha^{-1} applied to corn after emergence at nine locations in 2009 and 2010. Index of available K was calculated as initial soil test K (STK) plus apparent residual fertilizer K (K applied to alfalfa minus K removal in harvested herbage) in the last production year of alfalfa. When the slope was not significant, the mean and standard error were reported. The 95% confidence band is shown for corn that was not fertilized with K.

CHAPTER 3

Alfalfa Regrowth, Tillage Timing, and Fertilizer Nitrogen Management in Alfalfa-Corn Rotations

MATERIALS AND METHODS

Experiment (Exp.) One was established in 2008 and 2009 at 10 alfalfa fields in southern and central Minnesota in their final year of production to evaluate the yield and quality response of alfalfa to K fertilizer, and the K carryover to corn (Chapter 2). In this chapter, the effect of K applied to alfalfa on the N fertilizer requirement of the subsequent corn crop is reported. The experimental design was split plot arrangement in a randomized complete block with three or four replications at each location. Main plots in the alfalfa phase were topdressed with KCl at rates of 0, 19, 46, 93, and 186 kg K ha^{-1} and measured 18 m long by 14 m wide. Five subplots in the first-year corn phase were 0, 22, 45, 90, or 179 kg N ha^{-1} topdress-applied as ammonium nitrate and measured 10 m long by 3 m wide. Fertilizer N was applied 1 to 3 wk after corn planting. Detailed methods and background information are listed in Chapter 2.

Experiment Two was established in six final year alfalfa fields in southern and central Minnesota in 2009 with predominately medium- to fine-textured soils (Table 1) at the end of their second to sixth year of production (Table 2). Soil organic matter in the top 15 cm at these locations ranged from 43 to 50 g kg^{-1}. Two locations (Chatfield and Plainview) received dairy cow manure the fall before alfalfa seeding, whereas the remaining four locations had no recent manure history (≥15 yr). The experimental design was a split plot arrangement in randomized complete block with four replications. Main plots established at the end of the alfalfa phase were a factorial arrangement of two levels of alfalfa regrowth (present vs. absent) and two times of primary tillage (fall vs. spring), and measured 33 m long by 15 m wide. The 10 locations in Exp. One did not have regrowth or tillage timing treatments, but these factors were managed by the cooperating growers. Alfalfa herbage regrowth in Exp. One was either left in place or harvested and removed on about 15 Oct. 2009. Alfalfa regrowth height was the average of six plant heights measured before fall tillage in each main plot with regrowth remaining. Alfalfa regrowth herbage yield was measured in the fall shortly before tillage by hand-clipping two 1-m^2 quadrats within each main plot. Herbage regrowth samples were dried in a forced-air oven at 60°C, weighed to determine dry matter (DM) yield, ground to pass a 1-mm sieve, then analyzed for N concentration using an Elementar varioMax instrument (Elementar Analysensysteme GmbH, Hanau, Germany). Final alfalfa plant populations were measured at the same time as regrowth yield in two 0.67-m^2 quadrats within each main plot. Tillage treatments were applied using a disk-chisel in either fall (after 15 Oct. 2009) or in spring (about 15 Apr. 2010). Subplot treatments the following year were 0, 22, 45, 67, 90, or 179 kg N ha^{-1} broadcast applied as ammonium nitrate 1 to 2 wk after corn planting. When needed, soils were fertilized with P and K as triple super phosphate and topdressed KCl within 1 to 2 wk of corn planting at rates based on recommendations for corn production in Minnesota (Rehm et al., 2006). Corn hybrids of appropriate relative maturity for the area were planted and managed by cooperating growers (Table 2).

Corn was planted 5 cm deep between 20 Apr. and 18 May in 2009 and 2010 at seeding rates ranging from 74,100 to 93,500 seeds ha^{-1} (Table 2). Pre- and post-emergence herbicides were used by cooperating growers as needed to control pests and weeds. Starter fertilizer applications ($\leq$15 kg N ha^{-1}) were applied at planting by growers at the Albertville, Cannon Falls, and Mantorville sites in Exp. One and at the Lakefield and Plainview sites in Exp. Two. Due to an error, the Emmons site received 45 kg N ha^{-1} as topdressed urea before corn planting, but the fertilizer was not incorporated and there was no precipitation until 10 d after application. Thus, based on soil pH, nearly 30% of this applied urea was assumed to be lost through volatilization (Overdahl et al., 1991). Precipitation and air temperature data were obtained from the nearest National Weather Service station.

Corn Yield and Tissue Analysis

In both experiments, corn grain and cob yield was determined by hand harvesting 3 m of row within each subplot when the corn grain had attained physiological maturity, except at Albertville in Exp. One, which was harvested in mid-September because the field was harvested as silage by the grower. Corn stover was cut at typical harvest height (about 15 cm), weighed, chipped, and subsampled (about 1.5 kg) in the field. Corn cob and stover subsamples were dried at 60°C to determine DM yield. Grain and silage DM yields were adjusted to moisture contents of 155 and 655 g kg^{-1}, respectively, but stover yield was expressed as DM. Dried corn grain, cob, and stover subsamples from all 16 locations were ground to pass a 1-mm sieve and scanned at 1100-2500 nm by near-infrared reflectance spectroscopy with a Foss Model 6500 (Foss North America Inc., Eden Prairie, MN) to estimate N concentration. Grain, cob, and stover calibration samples (n = 97, 56, and 84, respectively) were selected using Intrasoft Int. (ISI, Port Matilda, PA) and analyzed for N by dry combustion with an Elementar varioMax instrument to develop calibration equations for the near infrared reflectance spectroscopy spectra (grain, $r^2 = 0.98$, $P < 0.001$; cob and stover were predicted with one equation, $r^2 = 0.96$, $P < 0.001$). Apparent fertilizer N uptake in grain, cob, stover, and silage was calculated as the difference in N uptake at each N rate from the control plots within a block.

Soil and Stalk Nitrate-Nitrogen

In Exp. One, residual soil NO_3-N was determined to the depth of 1.2 m by compositing three soil cores separated into 30-cm increments from each N rate subplot in the main plots with the highest alfalfa K rate (186 kg K ha^{-1}). Soils were dried in a forced-air oven at 35°C until constant mass and then ground to pass a 1-mm sieve. Soils collected in 2009 were extracted with 2M KCl and analyzed for NO_3-N concentration using a Lachat QuikChem 8000 series (Lachat Instruments, Loveland, CO), whereas soils from 2010 were sent to a certified commercial soil testing laboratory and extracted with 0.2M KCl and analyzed for NO_3-N with a Technicon Auto-Analyzer (Technicon Instruments, Tarrytown, NY). A subset of calibration samples ($n = 30$) were analyzed by both methods and used to adjust the 2010 data to match 2009 ($y = 3.14 + 0.973x$, $r^2 = 0.91$, $P < 0.001$). Soil bulk density was determined for each location from two 1.2-m-deep cores within each of the main plots. These samples were dried at 105°C, weighed, and the average dry bulk density for each depth increment was used to convert NO_3-N concentrations to content per unit area. Soil samples were collected 1 to 3 wk after the grower cooperator's corn grain harvest. The Cannon Falls and Norwood-2 sites were not sampled due to wet soil conditions and the Pierz site could only be sampled to 0.9 m due to excessively wet soil conditions at >0.9m. Therefore, these three locations were excluded from the analysis of soil residual NO_3-N in the top 1.2m.

In Exp. Two, basal stalk samples (15 to 35 cm) were collected from eight plants within the same row that was sampled for stover yield. Stalk samples were collected 1 to 3 wk after corn had reached physiological maturity according to the methods of Binford et al. (1990, 1992). Stalk samples were dried at 60°C until constant mass, ground to pass a 1-mm sieve, extracted for 30 min with a $CaCl_2$ extract, filtered using Whatman #2 filter paper, and analyzed by automated flow injection analysis at a certified commercial laboratory to determine NO_3-N concentration.

Data Analysis

Each experiment was analyzed separately at $P \leq 0.05$ using the MIXED procedure of SAS (SAS Institute, 2006) because treatments and N rates differed among experiments. Tillage timing, alfalfa regrowth, N rate, and K rate were considered fixed effects, whereas location, block (nested within location), and interactions involving location and block were considered random. The UNIVARIATE procedure of SAS was used to inspect residuals for normality and scatterplots of residuals vs. predicted values were used to assess common variance (Kutner et al., 2004). Regrowth N content was considered a covariate for all dependent variables in Exp. One; but it was not significant and therefore not used in the analysis. For each dependent variable, covariance parameter estimates were used to calculate the percent of total random variation associated with the effects of location and interactions between location and fixed effects. The two-tailed log likelihood ratio test was used to determine the significance of these random sources of variation. When the interaction between location and a fixed effect was significant ($P \leq 0.05$), best linear unbiased predictors (BLUPs) were used to determine the significance of the fixed effect for each location (Littell et al., 2006). When interactions between location and fixed effect were significant for multiple locations, all combinations of locations were evaluated with the two-tailed log likelihood ratio test in order to group locations that did not differ in their interaction with fixed effects. Linear and quadratic regression equations were developed using the MIXED procedure of SAS to describe the response of dependent variables to N rate. Non-linear regression equations were developed using the NLIN procedure of SAS to describe the response of dependent variables to N rate.

Several regression models were evaluated, but the regression models that produced the smallest residuals, were normally and randomly distributed, and were significant at $P \leq 0.05$ were used (Kutner et al., 2004). When regression models did not significantly fit the data, Fisher's protected LSD test ($P \leq 0.05$) was used for mean comparisons. Economic optimum N rates (EONR) within \$2.50 ha^{-1} maximum net return were calculated when the response of corn grain yield to N fertilizer was modeled with regression. Alfalfa N credits were calculated as the difference between the EONR in these alfalfa-corn rotations and the University of Minnesota EONR for continuous corn based on the 2006 Iowa State University Extension corn N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx).

RESULTS AND DISCUSSION

During the corn phase of Exp. One, warm season precipitation totals (May to September) were 27% below the 30-yr average (1979-2000) across five locations in 2009 and 28% above at the other five locations in 2010. In Exp. Two, precipitation totals for the fall of 2009 through spring of 2010 (October to April) at six locations were within 35 mm of the 30-yr average for every month except October, when average precipitation totals across locations were 203% (114 mm) above the 30-yr average. Warm season precipitation totals at these six locations ranged from 577 to 788 mm and were above the 30-yr average at all locations, ranging from about 70% above average for the two southwestern Minnesota locations (Brewster and Lakefield) to 28% above average at

Emmons (south-central Minnesota). Warm season average air temperatures for all 16 locations ranged from 18.3 to 19.4°C and were only slightly (2 to 7%) above the 30-yr average air temperature.

At the end of the alfalfa growing season, four locations in Exp. Two had nearly three times the amount of regrowth remaining before primary tillage than the Brewster and Emmons sites (Table 3). Regrowth yields across the locations in Exp. One ranged from 250 to 2040 kg DM ha^{-1} and regrowth N content ranged from 13 to 72 kg N ha^{-1}. Final plant populations were ≥43 plants m^{-2} (45 to 107 plants m^{-2}) at all locations in both experiments (Table 3).

Corn Yield

The interaction between location and K rate was significant for grain yield in Exp. One (Table 5), but only 2% of the total random variation in grain yield was accounted for by the interaction and no individual location had a significant response of grain yield to K based on BLUPs. Therefore, the effect of alfalfa K rate on grain yield was not further investigated and was generalized across locations. Averaged over 10 locations in Exp. One., K applied to alfalfa had no effect on first-year corn grain yield.

In Exp. Two, the interaction between location and N rate was significant for grain yield (Table 5) and BLUPs indicated that N fertilizer increased grain yield at only the Brewster location ($P < 0.001$). Average grain yield across the other 15 locations was 14.0 Mg ha^{-1} (12.0 to 16.1 Mg ha^{-1}), yet there was no response to N fertilizer even at these high yield levels (Table 4). Corn grain yield at the Brewster location was maximized with 101 kg N ha^{-1}, at which it was 16% greater than the nonfertilized control (13.6 Mg ha^{-1}) (Table 6). The EONR at this location was 85 kg N ha^{-1} and the N rates within \$2.50 ha^{-1} of maximum net return for grain yield were 80 to 90 kg N ha^{-1}, assuming average fertilizer and grain prices for 2008 to 2010 (\$0.87 kg^{-1} N as anhydrous ammonia, USDA-ERS, 2011; \$132 Mg^{-1} corn grain, Center for Farm Financial Management, 2011). Based on these prices and considering the EONR for continuous corn, the alfalfa N credit was 64 kg N ha^{-1} at this location. Alfalfa regrowth yield at this location contained 19 kg N ha^{-1} (Table 3), but the incorporated regrowth did not reduce the amount of N fertilizer required to maximize grain yield (Table 4). We are uncertain why corn at this location responded to N fertilizer, but suspect that it was due to inadequate soil drainage and excess precipitation, which may have reduced mineralization and increased denitrification compared to the other locations.

Corn cob yield averaged among treatments and locations ranged from 1.2 to 1.5 Mg ha^{-1} across both experiments. Cob yield at the 10 locations in Exp. One was not affected by N rate or K application to alfalfa (Table 4). Although the main effect of N fertilization was significant in Exp. Two, BLUPs indicated that fertilizer N increased cob yield only at Brewster and Montevideo, but not at the other four sites (Table 5). Cob yield increased by 15 and 10% at Brewster and Montevideo and was maximized when 117 and 91 kg N ha^{-1} was applied, respectively (Table 6). The N rate needed for maximum cob yield at Brewster was 16% higher than the N rate for maximum grain yield.

Stover yields ranged from 8.0 to 8.9 Mg ha^{-1}, while silage yields ranged from 30.6 to 44.5 Mg ha^{-1} among treatments, locations, and experiments. Application of N to corn and K to previous alfalfa had no effect on corn stover and silage yields in Exp. One (Table 4). However, averaged over six locations in Exp. Two, maximum stover and silage yields were attained with 103 and 52 kg N ha^{-1}, respectively, and in both cases yields were 4% greater than nonfertilized corn (Table 6). At average N fertilizer and corn silage prices for 2008 to 2010, the EONR for silage yield was 31 kg N ha^{-1} and the net return to N within \$2.50 ha^{-1} of maximum yield was 25 to 37 kg N ha^{-1} (\$0.87 kg^{-1} N as anhydrous ammonia, USDA-ERS, 2011; \$39 Mg^{-1} silage, Center for Farm Financial Management, 2011). In New York, Lawrence et al. (2008) concluded that application of starter N (≤ 34 kg N ha^{-1}) was sufficient to economically optimize silage yield and quality, which is consistent with these results, although we did not determine N needed to optimize silage quality.

Fertilizer Nitrogen Uptake

The log likelihood ratio test indicated that the interaction between location and K rate was significant for grain and silage ANU (Table 5), however BLUPs indicated that K rate was not significant for any location. The main effect of K rate was significant for cob ANU at the Albertville (P = 0.046) and Norwood-1 (P = 0.017) locations and stover ANU at three locations (Albertville, Norwood-1, and Pine Island; P = 0.014, <0.001, and 0.035, respectively), according to BLUPs. However, no regression models fit these data and the means for the nonfertilized and highest K rate (186 kg K ha^{-1}) main plots did not differ. Therefore the main effect of K on corn ANU was not further investigated.

Grain, stover, and silage ANU were increased by N fertilizer rate across locations in both experiments (Table 4). In Exp. One, grain ANU increased by 11 kg N ha^{-1} as N rate increased to 179 kg N ha^{-1}, whereas grain ANU was maximized with 55 kg N ha^{-1} and contained 12.5 kg ha^{-1} more N than nonfertilized corn in Exp. Two (Table 6). These increases in grain ANU were lower than those reported in Minnesota by Lory et al. (1995) for corn following alfalfa that did not respond in grain yield to N fertilizer (maximum ANU was 24 kg N ha^{-1} with 125 kg N ha^{-1} fertilizer). Corn following alfalfa in Wisconsin also had increased grain N concentration without a yield response to N (Bundy and Andraski, 1993).

Cob ANU across 10 locations in Exp. One increased by 1.3 kg N ha^{-1} as N application reached 179 kg N ha^{-1} (Table 6). In contrast, corn cobs did not contain more fertilizer N than nonfertilized corn across six locations in Exp. Two (Table 4), although there was an increase in cob yield at the Brewster and Montevideo (Table 6). According to BLUPs, alfalfa regrowth significantly improved cob ANU by 0.9 kg N ha^{-1} at the Montevideo location ($P = 0.019$) in Exp. Two, but reduced cob ANU by 1.0 kg N ha^{-1} at Brewster ($P = 0.029$). Therefore, it is unclear whether alfalfa regrowth N made any significant contribution to corn cob N uptake, but it is likely that any statistical differences were of no biological significance.

In Exp. One, stover and silage ANU increased 7 and 25 kg N ha^{-1} with 179 kg N ha^{-1} (Table 6). Although the interaction between location, tillage timing, and N rate in Exp. Two was significant for silage ANU ($P = 0.042$) according to the log likelihood test (Table 5), BLUPs indicated that the tillage by N rate interaction was not significant for any single location. The alfalfa regrowth herbage in Exp. Two contained 11 to 58 kg N ha^{-1} (Table 3), but there was no increase in corn N uptake from incorporated alfalfa regrowth even when only the nonfertilized control plots were considered ($P = 0.678$). Stover and silage ANU averaged over locations in Exp. Two were maximized when 110 and 98 kg N ha^{-1} was applied and contained 8 and 22 kg N ha^{-1} more N than nonfertilized corn (Table 6). The difference in the response of corn ANU to N fertilizer (linear vs. linear-plateau or quadratic-plateau) in Exp. One and Two, respectively, may have been influenced by the additional N rate (67 kg N ha^{-1}) in Exp. Two which helped define the junction in the non-linear models. At maximum silage N uptake, corn recovered only 14 to 22% of the applied fertilizer in Exp. One and Two, respectively. Even with low fertilizer uptake efficiencies, corn in both experiments recovered more fertilizer N than needed for economic optimum grain yield across 15 locations (excluding Brewster) and silage yield across 10 locations in Exp. One. The N rate needed to maximize silage ANU across six locations in Exp. Two was 25% higher (4.3 kg N ha^{-1}) than the amount needed for maximum silage yield. Luxury consumption of N is common in nonlegumes (Fowler, 2003). Our results confirm that when corn follows alfalfa, luxury consumption occurs, but that nearly 80% of the applied fertilizer may be susceptible to loss.

Residual Soil and Basal Stalk Nitrate-Nitrogen

When fertilizer N applications exceed the N requirements of first-year corn following alfalfa, growers lose profit and increase the risk for NO_3- N leaching into groundwater (Lory et al., 1995; Basso and Ritchie, 2005). According to the log likelihood test, the interaction between location and N rate was significant (Table 5) and accounted for 25% of the total random variability in soil residual NO_3- N. Therefore, BLUPs were used to investigate the effect of N fertilization at each location.

Four locations had linear increases in soil NO_3- N to 1.2 m, which averaged 74 kg NO_3- N ha^{-1} more than the nonfertilized corn when 179 kg N ha^{-1} had been applied (Table 6). At two locations (Paynesville and Rochester-2) and at Norwood-1, average soil NO_3-N increased by only 12 and 14 kg NO_3-N ha^{-1} when 45 kg N ha^{-1} was applied, respectively. As N application increased from 45 to 179 kg N ha^{-1}, soil NO_3- N levels increased by 117 kg NO_3-N ha^{-1} at the two locations and by 237 kg NO_3-N ha^{-1} at the one location. Confirming other reports, these results demonstrate that when N applications to corn following alfalfa exceed 45 kg N ha^{-1}, the risk of soil NO_3-N leaching greatly increases. When 157 kg N ha^{-1} was applied to corn in Minnesota, soil NO_3-N increased 45 kg N ha^{-1} more in first-year corn after alfalfa than in continuous corn (Lory et al., 1995). In Pennsylvania, application of 50 and 100 kg N ha^{-1} increased N fertilizer lost in leachate by 58 and 83 kg NO_3-N ha^{-1}, respectively, when no N fertilizer was needed for economic optimum corn grain yield (Toth and Fox, 1998). In comparison, annual application of 120 kg N ha^{-1} to first-year corn for 3 yr in Michigan had minimal effects on the cumulative NO_3-N leached (Basso and Ritchie, 2005).

Four out of six locations in Exp. Two had optimum or excessive BSN concentrations in the nonfertilized plots at the end of the season, yet stover and silage yields increased across locations (Table 6). The average BSN concentration for corn receiving no fertilizer N varied widely across locations (40, 310, 940, 1900, 2240, 6930 mg N kg^{-1} for Brewster, Montevideo, Plainview, Emmons, Lakefield, and Chatfield, respectively). The Lakefield site had no manure history, yet BSN concentrations were in the excessive category. Based on updated critical values of Binford et al. (1992), only 75% of 20 sites in Wisconsin had optimum or higher BSN concentration when corn followed alfalfa and no N fertilizer was required to maximize grain yield (Bundy and Andraski, 1993).

According to BLUPs, BSN concentrations across four locations were maximized with 106 kg N ha^{-1} and were 1.6-fold higher than the nonfertilized corn (Table 6). At the Montevideo site, BSN concentration increased by 8-fold to 5960 mg N kg^{-1} as N rate increased to 179 kg N ha^{-1}. At the only N responsive site (Brewster), the N rate needed to raise BSN concentration into the optimum range (94 kg N ha^{-1}) was within the profitable range of N rates for economic optimum grain yield. Therefore, the BSN test was successful in identifying the need additional N fertilizer at Brewster, but did not correctly identify the lack of grain yield response to N fertilizer at Montevideo. First-year corn after alfalfa in the Northern U.S. has responded to fertilizer N only 9% of the time (references cited within the introduction), therefore this test is likely to be more useful and profitable when corn follows crops other than alfalfa.

CONCLUSIONS

Over 10 site-years in Minnesota, carryover K from alfalfa had no influence on first-year N credits of alfalfa to corn. This provides further evidence that K fertilizer applications to alfalfa in the last production year may not be economical on soils that are medium testing in K (Chapter 2). Alfalfa regrowth, tillage timing, and their interaction had no significant effect on corn yield, fertilizer N uptake, BSN concentrations, or N fertilizer requirements of first-year corn after alfalfa. Therefore, on medium- to fine-textured soils, there was no short-term N benefit to leaving alfalfa regrowth in the field. Harvesting alfalfa regrowth in the fall before termination on these fields should be considered where feasible. Additionally, growers may have added flexibility for timing of alfalfa incorporation and may be able to capture some of the advantages of spring tillage (reduced N mineralization and NO_3-N accumulation in the fall, Peterson and Russelle, 1991) without reducing the alfalfa N credit to first-year corn. However, other factors concerning time of incorporation may need to be considered (e.g., delayed corn planting or less soil moisture).

Corn grain yield increased with N fertilizer at only one of 16 locations in this study, supporting and extending previous research, most of which had lower grain yields than obtained in these experiments. In the Corn Belt, the current N credit for first-year corn after alfalfa with plant populations of ≥43 or 53 plants m^{-2} on medium to fine-textured soils is 168 kg N ha^{-1}. This implies that additional fertilizer N can improve profit when corn prices are high relative to fertilizer price. Based on our results and those under similar conditions in the literature, it may be better to indicate that highest profit for grain production will be obtained by avoiding fertilizer N application when first-year corn follows alfalfa. When first-year corn silage is grown after alfalfa, small applications of N (approximately 30 kg N ha^{-1}) may be required in some instances to obtain economic optimum silage yields. In order to prevent yield loss and reduce over-application of fertilizer N in alfalfa-corn rotations, the focus of further research should be to identify the situations in which first-year corn will respond to N fertilizer.

Table 1. Background soil characteristics for 16 on-farm trials.

Exp.	Nearest town in Minnesota	Dominant soil series (classification)	Soil texture†	Soil pH‡	P§	K¶
					Mg kg^{-1}	
1	Albertville	Lester (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs)	l	5.9	15	111
	Cannon Falls	Estherville (sandy, mixed, mesic Typic Hapludolls)	sl	7.1	39	98
	Pierz	Nokay (coarse-loamy, mixed, superactive, frigid Udollic Epiaqualfs)	l	6.9	14	89
	Rochester-1	Port Byron (fine-silty, mixed, superactive, mesic Typic Hapludolls)	sil	6.4	12	108
	Rochester-2	Garwin (fine-silty, mixed, superactive, mesic Typic Endoaquolls)	scl	6.2	61	110
	Mantorville	Marquis (fine-loamy, mixed, superactive, mesic Oxyaquic Hapludolls)	sil	7.4	15	101
	Norwood-1	Le Sueur (fine-loamy, mixed, superactive, mesic Aquic Argiudolls)	l	6.7	61	85
	Norwood-2	Sparta (sandy, mixed, mesic Entic Hapludolls)	ls	7.7	17	79
	Paynesville	Tara (fine-silty, mixed, superactive, frigid Aquic Hapludolls)	sil	6.4	35	92
	Pine Island	Downs-Hersey complex (fine-silty, mixed, superactive, mesic Mollic Hapludalfs)	sil	6.5	-	95
2	Brewster	Crippin (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)	cl	6.5	22	170
	Chatfield	Tama (fine-silty, mixed, superactive, mesic Typic Argiudolls)	sil	6.3	100	135
	Emmons	Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls)	l	6.7	46	289
	Lakefield	Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)	cl	6.6	34	180

Montevideo	Colvin-Quam complex (fine-silty, mixed, superactive, frigid Typic Calciaquolls and fine-silty, mixed, superactive, frigid Cumulic Endoaquolls)	cl	7.0	16	183
Plainview	Downs-Hersey complex (fine-silty, mixed, superactive, mesic Mollic Hapludalfs)	sil	5.7	20	169

† Cl, clay loam; l, loam; ls, loamy sand; sl, sandy loam; scl, sandy clay loam; sil, silt loam.

‡ Average soil pH for the surface 0-15 cm of soil.

§ Average Bray-1 P for the surface 0-15 cm of soil sampled in main plots before K fertilizer application in Exp. One and before regrowth and tillage treatments in Exp. Two.

¶ Average ammonium acetate-exchangeable K for the surface 0-15 cm of soil sampled in main plots before K fertilizer application in Exp. One and before regrowth and tillage treatments in Exp. Two.

Table 2. Alfalfa and corn characteristics for 16 on-farm trials.

		Alfalfa		Corn			
Exp.	Nearest town in Minnesota	Cultivar	Stand age†	Planting date	Seeding rate	Hybrid	RM‡
			yr		seeds ha^{-1}		
1	Albertville	Croplan ‘Trailblazer 7.0’	5	25 Apr. 2009	74,100	Pioneer ‘38P40’	95
	Cannon Falls	Geerston Seed ‘Multi 5301’	3	9 May 2009	85,000	DeKalb ‘DKC52-59’	102
	Pierz	Pioneer ‘54V46’	4	2 May 2009	75,000	Producers ‘5732’	97
	Rochester-1	NK ‘Geneva’	4	7 May 2009	80,000	DeKalb ‘DKC52-62’	102
	Rochester-2	Pioneer ‘53Q60’	5	5 May 2009	75,000	Pioneer ‘37Y14’	99
	Mantorville	Pioneer ‘54V46’	3	20 Apr. 2010	90,000	Pioneer ‘34A85’	108
	Norwood-1	Mycogen ‘4A421’	4	22 Apr. 2010	82,500	Garst ‘86M39’	105
	Norwood-2	NK ‘Genoa’	4	27 Apr. 2010	77,500	Mycogen ‘2R430’	96
	Paynesville	Grassland ‘Dynamic’	5	18 May 2010	74,800	Wolf River Valley ‘2987’	87
	Pine Island	Producers ‘A30-06’	4	28 Apr. 2010	81,300	Producers ‘6372’	103
2	Brewster	Pioneer '54H91'	4	24 Apr. 2010	91,300	Pioneer '35F44'	105
	Chatfield	Jung 'Lighting III'	3	21 Apr. 2010	93,500	Jung '7475'	100
	Emmons	Midwest Genetics 'LH400'	6	21 Apr. 2010	87,500	Channel '202-83'	102
	Lakefield	Mycogen 'Multiplier 3'	7	23 Apr. 2010	85,000	DeKalb 'DKC50-47'	100

Montevideo	Nortec ‘Delta 625’	5	21 Apr. 2010	80,800	Nortec '8312'	95
Plainview	V.N.S (Variety Not Stated)	3	23 Apr. 2010	86,300	Pioneer '38N86'	97

† Establishment year included in stand age.

‡ Corn hybrid relative maturity.

Table 3. Final alfalfa plant population (FPP), alfalfa regrowth dry matter (DM) yield, alfalfa regrowth N and C content, and primary tillage timing, type, and depth for Experiment (Exp.) One and Two.

				Alfalfa regrowth†				Primary tillage‡		
Exp.	Year	Nearest town	FPP	Height	DM	N	C	Timing§	Type	Depth
			plants m^{-2}	cm	------- kg ha^{-1} -------					cm
1	2008	Albertville	76	-	-	-	-	F	MP	20
		Cannon Falls	73	7	1079	37	465	S	MP	30
		Pierz	107	-	874	44	382	S	MP	23
		Rochester-1	45	13	912	40	370	S	DC	13
		Rochester-2	54	9	330	13	139	F	DC	25
	2009	Mantorville	95	43	1160	47	506	F	DC	30
		Norwood-1	93	16	2040	72	882	F	MP	20
		Norwood-2	84	23	250	10	110	S	MP	15
		Paynesville	60	38	1740	70	771	F	MP	20
		Pine Island	63	15	537	22	235	F	MP	30
2	2009	Brewster	66	15	433	19	191	F/S	DC	20
		Chatfield	60	33	961	43	426	F/S	DC	13
		Emmons	47	10	360	11	158	F/S	DC	15

Lakefield	50	38	1530	53	676	F/S	DC	14
Montevideo	62	46	1622	58	717	F/S	DC	20
Plainview	88	25	798	37	357	F/S	DC	20

† Regrowth data for Exp. Two were averaged across main plots that did not have regrowth removed before tillage. Alfalfa regrowth was not a treatment in Exp. One, but subject to grower's standard practice. No alfalfa regrowth was present before primary tillage at Albertville and height data was not determined at Pierz.

‡ MP, Moldboard plow; DC, disk-chisel; F, fall; S, spring.

§ Tillage timing was not a treatment in Exp. One, but was subject to grower standard practice.

Table 4. Significance of the *F* tests for fixed effects of alfalfa K and corn N fertilization across 10 locations in Experiment (Exp.) One and alfalfa regrowth before termination (R), tillage timing (T), and N fertilization across six locations in Exp. Two.

	Source of	Yield†				Apparent fertilizer N uptake‡				Residual NO_3-N§	
Exp.	variation	Grain	Stover	Cob	Silage	Grain	Stover	Cob	Silage	Basal stalk	Soil
		-- *P* > *F* --									
1	N	NS	NS	NS	NS	***	***	*	**	-	**
	K	NS	NS	NS	NS	NS	NS	NS	NS	-	-#
	N x K	NS	NS	NS	NS	NS	NS	NS	NS	-	-
2	R	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	T	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	R x T	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	N	NS	*	**	**	*	**	NS	**	***	-
	R x N	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	T x N	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	R x T x N	NS	NS	NS	NS	NS	NS	NS	NS	NS	-

NS, not significant ($P > 0.05$). *, **, and ***, significance at the $P = 0.05$, 0.01, and 0.001 level, respectively.

† Stover and silage yields were analyzed for nine locations in Exp. One.

‡ Stover and silage apparent fertilizer N uptake were analyzed for nine locations in Exp. One.

§ Soil residual NO_3-N is for the top 1.2 m of soil and was analyzed for seven locations in Exp. One (three in 2009 and four in 2010). Basal stalk NO_3-N was determined only in Exp. Two.

¶ Soil samples were taken in all N rate subplots of only one K rate (186 kg K ha^{-1}).

Table 5. Significance of the two-tailed log likelihood ratio test for the interactions between location (L) and the fixed effects of alfalfa K and corn N fertilization across 10 locations in Experiment (Exp.) One and the fixed effects of alfalfa regrowth before termination (R), tillage timing (T), and N applied across six locations in Exp. Two.

		Yield†				Apparent fertilizer N uptake‡				Residual NO_3-N§	
Exp.	Source of variation	Grain	Stover	Cob	Silage	Grain	Stover	Cob	Silage	Basal stalk	Soil
		---------- $P > x^2$ ----------									
1	L x N	NS	NS	NS	NS	NS	NS	NS	NS	-	***
	L x K	**	NS	NS	NS	***	***	***	**	-	-
	L x N x K	NS	NS	NS	NS	NS	NS	NS	NS	-	-
2	L x R	NS	NS	NS	NS	NS	NS	*	NS	NS	-
	L x T	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	L x R x T	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	L x N	*	NS	*	NS	NS	NS	NS	NS	***	-
	L x R x N	NS	NS	NS	NS	NS	NS	NS	NS	NS	-
	L x T x N	NS	NS	NS	NS	NS	NS	NS	*	NS	-
	L x R x T x N	NS	NS	NS	NS	NS	NS	NS	NS	NS	-

NS, not significant ($P > 0.05$). *, **, and ***, significance at the $P = 0.05$, 0.01, and 0.001 level, respectively.

† Stover and silage yields were analyzed for nine locations in Exp. One.

‡ Stover and silage apparent fertilizer N uptake were analyzed for nine locations in Exp. One.

§ Soil residual NO_3-N was analyzed for seven locations in Exp. One (three in 2009 and four in 2010).

Table 6. Parameter estimates, r^2 values, and model significance values for regression models relating N application to apparent fertilizer N uptake (ANU) and soil residual NO_3-N in Experiment (Exp.) One, and corn yield, ANU, and basal stalk NO_3-N (BSN) concentration in Exp. Two.

				Parameter estimates§					
Exp.	Dependent variable	Location†	Model‡	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	X_0	r^2	Model significance
							kg N ha^{-1}		$P > F$
1	Grain ANU (kg N ha^{-1})	-	L	0	0.059	-	-	0.24	***
	Cob ANU (kg N ha^{-1})	-	L	0	0.0072	-	-	0.31	***
	Stover ANU (kg N ha^{-1})	-	L	0	0.040	-	-	0.88	**
	Silage ANU (kg N ha^{-1})	-	L	0	0.14	-	-	0.88	***
	Soil NO_3-N (kg ha^{-1})	ALB, MAN, ROC-2, PIN	L	46.1	0.37	-	-	0.86	*
		PAY, ROC-1	Q	70.5	0.11	0.0034	-	0.88	**
		NOR-1	Q	71.1	-0.047	0.0081	-	0.91	***
2	Grain yield (Mg ha^{-1})	BRE	QP	13.6	0.044	-0.00022	101	-	***

Cob yield (Mg ha^{-1})	BRE	QP	1.4	0.0041	-0.000020	117	-	***
	MON	QP	1.1	0.012	-0.00030	19	-	***
Stover yield (Mg ha^{-1})	-	Q	8.5	0.0062	-0.000030	-	0.73	**
Silage yield (Mg ha^{-1})	-	QP	36.0	0.056	-0.00054	52	-	*
Grain ANU (kg N ha^{-1})	-	LP	0	0.23	-	55	-	***
Stover ANU (kg N ha^{-1})	-	QP	0	0.15	-0.00069	110	-	***
Silage ANU (kg N ha^{-1})	-	QP	0	0.44	-0.0023	98	-	***
BSN (mg kg^{-1})	BRE	Q	87.7	-6.88	0.141	-	0.88	***
	MON	L	633	33.34	-	-	0.72	***
	CHA, EMM, LAK, PLA	LP	2943	29.48	-	106	-	***

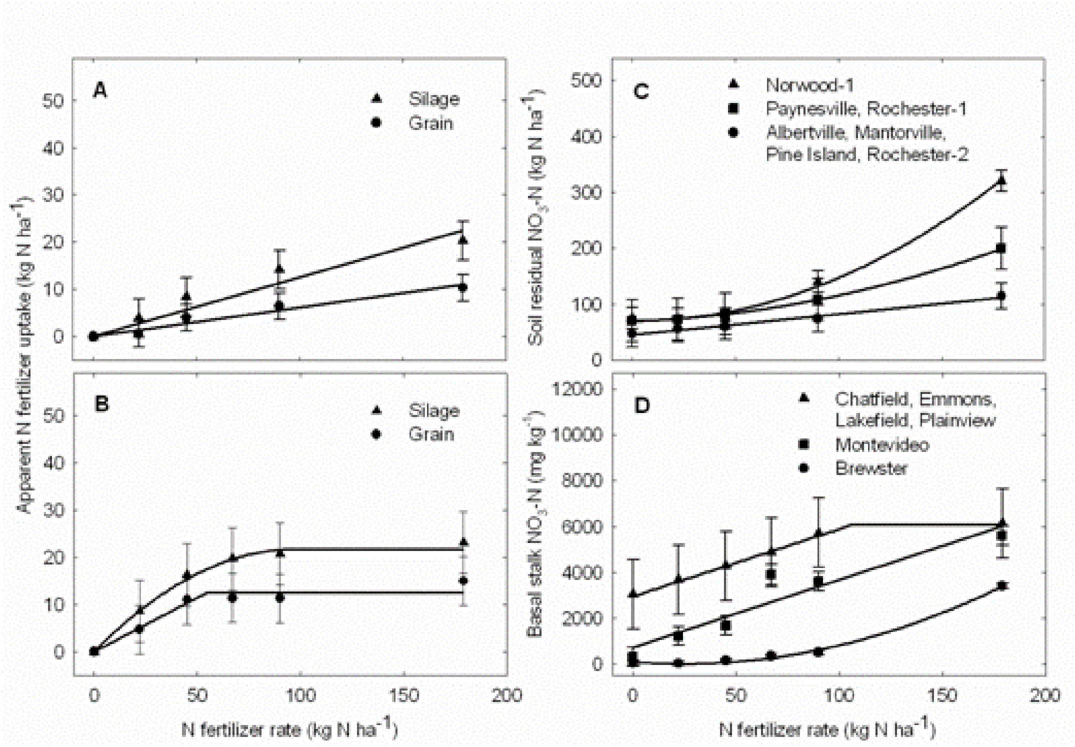
, significant at the 0.01 level; *, significant at the 0.001 level.

† Locations are shown as the first three letters of nearest town (see Table 3 for reference); otherwise the two-tailed log likelihood test was not significant and response was averaged across 10 or 6 locations in Exp. One or Two, respectively (-). The exception was stover and silage yield and ANU in Exp. One, which were averaged over nine locations.

‡ L, linear regression; LP, linear-plateau regression; Q, quadratic regression; QP, quadratic-plateau regression.

§ Beta zero, intercept; Beta one, linear coefficient; Beta two, quadratic coefficient.

Fig. 1. The response of apparent fertilizer N uptake for corn grain and silage in experiment (Exp.) One (A) and Exp. Two (B) to N fertilization, and the response of residual soil NO_3-N for seven locations in Exp. Two (C) and basal stalk NO_3-N concentration for six locations in Exp. Two (D) to N fertilization. Error bars represent the standard error of the means. Regression equations and fit statistics are stated in Table 6.



CHAPTER 4

Potassium and Nitrogen Management during the Rotation from Alfalfa to Corn: A Summary

Potassium fertilizer prices have nearly tripled in recent years, making it even more crucial for alfalfa growers to apply economically optimum rates of K fertilizer. There has been considerable research assessing the response of alfalfa to K, yet fertilizer recommendations still vary widely among states and no current recommendations change for the last alfalfa production year when stand persistence is not a major concern. This on-farm research across 10 site-years demonstrated that optimal K rates for alfalfa yield and quality in its last production year can be reduced without reducing alfalfa yield or quality when medium- to fine-textured soils have medium STK at the beginning of the last alfalfa production year. We have evidence from rising herbage K content that the crop absorbed fertilizer K, so the lack of response was not due to poor availability of the fertilizer. Over 60% of the fertilizer K was not used by alfalfa and should have been available to the corn. However, grain yield of nonfertilized corn equaled that of the fertilized corn only when the highest amounts of residual K were available. Furthermore, corn stover and silage yields were 8 and 10% higher, respectively, when K was applied to the corn rather than supplied by K carried over from alfalfa. Our results suggest that excess K applied to alfalfa may be less available to corn than newly applied K. Therefore, under similar conditions, growers could save money by withholding K fertilizer during the last year of alfalfa and saving it for corn.

In the second study, N fertilizer requirements were investigated at the previous 10 locations plus an additional six locations. Based on the results we obtained, carryover K from alfalfa had no influence on the N credit for corn production across 10 locations. This further supports K application to first-year corn rather than last-year alfalfa when STK is in the medium range. When alfalfa was terminated at six locations in 2009, alfalfa regrowth contained between 11 and 58 kg N ha^{-1}, but this regrowth and had no effect on corn grain and silage yield, fertilizer N uptake, basal stalk nitrate concentrations, or N fertilizer requirement of first-year corn after alfalfa, regardless of time of tillage. The results of this study suggest that growers could harvest alfalfa regrowth in the fall before alfalfa incorporation on fields with good stands ($\geq$43 plants m^{-2}) without altering the N credit from alfalfa to first-year corn. Furthermore, spring and fall tillage resulted in similar N credits to first-year corn following alfalfa, which allows growers added flexibility in tillage timing without reducing the N credit. Further research should investigate the effects of alfalfa regrowth and tillage timing when alfalfa plant populations are lower and on coarse textured soils.

Previous research over 125 site-years in the U.S. has shown that first-year corn following alfalfa required no N fertilizer to maximize corn yields in about 91% of the cases (references cited in intro.). At one of 16 locations in this study, the EONR for corn grain yield was 85 kg N ha^{-1}. We are uncertain why this site responded to N fertilizer, but suspect that it was due to inadequate soil drainage and excess precipitation. These results highlight the need for new and perhaps site-specific methods of determining which first-year corn fields will require fertilizer N to maximize grain yield. Relatively few studies have investigated optimal N rates needed for silage yield of first-year corn. The EONR for silage yield over six locations was 31 kg N ha^{-1}, which is consistent with results from New York that suggested starter N applications were sufficient to maximize silage yield (Lawrence, 2008). Current N credit recommendations suggest that fertilizer N applications should be reduced by 168 kg N ha^{-1} for first-year corn following alfalfa. However, recommendations do not take into the account the fact that growers often apply more than 168 kg N ha^{-1} when corn prices are high. According to our results and the majority (91%) of the literature, no additional N fertilizer is needed to maximize grain yield. Therefore, current N credit recommendations may need to be altered to suggest that no N fertilizer is needed for first-year corn grain yield, regardless of corn price, whereas corn silage may need small amounts of N ($\leq$31 kg N ha^{-1}) to optimize yield. Additional research is needed to determine whether N credits for poorer alfalfa plant populations (< 43 plants m^{-2}) should be altered when corn is harvested for silage.

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