Potassium Management during the Rotation from Alfalfa to Corn

Matt A. Yost,* Michael P. Russelle, Jeffrey A. Coulter, Craig C. Sheaffer, and Daniel E. Kaiser

ABSTRACT

High K fertilizer prices in recent years have made it imperative for growers to apply optimum K rates to alfalfa (*Medicago sativa* L.). Current university fertilizer guidelines in the Corn Belt do not change for the last production year, when alfalfa stand persistence is not a major concern. Furthermore, little is known about carryover of K applied to alfalfa on first-year corn (*Zea mays* L.) grain and silage yields. In 2008 to 2010, on-farm research was conducted on 10 fields with medium soil test potassium (STK) to determine response to K for alfalfa yield and quality in the last production year, and to estimate 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. When corn relied on carryover K alone, 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. Regardless of K rate applied to alfalfa, additional K applied to corn increased corn stover and silage yields by 10 and 8%, respectively. This suggests that carryover K was less available than K applied to corn. On medium STK soils going into the last year of alfalfa, applying fertilizer K to first-year corn rather than alfalfa may enhance economic return.

With 3.89 million ha harvested each year in U.S. Corn Belt states (Iowa, Illinois, Indiana, Michigan, Minnesota, North Dakota, Nebraska, Ohio, South Dakota, and 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), farmers in the upper 20th 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, Vitosch 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 ≥43 plants m⁻² in the last production year to maximize the N fertilizer replacement value 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 (1978–2007), 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


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**Abbreviations:** ADF, acid detergent fiber; CP, crude protein; DM, dry matter; FPP, final plant population; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; RFV, relative feed value; RFQ, relative feed quality; STK, soil test potassium.
risk of high forage K concentration. High dietary K concentrations in periparturient cow rations may increase the risk of par
turient 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.

The objectives of this 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 hypothe-
sized that alfalfa yield and quality would increase on medium
STK soils with K fertilizer topdressed in the last produc-
tion 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.

### MATERIALS AND METHODS

#### Field Experiments

On-farm experiments were established in alfalfa fields entering
their second to fourth year after seeding, and which the cooper-
ating growers intended to terminate and rotate to corn (Table 1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Dominant soil series (classification)</th>
<th>Soil pH</th>
<th>STK§</th>
<th>Alfalfa cultivar</th>
<th>Stand age¶</th>
<th>Harvests no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Albertville</td>
<td>Lester loam (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs)</td>
<td>6.5</td>
<td>200</td>
<td>Croplan ‘Trailblazer 7.0’</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2009</td>
<td>Norwood-1</td>
<td>Marquis silt loam (fine-loamy, mixed, superactive, mesic Oxyaquic Hapludolls)</td>
<td>6.7</td>
<td>85</td>
<td>NK ‘Genoa’</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Norwood-2</td>
<td>Sparta loamy sand (sandy, mixed, mesic Entic Hapludolls)</td>
<td>7.7</td>
<td>79</td>
<td>Mycogen ‘4A421’</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Pine Island</td>
<td>Downs-Hersey silt loam (fine-silty, mixed, superactive, mesic Mollic Hapludollfs)</td>
<td>6.5</td>
<td>95</td>
<td>Producers ‘A30–06’</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Paynesville</td>
<td>Tara silt loam (fine-silty, mixed, superactive, frigid Aquic Hapludolls)</td>
<td>6.4</td>
<td>92</td>
<td>Grassland ‘Dynamic’</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Dairy cow manure had sol 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 was ≤6.5, which is below
optimum (Rehm et al., 2000; Peters et al., 2005), at four loca-
tions (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 treat-
ments 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 before K fertilization of alfalfa.

Note: 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 potassium (STK) for the surface 0 to 15 cm for all main plots before 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 potassium (STK) of on-farm experiments in Minnesota.

<table>
<thead>
<tr>
<th>Location†</th>
<th>Seeding rate</th>
<th>Hybrid</th>
<th>Planting date</th>
<th>K fertilization date</th>
<th>STK‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albertville</td>
<td>74,100</td>
<td>Pioneer ‘38P40’</td>
<td>25 Apr. 2009</td>
<td>7 May 2009</td>
<td>91</td>
</tr>
<tr>
<td>Cannon Falls</td>
<td>85,000</td>
<td>DeKalb ‘DKC52–59’</td>
<td>9 May 2009</td>
<td>23 May 2009</td>
<td>85</td>
</tr>
<tr>
<td>Pierz</td>
<td>75,000</td>
<td>Producers ’5732’</td>
<td>2 May 2009</td>
<td>19 May 2009</td>
<td>67</td>
</tr>
<tr>
<td>Rochester-1</td>
<td>80,000</td>
<td>DeKalb ‘DKC52–62’</td>
<td>7 May 2009</td>
<td>1 June 2009</td>
<td>102</td>
</tr>
<tr>
<td>Rochester-2</td>
<td>75,000</td>
<td>Pioneer ‘37Y14’</td>
<td>5 May 2009</td>
<td>29 May 2009</td>
<td>109</td>
</tr>
<tr>
<td>Mantorville</td>
<td>90,000</td>
<td>Pioneer ‘34A85’</td>
<td>20 Apr. 2010</td>
<td>27 Apr. 2010</td>
<td>116</td>
</tr>
<tr>
<td>Norwood-1</td>
<td>82,500</td>
<td>Garst ’86M39’</td>
<td>22 Apr. 2010</td>
<td>28 Apr. 2010</td>
<td>106</td>
</tr>
<tr>
<td>Norwood-2</td>
<td>77,500</td>
<td>Mycogen ‘2R430’</td>
<td>26 Apr. 2010</td>
<td>2 June 2010</td>
<td>77</td>
</tr>
<tr>
<td>Paynesville</td>
<td>74,800</td>
<td>Wolf River Valley ‘2987’</td>
<td>18 May 2010</td>
<td>4 June 2010</td>
<td>86</td>
</tr>
<tr>
<td>Pine Island</td>
<td>81,300</td>
<td>Producers ‘6372’</td>
<td>28 Apr. 2010</td>
<td>27 May 2010</td>
<td>8</td>
</tr>
</tbody>
</table>

† 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.

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 before 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 air 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-m² 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-m² plots within each main plot to determine final plant population (FPP).

Alfalfa herbage samples from all harvests after K fertilization were scanned at 1100 to 2500 nm by near-infrared reflectance spectroscopy 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 neutral detergent fiber 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 near-infrared reflectance spectroscopy predictions were calibrated to the wet chemical analysis using regression (CP, R² = 0.76, P < 0.001; ADF, R² = 0.89, P < 0.001; NDF, R² = 0.86, P < 0.001; NDFD, R² = 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 0.5M HCl (Rao et al., 1998) and analyzing the extracts with atomic emission spectroscopy using a PerkinElmer Analyst 400 (PerkinElmer, Waltham, MA). To validate the 0.5M 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 PerkinElmer Optima model 3000 (PerkinElmer, 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 (R² = 0.99, P < 0.0001). 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
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.

<table>
<thead>
<tr>
<th>Dependent variable†</th>
<th>Fixed source of variation</th>
<th>K</th>
<th>H</th>
<th>K ( \times ) H</th>
<th>( P &gt; F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td></td>
<td>0.31</td>
<td>0.10</td>
<td>0.80</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>K conc.</td>
<td></td>
<td>&lt;0.001</td>
<td>0.91</td>
<td>0.47</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>App. K uptake</td>
<td></td>
<td>&lt;0.001</td>
<td>0.99</td>
<td>0.65</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>CP</td>
<td></td>
<td>&lt;0.001</td>
<td>0.28</td>
<td>0.18</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>ADF</td>
<td></td>
<td>0.046</td>
<td>0.43</td>
<td>0.45</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>NDF</td>
<td></td>
<td>0.72</td>
<td>0.43</td>
<td>0.82</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>NDFD</td>
<td></td>
<td>&lt;0.01</td>
<td>0.28</td>
<td>0.18</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>RFV</td>
<td></td>
<td>0.59</td>
<td>0.44</td>
<td>0.66</td>
<td>( &lt;0.001 )</td>
</tr>
<tr>
<td>RFQ</td>
<td></td>
<td>0.69</td>
<td>0.82</td>
<td>0.73</td>
<td>( &lt;0.001 )</td>
</tr>
</tbody>
</table>

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

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. 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 \( (P \leq 0.05, \text{linear and quadratic models}; P \leq 0.10, \text{logistic model}) \) (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 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–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-year-old alfalfa stands on soils with STK near 81 to 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; 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 MacGregor, 1966), 200 to 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; 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 ($1.03 \text{ kg}^{-1}$ K) (USDA-ERS, 2011), alfalfa growers following these guidelines would have spent about $67 \text{ ha}^{-1}$ 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 × 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 (21.1–27.1 g kg$^{-1}$) than before (17.5–24.4 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 farms 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 (9.0–24.1 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

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

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Before first harvest</th>
<th>After first harvest</th>
<th>$P &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>0.20</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>K conc.</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>App. K uptake</td>
<td>&lt;0.01</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>KUE</td>
<td>0.98</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>CP</td>
<td>0.64</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>ADF</td>
<td>&lt;0.001</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>NDF</td>
<td>&lt;0.01</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>NDFD</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>RFV</td>
<td>&lt;0.01</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>0.056</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>FPP</td>
<td>0.60</td>
<td>0.54</td>
<td></td>
</tr>
</tbody>
</table>

‡ Three locations in 2009.
§ Seven locations (five in 2008 and two in 2009).
Excess K uptake can be problematic when alfalfa is fed at high harvests and locations and that luxury consumption occurred. Fertilizer K was applied before the first harvest (Table 1). 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). Average apparent K uptake was 85% higher for the early application timing than the later timing (Table 4). Lissbrant et al. (2009) found 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 g kg⁻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 when K was applied before and after the first harvest, respectively (Fig. 3A). Lissbrant et al. (2009) found higher NDF concentrations when K was applied before the first harvest (Table 4). When K was applied before the first harvest, NDF averaged 3% lower with 65, 95, 96, and 85% 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 farms. 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.

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 farms. 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.
tolerance of these modern alfalfa cultivars (Lamb et al., 2006). As leniency of previous fall harvests (Kallenbach et al., 2002), other factors may have helped maintain plant populations, such as adequacy of soil pH (Peters et al., 2005), and improved stress from fertilized plots (Sheaffer et al., 1986; Burmester et al., 1991), but soils at the low end of the medium range for K in the nonferal detergent fiber (NDF) and relative feed value (RFV).†

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).‡

<table>
<thead>
<tr>
<th>K rate</th>
<th>Before first harvest§</th>
<th>After first harvest$</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg K ha$^{-1}$</td>
<td>NDF (g kg$^{-1}$)</td>
<td>RFV</td>
</tr>
<tr>
<td>0</td>
<td>359a††</td>
<td>180bc</td>
</tr>
<tr>
<td>19</td>
<td>350b</td>
<td>184a</td>
</tr>
<tr>
<td>46</td>
<td>357a</td>
<td>181ab</td>
</tr>
<tr>
<td>93</td>
<td>358a</td>
<td>180bc</td>
</tr>
<tr>
<td>186</td>
<td>362a</td>
<td>177c</td>
</tr>
</tbody>
</table>

† Weighted means over locations and alfalfa harvests following K fertilization.
‡ Averaged over three locations in 2009.
§ Averaged over seven locations (five in 2008 and two in 2009).
¶ Within a column, means followed by the same letter are not significantly different at P ≤ 0.05.

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 a 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; Alhadhrami 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 nonsulfurized 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 nonsulfurized 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 nonsulfurized 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$^{-1}$.

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Grain†</th>
<th>Silage‡</th>
<th>Stover</th>
<th>HI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>IAK</td>
<td>0.66</td>
<td>0.10</td>
<td>0.048</td>
<td>0.52</td>
</tr>
<tr>
<td>IAK × CK</td>
<td>0.04</td>
<td>0.051</td>
<td>0.25</td>
<td>0.64</td>
</tr>
</tbody>
</table>

† Grain yield for nine locations.
‡ Silage yield, stover yield, and HI for eight locations.

**Corn Yield and Potassium Uptake**

According to covariance parameter estimates, location accounted for 38% of the total random variability in corn yield, whereas the interactions among location, index of available K, and K applied to corn accounted for ≤5%. 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 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 also was 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.
ACKNOWLEDGMENTS

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REFERENCES


