Alfalfa Nitrogen Credit to First-Year Corn: Potassium, Regrowth, and Tillage Timing Effects

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ABSTRACT

Compared with corn (Zea mays L.) following corn, N guidelines for first-year corn following alfalfa (Medicago sativa L.) in the U.S. Corn Belt suggest that N rates can be reduced by about 168 kg N ha$^{-1}$ when 43 or 53 alfalfa plants m$^{-2}$ are present at termination. These guidelines have been questioned by practitioners, however, as corn grain yields have increased. We conducted experiments at 16 locations in Minnesota to address questions regarding N availability to first-year corn after alfalfa relating to the effect of carryover fertilizer K from alfalfa and the amount and timing of alfalfa regrowth incorporation. Corn grain yield, silage yield, and fertilizer N uptake were not affected by carryover K or amount or timing of regrowth incorporation. Maximum corn grain yield ranged from 12.0 to 16.1 Mg ha$^{-1}$ among locations but responded to fertilizer N at only one. At that location, which had inadequate soil drainage, the economically optimum N rate (EONR) was 85 kg N ha$^{-1}$, assuming prices of US$0.87 kg$^{-1}$ N and US$312 Mg$^{-1}$ grain. The EONR for silage yield across 6 of 15 locations where it was measured was 40 kg N ha$^{-1}$, assuming US$39 Mg$^{-1}$ silage. 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 yield is often maximized without fertilizer N, regardless of alfalfa regrowth management or timing of incorporation, but that small N applications may be needed to optimize silage yield.

EACH YEAR, CORN is grown after alfalfa on about 1.1 million ha in U.S. Corn Belt states (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin; National Agricultural Statistics Service, 2009), assuming that 28.6% of the alfalfa is rotated to corn annually (3.5-yr average stand life; Peterson and Russelle, 1991). Representing only 5% of the total field corn hectarage in the region (National Agricultural Statistics Service, 2009), this rotation may be the path to a more sustainable future because alfalfa usually increases corn yield potential and decreases the need for fertilizer N. In a long-term crop rotation trial in Wisconsin, for example, grain yield of first-year corn following at least one full production year of alfalfa was not affected by N rate and increased with time by 100 kg ha$^{-1}$ yr$^{-1}$ compared with 28 kg ha$^{-1}$ yr$^{-1}$ for continuous corn fertilized with 224 kg N ha$^{-1}$ (Stanger and Lauer, 2008). Furthermore, literature from Pennsylvania to Minnesota (125 site-years) indicates that 91% of the time no fertilizer N was required to maximize grain yield from Pennsylvania to Minnesota (125 site-years) indicates that 91% of the time no fertilizer N was required to maximize grain yield of first-year corn grown after a good stand (≥43 plants m$^{-2}$) of alfalfa on medium- or fine-textured soils (Trippett 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). Across the 11 responsive site-years in these studies, only 48 kg N ha$^{-1}$ was needed to maximize grain yield.

Most current university fertilizer N guidelines in Corn Belt states advise growers to reduce fertilizer N on first-year corn after alfalfa by 168 kg ha$^{-1}$ when 43 or 53 alfalfa plants m$^{-2}$ are present at the time of termination (Michigan, Ohio, Indiana, Vitos et al., 1995; Wisconsin, Laboski et al., 2006; Minnesota, Rehm et al., 2006); however, the literature indicates that in most cases first-year corn after alfalfa requires no fertilizer N to maximize yield. Instead of the traditional alfalfa N credit guidelines of most states, Iowa guidelines recommend that growers apply up to only 34 kg N ha$^{-1}$ to first-year corn following alfalfa (Blackmer et al., 1997). When a N credit recommendation of most states are followed, growers save about US$145 ha$^{-1}$ in fertilizer N costs at US$0.87 kg$^{-1}$ N, and the energy input to the corn crop decreases about 8100 MJ ha$^{-1}$, assuming an N credit of 168 kg N ha$^{-1}$ and 48.2 MJ kg$^{-1}$ N (Wang et al., 2011). Nevertheless, growers and their advisors still question whether alfalfa provides sufficient N for contemporary, high-yielding corn crops.

General reliability of the alfalfa fertilizer N replacement value or 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 yield the following year (Smith et al., 1992). In comparison, corn in Michigan on a medium-textured soil recovered more $^{15}$N from labeled alfalfa plants when alfalfa was incorporated in the spring rather than fall.
but tillage timing did not alter N recovery on a sandy loam soil (Harris and Hesterman, 1990). In New York, corn grain yield was reduced when alfalfa was incorporated in the spring rather than fall 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 the same state, although tillage timing was confounded with location in their study.

Fall-incorporated alfalfa regrowth increased first-year corn grain yield by 0.3 Mg ha$^{-1}$ compared with no regrowth across three locations in Minnesota that were not responsive to fertilizer K (Schmitt et al., 1996) and increased the N credit to first-year corn by 56 kg N ha$^{-1}$ in 1 yr on a sandy loam soil in Wisconsin (Kelling et al., 1992). Wisconsin is the only state in the northern United States, however, that recommends that a supplementary 45 kg N ha$^{-1}$ credit be given if >20 cm of regrowth is present when alfalfa grown on medium- and fine-textured soils is terminated (Bundy et al., 1992; Laboski et al., 2006). The amount of alfalfa regrowth incorporated may alter the effect of incorporation time, but we are aware of no studies that have directly measured how alfalfa N credits are affected by this interaction. If changing the tillage time or incorporating alfalfa regrowth increased the N credit by 45 kg N ha$^{-1}$, as suggested by Wisconsin guidelines (Laboski et al., 2006), a corn grower could save an additional US$39 ha$^{-1}$ in fertilizer N expenses for first-year corn.

The basal stalk nitrate (BSN) test was developed as a post-mortem test to assess the late-season N status of predominately continuous corn and corn following soybean [Glycine max (L.) Merr.] (Binford et al., 1990, 1992). Evidence concerning the effect of the previous crop on the effectiveness of the BSN test is still lacking. Statewide data from Iowa showed that when corn followed soybean rather than corn, BSN concentrations were less likely to test in a higher category; however, the researchers suggested that the previous crop effect was mainly due to excess precipitation (Kyveryga et al., 2010). Most studies investigating the effectiveness of the BSN test have evaluated corn following corn or soybean (Binford et al., 1990, 1992; Hooker and Morris, 1999; Broduer et al., 2000; Kyveryga et al., 2010; Forrestal et al., 2012). The few studies that have evaluated the BSN test for corn following alfalfa have had limited success with the test (Bundy and Andraski, 1993; Lawrence et al., 2008). Critical levels for the BSN test may need to be altered for corn following alfalfa compared with corn following corn because alfalfa promotes N mineralization during the entire corn growing season (Carpenter-Boggs et al., 2000).

Optimum rates of fertilizer N for corn yield can be influenced by soil K fertility. When sufficient 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 grain and stover yield (Welch and Flannery, 1985; Heckman and Kamprath, 1992). Therefore, the alfalfa N credit to first-year corn may be influenced by residual fertilizer K applied during the last alfalfa production year. On soils testing medium in exchangeable K at the beginning of the final alfalfa production year, we found that high amounts of carryover fertilizer K increased the grain yield of first-year corn (Yost et al., 2011). Thus, although carryover fertilizer K may impact the amount of N needed to optimize first-year corn yield, we found no published reports on the interaction of K fertility with response to N in first-year corn after alfalfa.

To address the need for information on these management variables, we conducted two independent, on-farm experiments in Minnesota to determine how carryover fertilizer K, alfalfa regrowth, and the time of alfalfa incorporation impact the fertilizer N requirement, apparent fertilizer N uptake (ANU), and residual NO$_3$–N of first-year corn after alfalfa.

**MATERIALS AND METHODS**

Experiment 1 was established in five fields in 2008 and another five fields in 2009 in southern and central Minnesota in the final year of alfalfa production (Tables 1 and 2) to evaluate the yield and quality responses of alfalfa to fertilizer K and the subsequent fertilizer K carryover to corn (Yost et al., 2011). We focus here on the effect that the K applied to alfalfa had on the fertilizer N requirement of the following corn crop. The experimental design was a split-plot treatment arrangement in a randomized complete block design with three or four replications at each location. Main plots in the alfalfa phase measured 18 m long by 14 m wide and received broadcast KCl in the beginning of the last alfalfa growing season at rates of 0, 19, 46, 93, and 186 kg K ha$^{-1}$. Alfalfa regrowth and the timing and method of tillage for alfalfa termination varied among locations and were not replicated treatments (Table 2). Regrowth height was measured before fall tillage and was the average of six plant heights (measured from the cutting height used by each grower) in each main plot. Regrowth biomass yield was measured in the fall shortly before tillage by hand clipping two 1-m$^2$ quadrats within each main plot. 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, and then analyzed for total N concentration using an Elementar VarioMax (Elementar Analysensysteme GmbH). Final alfalfa plant population was measured at the same time as regrowth yield in two 0.67-m$^2$ quadrats within each main plot by digging alfalfa plants, separating them from the soil, and counting crowns. During the first-year corn phase at each location, five subplots within each main plot, measuring 9 m long by 4.7 m wide, received broadcast NH$_4$NO$_3$ at rates of 0, 22, 45, 90, or 179 kg N ha$^{-1}$. Fertilizer N was applied 1 to 3 wk after corn planting. When needed, P was surface broadcast to corn at the time of N application according to University of Minnesota recommendations (Rehm et al., 2006). In both experiments, corn hybrids of appropriate relative maturity for the area were planted and managed by cooperating growers (Table 3). Corn was planted 5 cm deep between 20 April and 18 May in 2009 and 2010 at rates ranging from 74,100 to 93,500 seeds ha$^{-1}$ (Table 3). Pre- and post-emergence herbicides were used by growers as needed to control weeds. Starter fertilizer (10–25 kg N ha$^{-1}$) was applied at planting by growers at the Albertville, Cannon Falls, and Mantorville sites. Precipitation and air temperature data were obtained from the nearest National Weather Service station.

Experiment 2 was established in 2009 in six final-year alfalfa fields in southern and central Minnesota with predominately medium- to fine-textured soils (Table 1). The fields were at the end of the second to sixth year of production after the establishment year (Table 2). Soil organic matter in the surface 15 cm at these locations ranged from 43 to 50 g kg$^{-1}$. 

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Two locations (Chatfield and Plainview) received dairy cow (Bos taurus) manure the fall before alfalfa seeding, whereas the remaining four locations had not received manure for at least 15 yr. The experimental design was a split-plot treatment arrangement in a randomized complete block design with four replications. Main plots established at the end of the alfalfa phase measured 33 m long by 15 m wide and were a factorial arrangement of two levels of alfalfa regrowth (present vs. absent) and two times for primary tillage (fall vs. spring). Alfalfa regrowth was either left in place or cut and removed on about 15 Oct. 2009. Regrowth height, yield, and final alfalfa plant population were measured as described above for Exp. 1. Tillage treatments were applied using a disk-chisel in either fall (after 15 Oct. 2009) or spring (about 15 Apr. 2010). Subplot treatments the following year were broadcast as NH4NO3 at rates of 0, 22, 45, 67, 90, or 179 kg N ha–1 applied 1 to 2 wk.
Table 3. Corn planting date, seeding rate, hybrid, hybrid relative maturity (RM), and maximum grain and silage yield for 16 on-farm trials in Minnesota for Exp. 1 and 2.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Location</th>
<th>Planting date</th>
<th>Seeding rate</th>
<th>Hybrid</th>
<th>RM</th>
<th>Grain</th>
<th>Silage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Albertville</td>
<td>25 Apr. 2009</td>
<td>74,100</td>
<td>Pioneer 38P40</td>
<td>d</td>
<td>95</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td>Cannon Falls</td>
<td>9 May 2009</td>
<td>85,000</td>
<td>DeKalb DKC52–59</td>
<td>102</td>
<td>12.0</td>
<td>52.9</td>
</tr>
<tr>
<td></td>
<td>Pierz</td>
<td>2 May 2009</td>
<td>75,000</td>
<td>Producers 5732</td>
<td>97</td>
<td>14.2</td>
<td>63.2</td>
</tr>
<tr>
<td></td>
<td>Rochester-1</td>
<td>7 May 2009</td>
<td>80,000</td>
<td>DeKalb DKC52–62</td>
<td>102</td>
<td>15.0</td>
<td>61.3</td>
</tr>
<tr>
<td></td>
<td>Rochester-2</td>
<td>5 May 2009</td>
<td>75,000</td>
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<td>99</td>
<td>14.1</td>
<td>60.4</td>
</tr>
<tr>
<td></td>
<td>Mantorville</td>
<td>20 Apr. 2010</td>
<td>90,000</td>
<td>Pioneer 34A85</td>
<td>108</td>
<td>13.1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Norwood-1</td>
<td>22 Apr. 2010</td>
<td>82,500</td>
<td>Garst B6M39</td>
<td>105</td>
<td>15.6</td>
<td>65.7</td>
</tr>
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<td></td>
<td>Norwood-2</td>
<td>27 Apr. 2010</td>
<td>77,500</td>
<td>Mycogen 2R430</td>
<td>96</td>
<td>12.2</td>
<td>55.0</td>
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<td></td>
<td>Paynesville</td>
<td>18 May 2010</td>
<td>74,800</td>
<td>Wolf River Valley 2987</td>
<td>87</td>
<td>15.1</td>
<td>67.4</td>
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<tr>
<td></td>
<td>Pine Island</td>
<td>28 Apr. 2010</td>
<td>81,300</td>
<td>Producers 6372</td>
<td>103</td>
<td>14.5</td>
<td>61.4</td>
</tr>
<tr>
<td>2</td>
<td>Brewster</td>
<td>24 Apr. 2010</td>
<td>91,300</td>
<td>Pioneer 35F44</td>
<td>105</td>
<td>15.9</td>
<td>65.4</td>
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<tr>
<td></td>
<td>Chatfield</td>
<td>21 Apr. 2010</td>
<td>93,500</td>
<td>Jung 7475</td>
<td>100</td>
<td>16.1</td>
<td>76.8</td>
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<td></td>
<td>Emmons</td>
<td>21 Apr. 2010</td>
<td>87,500</td>
<td>Channel 202–83</td>
<td>102</td>
<td>14.4</td>
<td>60.9</td>
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<tr>
<td></td>
<td>Lakefield</td>
<td>23 Apr. 2010</td>
<td>85,000</td>
<td>DeKalb DKC50–47</td>
<td>100</td>
<td>14.6</td>
<td>62.0</td>
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<tr>
<td></td>
<td>Montevideo</td>
<td>21 Apr. 2010</td>
<td>80,800</td>
<td>Nortec 8312</td>
<td>95</td>
<td>12.6</td>
<td>56.2</td>
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<tr>
<td></td>
<td>Plainview</td>
<td>23 Apr. 2010</td>
<td>86,300</td>
<td>Pioneer 38N86</td>
<td>97</td>
<td>14.3</td>
<td>64.5</td>
</tr>
</tbody>
</table>

† Maximum grain and silage yield at 155 and 650 g kg⁻¹ moisture, respectively. Maximum yield was the average across N rates when there was no response of yield to fertilizer N. When fertilizer N was required to maximize yield, maximum yield was the regression-predicted yield at N rates corresponding to the plateau of the nonlinear response curves. Silage yield was not determined at Mantorville.

After corn planting. When needed, soils were fertilized with P and K by broadcasting triple super phosphate and KCl within 1 to 2 wk of corn planting at rates based on recommendations for corn production in Minnesota (Rehm et al., 2006). Starter fertilizer (12 kg N ha⁻¹) was applied at planting at the Lakefield and Plainview sites. The Emmons site mistakenly received 45 kg N ha⁻¹ as broadcast urea before corn planting, but the fertilizer was not incorporated.

**Corn Yield and Tissue Analysis**

In both experiments corn grain and cob yield were determined by hand harvesting 3 m of row within each subplot when the corn grain had attained physiological maturity. Corn stover was cut at typical harvest height (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 155 and 650 g kg⁻¹ moisture, 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 to 2500 nm by near-infrared reflectance spectroscopy with a Foss Model 6500 (Foss North America) to estimate N concentration. Grain, cob, and stover samples (n = 97, 56, and 84, respectively) were selected using WinISI III version 3.0 (Infrasoft International) and analyzed for N by dry combustion with an Elemental varioMax to determine N concentration using a Lachat QuikChem 8000 (Lachat Instruments), whereas soil from 2010 was sent to a certified commercial soil testing laboratory and extracted with 2 mol L⁻¹ KCl and analyzed for NO₃⁻–N concentration using a Lachat AutoAnalyzer (Technicon Instruments). A subset of calibration samples (n = 30) was analyzed by both methods and used to adjust the 2010 data to match the methods used in 2009 (γ = 3.14 + 0.973x, r² = 0.91, P < 0.001). Soil bulk density was determined for each location from two 1.2-m-deep cores collected within each of the main plots at the time of soil residual NO₃–N sampling. These samples were dried at 105°C, weighed, and the average dry bulk density for each 30-cm depth increment was used to convert the NO₃–N concentration to content per unit area. The Cannon Falls, Norwood-2, and Pierz sites were excluded from the analysis of soil residual NO₃–N because excessively wet soil conditions at these locations prevented sampling.

In Exp. 2, stalk samples were collected 1 to 3 wk after corn had reached physiological maturity according to the methods of Binford et al. (1990, 1992). Basal stalk samples (20 cm long, beginning 15 cm above the soil surface) were collected from eight plants within the same row that was sampled for grain and stover yield, dried at 60°C until constant mass, ground to pass a 1-mm sieve, extracted for 30 min with 0.005 mol L⁻¹ CaCl₂, filtered using Whatman no. 2 filter paper, and analyzed for NO₃–N by automated flow injection analysis at a certified commercial laboratory.
Data Analysis

Because treatments and N rates differed between experiments, each experiment was analyzed separately at $P \leq 0.05$ using the MIXED procedure of SAS (SAS Institute, 2006). Nitrogen and K rate in Exp. 1 and tillage timing, alfalfa regrowth, and N rate in Exp. 2 were considered fixed effects, whereas location, block (nested within location), and interactions involving location and block were considered random effects for both experiments. The UNIVARIATE procedure of SAS was used to inspect the residuals for normality and scatterplots of the residuals vs. predicted values were used to assess common variance (Kutner et al., 2004). For each dependent variable, covariance parameter estimates were used to calculate the percentage 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 BLUPs indicated that interactions between location and a fixed effect were significant for multiple locations, all combinations of locations were evaluated with the two-tailed log-likelihood ratio test to group locations that did not differ in their response to the fixed effect.

Regression analysis was used to describe the response of the dependent variables to fertilizer N. Several regression models were evaluated and we selected the regression models that were significant at $P \leq 0.05$ and produced the smallest residuals that were normally and randomly distributed (Kutner et al., 2004). Linear and quadratic regression equations were developed using the MIXED procedure of SAS, and nonlinear regression equations were developed using the NLIN procedure of SAS. When regression models did not fit the data, Fisher's protected LSD test ($P \leq 0.05$) was used for mean comparisons. When the response of corn grain or silage yield to fertilizer N was modeled with quadratic or quadratic-plateau regression equations, the EONR was calculated by setting the first derivative to the fertilizer N cost/corn price ratio. Nitrogen rates within US$2.50 ha$^{-1}$ maximum net return to fertilizer N were also calculated by subtracting US$2.50 ha$^{-1}$ from the maximum net return and solving for N rate using the parameter estimates from the regression models. Alfalfa N credits were estimated as the difference between the EONR in these alfalfa–corn rotations and the EONR for continuous corn in Minnesota (167 kg N ha$^{-1}$, assuming US$0.87 kg$^{-1}$ N and US$139 Mg^{-1}$ grain) obtained from the regional corn N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx) on 1 Feb. 2012.

RESULTS AND DISCUSSION

After alfalfa termination in Exp. 1, precipitation totals across five locations during the fall of 2008 (October–December) were within 7 mm (6%) of the 30-yr average (1981–2010), but the fall of 2009 was wetter than average, with precipitation totals being 92 mm (71%) above average across the other five locations. In contrast, the spring of 2009 and 2010 (March–May) was drier than average by 56 mm (27%) across all 10 locations. During the corn phase of Exp. 1, warm-season (June–September) precipitation totals were 88 mm (21%) below the 30-yr average across five locations in 2009, but 193 mm (44%) above average across the other five locations in 2010. Average air temperature during the corn growing season (May–September) was near average across all locations in both years.

As in Exp. 1, precipitation totals across six locations in Exp. 2 for the fall of 2009 were higher than average by 120 mm (94%), and the spring of 2010 was drier than average by 70 mm (33%). October precipitation explained most of the excess, being 112 mm above the 30-yr average. Warm-season precipitation totals at these six locations in 2010 ranged from 528 to 729 mm and were above the 30-yr average at all locations, ranging from about 326 mm (82%) above average for the two southwestern Minnesota locations (Brewster and Lakefield) to 205 mm (48%) above average across the other four locations. Average air temperature during the 2010 corn growing season ranged from 18.3 to 19.4°C across the six locations and was within 1.3° of the 30-yr average.

Corn Yield

Corn grain yield in Exp. 1 was not influenced by the location × N rate and location × N rate × K rate interactions (Table 4). The interaction between location and K rate was significant for grain yield, but only 2% of the total random variability in grain yield was accounted for by this interaction and no individual location had a significant response of grain yield to K according to the BLUPs ($P \geq 0.216$). Therefore, the response of corn grain yield to the fertilizer treatments was generalized across locations. Across 10 locations in Exp. 1, corn grain yield averaged 14.0 Mg ha$^{-1}$ (12.0–15.6 Mg ha$^{-1}$) and was not affected by N rate, K applied to alfalfa, or their interaction (Table 4).

At the end of the alfalfa growing season, the amount of regrowth remaining before primary tillage at four locations in Exp. 2 was nearly three times the amount at the Brewster and Emmons locations (Table 2). Alfalfa regrowth in Exp. 2 contained 11 to 58 kg N ha$^{-1}$ across locations, but neither alfalfa regrowth nor tillage timing affected corn grain, cob, stover, or silage yield or corn yield response to fertilizer N (Table 4). When only the nonfertilized control plots were compared, there was still no increase in grain, stover, or silage yield from incorporated alfalfa regrowth ($P \geq 0.571$). When 1.6 Mg ha$^{-1}$ of alfalfa regrowth was incorporated at the Montevideo site, however, cob yield in the nonfertilized plots was reduced by 0.15 Mg ha$^{-1}$ compared with regrowth removal treatments ($P = 0.005$). Therefore, regardless of tillage timing, incorporated alfalfa regrowth had no benefit to the following corn crop.

The interaction between location and N rate was significant for grain yield in Exp. 2 (Table 5), and BLUPs indicated that fertilizer N increased the grain yield only at the Brewster location ($P < 0.001$). Average grain yield across the other five locations was 14.4 Mg ha$^{-1}$ (12.6–16.1 Mg ha$^{-1}$), yet there was no response to fertilizer N (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 N rates ± US$2.50 ha$^{-1}$ of maximum net return to N for grain yield were 80 to 91 kg N ha$^{-1}$, assuming average fertilizer and grain prices for 2008 to 2010 (US$0.87 kg$^{-1}$ N as anhydrous NH$_3$, Economic Research Service,
kg N ha\(^{-1}\) at this location. We are uncertain why this corn crop responded to fertilizer N but suspect that it was due to inadequate soil drainage and excess precipitation, which may have reduced N mineralization and increased denitrification compared with the other locations. Alfalfa regrowth at this location contained 19 kg N ha\(^{-1}\) (Table 2), but the incorporated regrowth did not reduce the amount of fertilizer N required to optimize grain yield (Table 4). In Exp. 2, cob yield was affected by the location \(\times\) N rate interaction and BLUPs indicated that fertilizer N influenced cob yield only at the Brewster \(\left(P < 0.001\right)\) and Montevideo \(\left(P = 0.019\right)\) locations (Table 5). Cob yield increased by 15 and 10% at Brewster and Montevideo and was maximized when 117 and 19 kg N ha\(^{-1}\) was applied, respectively (Table 6). We did not attempt an economic analysis of cob yield response to N.

Stover DM yield ranged from 8.0 to 8.9 Mg ha\(^{-1}\), while silage yield ranged from 52.9 to 76.8 Mg ha\(^{-1}\) among treatments, locations, and experiments. Neither application of K at the beginning of the previous alfalfa growing season nor N applied to corn altered corn stover or silage yield in Exp. 1 (Table 4), and this was consistent across locations (Table 5). Averaged across six locations in Exp. 2, however, maximum stover and silage yields were attained with 103 and 52 kg N ha\(^{-1}\), respectively (Table 6).
respectively, and in both cases yield was 4% greater than nonfertilized corn (Table 6). At average fertilizer N and corn silage prices for 2008 to 2010 (US$0.87 kg⁻¹ N as anhydrous NH₃, Economic Research Service, 2011; US$39 Mg⁻¹ silage, Center for Farm Financial Management, 2011), the EONR for silage yield was 40 kg N ha⁻¹ and net return to N ± US$2.50 ha⁻¹ of the maximum was 35 to 45 kg N ha⁻¹. In New York, Lawrence et al. (2008) concluded that N applied as starter fertilizer (≤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 the fertilizer N needed to optimize silage quality.

**Apparent Fertilizer Nitrogen Uptake**

The log-likelihood ratio test indicated that the interaction between location and K rate was significant for grain, cob, stover, and silage ANU in Exp. 1 (Table 5), but we did not detect significant responses in grain or silage ANU to K rate at any individual location using BLUPs (P > 0.375 and 0.103, respectively). 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 for stover ANU at three locations (Albertville, Norwood-1, and Pine Island; P = 0.014, <0.001, and 0.035, respectively). No regression models fit these data, however, and the means for the nonfertilized and highest K rate (186 kg K ha⁻¹) main plots did not differ. Therefore, the effect of K on corn ANU at these locations was not investigated further.

Grain, stover, and silage ANU were increased by fertilizer N in both experiments (Table 4), and this was consistent across locations (Table 5). In Exp. 1, grain ANU increased by 11 kg N ha⁻¹ as the N rate increased to 179 kg N ha⁻¹, whereas grain ANU in Exp. 2 was maximized with 55 kg N ha⁻¹, at which it was 12.5 kg ha⁻¹ greater than nonfertilized corn (Table 6; Fig. 1). 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 fertilizer N (the 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). In contrast to the fertilizer N response we observed, alfalfa regrowth in Exp. 2 had no effect (P ≥ 0.678) on grain, cob, stover, or silage ANU in the nonfertilized control plots.

Cob ANU across locations in Exp. 1 increased by 1.3 kg N ha⁻¹ as the N rate increased from 0 to 179 kg N ha⁻¹ (Table 6). In contrast, cob ANU was not affected by fertilizer N in Exp. 2 (Table 4), although cob yield increased at the Brewster and Montevideo locations (Table 6). According to the BLUPs, alfalfa regrowth in Exp. 2 significantly improved cob ANU by 0.9 kg N ha⁻¹ at the Montevideo location (P = 0.019) and reduced cob ANU by 1 kg N ha⁻¹ at the Brewster location (P = 0.029), but these differences are of minimal practical significance.

In Exp. 1, stover and silage ANU increased by 7 and 25 kg N ha⁻¹, respectively, with 179 kg N ha⁻¹ of fertilizer (Table 6; Fig. 1). Although the interaction among location, tillage timing, and N rate in Exp. 2 was significant for silage ANU according to the log-likelihood ratio test (Table 5), BLUPs indicated that the tillage × N rate interaction was not significant for any
single location ($P \geq 0.561$). Stover and silage ANU averaged across locations in Exp. 2 were maximized when 110 and 98 kg N ha$^{-1}$ were applied, respectively, and the stover and silage contained 8 and 22 kg N ha$^{-1}$ more N, respectively, than nonfertilized corn (Table 6; Fig. 1). The difference in the response of corn ANU to fertilizer N (linear vs. linear-plateau or quadratic-plateau in Exp. 1 and 2, respectively) may have been influenced by the additional N rate (67 kg N ha$^{-1}$) in Exp. 2 that helped define the junction in the nonlinear models.

At maximum silage N uptake, corn recovered only 14 to 22% of the applied fertilizer in Exp. 1 and 2, respectively. Even with low fertilizer uptake efficiencies, corn recovered more fertilizer N than needed for economically optimum silage yield across the 10 locations in Exp. 1 and grain yield across 15 locations (excluding Brewster) in both experiments. The N rate needed to maximize silage ANU across the six locations in Exp. 2 was similar to the amount needed for maximum silage yield (within 4.3 kg N ha$^{-1}$). Luxury consumption of N is common in non-legume species (Macy, 1936). Our results confirm that when corn follows alfalfa, luxury consumption of N occurs, but 78 to 86% of the applied fertilizer may be susceptible to loss because it is not taken up by the crop.

**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; Toth and Fox, 1998). According to the log-likelihood ratio test, the interaction between location and N rate was significant in Exp. 1 (Table 5) and accounted for 25% of the total random variability in soil residual NO$_3^-$N in the 0- to 1.2-m depth. Therefore, BLUPs were used to investigate the effect of N fertilization at each location. The response of soil residual NO$_3^-$N to fertilizer N rate was significant at all locations ($P \leq 0.019$). The Albertville, Mantorville, Pine Island, and Rochester-2 locations had a similar response of soil residual NO$_3^-$N to fertilizer N ($P \geq 0.159$). Across these four locations, there was a linear increase in soil NO$_3^-$N in the 0- to 1.2-m depth, which averaged 74 kg NO$_3^-$N ha$^{-1}$ more than the nonfertilized corn when 179 kg N ha$^{-1}$ was applied (Table 6; Fig. 1). When compared with the nonfertilized control, soil NO$_3^-$N at two locations (Paynesville and Rochester-1, which responded similarly according to BLUPs [$P = 0.292$]) and at the Norwood-1 location increased by only 13 and 16 kg NO$_3^-$N ha$^{-1}$, respectively, when 45 kg N ha$^{-1}$ was applied. Soil NO$_3^-$N in the upper 1.2 m, however, increased by 145 kg NO$_3^-$N ha$^{-1}$ at Paynesville and Rochester-1 and by 281 kg NO$_3^-$N ha$^{-1}$ at Norwood-1 with an application of 179 kg N ha$^{-1}$.

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). When no fertilizer N was needed for economically optimum corn grain yield in Pennsylvania, the application of 50 and 100 kg N ha$^{-1}$ increased fertilizer N lost in leachate by 58 and 83 kg NO$_3^-$N ha$^{-1}$, respectively (Toth and Fox, 1998). An application of 120 kg N ha$^{-1}$ to first-year corn after alfalfa increased NO$_3^-$N leaching by 50% in Michigan (Basso and Ritchie, 2005).

Another measurement that reflects late-season soil NO$_3^-$N is the BSN test. The average BSN concentration for first-year corn receiving no fertilizer N varied widely across locations (40, 310, 940, 1900, 2240, and 6930 mg N kg$^{-1}$ at Brewster, Montevideo, Plainview, Emmons, Lakefield, and Chatfield, respectively). According to Iowa guidelines (Binford et al., 1992; Blackmer and Mallarino, 2000), four of six locations in Exp. 2 (Chatfield, Emmons, Lakefield, and Plainview) had optimum or excessive BSN concentrations with no fertilizer N, whereas Brewer and Montevideo concentrations had
low BSN concentrations. As discussed above, fertilizer N was required to maximize grain yield only at the Brewer location and not at Montevideo or the other four sites. Therefore, the Iowa critical level of 700 mg NO₃–N kg⁻¹ correctly identified N sufficiency at five of six locations, whereas the lower BSN critical level of 250 mg NO₃–N kg⁻¹ suggested for corn in eastern states by Fox et al. (2001) and Forrestal et al. (2012) correctly indentified N sufficiency at all six locations.

According to BLUPs, the BSN concentration across the Chatfield, Emmens, Lakefield, and Plainview locations was maximized with 106 kg N ha⁻¹ and was 1.6-fold higher than the nonfertilized corn (Table 6). At the Montevideo site, the BSN concentration increased eightfold to 5960 mg NO₃–N kg⁻¹ as the fertilizer N rate increased to 179 kg N ha⁻¹. At Brewer, the N rate needed to raise the BSN concentration above 700 mg NO₃–N kg⁻¹ (94 kg N ha⁻¹) was within the profitable range of N rates for economically optimum grain yield. Therefore, in addition to successfully indentifying the need for fertilizer N at the Brewer site, the Iowa critical BSN levels (Binford et al., 1992; Blackmer and Mallarino, 2000) were successful in identifying the EONR for grain yield. When alfalfa preceded corn in other studies using the BSN test, the success of the test has been limited. For example, Iowa guidelines inaccurately identified the fertilizer N need for five of 20 sites in Wisconsin that had below-optimum BSN concentrations, but these sites did not require fertilizer N to maximize grain yield (Bundy and Andraski, 1993). Even when the lower critical values of 250 mg NO₃–N kg⁻¹ (Fox et al., 2001; Forrestal et al., 2012) for first-year corn silage after alfalfa in New York were considered, three of 16 sites tested low in BSN concentration, but corn yield at these sites did not respond to fertilizer N (Lawrence et al., 2008). Our results, in conjunction with Bundy and Andraski, (1993) and Lawrence et al. (2008), suggest that BSN critical levels may need to be lower than 700 mg NO₃–N kg⁻¹ when corn follows alfalfa. On the other hand, first-year corn after alfalfa on medium- to fine-textured soils from Pennsylvania to Minnesota has responded to fertilizer N only about 9% of the time, suggesting that even though the BSN test correctly identified the responsive site in Exp. 2, the test is likely to be more useful when corn follows crops other than alfalfa on these soils.

CONCLUSIONS

Across 10 locations in Minnesota, carryover K from alfalfa had no influence on the first-year N credit of alfalfa to corn. This provides further evidence that fertilizer K applications to alfalfa in the last production year may not be economical on soils that test medium in K (Yost et al., 2011). Alfalfa regrowth, tillage timing, and their interaction did not affect corn yield, fertilizer N uptake, BSN concentration, or fertilizer N requirements of first-year corn after alfalfa. Therefore, on medium- to fine-textured soils, there was no apparent short-term N benefit to leaving alfalfa regrowth in the field. On the basis of these results, in combination with those from Schmitt et al. (1996) and Kelling et al. (1992), we conclude that alfalfa regrowth has minimal impacts on the first-year corn fertilizer N requirement and that there is insufficient evidence to change alfalfa N credit guidelines to account for regrowth management. Harvesting alfalfa regrowth in the fall before termination on these fields could be considered where feasible. Additionally, growers may have added flexibility for the timing of alfalfa incorporation and may be able to capture some of the advantages of spring tillage (reduced N mineralization and NO₃–N accumulation in the fall; Peterson and Russelle, 1991) without reducing the alfalfa N credit to first-year corn; however, other factors concerning the time of incorporation may need to be considered (e.g., soil moisture or delayed corn planting).

Corn grain yield following alfalfa increased with fertilizer N 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 U.S. 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 typically 168 kg N ha⁻¹. This implies that additional fertilizer N can improve profits when corn prices are high relative to the fertilizer price. Based on our results and those under similar conditions in the literature, it may be better to indicate that the highest net return to 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 40 kg N ha⁻¹) may be required to obtain economically optimum silage yield. To prevent yield loss and reduce overapplication 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 fertilizer N.

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