Nitrogen Requirements of First-Year Corn following Alfalfa Were Not Altered by Fall-Applied Manure

Matt A. Yost,* Michael P. Russelle, and Jeffrey A. Coulter

ABSTRACT

Although farmers in the midwestern United States often apply livestock manure when terminating alfalfa (*Medicago sativa* L.), there are no published reports on direct effects of fall manure application on alfalfa N credits to first-year corn (*Zea mays* L.). Therefore, eight on-farm experiments were conducted in Minnesota to test whether manure applied during alfalfa termination in fall affects the rate of fertilizer N needed for the subsequent corn crop. Manure application rates were determined by cooperating growers and N fertilizer rates were 0, 45, 90 or 179 kg N ha⁻¹ at planting and 45 kg N ha⁻¹ as a sidedress. At five locations, neither manure nor fertilizer N increased grain or silage yield. At three remaining locations, N fertilizer was needed to economically optimize grain (98 kg N ha⁻¹ at two locations) or silage yield (113 kg N ha⁻¹ at three locations), but manure did not alter the response to fertilizer N. The presidedress soil nitrate test (PSNT) predicted the need for N fertilizer to optimize grain yield 63% of the time and the basal stalk nitrate test (BSNT) identified the need for N fertilizer 75% of the time. When results of this study were combined with data from the literature, the PSNT was accurate only 55% of the time and the BSNT could not separate responsive and nonresponsive sites. These results confirm that first-year corn following alfalfa often does not require supplemental N for maximum grain yield, and that more accurate methods are needed to predict fertilizer N response.

Improved understanding and adoption of alfalfa fertilizer N credits (N replacement values) to corn could increase farm profitability and reduce nitrate leaching in cropping systems (Peterson and Russell, 1991; Dinnes et al., 2002). When growers neglect alfalfa N credits and apply too much N to first-year corn following alfalfa, it decreases net return, wastes resources, and increases the risk of nitrate leaching. However, under-applying N suppresses yield and net return.

Alfalfa–corn growers in the midwestern United States often apply manure when terminating alfalfa to replenish soil P and K after several years of intensive alfalfa cropping (Sanford et al., 2009). Even though most effects of manure application on corn yield are positive (Eghball and Power, 1999), manure with high C content can immobilize soil N (Kuzyakov et al., 2000) and increase the need for early-season N fertilizer (Russelle et al., 2009). Thus, when manure is applied during the rotation from alfalfa to corn, manure could reduce fertilizer N requirements or additional fertilizer N may be necessary to limit the effects of N immobilization. Spring-applied dairy cow (*Bos taurus*) manure (110–420 total Kjeldahl nitrogen [TKN] ha⁻¹) increased grain yield of first-year corn after alfalfa by 1.1 Mg ha⁻¹ at one of four sites in Minnesota (Lory et al., 1995) and at one of two sites in Pennsylvania (Sripada et al., 2008), but these and other studies have not addressed directly whether fall-applied manure affects the fertilizer N requirement of first-year corn.

The PSNT (Magdoff et al., 1984) and BSNT (Binford et al., 1992) are two tools available for growers seeking to predict and assess soil N sufficiency for corn production, respectively. However, based on the widely adopted critical concentration of 21 mg NO₃⁻N kg⁻¹ (Andraski and Bundy, 2002; Laboski and Peters, 2012), the reliability of the PSNT to predict the need for additional N when corn follows alfalfa has been variable among studies (Bundy and Andraski, 1993; Morris et al., 1993; Schmitt and Randall, 1994; Yost et al., 2013). Across 101 sites of corn with recent organic N inputs from alfalfa, manure, or soybean (*Glycine max* [L.] Merr.) in Wisconsin, the accuracy of the PSNT depended on early-season (May through June) average air temperatures, as below-average temperatures (>0.5°C below the 30-yr average) resulted in much lower accuracy of predicting N applications within 34 kg N ha⁻¹ of the economically optimum nitrogen rate (EONR) for corn grain yield (Andraski and Bundy, 2002). Thus, the limited accuracy of the PSNT for first-year corn following alfalfa noted in other research may be related, in part, to below-average early-season air temperatures in some trials. Andraski and Bundy (2002) found no effect of the previous type or quantity of organic N inputs on the accuracy of the PSNT in corn, but only two sites were first-year corn with manure applied during alfalfa termination and no direct evaluation of manure addition was made.

The majority of fertilizer N response trials in the literature that included the BSNT have been for corn following corn or soybean, and critical BSNT concentrations of 0.25, 0.50, and 0.70 g NO₃⁻N kg⁻¹ have been identified as sufficient for optimal corn grain yield (Binford et al., 1992; Hooker and Morris, 2012). There are no published reports on direct effects of fall manure application on alfalfa N credits to first-year corn.
1999; Fox et al., 2001; Forrestal et al., 2012). Variations in the defined critical concentrations have been attributed to late-season precipitation, sampling time (e.g., silage vs. grain harvest time), or environment (midwestern vs. eastern United States) (Blackmer and Mallarino, 1996; Fox et al., 2001; Lawrence et al., 2008; Forrestal et al., 2012), but little attention has been given to the residual effects of the previous crop. Critical BSNT levels for corn following alfalfa were similar to corn following other crops in the early 1990s in Iowa and Wisconsin (Morris et al., 1993; Bundy and Andraski, 1993), but more recent research (Blackmer and Mallarino, 1996; Fox et al., 2001; Forrestal et al., 2012) suggests that critical BSNT concentrations may need to be lower for corn following alfalfa. Critical BSNT concentrations have been attributed to late-season precipitation, sampling time (e.g., silage vs. grain harvest time), or environment (midwestern vs. eastern United States) (Blackmer and Mallarino, 1996; Fox et al., 2001; Lawrence et al., 2008; Forrestal et al., 2012), but little attention has been given to the residual effects of the previous crop. Critical BSNT levels for corn following alfalfa were similar to corn following other crops in the early 1990s in Iowa and Wisconsin (Morris et al., 1993; Bundy and Andraski, 1993), but more recent research (Blackmer and Mallarino, 1996; Fox et al., 2001; Forrestal et al., 2012) suggests that critical BSNT concentrations may need to be lower for corn following alfalfa (Lawrence et al., 2008; Yost et al., 2012) because of higher N mineralization during the corn growing season (Carpenter-Boggs et al., 2000) and low likelihood of corn response to fertilizer N.

No studies that we are aware of have studied directly the effect of fall manure application on the accuracy of the BSNT for first-year corn following alfalfa. Barklom et al. (2003) reported similar BSNT concentration ranges in fields with or without manure application, but no direct comparison of manure effects on the accuracy of the BSNT was made. The objectives of this research were to: (i) determine whether adjustments should be made to the alfalfa N credit for first-year corn to account for fall manure application and (ii) verify the accuracy of the PSNT and BSNT in identifying whether first-year corn requires fertilizer N to optimize yield.

### MATERIALS AND METHODS

On-farm experiments were established in 2010 in eight alfalfa fields on medium- to fine-textured soils in Minnesota (Tables 1 and 2). The alfalfa stands were 2- to 5-yr old, including the establishment year (Table 3). Alfalfa final plant populations were measured just before stand termination by excavating and counting alfalfa crowns in four 0.67 m–2 quadrats at each location and were ≥43 plants m–2 at all locations except Faribault and Stewartville (Table 3). At each location, the experimental design was a split plot arrangement in a randomized complete block with four replications. Main plots were manure treatments (with or without manure) and were applied by the cooperators growers prior to corn planting and a sidedress-only treatment of 45 kg N ha–1 broadcast as NH4NO3 at 1 to 2 wk after corn planting and a sidedress-only treatment of 45 kg N ha–1 as NH4NO3 banded midway between corn rows at the four to six leaf collar stage (Abendroth et al., 2011) in a 4-cm-deep by 8-cm-wide furrow that was opened with a wheel hoe and closed with a rake. Manure treatments were applied by the cooperating growers after the last alfalfa harvest and before primary tillage in the fall of 2010 (Table 2). Dairy cow manure was applied at all locations, but the method and rate of manure application varied. Manure application rate was determined with a rake. Manure treatments were applied by the cooperating growers after the last alfalfa harvest and before primary tillage in the fall of 2010 (Table 2). Dairy cow manure was applied at all locations, but the method and rate of manure application varied.

### Table 1. Background soil characteristics for eight on-farm locations in Minnesota.

<table>
<thead>
<tr>
<th>Location</th>
<th>Geographic coordinates</th>
<th>Dominant soil series (classification)</th>
<th>Soil texture</th>
<th>pH</th>
<th>P</th>
<th>K</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faribault</td>
<td>44°17′ N, 93°10′ W</td>
<td>Merton (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)</td>
<td>silt loam</td>
<td>7.1</td>
<td>80</td>
<td>129</td>
<td>13</td>
</tr>
<tr>
<td>Howard Lake</td>
<td>45° 1′ N, 94° 1′ W</td>
<td>Angus (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs)</td>
<td>loam</td>
<td>6.4</td>
<td>15</td>
<td>126</td>
<td>6</td>
</tr>
<tr>
<td>Medford</td>
<td>44° 9′ N, 93° 8′ W</td>
<td>N McLintic (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)</td>
<td>clay loam</td>
<td>6.6</td>
<td>134</td>
<td>298</td>
<td>13</td>
</tr>
<tr>
<td>Plainview</td>
<td>44° 9′ N, 92°13′ W</td>
<td>Tama (fine-loamy, mixed, superactive, mesic Typic Argiudolls)</td>
<td>clay loam</td>
<td>6.3</td>
<td>48</td>
<td>171</td>
<td>7</td>
</tr>
<tr>
<td>Randolph</td>
<td>44°32′ N, 92°59′ W</td>
<td>Cylinder (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aquic Hapludolls)</td>
<td>loam</td>
<td>6.8</td>
<td>89</td>
<td>277</td>
<td>7</td>
</tr>
<tr>
<td>Redwing</td>
<td>44°31′ N, 92°36′ W</td>
<td>Timula (coarse-silty, mixed, superactive, mesic Typic Eutrudepts)</td>
<td>silt loam</td>
<td>6.7</td>
<td>15</td>
<td>105</td>
<td>10</td>
</tr>
<tr>
<td>St. Rosa</td>
<td>45°45′ N, 94°42′ W</td>
<td>Waukon (fine-loamy, mixed, superactive, frigid Mollic Hapludolls)</td>
<td>loam</td>
<td>6.3</td>
<td>13</td>
<td>132</td>
<td>7</td>
</tr>
<tr>
<td>Stewartville</td>
<td>43°54′ N, 92°36′ W</td>
<td>Maxfeld (fine-loamy, mixed, superactive, mesic Typic Eutroaquepts)</td>
<td>silt loam</td>
<td>7.0</td>
<td>59</td>
<td>236</td>
<td>11</td>
</tr>
</tbody>
</table>

† Soil pH, Bray-1. P, ammonium-acetate exchangeable K, and calcium chloride-soluble sulfate-S are for the surface 15 cm.

### Table 2. Manure application date, rate, type, and as-applied analysis, along with primary tillage information for eight Minnesota locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Rate (Mg or 1000 L ha–1)</th>
<th>Type†</th>
<th>Dry matter</th>
<th>TKN‡</th>
<th>NH4–N</th>
<th>C/N</th>
<th>Date</th>
<th>Type§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faribault</td>
<td>14 Oct</td>
<td>3.0</td>
<td>BS</td>
<td>30</td>
<td>52</td>
<td>5</td>
<td>16</td>
<td>14 Oct</td>
<td>DC</td>
</tr>
<tr>
<td>Howard Lake</td>
<td>21 Oct</td>
<td>68.3</td>
<td>BL</td>
<td>2</td>
<td>245</td>
<td>155</td>
<td>3</td>
<td>21 Oct</td>
<td>DC</td>
</tr>
<tr>
<td>Medford</td>
<td>30 Sept</td>
<td>15.0</td>
<td>IL</td>
<td>8</td>
<td>73</td>
<td>43</td>
<td>–</td>
<td>15 Oct</td>
<td>MP</td>
</tr>
<tr>
<td>Plainview</td>
<td>9 Nov</td>
<td>20.3</td>
<td>BS</td>
<td>39</td>
<td>426</td>
<td>28</td>
<td>21</td>
<td>20 Nov</td>
<td>DC</td>
</tr>
<tr>
<td>Randolph</td>
<td>11 Nov</td>
<td>17.1</td>
<td>BS</td>
<td>24</td>
<td>211</td>
<td>97</td>
<td>12</td>
<td>12 Nov</td>
<td>DC</td>
</tr>
<tr>
<td>Redwing</td>
<td>7 Oct</td>
<td>22.9</td>
<td>BS</td>
<td>30</td>
<td>510</td>
<td>68</td>
<td>16</td>
<td>17 Nov</td>
<td>MP</td>
</tr>
<tr>
<td>St. Rosa</td>
<td>3 Nov</td>
<td>20.7</td>
<td>BS</td>
<td>42</td>
<td>167</td>
<td>63</td>
<td>13</td>
<td>4 Nov</td>
<td>DC</td>
</tr>
<tr>
<td>Stewartville</td>
<td>4 Nov</td>
<td>34.2</td>
<td>BS</td>
<td>18</td>
<td>507</td>
<td>84</td>
<td>12</td>
<td>9 Nov</td>
<td>DC</td>
</tr>
</tbody>
</table>

† BL, broadcast liquid manure; IL, injected liquid manure; BS, broadcast semi-solid manure.
‡ Total Kjeldahl nitrogen.
§ DC, disk-chisel; MP, moldboard plow.
¶ Cooperating grower provided the manure analysis, but it did not include manure C.

### Table 3. On-farm alfalfa yield and primary tillage information for eight Minnesota locations.

<table>
<thead>
<tr>
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<th>Type†</th>
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<th>NH4–N</th>
<th>C/N</th>
<th>Date</th>
<th>Type§</th>
</tr>
</thead>
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<td>3.0</td>
<td>BS</td>
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<td>52</td>
<td>5</td>
<td>16</td>
<td>14 Oct</td>
<td>DC</td>
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<tr>
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<td>21 Oct</td>
<td>68.3</td>
<td>BL</td>
<td>2</td>
<td>245</td>
<td>155</td>
<td>3</td>
<td>21 Oct</td>
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</tr>
<tr>
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<td>IL</td>
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<td>73</td>
<td>43</td>
<td>–</td>
<td>15 Oct</td>
<td>MP</td>
</tr>
<tr>
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<td>DC</td>
</tr>
</tbody>
</table>

† BL, broadcast liquid manure; IL, injected liquid manure; BS, broadcast semi-solid manure.
‡ Total Kjeldahl nitrogen.
§ DC, disk-chisel; MP, moldboard plow.
¶ Cooperating grower provided the manure analysis, but it did not include manure C.
A composite manure subsample was collected from the three tarps or directly from the manure applicator tank, frozen, and analyzed at the University of Wisconsin-Madison Soil and Forage Analysis Laboratory to determine C and N concentrations and to calculate N inputs (Table 2).

Alfalfa was terminated in the fall with disk-chisel or moldboard plow tillage and spring seedbed preparation for corn consisted of one or two passes with a field cultivator. The cooperating growers planted corn 5-cm deep in 76-cm rows with field-scale equipment between 1 and 19 May 2011 at 74,000 to 87,900 seeds ha–1, depending on location. Starter fertilizer (≤17 kg N ha–1) was applied at planting by the cooperating growers at all locations except Medford and Redwing. Broadcast P, K, and S were applied near planting according to soil test results and University of Minnesota guidelines (Kaiser et al., 2012) and soil pH was in the optimal range at all locations (Table 1). Corn at the Randolph location received 142 mm of irrigation water, and the remaining locations were not irrigated. Precipitation and air temperature data for 2010 and 2011 were obtained from the National Weather Service station nearest each location (Fig. 1A, 1B).

When corn had reached the four to six leaf collar stage (13–27 June), PSNT samples were obtained from each subplot that would receive sidedressed N fertilizer by compositing six to eight soil cores (2 cm i.d.) from the 0- to 30-cm depth. Immediately after soil samples were collected, the sidedress N fertilizer treatment was applied. Soil samples were dried to constant mass in a forced-air oven at 35°C, ground to pass a 2-mm sieve, extracted with 2 mol L–1 KCl, and analyzed for NO3–N concentration by Cd reduction using automated flow injection analysis (Lachat QuickChem 8000, Hach Company, Loveland, CO; Method 12-107-04-1-B).

Aft er corn had reached physiological maturity in the fall of 2011, corn ears were hand-harvested from 3 m of row within the center of each subplot. Corn ears were dried at 60°C to constant mass and shelled. Corn grain and cobs were weighed after shelling to calculate grain (adjusted to 155 g kg–1 water content) and cob (dry matter) yield. Corn stover was harvested at only five locations due to time constraints and conflicting harvest schedules for the cooperating growers. Stover was cut 15 cm above the soil surface from the same plants harvested for grain, weighed, chipped, and subsampled (about 1.5 kg) in the field. Stover subsamples were dried to constant mass in a forced-air oven at 60°C to determine water content and to calculate stover dry matter yield. Corn silage yield (the sum of grain, cob, and stover dry mass) was expressed at 650 g kg–1 water concentration. Relative yield was calculated separately by

<table>
<thead>
<tr>
<th>Location</th>
<th>Final plant population</th>
<th>Hybrid</th>
<th>Starter fertilizer</th>
<th>PSNT‡</th>
<th>Grain yield</th>
<th>Silage yield</th>
<th>BSNT§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faribault</td>
<td>5 32</td>
<td>Pioneer 34A85</td>
<td>10</td>
<td>8 (1)</td>
<td>12.4 (1.0)</td>
<td>71.5 (3.9)</td>
<td>–</td>
</tr>
<tr>
<td>Howard Lake</td>
<td>4 75</td>
<td>Pioneer 35F40</td>
<td>17</td>
<td>5 (1)</td>
<td>11.1 (0.4)</td>
<td>63.5 (2.2)</td>
<td>–</td>
</tr>
<tr>
<td>Medford</td>
<td>3 43</td>
<td>Croplon 42IVT</td>
<td>0</td>
<td>19 (1)</td>
<td>1.60 (0.3)</td>
<td>–</td>
<td>0.26 (0.20)</td>
</tr>
<tr>
<td>Plainview</td>
<td>4 54</td>
<td>Fielder’s Choice NG6440</td>
<td>16</td>
<td>22 (2)</td>
<td>14.0 (0.3)</td>
<td>–</td>
<td>4.07 (0.68)</td>
</tr>
<tr>
<td>Randolph</td>
<td>2 54</td>
<td>Trelch 5ST45</td>
<td>4</td>
<td>14 (1)</td>
<td>13.9 (0.5)</td>
<td>–</td>
<td>4.46 (2.04)</td>
</tr>
<tr>
<td>Redwing</td>
<td>3 75</td>
<td>Pioneer 34A85</td>
<td>0</td>
<td>22 (2)</td>
<td>1.47 (0.4)</td>
<td>82.5 (1.9)</td>
<td>–</td>
</tr>
<tr>
<td>St. Rosa</td>
<td>5 65</td>
<td>Mycogen MY2J337</td>
<td>2</td>
<td>7 (1)</td>
<td>10.9 (1.0)</td>
<td>56.7 (3.6)</td>
<td>0.004 (0.002)</td>
</tr>
<tr>
<td>Stewartville</td>
<td>5 32</td>
<td>DEKALB DKC59–35</td>
<td>9</td>
<td>27 (2)</td>
<td>15.2 (0.2)</td>
<td>72.7 (1.1)</td>
<td>–</td>
</tr>
</tbody>
</table>

† Establishment year included in alfalfa stand age.
‡ Nitrate-N concentration in the surface 30 cm of soil in nonfertilized and nonmanured corn.
§ The BSNT concentration for nonfertilized and nonmanured corn. The BSNT was not determined for four locations.
¶ Maximum grain and silage yield at 155 and 650 g kg–1 moisture, respectively. Maximum yield is the average across N rates applied shortly after planting and manure treatments when there was no response of yield to fertilizer N. When fertilizer N was required to maximize yield, maximum yield is the highest regression-predicted yield. Silage yield was not determined for three locations.

![Fig. 1. Departures from the 30-yr average (1981–2010) for (A) cumulative precipitation and (B) average air temperatures (B) in August through November 2010 and April through September 2011 for eight on-farm trials in Minnesota.](image-url)
manure treatment for each location by dividing the mean yield for each N rate, across replications, by the mean yield of the 179 kg N ha\(^{-1}\) treatment and multiplying by 100 (Bundy and Andrsaki, 1993; Forrestal et al., 2012).

Dried corn grain, cob, and stover subsamples were ground to pass a 1-mm sieve and scanned with near-infrared reflectance spectroscopy at 1100 to 2500 nm (Foss Model 6500, Foss North America Inc., Eden Prairie, MN) to estimate N concentration. To calibrate the estimates, 30 samples each of grain, cob, and stover were selected with principal component analysis using WinISI III version 3.0 (Intrasoft International, Port Matilda, PA) and analyzed by dry combustion with an Eastern varioMAX CN (Elementar Americas, Mount Laurel, NJ). Linear regression was used to calibrate the near-infrared reflectance spectroscopy N concentration predictions to dry combustion standards (grain calibration, \(R^2 = 0.90, P < 0.001\); cob and stover were predicted with one calibration equation, \(R^2 = 0.97, P < 0.001\)). Nitrogen content was calculated as N concentration multiplied by dry matter yield.

At four locations, basal stalk samples were collected from 10 plants not harvested for stover within the center two rows of each subplot during 1 to 3 wk after corn had reached physiological maturity (20 September–6 October), following the methods of Binford et al. (1992). Basal stalk samples were dried to constant mass in a forced-air oven at 60°C, ground to pass a 1-mm sieve, extracted for 10 min with distilled water, filtered using Whatman no. 2 filter paper (General Electric Company, Springfield Mill, UK), and analyzed for NO\(_3\)–N by automated flow injection analysis (Lachat QuickChem 8000, Hach Company, Loveland, CO; Method 13-107-04-1-B).

### Data Analysis

Data were analyzed using the MIXED procedure of SAS (SAS Institute, 2006). Manure, fertilizer N rate, and their interaction were considered fixed effects, while block (nested within location), location, and interactions involving block or location were considered random effects. Residuals were inspected for normality, and scatterplots of residuals vs. predicted values were used to assess homogeneity of variance using the UNIVARIATE procedure of SAS (Kutner et al., 2004). Residuals from the BSNT data did not meet the assumptions of normality and homogeneous variance and were therefore subjected to a square root transformation before analysis (Gomez and Gomez, 1984). The two-tailed log-likelihood ratio test was used to determine the significance (\(P \leq 0.05\)) of the random interactions between location and fixed effects (Neyman and Pearson, 1933). When these interactions were significant, best linear unbiased predictors (Harville, 1976) or mixed model contrasts were used to determine the significance of fixed effects by location as described by Littell et al. (2006). When the interaction between location and fixed effects was significant for multiple locations, the two-tailed log-likelihood ratio test was used to test for differences among locations. Locations were combined when the two-tailed log-likelihood ratio test was not significant (i.e., \(P > 0.05\)) for a group of locations.

When the main effect of fertilizer N rate was significant at \(P \leq 0.05\), linear or nonlinear regression equations were developed for the responses of corn yield, N concentration, N content, and square root BSNT to fertilizer N using the MIXED and NLIN procedures of SAS. When the response of corn grain or silage yield to fertilizer N fit regression equations (\(P \leq 0.05\)), the EONR and sidedress fertilizer N efficiency were calculated. To determine EONR, the first derivative of the regression model was set to the average N fertilizer cost/corn price ratio from 2009 to 2011 ($1.19 kg\(^{-1}\) N as urea, USDA-ERS, 2012; $183 Mg\(^{-1}\) corn grain and $39 Mg\(^{-1}\) corn silage, Center for Farm Financial Management, 2012). Sidedress N fertilizer efficiency was estimated in comparison to the N rate required at planting to attain the same grain yield, based on the cross-location regression. The relationship between relative corn grain yield and BSNT concentration was assessed using a quadratic-plateau regression model developed using the NLIN procedure of SAS. Fisher’s protected LSD test (\(P \leq 0.05\)) was used to compare treatment means of cob N content and stover N concentration because the response to treatments was significant, but no regression model significantly fit the data.

### Results and Discussion

#### Corn Yield

Corn grain yield ranged from 11.2 to 16.0 Mg ha\(^{-1}\) across the eight locations (Table 3). At six locations, grain yield was not affected by fertilizer N or manure, even when up to 510 kg TKN ha\(^{-1}\) was applied with manure (Table 4). However, fertilizer N increased grain yield at two locations (Howard Lake and St. Rosa), regardless of manure application (Fig. 2A). At these two locations, the EONR for grain yield was 98 kg N ha\(^{-1}\), while rates between 93 and 103 kg N ha\(^{-1}\) resulted in net returns that were within $2.50 ha\(^{-1}\) of the maximum (hereafter, \(\pm$2.50 ha\(^{-1}\)). These results demonstrate that fall-applied

### Table 4. Significance of F tests for the fixed effects of manure (M), fertilizer nitrogen (N), and their interaction on corn yield, N concentration, N content, presidedress soil nitrate test (PSNT) concentration, and basal stalk nitrate test (BSNT) concentration. Interactions of the fixed effects with location were evaluated with the two-tailed log-likelihood ratio test; significant outcomes of this test are noted by the footnote.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Component</th>
<th>M</th>
<th>N</th>
<th>M × N</th>
<th>P &gt; F</th>
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</thead>
<tbody>
<tr>
<td><strong>Yield</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Grain</td>
<td>0.15</td>
<td>0.008†</td>
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<tr>
<td>Cob</td>
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<td>0.003†</td>
<td>0.58</td>
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<td></td>
</tr>
<tr>
<td>Stover</td>
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<td>0.004</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silage</td>
<td>0.32</td>
<td>0.006†</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>N concentration</strong></td>
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<tr>
<td>Grain</td>
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<td>&lt;0.001†</td>
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<tr>
<td>Cob</td>
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<tr>
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<td>0.47</td>
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<td><strong>N content</strong></td>
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<tr>
<td>Grain</td>
<td>0.03</td>
<td>&lt;0.001†</td>
<td>0.28</td>
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</tr>
<tr>
<td>Cob</td>
<td>0.32</td>
<td>0.01</td>
<td>0.39</td>
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<tr>
<td>Stover</td>
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<td>0.01</td>
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<tr>
<td>Silage</td>
<td>0.18</td>
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<tr>
<td><strong>PSNT</strong></td>
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</tr>
<tr>
<td>Soil</td>
<td>0.11†</td>
<td>–‡</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BSNT</strong></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Stalk</td>
<td>0.004</td>
<td>0.032†</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† The two-tailed log-likelihood ratio test for a given interaction between location and a fixed effect was significant at \(P \leq 0.05\) which justified the use of best linear unbiased predictors to investigate fixed effects by location.

‡ The PSNT was measured only in nonfertilized control plots and the effect of fertilizer N rate on PSNT was not determined.
manure may not compensate for spring-applied fertilizer N in the few cases where first-year corn after alfalfa requires supplemental N to economically optimize grain yield.

Across manure treatments at these two locations, grain yield with a sidedress application of 45 kg N ha\(^{-1}\) was equivalent to yield with 54 kg N ha\(^{-1}\) of fertilizer applied shortly after planting. Therefore, fertilizer N use efficiency may be slightly enhanced in first-year corn after alfalfa when N fertilizer is sidedressed rather than applied shortly after planting. The average maximum grain yield across the two responsive locations (11.2 Mg ha\(^{-1}\)) was lower than that for the six locations that did not respond to fertilizer N (14.4 Mg ha\(^{-1}\)) (Table 3), but a multistate synthesis of previous research found no correlation between fertilizer N requirement and corn yield potential (Sawyer et al., 2006). Thus, lower yields at the two responsive locations likely were due to factors other than N supply.

Cob yield did not respond to applied manure or fertilizer N at four locations, but at the two locations where grain yield responded to fertilizer N and at two others (Randolph and Faribault), cob yield increased from 1.29 Mg ha\(^{-1}\) in nonfertilized plots to 1.66 Mg ha\(^{-1}\) when 179 kg N ha\(^{-1}\) was applied \(y = 1.29 + 0.00208x; R^2 = 0.86, P = 0.001\), regardless of manure application. Across manure treatments at these four responsive locations, the efficiency of sidedress N at increasing cob yield was equal to that for N applied shortly after planting. Stover yield averaged 7.3 Mg ha\(^{-1}\) at St. Rosa, but ranged from 9.2 and 12.6 Mg ha\(^{-1}\) across the four other locations where it was measured. Across these five locations, stover yield increased from 9.1 Mg ha\(^{-1}\) in nonfertilized control plots to a maximum of 10.1 Mg ha\(^{-1}\) when 130 kg N ha\(^{-1}\) of fertilizer N was applied \(y = 9.05 + 0.0156x - 0.0000600x^2; R^2 = 0.89, P = 0.002\), regardless of manure treatment (Table 4). Stover was the only yield component that responded to fertilizer N at all locations.

Consistent with its yield components described above, silage yield did not respond to manure (Table 4). In contrast, with fertilizer N, two locations showed no response of silage yield (Randolph and Stewartville), whereas the EONR for silage yield at the remaining three locations (Howard Lake, St. Rosa, and Faribault) was 113 kg N ha\(^{-1}\), while 106 to 120 kg N ha\(^{-1}\) resulted in net returns that were ≥$2.50 ha\(^{-1}\) of the maximum (Table 4, Fig. 2B). Across the three responsive locations, maximum silage yield was 63.3 Mg ha\(^{-1}\) while yield across the other two nonresponsive locations was 77.6 Mg ha\(^{-1}\) (Table 3). The lack of silage yield response to fertilizer N at Randolph and Stewartville is consistent with previous results from 23 sites in Minnesota (Yost et al., 2012, 2013), 12 sites in New York (Katsvairo et al., 2003; Lawrence et al., 2008), and two of three sites in Wisconsin with near-normal rainfall (Kelling et al., 2003). All of these authors found that either a small early-season N application (≤40 kg N ha\(^{-1}\)) or no fertilizer N at all was typically sufficient to economically optimize first-year corn silage yield. However, the large EONR (113 kg N ha\(^{-1}\) for silage yield at the three locations in this study is inconsistent with these previous studies and suggests that more evidence is needed before alfalfa N credits are decreased (i.e., recommended fertilizer N rates are increased) for corn grown for silage compared to grain.

As in our earlier research (Yost et al., 2012), we found no pre-season indicators that grain and silage yield of first-year corn after alfalfa would increase with fertilizer N at the two responsive sites, Howard Lake and St. Rosa. With alfalfa plant populations at these two locations exceeding 43 plants m\(^{-2}\) (Table 3), University of Minnesota Extension guidelines suggested the expected N credit would be 168 kg N ha\(^{-1}\) (Kaiser et al., 2012). Conversely, we anticipated a response of corn grain yield to fertilizer N at the Faribault location because the University N credit guideline for this final plant population (32 alfalfa plants m\(^{-2}\)) was 112 kg N ha\(^{-1}\) (Kaiser et al., 2012); however, only silage yield responded to fertilizer N at this location. The Faribault and Howard Lake locations received precipitation in excess of the 30-yr average (1981–2010) in the fall (August through November) and in the spring (April through May), which we speculate was the primary reason they required fertilizer N to maximize grain or silage yield. The Faribault location had the highest excess fall precipitation (220 mm) and was the only location with excess cumulative precipitation (65 mm) during April, May, and June (Fig. 1A). The Howard Lake location received 94 mm of excess precipitation during the fall of 2010 and was by far the wettest location in the spring, with 143 mm excess precipitation during April through May. The third responsive location (St. Rosa) had excess precipitation (140 mm) in the fall and near-normal precipitation in the spring (except for 35 mm excess precipitation in May). The remaining five locations, with no grain or silage yield response to N, had excess precipitation in the fall (106–173 mm), but precipitation totals within 29 mm of the 30-yr average during the months of April and May.

![Fig. 2. Response of first-year corn after alfalfa to fertilizer N for (A) grain yield at eight locations and (B) silage yield at five locations. Locations are labeled with the first three letters of each location name. Nonlinear regression equations with non-zero slopes are significant at P < 0.01; error bars represent the standard error of the mean.](image-url)
Nitrogen content at these locations increased by a maximum of 39 kg N ha\(^{-1}\) when 163 kg N ha\(^{-1}\) was applied near planting. Therefore, at the maximum grain N content, only 24% of the fertilizer applied was recovered in the grain. The increase in grain N content and lack of grain yield response to fertilizer N at the Randolph location demonstrates that luxury consumption of fertilizer N in grain occurred.

Cob N concentration did not respond to manure or fertilizer N, but cob N content increased from 5.9 kg N ha\(^{-1}\) in nonfertilized control plots to 6.5 kg N ha\(^{-1}\) when 179 kg N ha\(^{-1}\) was applied (Table 4). The interaction between manure and fertilizer N was significant for stover N concentration. When manure was applied, stover N concentration averaged 9.2 g N kg\(^{-1}\) and was not affected by fertilizer N. In the nonmanured plots, stover N concentration was the same in the nonfertilized and 40 kg N ha\(^{-1}\) plots (8.7 g N kg\(^{-1}\)), but rose to 9.4 g N kg\(^{-1}\) when at least 80 kg N ha\(^{-1}\) was applied. The lack of cob N concentration response to manure application coupled with only a slight increase in grain and stover N concentration with manure (0.26 and 0.51 g N kg\(^{-1}\), respectively) suggests that manure N was not as readily available to the corn as fertilizer N. Neither stover or silage N content were affected by manure application, but both increased across all five locations by a maximum of 14 and 27 kg N ha\(^{-1}\) when 152 and 107 kg N ha\(^{-1}\) of fertilizer N was applied shortly after planting, respectively (Fig. 3B). The fertilizer N rate for maximum silage N content was within the range of N rates for ±$2.50 ha\(^{-1}\) of maximum net return for corn silage at the Faribault, Howard Lake, and St. Rosa locations, but the remaining two locations had no response of silage yield to fertilizer N. The fertilizer N uptake efficiency at maximum N content for silage (25%) was similar to that for grain.

Presidedress Soil Nitrate Test

Manure application increased the PSNT concentration by 6 and 11 mg NO\(_3\)-N kg\(^{-1}\) at the Randolph and Redwing locations, where 211 and 510 kg TKN ha\(^{-1}\) was applied, respectively. These increases were similar to those in other studies with manure applied to corn following corn. When semi-solid and composted cow manure with >200 kg TKN ha\(^{-1}\) was applied to corn after corn in the spring on a sandy loam in Vermont (Jokela, 1992) and to a silt loam in Wisconsin (Muñoz et al., 2008), PSNT concentrations rose by 15 and 5 mg kg\(^{-1}\), respectively. It was surprising that fall-applied manure did not increase the PSNT concentration at the Howard Lake location, which received 245 kg TKN ha\(^{-1}\) (155 kg NH\(_4\)-N ha\(^{-1}\)) from the manure (Table 2). The lack of PSNT response to manure application across six locations in this study was consistent with the lack of grain yield response to manure across all eight locations and implies that one or more processes (e.g., low net N mineralization, immobilization of N, loss of nitrate N through leaching or denitrification) occurred in the top 30 cm of soil by the time PSNT samples were collected, especially when high rates of manure NH\(_4\)-N had been applied.

Based on the critical concentration of 21 mg N kg\(^{-1}\) (Andraski and Bundy, 2002; Laboski and Peters, 2012), the PSNT correctly identified the two locations that required N fertilizer to optimize grain yield; soil NO\(_3\)-N at these locations averaged just 6 mg N kg\(^{-1}\) (Table 3). Soil NO\(_3\)-N also was low (7 mg N kg\(^{-1}\)) at Faribault, where fertilizer N increased cob, stover, and silage yield, but not grain yield. The low PSNT concentrations at these locations were considered in future experiments on the N credit of organic sources. **Nitrogen Concentration and Content**

Across all eight locations, average air temperatures were warmer than average in the fall, cooler than average in the spring, and warmer than average in the summer (Fig. 1B). Therefore, it is likely that the excess fall and spring precipitation at Howard Lake and Faribault caused excessive N loss and reduced N mineralization, resulting in yield response to fertilizer N. These wet conditions at two of the three responsive locations also help explain why the EONRs were higher than expected and why fall-applied manure N was unable to compensate for the need for fertilizer N applied shortly after planting. Although there was excess fall precipitation at the St. Rosa location, weather conditions were similar to the non-responsive locations, and we speculate that poor drainage at St. Rosa contributed to fertilizer N response and lack of manure response at this location. Direct measurement of soil moisture content should be considered in future experiments on the N credit of organic sources.

![Fig. 3. Response of first-year corn after alfalfa to fertilizer N for (A) grain N concentration (conc.) and (B) N content in grain, stover, and silage. Locations are labeled with the first three letters of each name. All regression equations with non-zero slopes are significant at P < 0.01; error bars represent the standard error of the mean.](image-url)
three locations was likely related to excess late fall and early spring precipitation. The remaining five locations had no grain yield response to fertilizer N; two of these locations had PSNT concentrations below 21 mg NO$_3$–N kg$^{-1}$, whereas the other three had PSNT concentrations above 21 mg NO$_3$–N kg$^{-1}$. Therefore, three non-responsive locations (Faribault, Medford, and Randolph) would have been misclassified as responsive to fertilizer N, so the accuracy of the PSNT in identifying grain yield responsiveness or non-responsiveness to fertilizer N across the eight locations in this study was only 63%, according to the widely accepted critical level of 21 mg NO$_3$–N kg$^{-1}$. At this same critical level, the PSNT correctly identified all five of the locations where silage yield was measured as either responsive or non-responsive to fertilizer N. When comparing the accuracy of the PSNT for the five sites where grain and silage yield were measured, the PSNT was more accurate at predicting silage than grain yield response to N.

The overall accuracy of the PSNT at predicting the response of grain yield to fertilizer N across soil types decreased to 55% when data from the eight sites in this study were combined with an additional 86 sites of first-year corn after alfalfa in the literature (Bundy and Andraski, 1993; Morris et al., 1993; Randall and Vetsch, 1995; Schmitt and Randall, 1994; Andraski and Bundy, 2002; Pearson et al., 2003; Mulvaney et al., 2006; Sripada et al., 2008; Morrison et al., 2010; Cela et al., 2011; Yost et al., 2013) (Fig. 4). There was no evident correlation between grain yield response to fertilizer N and PSNT concentration; responsive sites had PSNT concentrations ranging from 3 to 37 mg NO$_3$–N kg$^{-1}$, and non-responsive sites had ranges of 8 to 74 mg NO$_3$–N kg$^{-1}$. The original research on the PSNT suggested that the test may be less accurate on coarse-textured or highly permeable soils where a greater likelihood of N leaching below the 30-cm soil depth might warrant the need for 60-cm sampling on these soils (Magdoff et al., 1984). The accuracy of the PSNT was higher for medium-textured (loams and silt loams, 59%) and fine-textured soils (clay loams, 67%) than with coarse-textured soils (sandy loams and fine sandy loams, 33%), but the limited number of sites for coarse- (15) and fine-textured soils (6) relative to medium-textured soils (73) indicate the need for further research to determine whether the accuracy of the test for first-year corn is dependent on soil texture. Across soil textural classes, these data indicate that the PSNT has poor predictive power for first-year corn following alfalfa over a wide range of environments. We do not recommend that the PSNT be used to predict fertilizer N requirements for first-year corn after alfalfa until its reliability is improved by further development.

**Basal Stalk Nitrate Test**

The mean BSNT concentration in plots with no fertilizer N or manure ranged from 0.004 g NO$_3$–N kg$^{-1}$ at St. Rosa to between 0.26 and 4.5 g NO$_3$–N kg$^{-1}$ across three non-responsive locations (Table 3). Based on Iowa State University’s critical level of 0.7 g NO$_3$–N kg$^{-1}$ (Blackmer and Mallarino, 1996), three of four locations in this study would have been identified correctly as responsive or non-responsive in grain yield to fertilizer N. Manure applied during fall alfalfa termination increased the mean BSNT concentration by 1.59 g NO$_3$–N kg$^{-1}$ across fertilizer N rates and locations (Table 4), indicating greater supply of nitrate late in corn growth. Transformed BSNT concentration also increased linearly with fertilizer N across all four locations, but the response to N differed between Medford (square root BSNT = 24.0 + 0.515x, $R^2 = 0.86$, $P < 0.001$) and the remaining three locations (Plainview, Randolph, St. Rosa); square root BSNT = 50.7 + 0.112x, $R^2 = 0.89$, $P = 0.018$. At Medford, mean BSNT concentration increased from 0.58 in nonfertilized plots to 13.5 g NO$_3$–N kg$^{-1}$ when 179 kg N ha$^{-1}$ was applied shortly after planting; an estimated fertilizer N rate of only 5 kg N ha$^{-1}$ was required to raise BSNT concentration to the lower limit of the optimal range in Iowa (0.70 g NO$_3$–N kg$^{-1}$; Binford et al., 1992; Blackmer and Mallarino, 1996). The low fertilizer N rate required to raise BSNT concentration to the optimal range aligns well with the lack of grain yield response to fertilizer N at Medford. Mean BSNT concentration at the remaining three locations was 2.57 and 5.29 g NO$_3$–N kg$^{-1}$ when 0 and 179 kg N ha$^{-1}$ were applied shortly after planting, respectively. Although the slope of the linear regression was similar for the three locations, the BSNT concentration at St. Rosa increased to 0.7 g NO$_3$–N kg$^{-1}$ only when 179 kg N ha$^{-1}$ was applied.

Basal stalk nitrate test guidelines developed in Iowa (Binford et al., 1992; Blackmer and Mallarino, 1996) are based on categories (low, marginal, optimum, and excessive) that distinguish an optimal concentration range with the division between the low and marginal range being the BSNT concentration where relative yield plateaus (linear-plateau regression model) and the division between the optimum and excessive range at the average concentration at the EONR for grain yield. When relative grain yield and mean BSNT concentration for the non-manured plots of the four sites of data from this experiment were combined with 13 sites of first-year corn from Minnesota and Wisconsin (Yost et al., 2012, 2013), the critical BSNT...
however, there was a wide range (0.23–7.0 g NO3–N kg–1) and
tified in eastern states (Fox et al., 2001; Forrestal et al., 2012);
tified in Iowa (Binford et al., 1992), but higher than levels iden-
tion was 0.94 g NO3–N kg–1. The box plot is the distribution of
concentration at the economically optimum N rates (EONR) for first-year corn following alfalfa. The average
concentration at the EONR in our study (Fig. 5).

In addition to the large variation across locations, there also
was large variability in BSNT concentration within locations.
The standard error in BSNT concentration for the nonfertil-
ized, nonmanured treatments in this study and in Yost et al.
(2012, 2013) averaged 39% (10–79%) of the mean (Table 3). We
anticipated that the critical and EONR concentration for the
optimal BSNT range for corn following alfalfa would be lower
than that for corn following corn or soybean (Lawrence et al.,
2008; Yost et al., 2012), but these estimated concentrations were
either not reliable or too variable for this rotation. The vari-
bility in BSNT concentration, the high relative yield for corn
following alfalfa, and the low likelihood of fertilizer N response
in corn following alfalfa suggest that more research is needed
before the BSNT can be considered a reliable tool for first-year
corn following alfalfa, in agreement with Yost et al. (2012).

CONCLUSIONS

Results from this study demonstrate that manure N is not
needed to increase grain or silage yield of corn following alfalfa
when soil P, K, and S are managed for optimal yield with fertil-
izer and soil pH is within the optimal range. Therefore, grow-
ers should apply manure for corn following crops other than
alfalfa to improve manure N use efficiency and to reduce the
potential for over-application of N. Based on the 35% higher
agronomic efficiency of sidedressed N compared to N applied
at planting in this study, growers who anticipate a response to
fertilizer N in corn following alfalfa due to weather or site
conditions (e.g., excessive precipitation, inadequate drainage)
may consider delaying N application. This would allow more
time to assess early-season precipitation, but growers planning
to sidedress N also should consider the risks of unexpected
delays in application due to wet soil conditions or of poor N
availability of sidedressed N if topsoils become too dry. We do
not recommend the PSNT at this time for first-year corn fol-
lowing alfalfa because the test was accurate in only 55% of the
94 sites from this study and those in the published literature.
The BSNT correctly identified sites as responsive or non-
responsive to fertilizer N at the majority of locations (three of
four) in this study, but when these data were considered with
13 sites of previous work, no accurate optimal BSNT range
could be identified because first-year corn following alfalfa had
high relative yield and large variation in BSNT concentration
at the EONR within and among locations. This variability was
especially apparent for control plots, which often represent the
lowest BSNT concentration at the EONR within locations. This variability was
especially apparent for control plots, which often represent the
EONR for first-year corn following alfalfa (i.e., <17 kg N ha–1).
These combined data suggest that additional research is needed
before the BSNT can accurately identify fertilizer N response
in first-year corn following alfalfa.

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names or commercial products in this article is solely for the purpose
of providing specific information and does not imply recommenda-
tion or endorsement by the U.S. Department of Agriculture.

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Fig. 5. Relationship between basal stalk nitrate test (BSNT) concentration and relative grain yield of first-year corn after alfalfa for nonmanured plots of four sites in 2011 (this study), six sites in 2010 (Yost et al., 2012), and seven sites in 2010 and 2011 (Yost et al., 2013). Solid symbols represent the two sites where there was a response of corn grain yield to fertilizer N and open symbols represent 15 sites with no response of corn grain yield to fertilizer N. The box plot is the distribution of BSNT concentrations at the economically optimum N rates (EONR) for first-year corn following alfalfa. The average BSNT concentration at the EONR was 1.75 g NO3–N kg–1; the median was 0.94 g NO3–N kg–1.

Median was 0.94 g NO3–N kg–1.


