Nitrogen Management for Corn Following Alfalfa: Field, Literature, and Geographic Analyses

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Dedication

I would like to dedicate this dissertation to my wife, Natalie Yost, and to Dr. Jared Williams. Their encouragement and support inspired me to pursue a graduate education. Natalie's endurance, encouragement, love, and support throughout my graduate career have been essential to my success. I dedicate this dissertation to my parents, Merlin and Jeanne Yost, who helped me develop a firm foundation of faith, diligence, and integrity. I also dedicate this dissertation to my advisors Michael Russelle and Jeff Coulter. Not only were they paramount to the success of this dissertation, they are great friends who have helped me in many aspects of my life.

Abstract

First- and second-year corn (*Zea mays* L.) following alfalfa (*Medicago sativa* L.) often require less supplemental N than corn grown continuously or following soybean [*Glycine max* (L.) Merr.]. The results of seven on-farm trials indicated that alfalfa can provide the entire N requirement of first-year corn no-till planted following alfalfa terminated in the fall. Eight other on-farm trials also indicated that first-year corn following alfalfa often does not require supplemental N (fertilizer or manure). The conclusion that first-year corn following alfalfa often requires no fertilizer N has been supported for decades, yet no research has identified site-specific conditions that cause first-year corn to respond to supplemental fertilizer N. The most widely used predictive test, the presidedress soil nitrate test (PSNT), had limited success in identifying response to N when trials from this study were combined with literature research; the test was 55% accurate across 94 site-years. An end-of-season test used to assess N supply to corn, the corn stalk nitrate test (CSNT), also was not successful in 11 trials at identifying when first-year corn would have required fertilizer N. An analysis of the literature was conducted to identify site-specific conditions that cause first-year corn following alfalfa to respond to N. Soil texture and alfalfa termination timing on medium-textured soils were significant covariates for identifying responsiveness to fertilizer N in first-year corn. First-year corn following alfalfa rarely required fertilizer N when alfalfa harvested for ≥2 yr was fall-terminated on medium-textured soils; corn following alfalfa harvested 1 yr responded more frequently. The frequency of response to fertilizer N increased greatly when alfalfa was grown on coarse- or fine-textured soils and when alfalfa was terminated in the spring on medium-textured soils. For these conditions, combinations of alfalfa stand age and weather conditions explained much of the variation in whether a site would respond to N and the economically optimum N rate (EONR) at various price ratios (PRs) of fertilizer N/corn grain. The regression models developed to predict fertilizer N response appear robust, but require independent validation. Alfalfa also provides N to the second consecutive corn crop following alfalfa termination. Results from 28 on-farm trials in Minnesota and Iowa revealed that second-year corn required fertilizer N only 50% of the time. The same trend occurred when these trials were combined with 39 trials in the literature. The PSNT had higher accuracy for second-year corn (65%) than for first-year corn, but improvements in accuracy are still necessary in order for this test to be a reliable tool for growers. A geographic analysis revealed that growers in the U.S. Corn Belt region of the upper midwestern United States (North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin) rotate alfalfa more frequently than in other parts of this region and that alfalfa phase length, soil texture, and year affect the type of crops grown for 2 yr following alfalfa termination. Supplemental files include data and references used for the literature analysis (Supplemental Table S4.1; Supplement S4.2), data used for analysis of second-year corn response to N (Supplemental Table S5.1), and alfalfa hectare estimates by state and year for the geographic analysis (Supplemental Table S6.1).

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List of Abbreviations

CDL, cropland data layer.

CSNT, corn stalk nitrate test.

DD_0, total monthly degree days, based on air temperature with a base temperature of 0°C.

EONR, economically optimum N rate.

PSNT, presidedress soil nitrate test.

PR, price ratio of fertilizer N (US$ kg^{-1} N)/corn grain (US$ kg^{-1}).

TKN, total Kjeldahl N.

RSN, residual soil N.

USDA-NASS, United States Department of Agriculture-National Agricultural Statistics Service.

CHAPTER 1: Nitrogen Management for First- and Second-Year Corn Following Alfalfa: An Introduction

This dissertation is an integrated effort of field and exploratory research focused on understanding the agronomic and environmental factors that affect fertilizer N response in first- and second-year corn following alfalfa. Two field studies investigated: the effects of no-tillage and manure on the fertilizer N requirement of first-year corn following alfalfa (Chapters 2 and 3). These field experiments should help growers know how to more accurately credit N from alfalfa to first-year corn to improve their net returns to manure and fertilizer N and to reduce the amount of excess N susceptible for loss to the environment. However, because fewer than 13% of these site-years showed a corn yield response to fertilizer N, these 15 site-years of field research were not sufficient to determine the site-specific conditions that caused corn following alfalfa to require supplemental N. Therefore, a literature analysis on the fertilizer N response of first-year corn following alfalfa was conducted to develop regression equations that may predict site-specific fertilizer N requirements (Chapter 4). Alfalfa also provides N to the second subsequent corn crop and another set of field trials were conducted to study the effects of first-year corn stover removal on the fertilizer N requirements of second-year corn following alfalfa (Chapter 5). To gain perspective on the management of cropping systems with alfalfa in upper midwestern United States, a geographic analysis of this region was conducted to determine trends in how long alfalfa stands are maintained and which crops follow alfalfa in the rotation (Chapter 6). This exploratory research is the most comprehensive review and analysis of alfalfa N credit research and geographic trends for alfalfa-corn rotations to date. In combination with the field studies, these analyses may form the basis for updated alfalfa N credit recommendations that will be more accurate and site-specific, thereby improving grower adoption of alfalfa N credits to corn.

CHAPTER 2: First-Year Corn after Alfalfa Showed No Response to Fertilizer Nitrogen under No-Tillage

INTRODUCTION

The majority of current university N fertilizer guidelines in the midwestern United States advise growers to use an alfalfa N credit (fertilizer N replacement value) of 112 to 168 kg ha^{-1} for first-year corn, regardless of tillage management, when ≥43 or 53 alfalfa plants m^{-2} are present at the time of alfalfa termination (Michigan, Ohio, Indiana, Vitosh et al., 1995; Wisconsin, Laboski and Peters, 2012; Nebraska, Shapiro et al., 2008; Illinois, Fernández et al., 2009; Minnesota, Kaiser et al., 2011). Additionally, Missouri and Iowa N fertilizer guidelines for first-year corn do not change for tillage (Killpack and Buchholz, 1993; Blackmer et al., 1997). The basis for tillage considerations in some of these state N credit recommendations was research conducted nearly two decades ago. Direct comparisons between moldboard plow and no-tillage systems on medium-textured (silt loam and loam) soils in Ohio, Ontario, and Pennsylvania resulted in similar alfalfa N credits for first-year corn grain yield (Triplett et al., 1979; Levin et al., 1987; Aflakpui et al., 1993). Wolkowski (1992) also found similar alfalfa N credits to first-year corn grain yield with moldboard-, chisel-, and no-tillage systems on two silt loam soils in Wisconsin. In all four studies, the alfalfa N credit was the same across tillage systems, regardless of whether N fertilizer was required to maximize corn grain yield.

In contrast, current university guidelines from Kansas and South Dakota advise growers to reduce the alfalfa N credit to first-year corn by one-half when no-tillage rather than a full-width tillage system is used to terminate alfalfa (Leikam et al., 2003; Gerwing and Gelderman, 2005). It is reasonable to expect that the N credit would be lower under no-tillage because mineralization of organic matter can be delayed compared to tilled systems (Phillips et al., 1980; Kitur et al., 1984). The disparate recommendations among neighboring states indicate that questions about tillage effects on alfalfa N credits are still relevant.

Current recommendations in the midwestern United States also advise growers to apply the same N credit whether first-year corn is harvested as grain or silage. However, recent research on tilled soils in Minnesota suggests that first-year silage corn can respond to higher rates of fertilizer N than corn harvested as grain (Yost et al., 2012). In no-tillage systems, few studies have evaluated the response of first-year corn grain yield to fertilizer N [only 17 (Table 2.1) of more than 350 site-years of research on first-year N credits (Yost et al., unpublished data, 2012)]. Even fewer (only 3 site-years) have measured silage yield and they [Rasse and Smucker (1999); Meek et al. (1994)] found no difference in the response of first-year silage corn to fertilizer N between moldboard plow and no-tillage systems on a loam soil in Michigan and an irrigated silt loam soil in Idaho, respectively. Neither article reported grain yield. Additional research is needed to determine whether N fertilizer requirements for first-year corn are different for grain and silage yield in a no-tillage system.

More research also is needed to determine the validity of using the presidedress soil nitrate test (PSNT) and the corn stalk nitrate test (CSNT) for no-tillage corn following alfalfa. The PSNT (Magdoff et al., 1984) is one of the most reliable and widely used tests to predict in-season corn yield response to sidedressed N and was estimated to be used on 14% of the 25 million ha of corn in the North Central Region in 1999 (Kitchen et al., 2008). Although this adoption estimate is outdated, it does suggest that a large number of growers do not use the PSNT, which may, in part, be related to the increase in no-tillage adoption and lack of data on the effectiveness of the test for no-tillage corn. Soil temperature between corn planting and PSNT sampling time is typically lower with no-tillage than full-width tillage systems (Al-Darby and Lowery, 1987; Cox et al., 1990; Smith et al., 1992), and cooler soils may reduce the reliability of the PSNT (Magdoff, 1991; Rozas et al., 2000; Andraski and Bundy, 2002). The PSNT has been evaluated in only 2 of the 17 site-years of research with first-year, no-tillage corn harvested for grain (cited earlier), and PSNT concentrations were 27 mg NO_3-N kg^{-1} at both locations, with one site (loam soil) responding to sidedressed N fertilizer, but not the other (silt loam soil; Bundy and Andraski, 1993; Morris et al., 1993).

The CSNT is a postmortem test developed to indicate late-season availability of N to corn (Binford et al., 1992) and is used to guide grower's future N fertilizer applications, but acceptance of the test by growers is much lower than the PSNT (<1%) (Kitchen et al., 2008). If the PSNT is less reliable for corn after alfalfa under no-tillage than full-width tillage management, the accuracy of the CSNT also may be affected because total corn N uptake can differ among tillage systems. For example, in comparison with other full-width tillage systems, the total N uptake of no-tillage corn following alfalfa was 17 kg N ha^{-1} lower on an irrigated sandy loam soil in Minnesota (Moncrief et al., 1991), 24 kg N ha^{-1} higher on a silt loam soil in Pennsylvania (Levin et al., 1987), and the same in one site-year on silt loam soil in Pennsylvania (Levin et al., 1987) and two site-years on silt loam soils in Wisconsin (Wolkowski, 1992). However, we are aware of no studies on first-year, no-tillage corn that have evaluated the CSNT. The objectives of this study were to evaluate the response of first-year corn grain and silage yield to fertilizer N in a no-tillage system, and to verify the accuracy of the PSNT and CSNT in identifying the need for supplemental N to optimize grain and silage yield in first-year corn after alfalfa.

MATERIALS AND METHODS

On-farm experiments were established on medium- to fine-textured soils in autumn 2009 and 2010 on seven alfalfa fields spanning 5 degrees of longitude across southern Minnesota and southwestern Wisconsin (Table 2.2). The alfalfa fields were 2 to

7 yr old and all had final alfalfa plant populations ≥43 plants m^{-2} (Table 2.3). Final alfalfa plant populations were measured by removing alfalfa plants within three 0.67-m^2 quadrats at each location and counting crowns. Alfalfa was terminated by herbicide in autumn at Goodhue, Lakefield, and Okabena, and in early spring at the remaining four locations. At each location, the experimental design was a randomized complete block with four replications of five or six N fertilizer treatments applied to first-year corn at one location in 2010 and six locations in 2011. Broadcast NH_4NO_3 was applied 1 to 2 wk after corn planting at rates of 0, 22, 45, 90, or 179 kg N ha^{-1} at all seven locations; a sixth treatment at the six locations in 2011 was a sidedress rate of 45 kg N ha^{-1} on plots that had received no N fertilizer shortly after planting. Sidedress N was banded midway between corn rows at the fourth to sixth leaf collar stage (Abendroth et al., 2011) by opening a 4-cm deep by 8-cm wide furrow with a wheel hoe, hand-applying NH_4NO_3 in the furrow, and then closing the furrow with a rake. Individual plots (experimental units) were 4.7 m (six rows) wide by 7.5 m long.

Cooperating growers planted and managed corn hybrids of appropriate relative maturity for their respective area (Table 2.3) using commercial field-scale equipment. Corn was planted 5 cm deep in 76-cm rows on 23 Apr. 2010 and between 6 and 19 May 2011 at 81,500 to 89,100 seeds ha^{-1}. Cooperators applied pre- and post-emergence herbicides as needed to control weeds and applied starter fertilizer (≤22 kg N ha^{-1}) at planting (Table 2.3). Plot areas were fertilized as needed with broadcast $CaH_4P_2O_8$ and KCl 1 to 2 wk after corn planting at rates recommended for corn production in Minnesota

(Kaiser et al., 2011). At the same time, $CaSO_4 \cdot 2H_2O$ was broadcast to supply 17 kg S ha^{-1}. None of the seven locations were irrigated. Precipitation and air temperature data were obtained from the National Weather Service station nearest each site (Table 2.4) and are included as background data.

Nitrate Tests and Corn Yield

Immediately before sidedress N application at six locations in 2011, six to eight soil cores (2 cm i.d. × 30 cm deep) were collected between 17 and 24 June to form a composite soil sample for each plot that would receive sidedress N following the PSNT methods of Magdoff et al. (1984). Soil samples were dried in a forced-air oven at 35°C until constant mass, ground to pass a 2-mm sieve, extracted with 2 mol L^{-1} KCl, and analyzed for NO_3-N concentration on a Lachat QuikChem 8000 (QuickChem Method 12-107-04-1-B, Lachat Instruments, Loveland, CO).

When corn had reached physiological maturity, corn ears were hand harvested from 3 m of row near the center of each plot. This sample size of 3 m of row was adequate for detecting treatments differences in earlier work (Yost et al., 2012), and was adequate in this experiment, based on an average coefficient of variation of 8% at six locations and 13% at Goodhue. Corn ears were dried at 60°C until constant mass, shelled, and weighed. Grain yield was adjusted to 155 g kg^{-1} moisture and cob yield was expressed as dry matter. Corn stover was not harvested at three of the seven locations due to time constraints and conflicting grower harvest schedules. At the other locations, corn stover was cut about 15 cm above the soil surface from the same plants that were harvested for grain, and was weighed, chipped, and subsampled (about 1.5 kg) in the field. Stover subsamples were weighed wet, dried at 60°C until constant mass, and weighed again to determine stover moisture and allow calculation of stover dry matter yield. Corn grain, cob, and stover dry matter yield were combined to calculate corn silage yield, which was expressed at 650 g kg^{-1} moisture.

Following the CSNT methods of Binford et al. (1992), basal corn stalk samples were collected from 10 plants at the time of grain harvest (first two weeks of October). Stalk samples were dried at 60°C until constant mass, ground to pass a 1-mm sieve, extracted for 10 min with distilled water, filtered using Whatman no. 2 filter paper, and the filtrate was analyzed for NO_3-N by automated flow injection analysis on a Lachat QuikChem 8000 (QuickChem Method 13-107-04-1-B).

Data Analysis

Data were analyzed using the MIXED procedure of SAS (SAS Institute, 2006) at $P \leq 0.05$ with fertilizer N treatments as a fixed effect and location and block (nested within location) as random effects. The UNIVARIATE procedure of SAS was used to inspect residuals for normality and scatterplots of residuals vs. predicted values were used to assess homogeneity of variance (Kutner et al., 2004). The two-tailed log-likelihood ratio test was used to determine the significance of the location × N interaction. The CSNT data did not meet the assumptions of normality and homogeneous variance, and were therefore subjected to a square root transformation prior to data analysis. Regression analysis was used to describe the response of CSNT to fertilizer N applied shortly after planting. Several regression models were evaluated using the MIXED procedure of SAS and the model that was significant at $P \leq 0.05$ and produced the smallest residuals that were normally and randomly distributed was selected (Kutner et al., 2004). Parameter estimates and least squares means for the CSNT were back-transformed prior to their inclusion in this manuscript. The estimated economically optimum N rates (EONR) reported for grain and silage yield were determined by setting the first derivative of quadratic regression models to the price ratio of fertilizer N/corn grain or silage (PR) and assuming average urea fertilizer and corn grain and silage prices for 2009 to 2011 (\$1.19 kg^{-1} N, \$182 Mg^{-1} grain and \$39 Mg^{-1} silage; USDA-ERS, 2013; Center for Farm Financial Management, 2013).

RESULTS AND DISCUSSION

Weather conditions during the corn growing season varied among the seven site-years. Precipitation totals during the 2010 corn growing season at Okabena were near the 30-yr average (1981-2010) in April, 47 mm below average in May, 68 to 82 mm above average in June and July, near average in August, and much wetter than average in September (Table 2.4). Monthly average air temperatures in 2010 were much warmer (3.8°C) than normal in April, near average from May through July, 2.1°C above average in August, and near average in September. In general, the 2011 corn growing season across the four locations in Minnesota was cool (0.8°C below average) in the early spring, hot (2.9°C above average) and wet (82 mm above average) in the mid-summer, and dry (73 mm below average) in the early fall. The growing season at the two Wisconsin sites was similar to Minnesota sites except that July was drier (-34 mm) than normal and September was wetter (45 mm) than normal. The early growing season (April through May) across all six locations in 2011 had near normal precipitation totals, but the cooler than average air temperatures (-1.3°C) at five of the six sites suggests that early-season N mineralization may have been slower than usual.

Corn Yield Response to Fertilizer Nitrogen

Corn grain yield ranged from 13.9 to 15.3 Mg ha^{-1} at the seven locations where no-tillage corn was planted as the first crop after alfalfa (Table 2.5). The mean yield obtained in this experiment (14.6 Mg ha^{-1}) was 18% higher than the maximum yield of 17 site-years of no-tillage corn following alfalfa reported in the North American literature (Table 2.1). Even at these high yield levels, N fertilizer applied shortly after planting did not increase grain (P = 0.35) (Fig. 2.1) or cob yield (P = 0.48). According to the two-tailed log-likelihood ratio test, the lack of grain and cob yield response to fertilizer N was consistent among locations ($P \geq 0.95$). Similarly, sidedressed N did not increase corn grain (P = 0.73) or cob yield (P = 0.27) compared to the control plots with no fertilizer N across six locations where it was measured.

The lack of grain yield response to fertilizer N (Fig. 2.1) in our study is consistent with literature data from 10 of 17 site-years under no-tillage management (Table 2.1). The estimated EONR at the remaining seven site-years of published data was large for three site-years (≥93 and 117 kg N ha^{-1} for two site-years on irrigated coarse-textured soils in Minnesota and 105 kg N ha^{-1} for one medium-textured site-year in Ohio), but was estimated as zero at the remaining four site-years in Iowa, Pennsylvania, and Wisconsin at current prices even though they reported a significant response to fertilizer N (Table 2.1). At the three sites in the literature where the EONR could be determined, the response of grain yield at the EONR averaged 2.4 Mg ha^{-1} (a 29% average increase). Considered together, our data and published data on first-year no-tillage corn following alfalfa harvested for grain indicate that an N response occurred about 29% of the time (7 of 24 site-years). Nearly the same probability (32%) existed for fertilizer N response in 335 site-years of this rotation under full-width tillage (Yost et al., unpublished results, 2012), suggesting that the likelihood of fertilizer N response in first-year corn is similar across tillage systems.

Corn silage yield ranged from 52.5 to 75.4 Mg ha^{-1} across four locations in 2011 where it was measured (Table 2.5), but fertilizer N was not needed to maximize silage ($P = 0.79$) (Fig. 2.1) or stover yield ($P = 0.89$) across these four locations. According to the two-tailed log-likelihood ratio test, the lack of stover and silage yield response to fertilizer N was consistent among locations ($P \geq 0.24$). Delaying N fertilizer application until sidedressing did not increase corn silage ($P = 0.11$) or stover yield ($P = 0.44$) compared to the nonfertilized control plots across four locations in 2011. These data indicate that alfalfa may provide the entire N requirement for first-year, no-tillage silage corn. In contrast, silage yield increased by 12 Mg ha^{-1} at one of two site-years on medium-textured soil in Michigan (Rasse and Smucker, 1999) and by 6 Mg ha^{-1} on an irrigated silt loam soil in Idaho (Meek et al., 1994). The EONR for corn silage in Idaho was ≤ 82 kg N ha^{-1} (only three N rates were used), but the EONR for the Michigan site could not be determined because only two N rates were used. The combined results of our study and these two studies in the literature suggest that supplemental N is often not needed for no-tillage silage corn following alfalfa, but this conclusion should be tested at more site-years.

Reliability of the PSNT and CSNT

Soil NO_3-N concentration in PSNT samples collected from plots that would receive only sidedressed N was ≤18 mg kg^{-1} at the six locations in 2011 (Table 2.5), below the range of critical PSNT concentrations identified for the Midwestern and North Central U.S. (19-30 mg kg^{-1}) (Bast et al., 2012), and yet sidedressed N did not increase corn yield. Thus, the PSNT failed to identify the adequacy of soil N, suggesting that the critical PSNT concentration may need to be lower for no-tillage corn following alfalfa. Given the lack of N response at PSNT levels as low as 8 mg kg^{-1}, it also may be that the PSNT is not reliable in this no-tillage rotation.

The poor predictability of the PSNT in this study may be related to early-season weather conditions. On tilled soils in Wisconsin, the accuracy of the PSNT was related to May through June air temperatures across 101 site-years of corn: 21 site-years of first-year corn following alfalfa and 80 site-years of corn with recent (1-3 yr) organic N inputs. The accuracy of the PSNT in predicting N applications within 34 kg N ha^{-1} of the EONR improved from 37 to 76% when average air temperature rose from below average

[>0.56°C below the 30-yr average (1971-2000)] to near average or above (Andraski and Bundy, 2002). Additionally, air temperatures below average resulted in 43% more cases of over-application of N fertilizer (>34 kg N ha^{-1} of the EONR) compared to cases with average or above-average temperatures. Based on the classification of Andraski and Bundy (2002), Goodhue and Lake City had average or above-average air temperatures, whereas the remaining four locations with the sidedress treatment had below-average temperatures (Table 2.4). Thus, below-average air temperatures in May through June may have contributed to the inaccuracy of the PSNT at predicting corn yield response to sidedressed N at four of the six nonresponsive sites.

Andraski and Bundy (2002) found that early-season precipitation did not affect the accuracy of the PSNT for corn with recent organic N inputs in Wisconsin. In contrast, current Iowa recommendations suggest that the critical PSNT concentration should be lowered from 25 to 16 mg NO_3-N kg^{-1} when precipitation totals in May exceed the 30-yr average by 127 mm (Blackmer et al., 1997). None of the sites in our study received more than 74 mm above the 30-yr average (1981-2010), indicating that Iowa's lower critical level would not have applied to these site-years. The data from our six site-years in 2011 indicate that current critical PSNT concentrations may need to be lower for no-tillage corn following alfalfa, but do not provide evidence for establishing a new PSNT threshold.

Average CSNT concentration in the nonfertilized corn plots ranged from 250 to 1660 mg NO_3-N kg^{-1} (Table 2.5). According to Iowa recommendations (Blackmer and

Mallarino, 1996), five of our seven locations had CSNT concentrations in the optimum (>700 and <2000 mg NO_3-N kg^{-1}) or excessive range (>2000 mg NO_3-N kg^{-1}), whereas Norwalk and Lakefield had CSNT concentrations in the marginal range (>250 and <700 mg NO_3-N kg^{-1}). September precipitation totals at the five Minnesota sites in 2011 were 64 mm below the 30-yr average, whereas the two Wisconsin locations (Cashton and Norwalk) and the 2010 Minnesota site had 64 and 188 mm of precipitation above the 30-yr average, respectively (Table 2.4). When drought or excess precipitation occurs near the end of the growing season, CSNT concentrations can be inflated or deflated, respectively (Bundy and Andraski, 1996). Thus, the mean CSNT concentration at Lakefield (570 mg NO_3-N kg^{-1}) may have been inflated and the mean CSNT concentration at Norwalk (250 mg NO_3-N kg^{-1}) may have been deflated (Table 2.5) in comparison to years with normal end-of-season precipitation.

The lack of yield response to supplemental N at the two locations in 2011 with marginal CSNT concentrations raises questions about the use of this test for no-tillage corn following alfalfa, and suggests that critical levels may be lower for this rotation and tillage system. However, this conclusion should be tested directly among tillage systems and across more growing conditions that include sites that respond to fertilizer N. Across locations, fertilizer N rate increased CSNT concentration to 5340 mg NO_3-N kg^{-1} when 179 kg N ha^{-1} was applied shortly after planting ($P < 0.001$; Fig. 2.2). Under chisel plow tillage, CSNT in first-year corn after alfalfa exhibited a similar plateau response (6070 mg kg^{-1}) in four site-years in which grain yield did not respond to fertilizer N (Yost et al., 2012).

CONCLUSIONS

This research on N response of first-year corn after alfalfa under no-tillage adds substantially to the mere 17 site-years in the literature on corn grain and the three site-years of first-year no-tillage silage corn, and it demonstrates that high-yielding no-tillage corn planted after a good stand of alfalfa required no additional N to maximize first-year corn grain or silage yield. This lack of corn grain yield response was consistent across seven site-years with a range of precipitation and air temperature levels (five sites had cooler than normal air temperatures in the spring), medium- to fine-textured soils, and 2- to 7-yr-old alfalfa stands. This supports previous research on alfalfa N credits to first-year corn from locations with full-width tillage and suggests that N credit recommendations in the U.S. Corn Belt do not need to be altered for tillage system when first-year grain or silage corn is grown after alfalfa. The most widely accepted critical PSNT concentration (21 mg NO_3-N kg^{-1}) was unsuccessful at identifying the lack of corn yield response to supplemental N across six locations in 2011. Based on the published critical concentration of 700 mg NO_3-N kg^{-1}, the CSNT correctly identified the N sufficiency at five of seven locations, but not at two others. Critical concentrations for these two tests may need to be lower for first-year no-tillage corn following alfalfa in order to accurately reflect the need for supplemental N.

Table 2.1. Location, soil texture, alfalfa age and final plant population, economically optimum N rate (EONR), and maximum grain yield of 17 site-years of published data on fertilizer N response of first-year, no-tillage corn following alfalfa.

Reference	Location	Soil texture	Age†	Final plant population	EONR	Max. yield¶
			yr	plants m^{-2}	kg N ha^{-1}	Mg ha^{-1}
Aflakpui et al., 1993	ON	Loam	5	-‡	0	10.0
Aflakpui et al., 1993	ON	Loam	4	-	0	11.0
Bundy and Andraski, 1993	WI	Silt loam	3	65	0	11.2
Levin et al., 1987	PA	Silt loam	5	97	0	6.7
Levin et al., 1987	PA	Silt loam	4	172	0§	8.7
Moncrief et al., 1988	MN	Sandy loam	3	32	117	12.4
Moncrief et al., 1991	MN	Sandy loam	3	97	≥93	11.4
Morris et al., 1993	IA	Loam	4	54	0§	8.0
Pearson et al., 2003	WI	Sandy loam	1	161	0	9.8
Sripada et al., 2008	PA	Silt loam	5	-	0	11.4
Triplett et al., 1979	OH	Silt loam	2	-	0	5.4
Triplett et al., 1979	OH	Silt loam	2	-	0	9.0
Triplett et al., 1979	OH	Silt loam	3	-	105	8.4
Wolkowski, 1992	WI	Silt loam	3	54	0	11.5
Wolkowski, 1992	WI	Silt loam	4	43	0	11.3
Wolkowski, 1992	WI	Silt loam	3	38	0§	10.7
Wolkowski, 1992	WI	Silt loam	4	43	0§	9.8

† Establishment year was included in alfalfa stand age.
‡ Final plant populations were not measured in these studies.
§ These sites had a significant response to fertilizer N, but the estimated EONR was zero at \$1.19 kg^{-1} N and \$182 Mg^{-1} grain.
¶ Maximum grain yield at 155 g kg^{-1} moisture. Maximum yield was the average across N rates when there was no response to fertilizer N. When fertilizer N was required to maximize yield, the maximum regression-predicted yield was used.

Table 2.2 Background soil characteristics for seven no-tillage locations in Minnesota and Wisconsin.

Location†	Geographic coordinates	Dominant soil series (classification)	Soil texture	Soil‡ pH	P	K	S
					--- mg kg^{-1} ---		
Cashton	43°41'N, 90°42'W	Fayette (fine-silty, mixed, superactive, mesic Typic Hapludalfs)	Silt loam	7.2	69	72	10
Goodhue	44°29'N, 92°38'W	Port Byron (fine-silty, mixed, superactive, mesic Typic Hapludolls)	Silt loam	6.9	17	162	7
Lake City	44°19'N, 92°13'W	Hersey (fine-silty, mixed, superactive, mesic Mollic Hapludalfs)	Silt loam	7.3	19	120	12
Lakefield	43°36'N, 95°16'W	Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls)	Loam	7.4	5	147	5
Norwalk	43°47'N, 90°40'W	Wildale (fine, mixed, active, mesic Mollic Paleudalfs)	Silt loam	6.4	10	69	9
Okabena	43°40'N, 95°16'W	Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)	Clay loam	6.6	34	180	-
Plainview	44°10'N, 92°17'W	Downs (fine-silty, mixed, superactive, mesic Mollic Hapludalfs)	Silt loam	6.3	48	171	7

† Cashton and Norwalk are Wisconsin towns and the remaining towns are in Minnesota. Okabena was first-year corn in 2010, whereas the remaining locations were first-year corn in 2011.

‡ Soil pH, Bray-1 P (pH ≤7.2) or Olsen P (pH >7.2), ammonium-acetate exchangeable K, and calcium-chloride SO_4-S are for the surface 15 cm. Sulfur data from Okabena were not available.

Table 2.3. Alfalfa age, final plant population, and regrowth height and corn hybrid, seeding rate, and starter fertilizer rate for seven on-farm trials in Minnesota and Wisconsin.

	Alfalfa, 2009 or 2010			Corn, 2010 or 2011		
Location†	Age‡	Final plant population	Regrowth height	Hybrid	Seeding rate	Starter fertilizer rate
	yr	plants m^{-2}	cm		seed ha^{-1}	kg N ha^{-1}
Cashton	3	54	7	Croplan 4022	86,400	6
Goodhue	3	86	28	Pioneer 36V51	84,000	7
Lake City	2	65	20	Producers 5004	89,100	20
Lakefield	6	43	7	Croplan 4421	81,500	9
Norwalk	4	43	20	Pioneer P0448AM1	84,000	3
Okabena	7	50	38	DEKALB DKC50-47	85,000	9
Plainview	3	86	23	DEKALB DKC48-40	84,000	22

† Cashton and Norwalk are Wisconsin towns and the remaining towns are in Minnesota. Okabena was alfalfa in 2009 and corn in 2010, whereas the remaining locations were alfalfa in 2010 and corn in 2011.

‡ Establishment year was included in alfalfa stand age.

Table 2.4. Cumulative precipitation and average air temperature for seven on-farm trials, with departures from the 30-yr average (1981-2010) in parentheses.

Location†	April	May	June	July	August	September
	--------------------------------- Precipitation, mm ---------------------------------					
Cashton	95 (8)	85 (-11)	90 (-17)	89 (-34)	37 (-80)	136 (45)
Goodhue	73 (-2)	91 (-4)	112 (-2)	179 (72)	38 (-81)	25 (-80)
Lake City	91 (13)	76 (-21)	166 (52)	165 (50)	52 (-66)	33 (-68)
Lakefield	68 (-8)	119 (27)	164 (48)	212 (120)	27 (-71)	11 (-69)
Norwalk	95 (8)	85 (-11)	90 (-17)	89 (-34)	37 (-80)	136 (45)
Okabena	76 (-3)	42 (-47)	184 (68)	177 (82)	85 (-15)	270 (188)
Plainview	98 (15)	81 (-14)	118 (4)	197 (84)	52 (-72)	55 (-38)
	-------------------------- Average air temperature, °C --------------------------					
Cashton	7 (-1.9)	13 (-1.2)	20 (-0.1)	24 (2.5)	21 (0.6)	15 (-1.6)
Goodhue	7 (-0.1)	14 (0.6)	20 (0.7)	25 (4.0)	22 (2.4)	16 (1.0)
Lake City	7 (-1.1)	13 (-0.6)	19 (-0.03)	24 (2.5)	21 (0.4)	15 (-0.6)
Lakefield	6 (-1.1)	13 (-1.4)	19 (-0.3)	24 (2.6)	20 (0.1)	15 (-0.9)
Norwalk	7 (-1.9)	13 (-1.2)	20 (-0.1)	24 (2.5)	21 (0.6)	15 (-1.6)
Okabena	11 (3.8)	14 (-0.4)	19 (-0.1)	22 (0.3)	23 (2.1)	15 (-0.7)
Plainview	7 (-1.6)	13 (-1.2)	19 (-0.3)	24 (2.4)	21 (0.4)	15 (-0.9)

† Cashton and Norwalk are Wisconsin towns and the remaining towns are in Minnesota. Okabena was first-year corn in 2010, whereas the remaining locations were first-year corn in 2011.

Table 2.5. Presidedress soil nitrate test (PSNT) concentration, maximum grain and silage yield, and corn stalk nitrate test (CSNT) concentration for seven on-farm trials in Minnesota and Wisconsin.

Location†	PSNT‡	Grain yield	Silage yield	CSNT§
	mg kg^{-1}	----- Mg ha^{-1}¶ -----		mg kg^{-1}
Cashton	12 (0.4)	13.9 (0.3)	69.5 (1.3)	1660 (390)
Goodhue	13 (0.7)	14.2 (0.4)	52.5 (1.4)	930 (300)
Lake City	8 (0.5)	15.3 (0.3)	-	720 (120)
Lakefield	18 (1.0)	14.8 (0.2)	61.0 (1.0)	570 (390)
Norwalk	13 (1.5)	14.7 (0.3)	75.4 (1.4)	250 (170)
Okabena	-	14.6 (0.3)	-	1470 (830)
Plainview	10 (0.8)	14.7 (0.2)	-	1270 (800)

† Cashton and Norwalk are Wisconsin towns and the remaining towns are in Minnesota. Okabena was first-year corn in 2010, whereas the remaining locations were first-year corn in 2011.

‡ Nitrate-N concentration (standard error) in the surface 30 cm of soil immediately before sidedressing in plots that would receive sidedressed N only. Samples were not collected at Okabena.

§ Average CSNT concentration (standard error) for the plots not fertilized with N.

¶ Mean yield across all N treatments (standard error). Grain expressed as 155 g kg^{-1} moisture and silage expressed at 650 g kg^{-1} moisture. Silage yield was not determined at three locations.

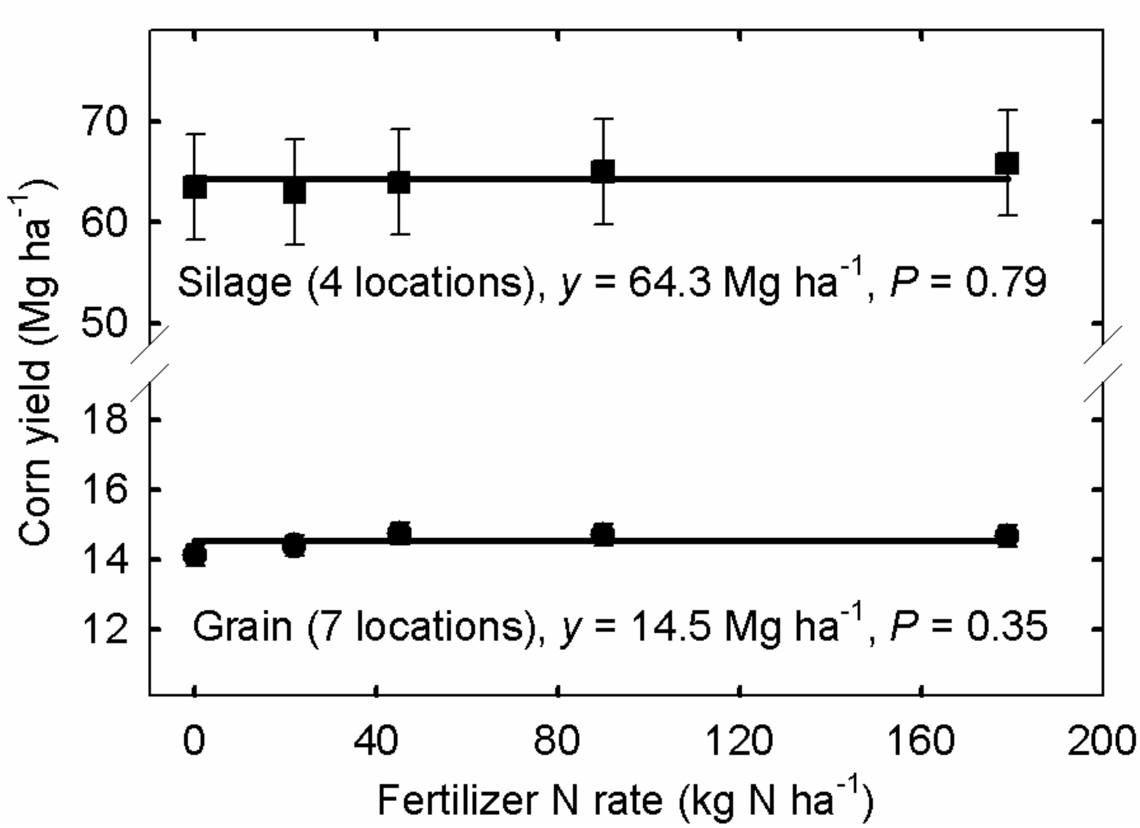

Fig. 2.1. Grain and silage yield response of first-year corn after alfalfa to fertilizer N applied shortly after planting under no-tillage management. Silage yield (650 g kg^{-1} moisture) was not measured at the Lake City, Plainview, and Okabena sites.

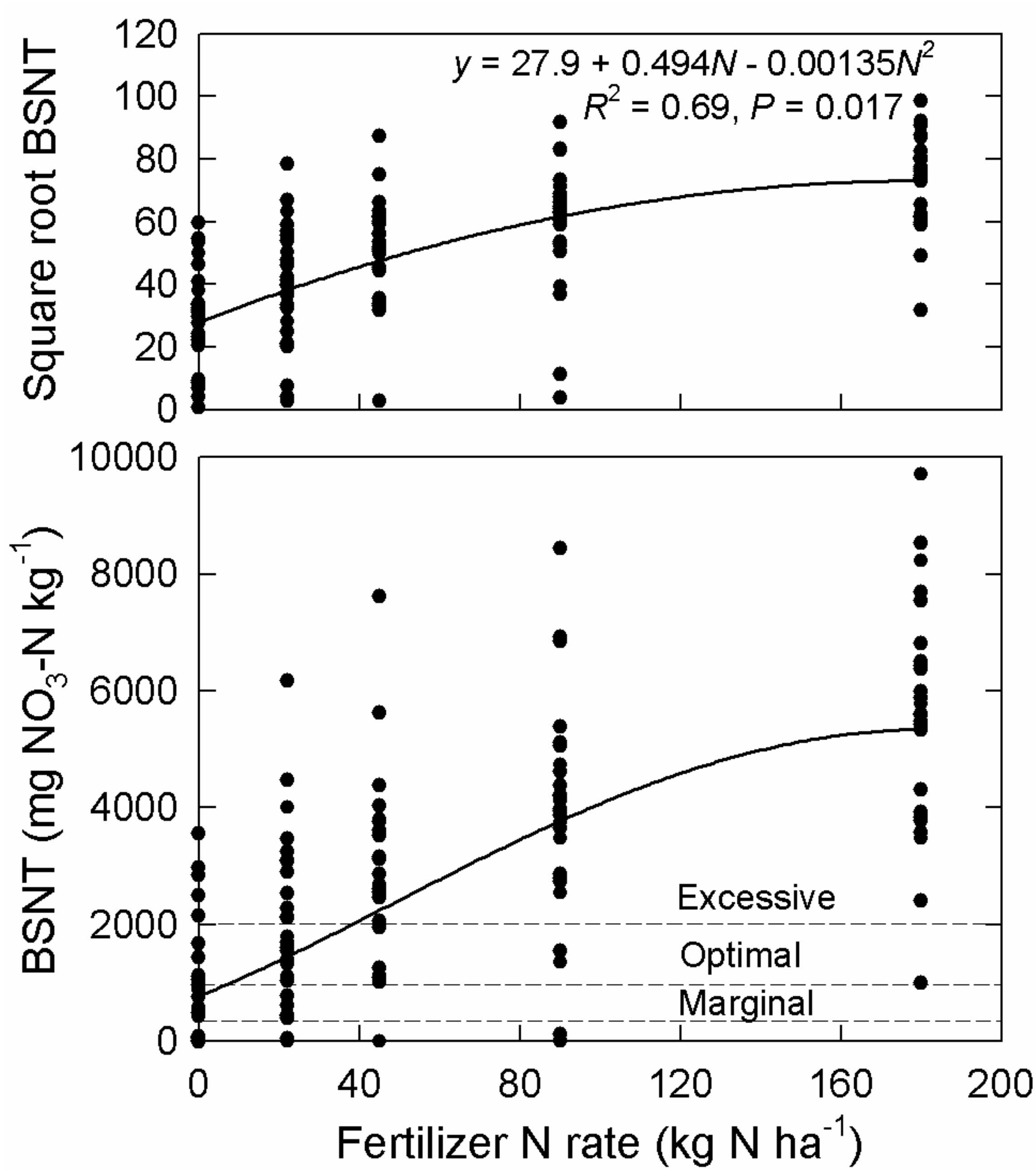

Fig. 2.2. Corn stalk nitrate test (CSNT) response to N fertilizer applied shortly after planting across six locations of first-year, no-tillage corn following alfalfa in 2011 and one location in 2010. Original analyses were conducted on the square root of CSNT to meet homogeneity of variance requirements. The horizontal dashed lines represent excessive, optimal, and marginal CSNT categories as defined in Iowa State CSNT recommendations (Blackmer and Mallarino, 1996).

CHAPTER 3. Nitrogen Requirements of First-Year Corn Following Alfalfa Were Not Altered by Fall-Applied Manure

INTRODUCTION

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 Russelle, 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 to 420 total Kjeldahl N (TKN) ha^{-1}] increased grain yield of first-year corn after alfalfa by 1.1 Mg ha^{-1} in 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 presidedress soil nitrate test (PSNT; Magdoff et al., 1984) and the corn stalk nitrate test (CSNT; 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 NO_3-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 in Wisconsin, the accuracy of the PSNT depended on early-season (May through June) average air temperatures, as below-average temperatures (>0.56°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 N rate (EONR) for corn grain (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 CSNT have been for corn following corn or soybean, and critical CSNT concentrations of 0.25, 0.50, and 0.70 g NO_3-N kg^{-1} have been identified as sufficient for optimal corn grain yield (Binford et al., 1992; Hooker and Morris, 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 CSNT 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 in New York and Minnesota suggest that critical CSNT 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 CSNT for first-year corn following alfalfa. Balkcom et al. (2003) reported similar CSNT concentration ranges in fields with or without manure application, but no direct comparison of manure effects on the accuracy of the CSNT was made. The objectives of this research were to: 1) determine whether adjustments should be made to the alfalfa N credit for first-year corn to account for fall manure application;

and 2) verify the accuracy of the PSNT and CSNT 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 3.1 and 3.2). The alfalfa stands were 2 to 5 yr old, including the establishment year (Table 3.3). Alfalfa final plant populations were measured just prior to 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 3.3). 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 4.7 m (six 76-cm rows) wide by 37.5 m long. Subplots (4.7 m wide by 7.5 m long) consisted of four N fertilizer rates (0, 45, 90, or 179 kg N ha^{-1}) broadcast as NH_4NO_3 at 1 to 2 wk after corn planting and a sidedress-only treatment of 45 kg N ha^{-1} as NH_4NO_3 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 3.2). Dairy cow manure was applied at all locations, but the method and rate of manure application varied. Manure application rate was determined with three plastic tarps (2 m x 2 m) on which semi-solid manure was collected and weighed during broadcast spreading, or by measuring the area covered by one full tank of liquid manure. 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 3.2).

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 upon location (Table 3.3). Starter fertilizer ($\leq$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 3.1).

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. 3.1A, Fig. 3.1B).

When corn had reached the four to six leaf collar stage (13 to 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 NO_3-N concentration by Cd reduction using automated flow injection analysis (Lachat QuickChem 8000, Hach Company, Loveland, CO; Method 12-107-04-1-B).

After 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 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 Andraski, 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. In order 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 Elementar 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, corn 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 to 6 October), following the methods of Binford et al. (1992). Basal corn 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 CSNT data did not meet the assumptions of normality and homogeneous variance and were therefore subjected to a square root transformation prior to analysis because a few concentrations were zero (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 were 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 non-linear regression equations were developed for the responses of corn yield, N concentration, N content, and square root CSNT 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 price ratio of fertilizer N/corn grain or silage (PR) from 2009 to 2011 (\$1.19 kg^{-1} N as urea, USDA-ERS, 2013; \$183 Mg^{-1} corn grain and \$39 Mg^{-1} corn silage, Center for Farm Financial Management, 2013). 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 CSNT 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 3.3). 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 3.4). However, fertilizer N increased grain yield at two locations (Howard Lake and St. Rosa), regardless of manure application (Fig. 3.2A). 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, ±\$2.50 ha^{-1}). These results demonstrate that fall-applied 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 (Fig. 3.2A). 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 3.3), but a multi-state 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 only 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 3.4). 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 3.4). 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 3.4; Fig. 3.2B). 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 3.3). 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 3.3), University of Minnesota Extension guidelines suggested the expected N credit would be 168 kg N ha^{-1} (Kaiser et al., 2011). 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., 2011); 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. 3.1A). 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.

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.

3.1B). 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 nonresponsive 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.

Nitrogen Concentration and Content

Across all eight locations, grain N concentration increased by 0.26 g N kg^{-1} when manure was applied (Table 3.4) and increased with fertilizer N at five of eight locations (Fig. 3.3A). The increase in grain N concentration with 179 kg N ha^{-1} of fertilizer N at Howard Lake (1.8 g N kg^{-1}) was three times the increase at four other locations (Faribault, Medford, Randolph, and St. Rosa; 0.56 g N kg^{-1}). All but one of these locations also had an increase in grain N content with fertilizer N (Fig. 3.3B). 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 3.4). 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. 3.3B). 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 3.2). 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 3.3). 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 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 nonresponsive 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 nonresponsiveness 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 nonresponsive 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, 1994; 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. 3.4). 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 nonresponsive 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.

Corn Stalk Nitrate Test

The mean CSNT 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 nonresponsive locations (Table 3.3). 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 nonresponsive in grain yield to fertilizer N. Manure applied during fall alfalfa termination increased the mean CSNT concentration by 1.59 g NO_3-N kg^{-1} across fertilizer N rates and locations (Table 3.4), indicating greater supply of nitrate late in corn growth. Transformed CSNT concentration also increased linearly with fertilizer N across all four locations, but the response to N differed between Medford (square root CSNT = 24.0 + 0.515x, R^2 = 0.86, P < 0.001) and the remaining three locations (Plainview, Randolph, St. Rosa); square root CSNT = 50.7 + 0.123x, R^2 = 0.89, P = 0.018. At Medford, mean CSNT 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 CSNT 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 CSNT concentration to the optimal range aligns well with the lack of grain yield response to fertilizer N at Medford. Mean CSNT 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 CSNT concentration at St. Rosa increased to 0.7 g NO_3-N kg^{-1} only when 179 kg N ha^{-1} was applied.

Basal corn 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 CSNT 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 CSNT concentration for the nonmanured 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 CSNT concentration at the relative yield plateau could not be determined with a linear-plateau regression model because the lowest relative yield observed was 84% and only 13 observations had relative yields below 95%. We considered a quadratic-plateau regression model, but the critical CSNT concentration with this model (2.59 g NO_3-N kg^{-1}) was overestimated, as suggested by Binford et al. (1992), and was more than three times the previously identified critical concentrations for corn following corn or soybean in Iowa (Binford et al., 1992) or other states (Fox et al., 2001; Forrestal et al., 2012). The upper limit of the optimal range or average CSNT concentration at the EONR was 1.75 g NO_3-N kg^{-1} and was lower than the critical concentration identified in Iowa (Binford et al, 1992), but higher than levels identified in eastern states (Fox et al., 2001; Forrestal et al., 2012); however, there was a wide range (0.23-7.0 g NO_3-N kg^{-1}) and large standard error (0.45 g NO_3-N kg^{-1}) in the estimated concentration at the EONR in our study (Fig. 3.5).

In addition to the large variation across locations, there also was large variability in CSNT concentration within locations. The standard error in CSNT concentration for the nonfertilized, nonmanured treatments in this study and in Yost et al. (2012, 2013) averaged 39% (10 to 79%) of the mean (Table 3.3). We anticipated that the critical and EONR concentration for the optimal CSNT 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 variability in CSNT 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 CSNT 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 fertilizer and soil pH is within the optimal range. Therefore, growers 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 following alfalfa because the test was accurate in only 55% of the 94 sites from this study and those in the published literature. The CSNT correctly identified sites as responsive or nonresponsive to fertilizer N at the majority of locations (3 of 4) in this study, but when these data were considered with 13 sites of previous work, no accurate optimal CSNT range could be identified because first-year corn following alfalfa had high relative yield and large variation in CSNT concentration at the EONR within and among 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 CSNT can accurately identify fertilizer N response in first-year corn following alfalfa.

Table 3.1. Background soil characteristics for eight on-farm locations in Minnesota.

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

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

Table 3.2. Manure application date, rate, type, and as-applied analysis, along with primary tillage information for eight Minnesota locations.

Location	Fall 2010 manure application							Fall 2010 tillage	
	Date	Rate	Type†	Dry matter	TKN‡	NH_4-N	C:N	Date	Type§
		Mg or 1000 L ha^{-1}		%	----- kg ha^{-1} ----				
Faribault	14 Oct.	3.0	BS	30	52	5	16	14 Oct.	DC
Howard Lake	21 Oct.	68.3	BL	2	245	155	3	21 Oct.	DC
Medford	30 Sept.	15.0	IL	8	73	43	-¶	15 Oct.	MP
Plainview	9 Nov.	20.3	BS	39	426	28	21	20 Nov.	DC
Randolph	11 Nov.	17.1	BS	24	211	97	12	12 Nov.	DC
Redwing	7 Oct.	22.9	BS	30	510	68	16	17 Nov.	MP
St. Rosa	3 Nov.	20.7	BS	42	167	63	13	4 Nov.	DC
Stewartville	4 Nov.	34.2	BS	18	507	84	12	9 Nov.	DC

† BL, broadcast liquid manure; IL, injected liquid manure; BS, broadcast semi-solid manure.

‡ Total Kjeldahl N.

§ DC, disk-chisel; MP, moldboard plow.

¶ Cooperating grower provided the manure analysis, but it did not include manure C.

Table 3.3. Alfalfa and corn characteristics, presidedress soil nitrate test (PSNT) concentration, maximum grain and silage yield, and corn stalk nitrate test (CSNT) concentration for eight Minnesota locations, with standard errors in parentheses.

	Alfalfa, 2010		Corn, 2011					
Location	Age†	Final plant population	Hybrid	Starter fertilizer	PSNT‡	Grain yield	Silage yield	CSNT§
	yr	plants m^{-2}		kg N ha^{-1}	mg kg^{-1}	------- Mg ha^{-1}¶ ------		g kg^{-1}
Faribault	5	32	Pioneer 34A85	10	8 (1)	12.4 (1.0)	71.5 (3.9)	-
Howard Lake	4	75	Pioneer 35F40	17	5 (1)	11.1 (0.4)	63.5 (2.2)	-
Medford	3	43	Croplan 421VT	0	19 (1)	16.0 (0.3)	-	0.26 (0.20)
Plainview	4	54	Fielder's Choice NG6440	16	22 (2)	14.0 (0.3)	-	4.07 (0.68)
Randolph	2	54	Trelay 4ST456	4	14 (1)	13.9 (0.5)	-	4.46 (2.04)
Redwing	3	75	Pioneer 34A85	0	22 (2)	14.7 (0.4)	82.5 (1.9)	-
St. Rosa	5	65	Mycogen MY2J337	2	7 (1)	10.9 (1.0)	56.7 (3.6)	0.004 (0.002)
Stewartville	5	32	DEKALB DKC59-35	9	27 (2)	15.2 (0.2)	72.7 (1.1)	-

† Establishment year included in alfalfa stand age.

‡ Nitrate-N concentration in the surface 30 cm of soil in nonfertilized and nonmanured corn.

§ The CSNT concentration for nonfertilized and nonmanured corn. The CSNT 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 (Table 5). When fertilizer N was required to maximize yield, maximum yield is the highest regression-predicted yield. Silage yield was not determined for three locations.

Table 3.4. Significance of *F* tests for the fixed effects of manure (M), fertilizer N (N), and their interaction on corn yield, N concentration, N content, presidedress soil nitrate test (PSNT) concentration, and corn stalk nitrate test (CSNT) 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.

Variable	Component	M	N	M x N
		---------------	*P* > *F*	--------------
Yield	Grain	0.15	0.008†	0.28
	Cob	0.80†	0.003†	0.58
	Stover	0.14	0.004	0.09
	Silage	0.32	0.006†	0.17
N conc.	Grain	0.02	<0.001†	0.79
	Cob	0.21	0.45	0.58
	Stover	0.47	0.15	0.01
N content	Grain	0.03	<0.001†	0.28
	Cob	0.32	0.01	0.39
	Stover	0.20	0.01	0.94
	Silage	0.18	0.001	0.59
PSNT	Soil	0.11†	-‡	-
CSNT	Stalk	0.004	0.032†	0.48

† 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.
‡ PSNT was measured only in nonfertilized control plots and the effect of fertilizer N rate on PSNT was not determined.

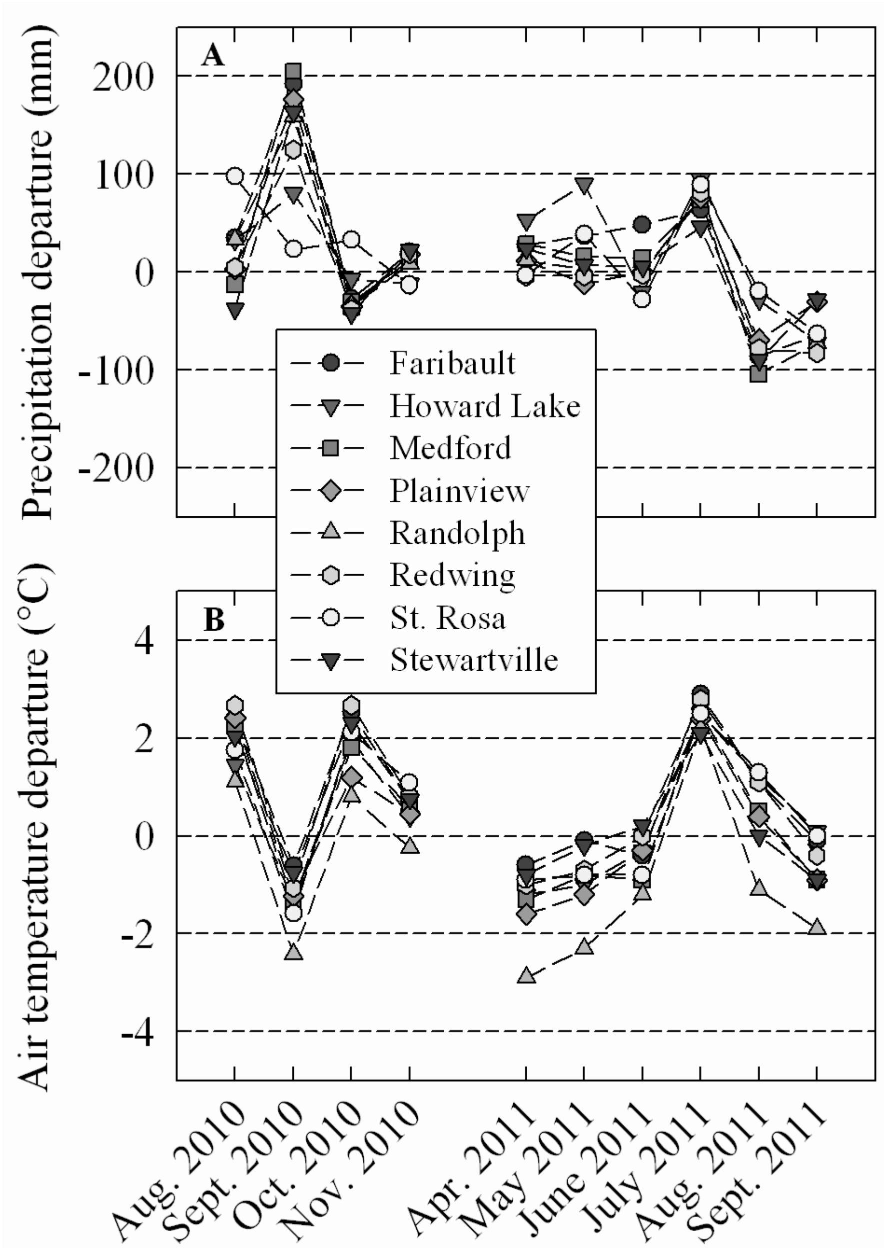

Fig. 3.1. Departures from the 30-yr average (1981-2010) for cumulative precipitation (A) and average air temperatures (B) in August through November 2010 and April through September 2011 for eight on-farm trials in Minnesota.

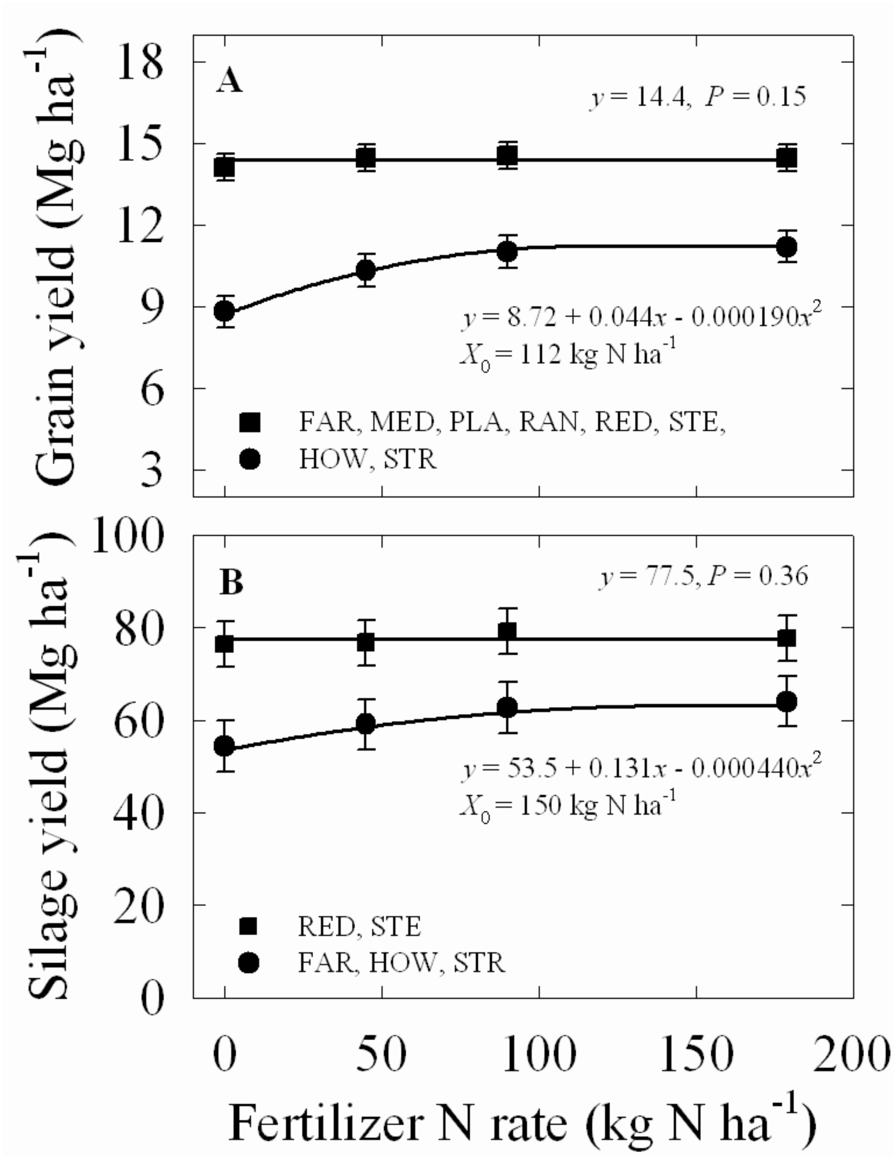

Fig. 3.2. Response of first-year corn after alfalfa to fertilizer N for (A) grain yield at eight locations and (B) silage yield at five locations. Locations are labeled with the first three letters of each location name (see Table 3.1). Non-linear regression equations with non-zero slopes are significant at $P < 0.01$; error bars represent the standard error of the mean.

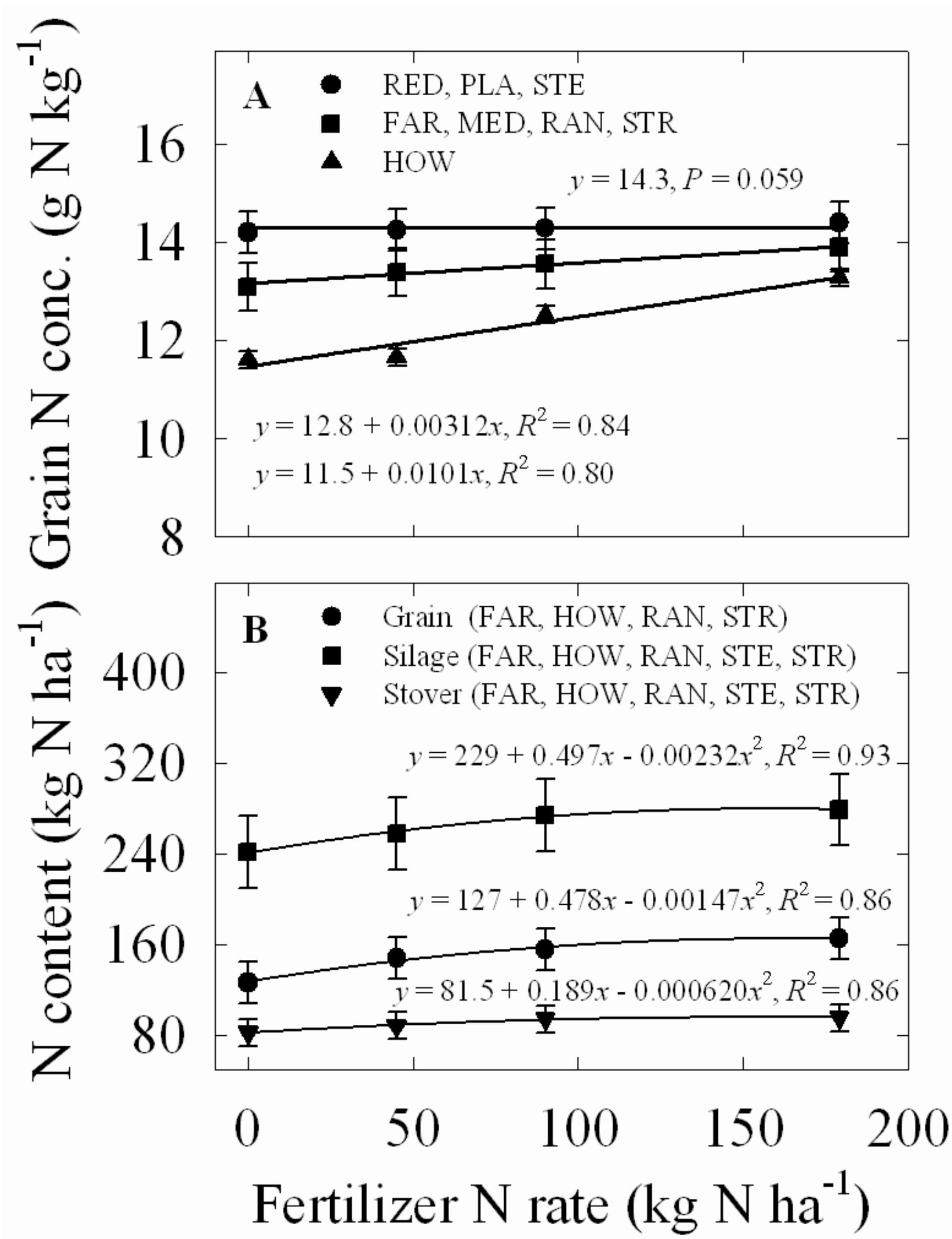

Fig. 3.3. Response of first-year corn after alfalfa to fertilizer N for (A) grain N concentration (conc.) and (B) N content in grain, stover, and silage. Locations are labeled with the first three letters of each name (see Table 3.1). All regression equations with non-zero slopes are significant at $P < 0.01$; error bars represent the standard error of the mean.

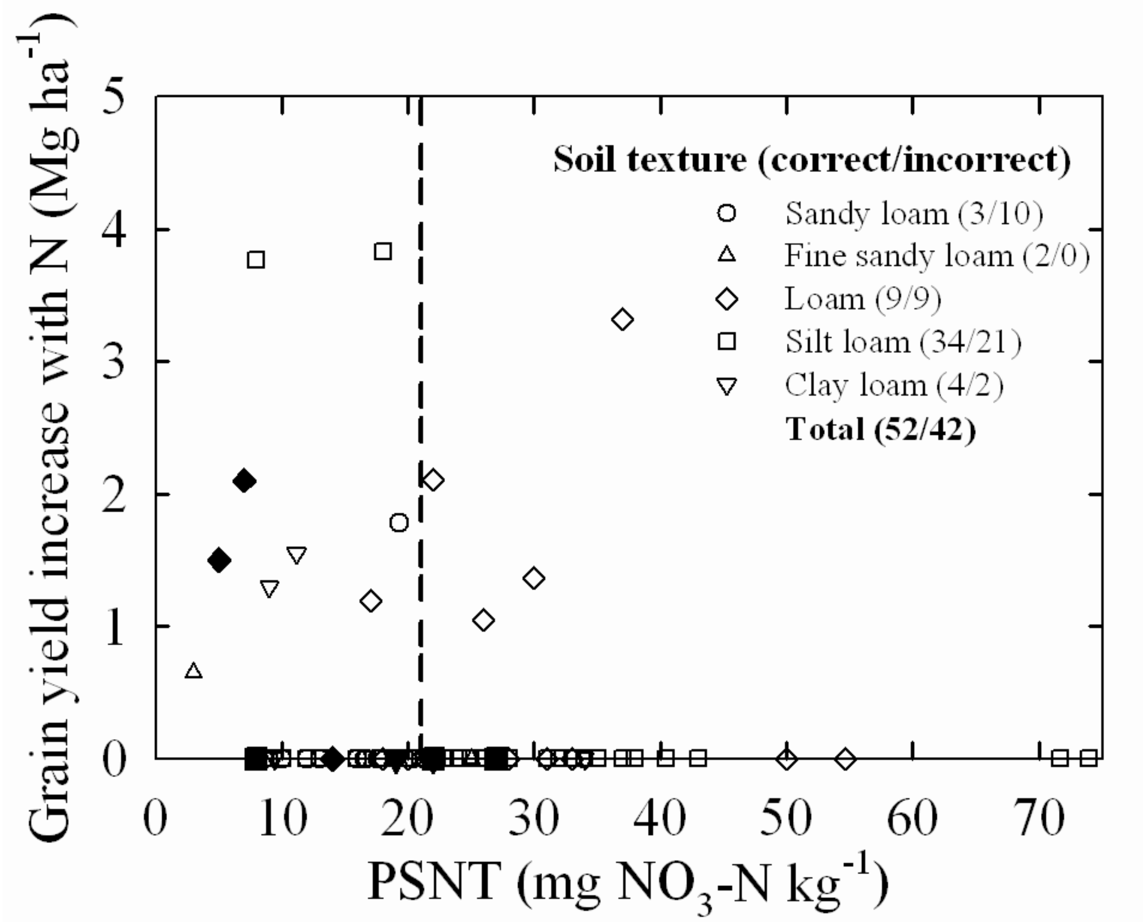

Fig. 3.4. Relationship between the presidedress soil nitrate test (PSNT) concentration and grain yield increase with fertilizer N in first-year corn after alfalfa. Bold symbols represent the plots without manure from the 8 sites in this study, whereas open symbols represent 86 sites without manure from the literature (Bundy and Andraski, 1993; Morris et al., 1993; Randall and Vetsch, 1994; 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., 2012a). The vertical dashed line represents the most widely accepted critical PSNT concentration (21 mg NO_3-N kg^{-1}). The number of sites correctly identified and incorrectly identified as either responsive or nonresponsive to fertilizer N are listed after each soil texture class.

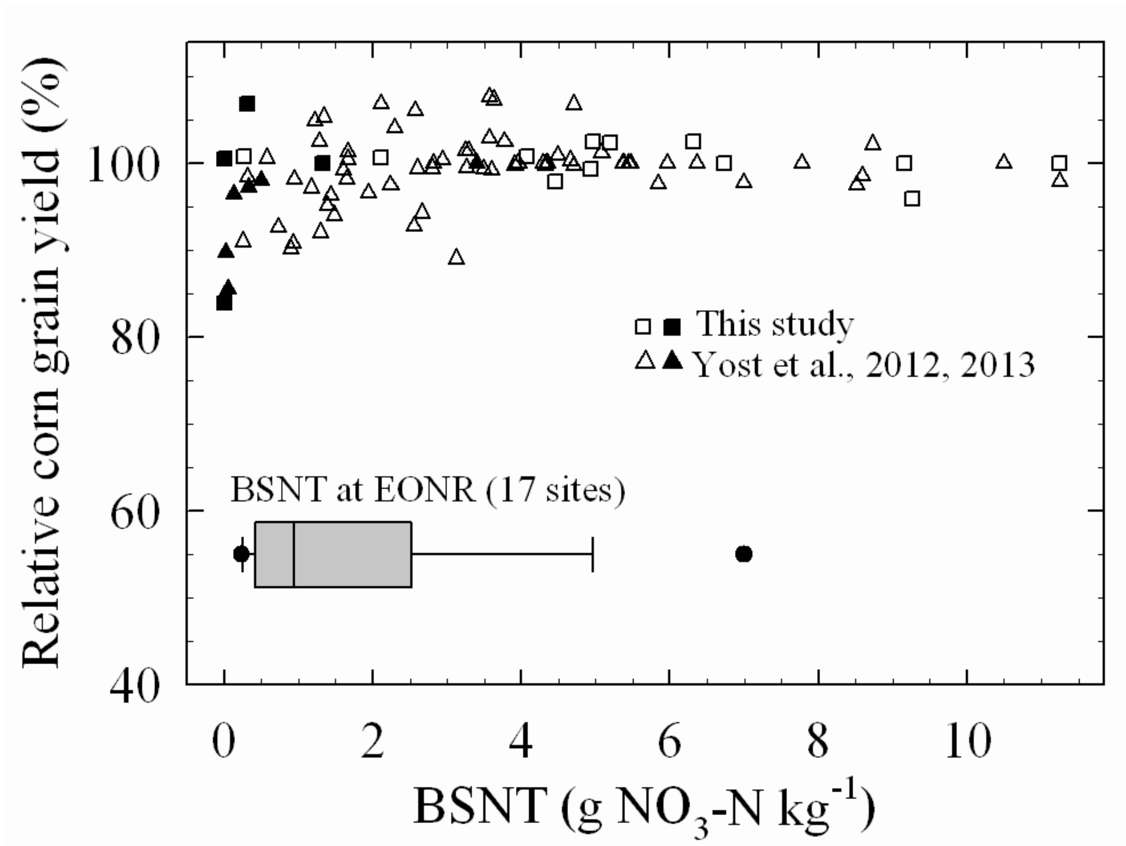

Fig. 3.5. Relationship between corn stalk nitrate test (CSNT) concentration and relative grain yield of first-year corn after alfalfa for nonmanured plots of four sites in 2011 (this study), six sites in 2010 (Yost et al., 2012), and seven sites in 2010 and 2011 (Yost et al., 2013). Solid symbols represent 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 CSNT concentrations at the economically optimum N rates (EONR) for first-year corn following alfalfa. The average CSNT concentration at the EONR was 1.75 g NO_3-N kg^{-1}; the median was 0.94 g NO_3-N kg^{-1}.

CHAPTER 4. Site-Specific Fertilizer Nitrogen Requirements for First-Year Corn Following Alfalfa

INTRODUCTION

The fertilizer N requirement for the first crop of corn following alfalfa can be much lower than the requirement following corn or soybean. The reduction in fertilizer N requirement for first-year corn compared to continuous corn is known as the alfalfa fertilizer N replacement value or N credit. Alfalfa N credits have been attributed mainly to increases in the soil N supply, which accumulates from N_2 fixation by alfalfa and soil rhizobacteria, and to decomposition of alfalfa residue that is rich in N (Heichel et al., 1984; Harris and Hesterman, 1990; Kelner et al., 1997), and to other diverse rotation benefits of alfalfa such as improved soil structure and disturbances in pest and disease cycles that enhance N use efficiency. In attempts to better define the alfalfa N credit, the influence of various alfalfa, tillage, and soil management factors on the fertilizer N requirement of first-year corn following alfalfa has been investigated during the past several decades. These factors have included the effects of alfalfa cutting management, alfalfa regrowth and stand density present at termination, and alfalfa termination timing and method.

Alfalfa cutting management during the last production year and the amount of alfalfa regrowth present at termination have had minimal impact on the fertilizer N response of first-year corn. Research from nine site-years in Wisconsin found that cutting management of alfalfa during the last production year had no influence on the fertilizer N requirement for grain yield of first-year corn on medium- and coarse-textured soils (Kelling et al.,1992). Additionally, the interaction between alfalfa regrowth and termination time did not affect the response of first-year corn grain yield to fertilizer N across six sites in Minnesota with medium- and fine-textured soils (Yost et al., 2012).

The effect of alfalfa stand density (plants m^{-2}) on the fertilizer N requirement of first-year corn following alfalfa has been studied in Pennsylvania and Wisconsin, but results of these studies lack sufficient evidence to conclude that stand density is related to fertilizer N response. In only one site-year in Pennsylvania, grain yield of first-year corn responded to N when following an alfalfa stand of 37 plants m^{-2}, but not when following a stand of 57 plants m^{-2} (Fox and Piekielek, 1993). In Wisconsin, the interaction between alfalfa stand density and fertilizer N rate for first-year corn was significant in only 1 of 3 yr at one of three locations (Kelling et al., 2003). The one site-year where corn responded to fertilizer N in this study was conducted in 1989 (the growing season following the 1988 midwestern United States drought) and was on a coarse-textured soil.

Five studies in Ontario, Minnesota, Pennsylvania, and Wisconsin investigated the effects of alfalfa termination method (moldboard plow tillage, chisel plow tillage, or no-tillage with herbicide) and only 1 of 13 site-years in these experiments exhibited a fertilizer N response in first-year corn that was dependent on termination method (Triplett et al., 1979; Levin et al., 1987; Moncrief et al., 1988, 1991; Wolkowski, 1992; Aflakpui et al., 1993). Two additional studies in Minnesota and Wisconsin found that alfalfa termination timing (fall vs. spring moldboard or chisel plow tillage) had no influence on the fertilizer N requirement of first-year corn (Kelling et al., 1992; Yost et al., 2012).

Conclusions of the aforementioned and many other studies (e.g., Bundy and Andraski, 1993; Morris et al., 1993; Schmitt and Randall, 1994; Lory et al., 1995; Andraski and Bundy, 2002) have formed the basis of most land grant university fertilizer N guidelines for first-year corn following alfalfa in the United States. Surprisingly, most states except Iowa (Blackmer et al., 1997) use alfalfa stand density (or percentage of alfalfa in the stand) at alfalfa termination to determine the size of the alfalfa N credit to first-year corn; states other than Iowa recommend that fertilizer N applications to first-year corn following 'good' alfalfa stands (≥43 plants m^{-2} or ≥80% in the stand) be reduced by 112 to 168 kg N ha^{-1} compared to continuous corn (Table 1 in Yost et al., 2014b). However, to our knowledge, only the two published studies discussed above have directly addressed the influence of alfalfa stand density. Some states use other factors in addition to alfalfa stand density to estimate alfalfa N credits. For example, Kansas and South Dakota fertilizer N guidelines for first-year corn include termination method as a factor (reduction in N credit by one-half for no-tillage compared to full-width tillage; Liekam et al., 2003; Gerwing and Gelderman, 2005) and Wisconsin uses soil texture and alfalfa regrowth amount as factors in determining N credits (reduction of 56 kg N ha^{-1} in N credit for coarse-textured soil and reduction of 45 kg N ha^{-1} when <20 cm of regrowth is remaining at termination; Laboski and Peters, 2012). The variation in the factors used in current university fertilizer N guidelines for first-year corn following alfalfa and the lack of adequate supporting data for these factors suggest that guidelines need to be reassessed.

Although past research has answered important questions regarding N requirements of first-year corn, it is still unclear as to when it will require substantial amounts of fertilizer N to increase grain yield. In most of the aforementioned studies, relatively few site-years responded to fertilizer N and most authors concluded that no N or a small amount of starter fertilizer N is typically sufficient to maximize grain yield of first-year corn following alfalfa, except when particular factors (e.g., poor alfalfa stand, alfalfa termination method, etc.) limit mineralized N supply. However, when the recommended rate is based on an average, the likelihood of over- or under- application of fertilizer N increases.

More accurate forecasting of fertilizer N response in these situations would improve the potential for optimum fertilizer N management for first-year corn, increase net returns for growers, and reduce N losses to the environment. Therefore, we compiled published data for first-year corn after alfalfa and conducted an analysis to: i) determine when first-year corn requires fertilizer N to increase grain yield; and ii) estimate the economically optimum N rate (EONR) and the N rate range for net return to N within \$2.50 ha^{-1} of the maximum for a range of price ratios of fertilizer N/corn grain (PRs) for responsive site-years. We used independent variables that were likely to affect N mineralization and loss and that should be readily available in future research and application.

MATERIALS AND METHODS

We compiled literature data on the response of grain yield to fertilizer N for first-year corn following alfalfa from North America. Entries were restricted to studies with at least two replications of fertilizer N rate treatments (≥2 N rates, including the nonfertilized control) for first-year corn and no recent manure history (i.e., no manure applied during the life of the alfalfa or applied between the time of alfalfa termination and corn planting). For each study, each combination of treatment factor (other than fertilizer N rate) and year were considered a single site-year regardless of whether treatment effects were declared nonsignificant ($P \geq 0.05$) by the original authors.

The data recorded for each site-year (where available from publications or from authors) included: i) soil characteristics (surface texture and surface soil organic matter percentage); ii) alfalfa characteristics (stand density or percentage of alfalfa in the stand at the time of termination, and stand age [including establishment year]); iii) alfalfa termination timing and method; iv) presidedress soil nitrate test concentration to the 30-cm depth; and v) corn characteristics (maximum grain yield [155 g kg^{-1} moisture], responsiveness to fertilizer N, increase in grain yield with fertilizer N). Surface soil pH and organic matter varied by study, but most were to 15 cm. Maximum grain yield was calculated as the mean across N rates for nonresponsive site-years or as the maximum regression-predicted yield for responsive site-years. Soil texture was categorized as fine, medium, or coarse (Table 4.1). The fine-textured category included site-years with clay loam and silty clay loam soils; no site-years with clay soils were found. The medium-textured category included site-years with loam, silt loam, sandy loam, fine sandy loam, and sandy clay loam soils. The coarse-textured category included site-years with loamy sand soils; no trials on sands were found.

Total monthly precipitation (millimeters) and daily average air temperature (degrees Celsius) were obtained from the Utah Climate Center (http://climate.usurf.usu.edu) for each site-year using the nearest Global Historical Climatology Network station. When the nearest town for a site-year was unknown, weather data from two to three stations at the county level were averaged. Total monthly degree days (DD_0) were calculated by summing daily average air temperatures above the base temperature of 0°C. Monthly total precipitation and DD_0 were obtained for the months of October of the last alfalfa year through September of the subsequent corn year.

The compilation of fertilizer N response trials of first-year corn following alfalfa in North America resulted in 471 site-years of data with predominately rainfed growing conditions (Supplemental Table S4.1; Supplement S4.2). However, 74 site-years were excluded from the analysis because of missing alfalfa stand age or alfalfa termination timing and four site-years were excluded when drought (mainly in 1988 and 1989) or other site conditions caused low maximum grain yield (≤6.2 Mg ha^{-1}). Forty site-years from long-term trials on a sandy clay loam soil in South Dakota (Pikul et al., 2005) and on a clay loam soil in Ontario (Drury and Tan, 1995) were excluded because corn grain yields declined over time, in contrast to well documented increases in corn yield under other conditions (on clay loam and loam soils in Iowa [Mallarino and Ortiz-Torres, 2006] and on silt loam soil in Wisconsin [Stanger and Lauer, 2008]). Therefore, the total number of site-years considered for analysis was 353.

Analytical Approach

Identification of responsive site-years. The responsiveness of corn grain yield to fertilizer N in each site-year was based on the statistical analysis results ($P \leq 0.05$) reported for each study. When site-years for individual studies were analyzed by authors at $P \leq 0.10$ and had been considered responsive to fertilizer N, raw data or statistical analysis results were obtained and the responsiveness to N was re-evaluated at $P \leq 0.05$ for each site-year. Data from Stanger and Lauer (2008) were analyzed for each rotation and year at $P \leq 0.05$. The responsiveness of corn grain yield to fertilizer N was presented by site-year in all other studies included in this analysis. Multiple logistic regression was used to separate site-years with a response of grain yield to fertilizer N from site-years without a response. The models were developed using the LOGISTIC procedure of SAS (SAS Institute, 2006) with the stepwise selection method, using $P \leq 0.10$ for entry of variables into models and $P \geq 0.15$ for exit of variables from models (Kutner et al., 2004).

The significance of regression predictors, percent of concordant/discordant pairs, Somers' *D* statistic, and the *c* statistic were used to evaluate and select models with the highest accuracy (Allison, 2012). Concordance occurred when responsive trials were classified as responsive and discordance occurred when nonresponsive trials had a higher probability of being classified as responsive. In order to classify site-years as responsive or nonresponsive to fertilizer N, probability critical levels were selected for each logistic model by selecting the critical levels between 0.02 to 0.98 that produced the most similar and maximum sensitivity (percentage of responsive site-years correctly classified) and specificity (percentage of nonresponsive site-years correctly classified) (Allison, 2012). The FREQ procedure of SAS (SAS Institute, 2006) was used to obtain frequency tables of model sensitivity and specificity. Pearson residuals, deviance deletion difference, and leverage diagnostics were visually examined for extreme outliers (Bedrick and Hill, 1990), which led to exclusion of 13 site-years with spring alfalfa termination on medium-textured soils from Wolkowski (1992) and Fox and Piekielek (2002).

Logistic regression uses odds ratios instead of probability to predict the odds of an event (fertilizer N response) (Allison, 2012). Multiple logistic regression models are based on the equation $y_{\mathrm{i}} = \{1 + \exp[-(\ _{0} + \ _{\mathrm{i}} x_{\mathrm{i}})]\}^{-1}$, where y_{i} is the predicted odds ratio for response of grain yield to fertilizer N, $\ _{0}$ is the intercept, $\ _{\mathrm{i}}$ is the linear independent predictor(s), and x_{i} is the independent variable(s). The initial set of potential linear predictors were surface soil texture (coarse, medium, fine), surface soil organic matter percentage, presidedress soil nitrate test concentration for first-year corn, alfalfa stand age (year) and stand condition at the time of termination (poor [≤16 alfalfa plants m^{-2} or ≤33% alfalfa in the stand], fair [17-37 alfalfa plants m^{-2} or 34-66% alfalfa in the stand], or good [≥38 plants m^{-2} or ≥67% alfalfa in the stand]), time when alfalfa stand was terminated with herbicide or tillage (fall or spring), termination method (moldboard/chisel plow tillage or no-tillage), total or monthly precipitation in millimeters, and monthly DD_0 in October, November, and December of the last alfalfa production year and March, April, and May of the subsequent year. Climate data from January and February were not used because low soil biological activity typically prevails during winter months in northern climates. Weather conditions through March were used to develop predictions prior to the time of typical spring preplant fertilizer N application in the midwestern and northeastern United States (our first priority), while weather conditions through May were used to develop predictions prior to the time of typical sidedress fertilizer N application in this region (our second priority). Two separate models were developed using either total or individual monthly precipitation, but only the most accurate model was used. Total precipitation was the sum of October, November, December, and March precipitation for preplant predictions and the sum of October, November, December, March, April, and May precipitation for sidedress predictions. Potential two-way interactions included categorical × continuous predictors, categorical × categorical predictors, and select continuous × continuous predictors (precipitation × DD_0 and alfalfa stand age × precipitation or DD_0). The quadratic forms of all continuous predictors except DD_0 were included as potential predictors.

Surface soil organic matter percentage, alfalfa stand condition, alfalfa termination method, and presidedress soil nitrate test concentration for first-year corn were considered individually and collectively in model predictions, but these variables were removed as potential predictors because they did not significantly account for variability in N responsiveness, and because retaining them greatly limited the dataset due to missing observations. To avoid pseudo-replication, site-years with identical values for all of the remaining predictors were condensed into single observations. Additional condensing occurred when insufficient data were available for a given potential predictor (e.g., when alfalfa variety or alfalfa cutting management varied within a study [Hesterman et al., 1986; Kelling et al., 1992]) or when multiple site-years had the same alfalfa stand age and identical weather conditions (i.e., site-years from Morris et al. [1993] and Stanger and Lauer [2008]). Site-years with identical predictors other than alfalfa termination timing were condensed only if timing was not a significant predictor within a given model.

After condensing, the total number of site-years used in the final analyses was 259. The odds of first-year corn grain yield responding to fertilizer N was dependent on soil texture; therefore, separate logistic regression models were developed by soil texture to improve accuracy, account for differences in sample size among texture groups, and simplify models. Data with medium-textured soil were analyzed separately by termination timing because the accuracy of predicting responsive and nonresponsive site-years increased from 73% across termination timings to 81% for fall termination and 93% for spring termination. In addition, medium-textured soil with fall termination was analyzed separately by alfalfa stand age category (1-yr-old, 2-yr-old, and ≥3-yr-old alfalfa) to improve accuracy. A logistic model could not be developed to predict whether corn grain yield would respond to fertilizer N on coarse-textured soils, because yield did not respond to fertilizer N in only 1 of 11 site-years.

To assess the applicability of the predictive multiple logistic regression models developed for fine- and medium-textured soils, we applied the models to 30-yr (1983-2012) weather data (http://climate.usurf.usu.edu) for one county in each of the seven states in the dataset of responsive site-years. Within each state, we selected the county with the largest number of hectares of harvested alfalfa in 2011 (USDA-NASS, 2013). Selected counties were Clayton County, IA, Jo Daviess County, IL, Ottertail County, MN, Nodaway County, MO, Wayne County, OH, Lancaster County, PA, and Shawano County, WI. For brevity and clarity, we often refer to a particular state name, rather than to the county name, recognizing that results of analyses for the conditions at one location do not represent the results for an entire state.

Estimation of EONR in responsive site-years. Regression equations were developed in the NLIN procedure of SAS (SAS Institute, 2006) to describe the response of corn grain yield to fertilizer N rate when ≥3 fertilizer N rates were used. Linear, linear-plateau, quadratic, and quadratic-plateau regression models were evaluated, and the selected model had the smallest residuals and resulted in normally and randomly distributed residuals of predicted values (Kutner et al., 2004). The EONR was calculated for responsive site-years by setting the first derivative of the regression models to the range of PRs over the last 25 yr (4.48 to 11.2 in 0.56 increments as US\$ kg^{-1} N/US\$ kg^{-1} grain [0.08 to 0.20 in 0.01 increments; US\$ lb^{-1} N/US\$ bu^{-1} grain] USDA-ERS, 2013a, 2013b). Price ratios in metric units may be divided by 56 to convert to English units**.**

To achieve higher accuracy than with more general models, as in the case with multiple logistic regression, we developed separate multiple linear regression models where possible using the REG procedure of SAS (SAS Institute, 2006) for fine-textured soil, medium-textured soil with spring termination, medium-textured soil with fall alfalfa termination and with 1-yr-old alfalfa stands, and coarse-textured soils. Models could not be developed for fall termination of 2-yr-old alfalfa seeded with or without oat (*Avena sativa* L.) or with ≥3-yr-old alfalfa on medium-textured soils, because of insufficient data or lack of fit. Dependent variables were EONR or the lowest or highest N rate for net return to N within \$2.50 ha^{-1} of the maximum at PRs ranging from 4.48 to 11.2 in 0.56 increments for responsive site-years only. The potential predictors were the same variables considered for corresponding multiple logistic regression models. The noncondensed data were analyzed first, and then data were re-condensed when potential predictors were nonsignificant. When condensing occurred, grain yield was averaged across levels of nonsignificant independent variables within a study and then a single EONR was calculated.

Multiple linear regression models were developed using stepwise selection with an entry level of $P \leq 0.10$ and an exit level of $P \geq 0.15$. When selected models were not identical for all PRs within a given soil texture, alfalfa termination timing, or alfalfa stand age category, the set of independent variables that fit the majority of PRs was fit to each PR from 4.48 to 11.2 in 0.56 increments. Then, within these same categories, linear and quadratic regression models were developed using the REG procedure of SAS (SAS

Institute, 2006) to relate independent variable coefficients across PRs separately for three dependent variables (the EONR and the lowest and highest N rates for net return to N within \$2.50 ha^{-1} of the maximum). To check for multicollinearity among predictors, the CORR and REG procedures of SAS (SAS Institute, 2006) were used to examine correlation, tolerance, and variance inflation factors for each coefficient selected by multiple regression models (Allison, 2012). The multiple linear regression model for the EONR at a PR of 5.6 (0.10 in English units) was applied to same historic 30-yr (1983-2012) weather data as the seven counties listed above to test the applicability of the logistic regression models; however, EONR estimates were made only for site-years predicted to be responsive by logistic regression models.

RESULTS AND DISCUSSION

Before the dataset was condensed for nonsignificant predictors, we tested the effects of alfalfa termination method and alfalfa stand condition on the frequency of fertilizer N response in first-year corn following alfalfa with 340 site-years (Supplemental Table S4.1; Supplement S4.2). Tillage (moldboard plow, chisel plow, or disk-chisel plow) was used to terminate alfalfa in 84% of the site-years and the remaining 16% used no-tillage. Alfalfa termination method was not a significant predictor of grain yield response to fertilizer N in first-year corn, either as a main effect or interacting with other variables ($P > 0.15$). This supports the results of many studies which concluded that alfalfa termination method had no effect on fertilizer N response of first-year corn (Table

1 in Yost et al., 2013a). Of the reports that included a description of alfalfa stand condition at termination, there were only 11 site-years with poor alfalfa stands, 41 site-years with fair stands, and 80 site-years with good alfalfa stands. This skewed distribution of alfalfa stand condition indicates that more data are needed on fertilizer N response in first-year corn following poor and fair alfalfa stands. Although 132 site-years included alfalfa stand density or percent alfalfa in the stand, responsiveness to fertilizer N was not related to these predictors alone or in combination with alfalfa stand age, termination timing or method, or weather predictors ($P > 0.10$). These results indicate that neither alfalfa stand density nor percent alfalfa in the stand are reliable predictors of whether first-year corn will respond to fertilizer N, contrary to most guidelines from land grant universities in the United States (Table 1 in Yost et al., 2014b).

The condensed and final dataset included 259 site-years (Table 4.1) with the majority of site-years from the upper midwestern United States (13% from Iowa, 19% from Minnesota, 60% from Wisconsin), but data from other states and the Province of Ontario were included. Our analysis of these site-years indicated that the response of grain yield to fertilizer N in first-year corn following alfalfa was dependent on soil texture and, within medium-textured soils, on alfalfa termination timing. The frequency of response to fertilizer N of grain yield in first-year corn following alfalfa was highest (96%) for coarse-textured soils, lowest (18%) for medium-textured soils, and intermediate (53%) for fine-textured soils. These results are similar to those of Tremblay et al. (2012), who found that fertilizer N response in 51 site-years of continuous corn was dependent on soil texture and that the magnitude of response to fertilizer N on fine-textured soils (clay, silty clay, silty clay loam, and clay loam; more broadly defined than our category) was 1.1-fold greater than that on medium-textured soils (loam, silt loam, sandy loam, sandy clay loam, and loamy fine sand soils). Other research has also shown that soil texture and climatic conditions affect the response of corn grain yield to fertilizer N (e.g., Chivenge et al., 2011; Shahandeh et al., 2011), and have declared the need for site-specific fertilizer N recommendations.

Fine-Textured Soils

Two predictors were significant in the logistic regression model developed for the 19 site-years with fine-textured soils (Table 4.2). For this model, the odds that grain yield of first-year corn after alfalfa responded to fertilizer N decreased with increasing alfalfa stand age and increased with increasing DD_0 in March. This model was 90 and 89% accurate at identifying responsive and nonresponsive site-years, respectively, in this data set (Fig. 4.1). Therefore, with high accuracy, both responsive and nonresponsive sites of first-year corn could be identified at the end of March, which would allow growers in northern states adequate time to apply preplant fertilizer N where necessary.

To examine the predicted frequency of fertilizer N response of first-year corn on fine-textured soils, the logistic regression equation for fine-textured soils was applied to 30 yr of weather data for one county in each of seven states (Fig. 4.2). The range in weather conditions from the site-years used to create the logistic model (Table 4.4) applied to 73% of the 30 yr in Minnesota and ≥93% of the years in the remaining six states. As alfalfa stand age increased from 1 to 5 yr, the predicted frequency of fertilizer N response in first-year corn decreased by 5 percentage points across Pennsylvania and Missouri, which had high average March air temperatures (175 DD_0) (Fig. 4.2). The predicted frequency of fertilizer N response also decreased by 20 percentage points across Iowa and Ohio with intermediate average DD_0 in March (126 DD_0), and by 43 percentage points across Illinois, Minnesota, and Wisconsin, which were characterized by low average DD_0 in March (74 DD_0). Therefore, alfalfa stand age had minor effects on the frequency of N response in first-year corn when DD_0 in March were high. Across alfalfa stand ages, the two states with the lowest March DD_0 (Minnesota and Wisconsin) had the lowest frequency of predicted fertilizer N response (20-40% of the years between 1983 and 2012), in contrast to the other five states, in which fertilizer N would be required for corn in 77 to 100% of the years on fine-textured soils. Low March air temperatures likely delay soil warming and decrease N mineralization, resulting in smaller N losses in the early spring when young corn plants cannot yet take up much N from the soil (Randall and Vetsch, 2005).

The median EONR at a PR of 5.6 was 101 kg N ha^{-1} for the nine responsive site-years of first-year corn following alfalfa on fine-textured soils, but ranged from 24 to 168 kg N ha^{-1} (Fig. 4.3). Seventy two to 85% of the variation in the EONR at PRs of 4.48 to 11.2 was explained by alfalfa stand age and weather conditions prior to corn planting. The coefficients for the variables used to predict these N rates for fine-textured soils can be calculated using the coefficients in columns 3 to 9 in Table 4.3 for any PR between

4.48 and 11.2. One case, the EONR at a PR of 5.6, is presented here as an example. These numbers are from the top section (fine-textured soils with fall or spring termination) of the $_0$ and $_1$ columns under EONR (Table 4.3).

1. Calculate the intercept at a PR of 5.6:

   y = 154 - (11.5*PR) = 154 - (11.7*5.6) = 88.5

2. Calculate the coefficient for the predictor variable Alfalfa age × Pnov:

   y = -0.379 + (0.0304*PR) = -0.379 + (0.0304*5.6) = -0.209

3. Calculate the coefficient for predictor variable DD_0 oct × Pdec:

   y = 0.000773 + (0.000202*PR) = 0.000773 + (0.000202*5.6) = 0.00190

4. The equation for the EONR at a PR of 5.6:

   EONR (PR5.6) = 88.5 - (0.209*Alfalfa age × Pnov) + (0.00190*DD_0 oct × Pdec)

Thus, based on the regression equations in Table 4.3, the predicted coefficients for the EONR at a PR of 5.6 indicate that the EONR decreased by 0.209 kg N ha^{-1} with each unit increase in the product of alfalfa stand age and November DD_0, and increased by 0.0019 kg N ha^{-1} with each unit increase in the product of October DD_0 and December precipitation. The estimated EONR for a fine-textured soil at a PR of 5.6 is 101 kg N ha^{-1} when this equation is applied to the data from Lory et al. (1995) at Waseca in 1991 (3-yr-old alfalfa; 270 DD_0 in October; 13mm precipitation in November; 41mm precipitation in December; see line 183 in Supplemental Table S4.1).

The multiple linear regression model developed to estimate EONR for these site-years was applied to the same historic weather data as the seven states used for logistic models (Fig. 4.4). The EONR for 4- and 5-yr-old alfalfa stands in Minnesota and Wisconsin had small or no variation because few years were predicted to be responsive by logistic regression (Fig. 4.2). The highest EONR for each stand age in Ohio were caused by high November precipitation and high values for the interaction between October DD_0 and December precipitation (Fig. 4.4). One-third of the years from Pennsylvania had weather conditions outside of the range of the independent weather variables used to develop the EONR model; these years were outside the range because precipitation totals were high in December. Therefore, this model may require additional data to represent weather conditions in the northeastern United States.

The median EONR at a PR of 5.6 across the seven states was 80 to 96 kg N ha^{-1} and decreased by 46 to 60 kg N ha^{-1} as alfalfa stand age increased from 1 to 5 yr on fine-textured soils (Fig. 4.4). However, due to varying weather conditions among years and alfalfa stand differences, the range of EONR for a given alfalfa stand age and state was as narrow as 27 kg N ha^{-1} (5-yr old stands in Minnesota) or as wide as 150 kg N ha^{-1} (1-yr-old stands in Pennsylvania). These results indicate that the average or median EONR often would be inaccurate and that site-specific recommendations are needed. Although the EONR equation was developed using only N-responsive site-years, predicted EONR occasionally was negative and we show them here as zero. These negative estimates of EONR may be due to use of weather conditions outside the range of those in the database, but they also may identify site-years where grain yield response to fertilizer N was significant but not economical.

Medium-Textured Soils with Fall Alfalfa Termination

The multiple logistic regression model for medium-textured soils with fall alfalfa termination contained the highest number of site-years (181) because it included long-term trials from Wisconsin (Stanger and Lauer, 2008) and Iowa (Mallarino and Ortiz-Torres, 2006). As was the case for fine-textured soils, alfalfa stand age was a critical factor in determining the frequency of fertilizer N response in first-year corn. Grain yield of first-year corn responded to fertilizer N 56% of the time (9 of 16 site-years) when following 1-yr-old alfalfa stands, 27% of the time (21 of 79 site-years) when following 2-yr-old stands, and only 5% of the time (4 of 86 site-years) when following ≥3-yr-old stands. When data from all alfalfa stand ages were analyzed together, the frequency of fertilizer N response was severely over-predicted for 1- and 2-yr-old stands; model predictions were that corn grain yield would increase with fertilizer N in 100% and 49% of the cases for first-year corn following 1- and 2-yr-old alfalfa stands, respectively. To improve accuracy, we developed predictive models for different alfalfa stand ages.

We could not identify a set of variables that separated responsive and nonresponsive site-years for fall terminated 1-yr-old alfalfa stands on medium-textured soils. Although 1-yr-old stands provided the entire N requirement for first-year corn 44% of the time in this dataset, more research is needed to separate responsive and nonresponsive site-years. The remaining 56% of the time (9 of 16 site-years) when grain yield of first-year corn responded to fertilizer N, the median EONR at a PR of 5.6 was 142 kg N ha^{-1} and 68 to 89% of the variation in the EONR at PRs ranging from 4.48 to 11.2 could be explained by weather conditions prior to the time of sidedressing (Table 4.3; Fig. 4.3). The EONR at a PR of 5.6 increased by 0.02 kg N ha^{-1} for each unit increase in the product of December DD_0 and May precipitation, and decreased by 0.02 kg N ha^{-1} with each unit increase in the product of March DD_0 and April precipitation. Warm air temperature in December and higher precipitation in May likely contribute to greater N mineralization and reduced EONR for first-year corn under conditions that are less susceptible to N loss, whereas warm air temperature in March and more precipitation in April may increase early-season N mineralization and N loss through leaching and denitrification, thereby increasing the EONR.

The data for 2-yr-old stands represented two methods of alfalfa establishment and first-year harvest management. Alfalfa was seeded with oat and not harvested during the establishment year at the long-term trials in Iowa (Mallarino and Ortiz-Torres, 2006) and in one of the long-term rotations in Wisconsin (Stanger and Lauer, 2008). In contrast, alfalfa was direct-seeded and harvested during the establishment year in additional rotations at Wisconsin and at two Minnesota site-years (Yost et al., 2013b). First-year corn responded to fertilizer N 35% of the time (19 of 54 site-years) when following alfalfa seeded with oat and harvested only in the second year, but only 8% of the time (2 of 25 site-years) when following direct-seeded alfalfa harvested for 2 yr. Therefore, we used establishment method as a new potential predictor for 2-yr-old stands. For first-year corn following 2-yr-old alfalfa stands, the odds of a response of grain yield to fertilizer N increased with higher DD_0 during October when alfalfa was seeded with oat compared to corn following 2-yr-old direct-seeded alfalfa (Table 4.2). This model correctly identified 76 and 81% of the site-years as either nonresponsive or responsive to fertilizer N, respectively (Fig. 4.1).

The range of data used to create the logistic regression model (Table 4.4) applied to 72% of the historic 30-yr weather for Minnesota and Wisconsin and ≥90% of the years in the remaining five states. When this logistic model was applied to historic weather data, the predicted frequency of a fertilizer N response in first-year corn was lowest in Minnesota and Wisconsin (Fig. 4.2). During the past 30 yr in these two states, October averaged 250 DD_0, compared to 344 DD_0 for the five other states. For young alfalfa stands, cool air temperature in October may postpone alfalfa residue decomposition (and N loss) in the fall and improve N supply to first-year corn during the subsequent growing season. Predictions based on the logistic model indicate that grain yield of first-year corn following 2-yr-old alfalfa seeded with oat would have responded to fertilizer N much more frequently than following 2-yr-old direct-seeded alfalfa. This is likely related to reduced alfalfa yield and total plant N yield during the establishment year when alfalfa is seeded with an oat companion crop than when alfalfa is direct-seeded (Sheaffer et al., 1988; Lanini et al., 1991). In contrast, and across all states, a response to fertilizer N would be rare in corn following fall-terminated 2-yr-old, direct-seeded alfalfa on medium-textured soils.

On medium-textured soils with fall termination of 2-yr-old alfalfa stands seeded with oat, the median EONR at a PR of 5.6 (151 kg N ha^{-1}) was similar to the median for first-year corn following 1-yr-old alfalfa stands (142 kg N ha^{-1}). The EONR for corn following 2-yr-old stands seeded with oat ranged from 56 to 269 kg N ha^{-1}. Less than 25% of the variation in the EONR at PRs ranging from 4.48 to 11.2 was explained either before corn planting or sidedress time. This poor accuracy of EONR prediction is likely related to the fact that all of the responsive trials were from only two locations over multiple years (Mallarino and Ortiz-Torres, 2006; Stanger and Lauer, 2008); for these reasons, the predictions are neither presented nor applied to 30-yr weather data. Additional research or predictors are needed to estimate EONR and profitable fertilizer N rates for first-year corn following fall-terminated 2-yr-old alfalfa seeded with oat on medium-textured soils. We did not attempt to predict the EONR for first-year corn following 2-yr-old direct-seeded alfalfa because only 2 of 25 site-years responded to N; the EONRs at a PR of 5.6 at these two locations were 56 and 167 kg N ha^{-1}.

Similarly, the frequency of a fertilizer N response was low for first-year corn following 3- to 6-yr-old alfalfa stands terminated in the fall; only 4 of 86 site-years responded to fertilizer N. With logistic regression, two of four responsive site-years were correctly predicted as responsive and 79 of 82 nonresponsive site-years were correctly predicted as nonresponsive to N prior to the time of sidedressing (Table 4.2; Fig. 4.1). The only apparent difference in the responsive and nonresponsive site-years was May precipitation, which averaged 179 mm (127-280 mm) across the four responsive site-years compared to 101 mm (20-210 mm) across the 82 nonresponsive site-years. The odds of a fertilizer N response increased as May precipitation increased. The range in weather conditions for site-years used to build this logistic model (Table 4.4) was applicable to ≥97% of the 30-yr weather data from all seven states. First-year corn was predicted to respond to fertilizer N in only three states (Iowa, Missouri, and Pennsylvania), and only 1 of 30 yr was predicted responsive in each state (Fig. 4.2).

We did not attempt to predict the EONR for first-year corn following 3- to 6-yr-old alfalfa stands because only four site-years responded to N. These four site-years had 3-, 4-, and 5-yr-old stands (two from Yost et al. [2013b]; one from Morris et al. [1993], and one from Stanger and Lauer [2008]), with estimated EONRs of 122, 91, 0, and 173 kg N ha^{-1} at a PR of 5.6, respectively. The EONR for the site-year from Morris et al. (1993) was above zero only for a PR of 4.48 and 5.04, indicating that the grain yield response to fertilizer N was weak. Although additional responsive site-years would be needed to develop EONR predictions for first-year corn following 3- to 6-yr-old stands, 82 of 86 site-years were nonresponsive, which is strong evidence that first-year corn following 3- to 6-yr-old alfalfa stands seldom responds to fertilizer N. On medium-textured soils, growers may choose to terminate alfalfa in the fall in order to maximize the N credit from alfalfa to first-year corn. If they do so, no more than a low starter rate of fertilizer N should be applied to first-year corn unless spring weather conditions are excessively wet.

Medium-Textured Soils with Spring Alfalfa Termination

There were 48 site-years of first-year corn following alfalfa that were terminated in the spring on medium-textured soils. Only 1 of 48 site-years was first-year corn following spring-terminated alfalfa grown for <3 yr, yet eight site-years (17%) responded to fertilizer N. These data indicate that first-year corn following well-established alfalfa on medium-textured soils is more responsive with spring than with fall alfalfa termination, contrary to earlier conclusions (Harris and Hesterman, 1990; Kelling et al., 1992; Yost et al., 2012). We speculate that relative to fall termination, spring termination may delay decomposition of alfalfa roots and crowns and thereby reduce the total amount of N available to first-year corn. A higher proportion (77%) of these 48 site-years with spring termination had alfalfa stand condition measurements (stand density or percent alfalfa in stand) than on other soil textures or on medium-textured soils with fall termination, but neither stand condition alone nor interactions of stand condition with stand age or weather adequately separated responsive and nonresponsive site-years, indicating that alfalfa stand condition is not a good predictor of first-year corn N response.

The logistic prediction model developed for medium-textured soils with spring alfalfa termination had four statistically significant predictors (Table 4.2). For this model, the odds that grain yield of first-year corn after alfalfa will respond to fertilizer N increased with an increase in the product of October DD_0 and November precipitation, and with an increase in the product of December DD_0 and October precipitation. In addition, the predicted odds decreased with an increase in the product of alfalfa stand age and December precipitation, and with an increase in the product of March DD_0 and March precipitation. This model correctly predicted 98% (39 of 40) of the nonresponsive site-years and 88% (7 of 8) of the responsive site-years before corn planting (Fig. 4.1).

The weather conditions for site-years used to develop the logistic regression model (Table 4.4) for medium-textured soils with spring termination were applicable to only 23% of the historic 30-yr weather data from Pennsylvania, 47% of the years from Minnesota and Ohio, and ≥63% of the years from the remaining three states, indicating a more limited range of application than other logistic models. When this logistic model was applied to historic data from seven states, the number of years with response to fertilizer N decreased from 62 to 26% as alfalfa stand age increased from 2 to 5 yr across all states except Missouri (Fig. 4.2). In Missouri, response to N decreased only to 40% as stand age increased. For 3-yr-old alfalfa stands, this model predicts that first-year corn would have responded to fertilizer N 37% of the time in Minnesota, 49% of the time across Iowa, Illinois, Missouri, and Wisconsin, and 73% of the time in Pennsylvania. However, these estimates may be less accurate than in other situations discussed in this paper, because of the limited range of weather conditions included in the dataset.

The EONR at a PR of 5.6 for eight site-years of first-year corn following alfalfa terminated in the spring ranged from 48 to 176 kg N ha^{-1}. Prior to corn planting, 83 to 90% of the variation in EONR at PRs ranging from 4.48 to 11.2 could be explained with weather conditions (Table 4.3; Fig. 4.3). The predicted EONR at a PR of 5.6 increased by

0.8 kg N ha^{-1} with each unit increase in November DD_0, and decreased by 0.002 kg N ha^{-1} with each unit increase in the product of November precipitation and March DD_0 and by 2.9 kg N ha^{-1} with each 1-mm increase in December precipitation. Alfalfa stand age was a significant predictor for separating responsive and nonresponsive site-years of first-year corn following spring-terminated alfalfa on medium-textured soils (Table 4.2), but was not significant for EONR prediction because the model included no responsive site-years with 1- or 2-yr-old alfalfa. Thus, more data are needed to predict the EONR of first-year corn following young (≤2-yr-old stands) alfalfa terminated in the spring, but EONR predictions for first-year corn following 3- to 5-yr-old alfalfa appear accurate (Fig. 4.3).

The likelihood of a fertilizer N response in first-year corn following spring-terminated alfalfa on medium-textured soils was relatively low compared to fine-textured soils; only 13 to 43% of the years from the 30-yr data were predicted as responsive to fertilizer N by logistic regression compared to 50 to 100% of the years for fine-textured soils (Table 4.2; Fig. 4.2). When the EONR model was applied to the 30-yr weather data, the median EONR at a PR of 5.6 for first-year corn following 3- to 5-yr old alfalfa was 65 kg N ha^{-1} across Ohio and Pennsylvania, 117 kg N ha^{-1} across Illinois, Minnesota, and Wisconsin, and 149 kg N ha^{-1} across Iowa and Missouri (Fig. 4.5). However, the range in EONR among responsive site-years was as wide as 139 kg N ha^{-1} in Wisconsin to 221 kg N ha^{-1} in Pennsylvania, which indicates the need for site-specific fertilizer N recommendations. The highest EONR prediction for Missouri (313 kg N ha^{-1}) was caused by low December precipitation and high November DD_0 in 2002, respectively, and likely was an outlier. All 13 years from Pennsylvania that were predicted to be responsive to fertilizer N, had weather conditions that were outside the range of independent weather variables used in the EONR model, which indicates the need for more responsive site-years for northeastern United States weather conditions.

Coarse-Textured Soils

Grain yield of first-year corn following alfalfa responded to fertilizer N in 10 of 11 site-years on coarse-textured soils, which prevented development of a logistic regression model to identify which sites would or would not respond. The high frequency of response to N on coarse-textured soils was likely due to high potential for leaching of mineralized N from alfalfa residue and soil organic matter. In the 10 site-years where corn grain yield responded to fertilizer N, the EONR at a PR of 5.6 ranged from 96 to 235 kg N ha^{-1} and 77 to 80% of the variation in the EONR at PRs ranging from 4.48 to 11.2 could be explained by alfalfa termination time and weather conditions prior to corn planting (Table 4.3; Fig. 4.3). The EONR at a PR of 5.6 for first-year corn following alfalfa increased by 3.5 kg N ha^{-1} with each unit increase in December DD_0 when alfalfa was terminated in the spring. The EONR also increased by 0.0020 kg N ha^{-1} with each 1-mm increase in total precipitation prior to planting (October-December, and March). The prediction of EONR for first-year corn following alfalfa on coarse-textured soils appears robust, but should be validated with independent site-years. The wide range in actual EONR implies that an N credit should be applied for previous alfalfa under some conditions. Additional research is needed on coarse-textured soils to identify conditions that reduce the likelihood of corn response to additional N. Such research should be conducted over a range of alfalfa stand ages and alfalfa termination timings.

CONCLUSIONS

Our conclusions are that growers should not apply more than a small amount of starter fertilizer to first-year corn grown after 2-yr-old direct-seeded alfalfa or ≥3-yr-old alfalfa terminated in the fall on medium-textured soils. The likelihood of fertilizer N response are higher when first-year corn follows fall-terminated 1-yr-old alfalfa or 2-yr-old alfalfa seeded with oat on medium textured soils (46% of the time), alfalfa terminated in the spring on medium-textured soils (17% of the time), and when corn is grown on coarse- (91% of the time) or fine-textured soils (54% of the time). For medium- and fine-textured soils, four simple and readily available predictors (soil texture, alfalfa stand age, alfalfa termination time, and weather conditions prior to planting or sidedress time) appear to predict with high accuracy when first-year corn will respond to fertilizer N, and to estimate the EONR and the lowest or highest N rate with net return to N within \$2.50 ha^{-1} of the maximum at various PRs. However, prediction of which sites would respond to N was not possible for first-year corn following 1-yr-old alfalfa grown on medium-textured soils or for corn following alfalfa on coarse-textured soils.

In this analysis, we combined fixed and variable conditions at the site level that appear to both identify whether corn will respond to fertilizer N after alfalfa and to estimate the EONR. This site-specific approach should help reduce risk of under- or over-application of fertilizer N, improve net returns to growers, and reduce the environmental harm of excessive N loss. These models appear to be robust, but should be independently validated for their predictive capacity. Intuitively, this site-specific approach may help identify fertilizer N responsiveness and requirements for crops in other rotations.

Table 4.1. Source of data for 259 site-years of research on the response of grain yield to fertilizer N in first-year corn following alfalfa, including years and location in which the field research was conducted, soil texture, alfalfa stand age (including establishment year) at termination (term.), alfalfa termination timing and method, number of nonresponsive and responsive site-years, and number of site-years with the indicated alfalfa stand condition or missing data at termination.

Publication	State	Year(s)	Soil texture(s)†	Stand age(s)	Term. time(s)‡	Term. type(s)§	Fertilizer N response (no/yes)	Stand condition (poor/fair/ good/missing)¶
				yr			-------- no. of site-years -------	
Anderson et al., 1997	IA	1994	f	6	f	m	0/1	0/0/0/1
Mallarino and Ortiz-Torres, 2006	IA	1982-04	m	2	f	m	7/14	0/0/0/21
Morris et al., 1993	IA	1987-90	f,m	3-6	f,s	c,m	10/3	0/2/6/5
Morrison et al., 2010	IL	2007-09	f,m	1,3,4	f,s	c,m,n	3/2	0/0/5/0
Mulvaney et al., 2006	IL	2003	c	-#	f	m	0/1	0/0/0/1
Hesterman et al., 1986	MN	1983	c,m,f	1	f	m	2/2	0/0/0/4
Lory et al., 1995	MN	1990-91	f,m	3	f,s	c,m	2/2	1/2/1/0
Moncrief et al., 1988	MN	1987	m	3	s	c,m,n	0/1	0/1/0/0
Moncrief et al., 1991	MN	1990	m	3	s	c,m,n	0/1	0/0/1/0
Randall and Vetsch, 1994	MN	1994	m	3	f	c	1/0	0/0/0/1
Schmitt and Randall, 1994	MN	1991-92	f,m	3	f,s	c,m	4/1	0/0/0/5
Yost et al., 2012	MN	2009-10	c,m,f	3-7	f,s	c,m	18/1	0/0/19/0
Yost et al., 2013a	MN	2011	f,m	2-4,6-7	f,s	n	7/0	0/0/7/0
Yost et al., 2013b	MN	2011	f,m	2-5	f	c,m	6/2	0/2/6/0
Scharf and Lory, 1997††	MO	1997	f	3	-#	m	0/1	0/0/0/1
Scharf, 2001	MO	1996	m	5	s	c	0/1	0/0/0/1
Katsvairo et al., 2003	NY	1992	f	3	f	m	1/0	0/0/1/0
Triplett et al., 1979	OH	1974,76	m	2,3	s	m,n	1/1	0/2/0/0

Aflakpui et al., 1993	ON	1988-89	m	4,5	f	m,n	2/0	0/0/2/0
Fox and Piekielek, 1988	PA	1984	m	3	s	m	1/0	0/0/1/0
Fox and Piekielek, 1993	PA	1990	m	3	s	m	0/1	0/0/1/0
Levin et al., 1987	PA	1983	m	4,5	s	m,n	1/1	1/1/0/0
Sripada et al., 2008	PA	2005-06	m	5,6	f,s	m,n	2/0	0/0/0/2
Andraski and Bundy, 2002	WI	1989,96	m	4	f	m	2/0	1/0/1/0
Bundy and Andraski, 1993	WI	1988-91	m	3-6	f,s	c,m	22/0	0/11/8/3
Kelling et al., 1992	WI	1989-91	c,m	2-3	f,s	m	12/6	0/0/0/18‡‡
Kelling et al., 2003	WI	2002	c,m	3,4	s	m	0/3	0/0/3/0
Stanger and Lauer, 2008	WI	1970-04	m	1-4	f	m,n	93/17	0/0/0/110

† c, coarse-textured soil (loamy sand); f, fine-textured soil (clay loam, silty clay loam); m, medium-textured soil (loam, sandy loam, silt loam, and fine sandy loam).

‡ f, fall termination of alfalfa with herbicide or tillage; s, spring termination with herbicide or tillage.

§ c, chisel plow or disk-chisel tillage; m, moldboard plow tillage; n, no-tillage.

¶ poor (≤16 alfalfa plants m^{-2} or ≤33% alfalfa in the stand), fair (17-37 alfalfa plants m^{-2} or 34-66% alfalfa in the stand), or good (≥38 alfalfa plants m^{-2} or ≥67% alfalfa in the stand).

Data not available.

†† P. Scharf and J.A. Lory, unpublished data, 1997.

‡‡ Alfalfa stand density was a treatment in this study (Supplemental Table S4.1), but data were analyzed across stand densities for our analysis.

Table 4.2. Parameter estimates with associated probabilities of Chi-squared tests, odds ratios with 95% Wald confidence intervals (CI), and measures of association for multiple logistic regression models used to predict the response of grain yield to fertilizer N in first-year corn following alfalfa on site-years with fine-textured and medium-textured soil with fall and spring alfalfa termination (term.).

Soil texture model	Parameter†	Parameter estimate	Odds ratio	95% CI	Measures of association‡: Concordant (discordant) pairs	Measures of association‡: Somers' D
					%	
Fine – fall or spring term.	Intercept	-3.18	-	-	92.2 (7.8)	0.84
	Alfalfa age	-1.20*	0.300	0.080-1.133		
	DD_0 mar	0.106§	1.112	0.975-1.269		
Medium – fall term.	Intercept	-2.71**	-	-	75.7 (20.5)	0.55
2-yr alfalfa	With oat × DD_0 oct	0.00680**	1.007	1.002-1.012		
Medium – fall term.	Intercept	-7.14**	-	-	86.3 (13.1)	0.73
≥3-yr alfalfa	Pmay	0.0306**	1.031	1.007-1.056		
Medium –	Intercept	0.147	-	-	97.2 (2.8)	0.94
spring term.	Alfalfa age × Pdec	-0.0794*	0.924	0.864-0.987		
	DD_0 oct × Pnov	0.000445*	1.000	1.000-1.001		
	Poct × DD_0 dec	0.00391*	1.004	1.001-1.007		
	Pmar × DD_0 mar	-0.000990§	0.999	0.998-1.000		

* and **, significant at $P \leq 0.05$ and 0.01, respectively.

† Alfalfa age in years (including establishment year); P, total monthly precipitation (millimeters); DD_0, total monthly degree-days (degrees Celsius) based on daily mean air temperature >0°C. The three-letter

abbreviation behind P and DD_0 is the first three letters of the month. ‘With oat’ refers to alfalfa seeded with oat and not harvested during the establishment year compared to alfalfa that was direct seeded and harvested in the establishment year.

‡ Concordance occurred when responsive trials were classified as responsive and discordance occurred when nonresponsive trials were classified as responsive; tied pairs are not shown. Somers’ D = (no. of concordant pairs – no. of discordant pairs)/total no. of pairs.

§ Significance at the $P \leq 0.10$ level.

Table 4.3. Parameter estimates for linear and quadratic regression models used to calculate coefficients for independent variables used for prediction of the economically optimum N rate (EONR) and the lowest/highest fertilizer N rate for net return to N within \$2.50 ha^{-1} of the maximum at fertilizer N/corn grain price ratios (PRs) ranging from 4.48 to 11.2 (0.08 to 0.20 US\$ lb^{-1} N/US\$ bu^{-1}) for site-years of first-year corn following alfalfa that had a response of grain yield to fertilizer N. All regression models were significant ($P \leq 0.05$) and fit the data ($R^2 \geq 0.90$).

Soil texture model	Parameter†	Lowest N rate within \$2.50 ha^{-1}‡			EONR (kg N ha^{-1})‡			Highest N rate within \$2.50 ha^{-1}‡		
		$_0$	$_1$	$_2$	$_0$	$_1$	$_2$	$_0$	$_1$	$_2$
Fine – fall or	Intercept	142	-11.5	-	154	-11.7	-	165	-11.6	-
spring term.	Alfalfa age × Pnov	-0.360	0.0309	-	-0.379	0.0304	-	-0.398	0.0296	-
	DD_0 oct × Pdec	9.69§	1.88§	-	7.73§	2.02§	-	6.33§	2.05§	-
Medium –	Intercept	247	-6.64	-	253	-6.45	-	258	-6.09	-
fall term.¶	DD_0 dec × Pmay	-0.0228	6.89§	-	-0.0234	6.63§	-	-0.0237	6.00§	-
1-yr alfalfa	DD_0 mar × Papr	0.0179	-5.43§	0.0705§	0.0177	-3.23§	-0.0580§	0.0164	1.33§	-0.303§
Medium –	Intercept	101	1.73	-0.0922	104	1.26	-0.0511	107	0.816	-0.0176
spring term.	DD_0 nov	0.633	0.0781	-89.4§	0.849	0.0176	-43.6§	1.03	-0.0306	-8.18§
	Pnov × DD_0 mar	118§	-36.5§	1.45§	135§	-35.0§	1.20§	91.4§	-19.4§	0.183§
	Pdec	-4.79	0.388	-	-5.05	0.381	-	-5.29	0.374	-
Coarse	Intercept	22.5	-4.48	-	30.8	-4.41	-	38.1	-4.21	-
	Spring term. × DD_0 dec	3.19	0.0720	-	3.09	0.0666	-	2.98	0.0654	-
	Poct-dec, mar	18.0§	0.638§	-0.0232§	18.3§	0.329§	-0.00239§	18.2§	0.195§	0.00494§

† Alfalfa age in years (including establishment year); P, total monthly precipitation (millimeters); DD_0, total monthly degree-days (degrees Celsius) based on daily mean air temperature >0°C. The three-letter abbreviation behind P and DD_0 is the first three letters of the month.

‡ $_0$, intercept; $_1$, linear coefficient; $_2$, quadratic coefficient for linear regression models. Multiply $_1$ by 56 and $_2$ by 3136 to convert to PRs in US\$ lb^{-1} N/US\$ bu^{-1}.

§ Multiply by 0.0001 for coefficient value.

¶ The EONR was not predicted for first-year corn following fall-terminated (term.) 2-yr-old alfalfa seeded without oat or for ≥3-yr-old alfalfa because only 2 and 3 site-years responded to fertilizer N, respectively.

Table 4.4. Range of weather parameters from site-years used to develop multiple logistic and linear regression models (Tables 4.2 and 4.3) to predict the probability of grain yield response to fertilizer N and economically optimum N rate (EONR) in first-year corn for soil texture, alfalfa termination (term.) time, and alfalfa stand age categories. When weather parameters were interactions, the range was shown for the interaction and both variables (V) in respective order as V1 and V2.

Soil texture model	Response weather parameters†	Range	V1	V2	EONR weather parameters†	Range	V1	V2
Fine – fall or spring term.	DD_0 mar	23-237	NA‡	NA	Pnov	14-189	NA	NA
					DD_0 oct × Pdec	2669-38,685	154-444	8-88
Medium – fall term. 1-yr alfalfa	-§	-	-	-	DD_0 dec × Pmay	0-11,673	0-76	18-136
	-	-	-	-	DD_0 mar × Papr	2543-16,349	31-158	37-212
Medium – fall term. 2-yr alfalfa	DD_0 oct	231-445	NA	NA	-	-	-	-
Medium – fall term. ≥3-yr alfalfa	Pmay	23-280	NA	NA	-	-	-	-
Medium – spring term.	Poct × DD_0 dec	0-6734	6-201	0-120	DD_0 nov	13-198	NA	NA
	DD_0 oct × Pnov	0-36,014	140-402	0-120	Pnov × DD_0 mar	1417-12,732	35-116	23-171
	Pdec	1-168	NA	NA	Pdec	1-60	NA	NA
	Pmar × DD_0 mar	1527-30,175	17-143	23-241				
Coarse	-	-	-	-	DD_0 dec	0-87	NA	NA
					Poct-dec, mar	196-287	NA	NA

† P, total monthly precipitation (millimeters); DD_0, total monthly degree-days (degrees Celsius) based on daily mean air

temperature >0°C. The three-letter abbreviation behind P and DD_0 is the first three letters of the month.

‡ NA, not applicable.

§ Model predictions were not possible due to insufficient data or lack of fit.

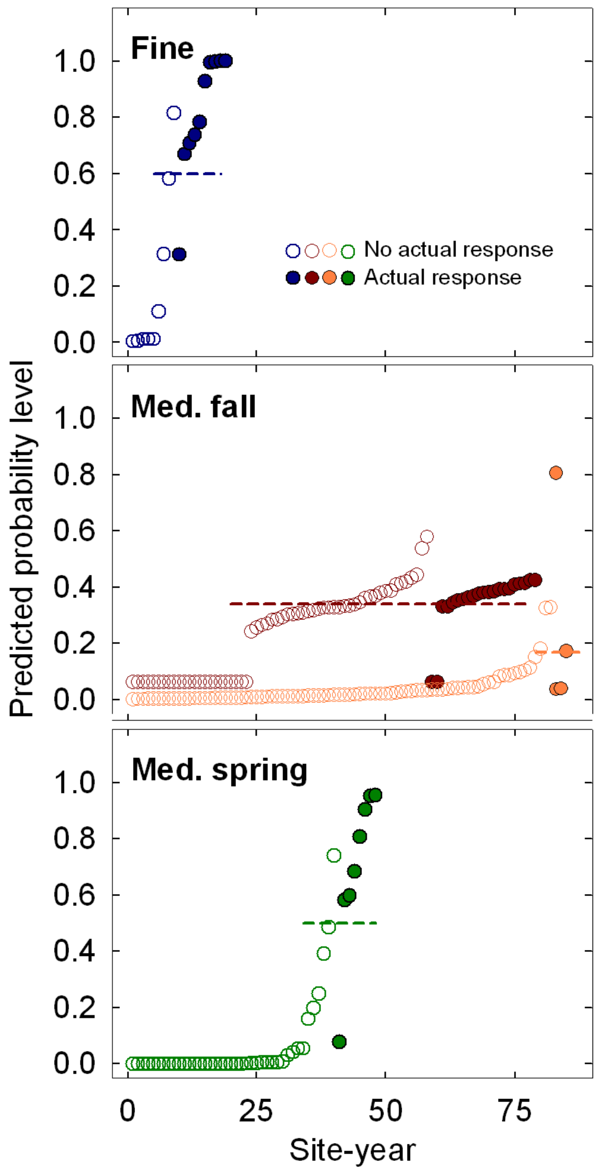

Fig. 4.1. Predicted probability for response of grain yield to fertilizer N in first-year corn following alfalfa for fine-textured soils, medium-textured soils with fall alfalfa termination with 2-yr-old alfalfa stands (red circles) and ≥3-yr-old alfalfa stands (orange circles), and medium-textured soils with spring alfalfa termination. Predicted probabilities by site-year for multiple logistic regression are

listed in ascending order. Dashed lines represent the probability critical levels (i.e., symbols above a critical level were predicted as responsive to fertilizer N and symbols below were predicted as nonresponsive to fertilizer N). Solid symbols represent actual response to fertilizer N and open symbols represent actual lack of response to fertilizer N.

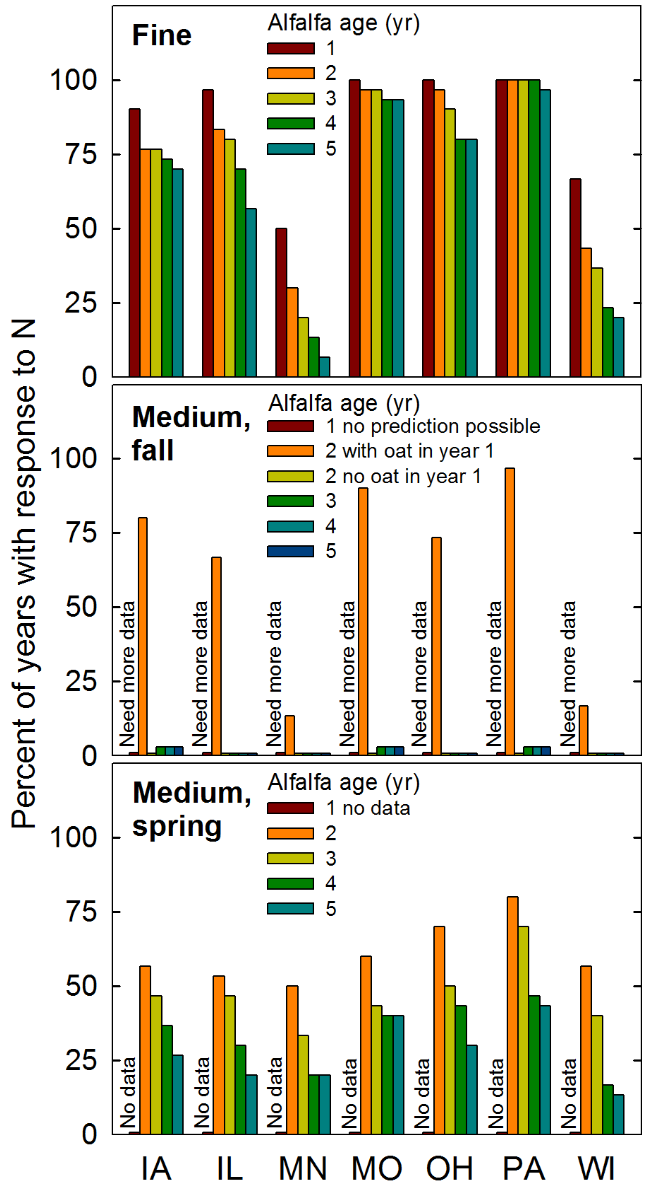

Fig. 4.2. Percentage of site-years predicted to have had a response of first-year corn grain yield to fertilizer N following alfalfa during 30 yr (1983-2012) for fine-textured soils, medium-textured soils with fall alfalfa termination, and medium-textured soils with spring alfalfa termination. Logistic regression models (Table 4.2) were applied to seven counties (Clayton, IA; Jo Daviess, IL; Ottertail,

MN; Nodaway, MO; Wayne, OH; Lancaster, PA; Shawano, WI).

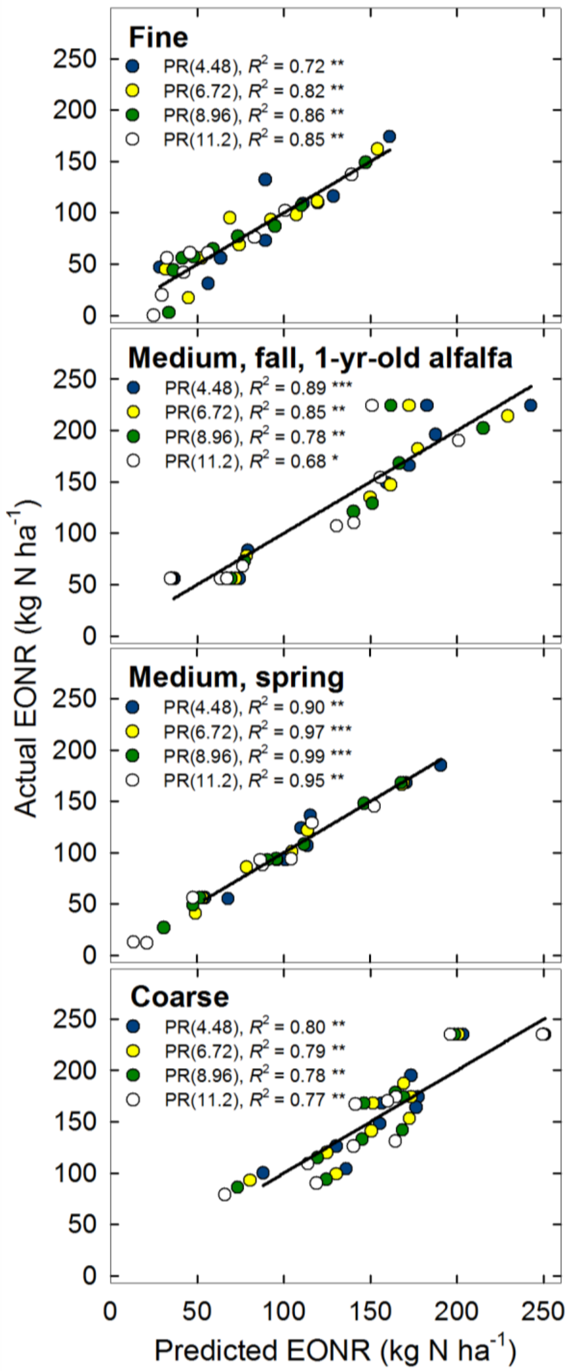

Fig. 4.3. Measured economically optimum N rate (EONR) at fertilizer N/corn grain price ratios (PRs) ranging from 4.48 to 11.2 (0.08 to 0.20, US\$ lb^{-1} N/US\$ bu^{-1}) vs. the

predicted EONR from multiple linear regression models (Table 4.3) for site-years with a response of grain yield to fertilizer N in first-year corn following alfalfa on fine-textured soils, medium-textured soils with fall termination of 1-yr-old alfalfa, medium-textured soils with spring alfalfa termination, and coarse-textured soils. The significance of the multiple linear regression models at $P \leq 0.05, 0.01$, and 0.001 are indicated as *, **, and ***, respectively. The regression line is shown only for the PR of 4.48.

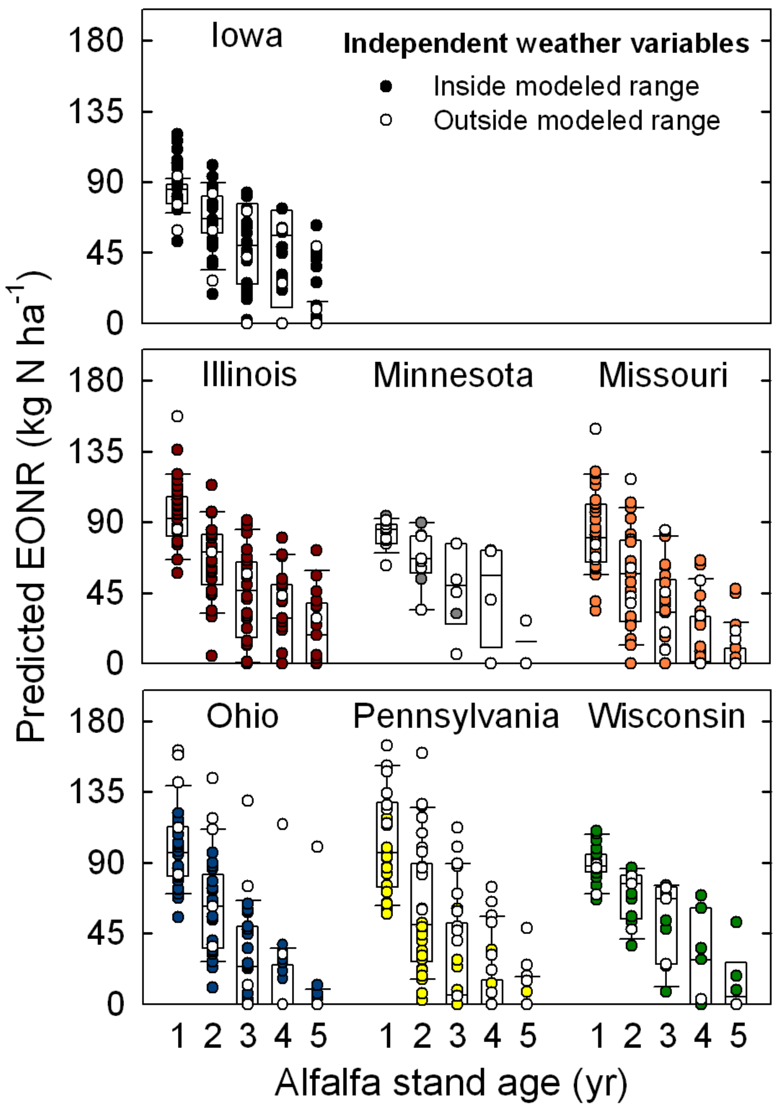

Fig. 4.4. Predicted economically optimum N rate (EONR) at the fertilizer N/corn grain price ratio of 5.6 (0.10, US\$ lb^{-1} N/US\$ bu^{-1}) according to multiple linear regression models (Table 4.3) for Clayton County, IA, Jo Daviess County, IL, Ottertail County, MN, Nodaway County, MO, Wayne County, OH, Lancaster County, PA, and Shawano County, WI during 30 yr (1983-2012) for fine-textured soils. The EONR was calculated only for years that were predicted to be responsive to fertilizer N by logistic regression models (Table 4.2). Solid colored circles represent years that had

weather conditions inside the range of the prediction model;
open circles were years outside of the range.

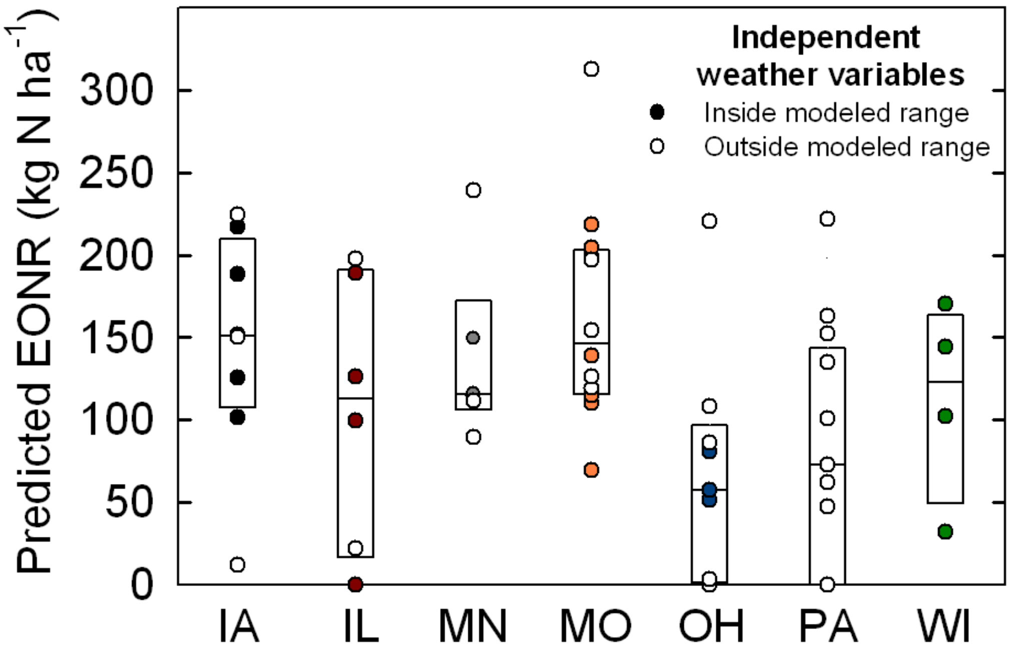

Fig. 4.5. Predicted economically optimum N rate (EONR) at the fertilizer N/corn grain price ratio of 5.6 (0.10, US$ lb^{-1} N/US$ bu^{-1}) according to multiple linear regression models (Table 4.3) for Clayton County, IA, Jo Daviess County, IL, Ottertail County, MN, Nodaway County, MO, Wayne County, OH, Lancaster County, PA, and Shawano County, WI during 30 yr (1983-2012) for first-year corn following 3- to 5-yr-old alfalfa terminated in the spring on medium-textured soils. The EONR was calculated only for years that were predicted to be responsive to fertilizer N by logistic regression models (Table 4.2). Solid colored circles represent years that had weather conditions inside the range of the prediction model; open circles were years outside of the range.

CHAPTER 5. Second-Year Corn after Alfalfa Often Requires No Fertilizer Nitrogen

INTRODUCTION

When alfalfa is terminated, soil organic matter accumulation during alfalfa production and decomposing alfalfa shoots, crowns, and roots provide N to at least 2 yr of subsequent corn crops (Levin et al., 1987; Fox and Piekielek, 1988; Aflakpui et al., 1993; Bundy and Andraski, 1995; Lory et al., 1995a). The contribution of N from alfalfa and subsequent reduction in the fertilizer N requirement for corn is known as the alfalfa fertilizer N replacement value or N credit. The response of grain yield to fertilizer N in first-year corn after alfalfa is rare, due to the large N credit from alfalfa (Yost et al., 2012, 2013a, 2013b and references therein). Despite decades of research on first-year alfalfa N credits to corn, surveys indicate that many growers still hesitate to fully accept first-year corn N credits (El-Hout and Blackmer, 1990; Shepard, 2000; Yost et al., unpublished data, 2013). Therefore, it is likely that even more growers and advisors neglect second-year N credits from alfalfa to corn.

Grower hesitation to accept alfalfa N credits for second-year corn may be a response to variation in extension guidelines from land-grant universities (Table 5.1). In the midwestern United States, some states (Minnesota, North Dakota, South Dakota) recommend about one-half the N credit for first-year corn (84 kg N ha^{-1}), others recommend less than one-half the first-year credit (34 to 56 kg N ha^{-1}) (Illinois, Wisconsin), and many states do not have a recommendation (Kansas, Michigan, Missouri, Nebraska, Ohio). Iowa is the only state that does not use book value alfalfa N credits for second-year corn, and instead recommends that growers apply 0 to 67 kg N ha^{-1} for second-year corn after alfalfa (Blackmer et al., 1997). This lack of uniformity among guidelines may be due to lack of adequate field data.

The number of studies on fertilizer N response in second-year corn after alfalfa is far fewer than those in first-year corn after alfalfa. Research in Minnesota, New York, Ontario, Pennsylvania, and Wisconsin has shown that the response to fertilizer N for second-year corn after alfalfa is highly variable. Assuming $1.19 kg N^{-1}, $183 Mg^{-1} corn grain, and $35 Mg^{-1} corn silage, the EONR for second-year corn after alfalfa was 0 to 202 kg N ha^{-1} in 17 trials conducted in Minnesota (Moncrief et al., 1988, 1991; Lory et al., 1995a; Randall and Vetsch, 1996; Schmitt and Randall, 1994), 0 to 135 kg N ha^{-1} in 10 trials conducted in Wisconsin (Bundy and Andraski, 1995; Andraski and Bundy, 2002), and 0 to 200 kg N ha^{-1} in 11 trials conducted in New York, Ontario, and Pennsylvania (Levin et al., 1987; Fox and Piekelek, 1988; Aflakpui et al., 1993; Katsvario et al., 2003; Lawrence et al., 2009). These disparities in university guidelines and the literature indicate that better predictability of fertilizer N requirements is needed for second-year corn after alfalfa.

The variation in fertilizer N requirements of second-year corn after alfalfa may be related, in part, to the effects of the prior year corn stover management, which influences the fertilizer N requirement in continuous corn. In Illinois, Iowa, and Minnesota, ≥80%

stover removal in continuous corn decreased the EONR for grain yield by 13, 17, and 5%, respectively, across tillage systems (Coulter and Nazfiger, 2008; Pantoja et al., 2011; Sindelar et al., 2013). Therefore, stover removal may reduce the EONR for second-year corn after alfalfa.

The reliability of the PSNT (Magdoff et al., 1984) for predicting second-year corn N needs also may be affected by stover management because stover can affect early-season soil temperature, water content, and N mineralization (Wilhelm et al., 1986; Andraski and Bundy, 2008). The PSNT is recommended for use in first-year corn after alfalfa in many states, but the test is not needed in most cases because first-year corn often does not respond to fertilizer N above a small early-season application (Yost et al., 2013b). The PSNT should be more useful for second-year corn after alfalfa because higher fertilizer N rates typically are needed for second-year corn than for first-year corn. Across 21 trials in Minnesota (Schmitt and Randall, 1994; Randall and Vetsch, 1996) and Wisconsin (Bundy and Andraski, 1995; Andraski and Bundy, 2002), the PSNT was accurate at predicting response and nonresponse of grain yield to fertilizer N in 67% of second-year corn trials when using the critical concentration of 21 mg NO_3–N kg^{-1} (Fox et al., 1989; Bundy and Andraski, 1995; Laboski and Peters, 2012). Thus, the accuracy of the PSNT for second-year corn was slightly better than the 55% accuracy for 94 trials of first-year corn after alfalfa (Yost et al., 2013b). However, increasing the database of N response trials with second-year corn after alfalfa should provide an improved evaluation of the accuracy of the PSNT in predicting fertilizer N response and provide better understanding of conditions that affect PSNT accuracy for second-year corn after alfalfa.

Better predictions of fertilizer N requirements of second-year corn after alfalfa would enhance net return for growers, and potentially increase the hectares of corn grown in the second year after alfalfa. When growers apply too much fertilizer N to second-year corn after alfalfa, net return declines, resources are wasted, and risk of NO_3–N loss to ground and surface water increases. However, inadequate N supply limits corn yield and net return. Therefore, growers need to have reliable fertilizer N guidelines for second-year corn after alfalfa. The objectives of this study were to use field trials to: 1) determine the effect of first-year corn stover incorporation or removal on response to fertilizer N in second-year corn after alfalfa; and to use field trials with literature research to: 2) quantify the response to fertilizer N in second-year corn after alfalfa; and 3) assess the accuracy of the PSNT for second-year corn after alfalfa. To meet these objectives, on-farm experiments were conducted at 17 sites in Iowa during 1989 to 1991 and at 11 sites in Minnesota during 2011 to 2012, and results of these experiments were combined with literature research.

MATERIALS AND METHODS

Iowa Experiments

Seventeen fertilizer N trials for second-year corn after 3- to 5-yr-old alfalfa were conducted in northeastern Iowa from 1989 to 1991 on fine sandy loam, loam, and silt loam soils (Tables 5.2,5.3). A randomized complete block design with three replications of fertilizer N rate treatments was used for all trials. Plot dimensions were 12.2 m long by four 97-cm rows or six 76-cm rows wide. Nine fertilizer N treatments (0 to 280 kg N ha^{-1} in 28 kg N ha^{-1} increments) were hand-applied to second-year corn as broadcast and incorporated NH_4SO_4 shortly before planting. No fertilizer N had been applied to first-year corn after alfalfa. Background characteristics and fertilizer N response for first-year corn at these sites were summarized in Morris et al. (1993); these results for first-year corn will not be described in detail in this manuscript, but will be used to summarize the EONR for both first- and second-year corn.

Information on the soils, crops, tillage, and starter fertilizer N application for each trial are described in Tables 5.2 and 5.3. Alfalfa was managed for dry hay production with three harvests per year after the year of establishment. No sites had received animal manure for at least 4 yr before planting first-year corn. Cooperating growers managed the corn in the trials identical to the remainder of the field. The growers made the decisions about crop management, such as corn hybrid, planting date, plant population, and fertilizer and herbicide applications, except that N fertilizer applications were applied by hand as noted above. Corn plant density at harvest ranged from 40,800 to 72,000 plants ha^{-1}, depending on the trial. Corn grain yield was determined by hand harvesting ears from 7.6-m of the center portion in the center two rows of each plot, drying samples at 60°C to constant mass, shelling, and weighing samples. Grain yield was adjusted to 155 g kg^{-1} moisture content.

Minnesota Experiments

Eleven fertilizer N trials for second-year corn after 2- to 7-yr-old alfalfa were conducted in southern and central Minnesota from 2011 to 2012 on loam, silt loam, silty clay loam, and clay loam soils (Tables 5.2,5.3). Three of the eleven trials were conducted in 2011 and were second-year corn after good alfalfa stands (≥47 plants m^{-2}) that were terminated in the fall of 2009 with chisel plow tillage. First-year corn in 2010 received 22 kg N ha^{-1} as broadcast NH_4NO_3 immediately after planting. The results of grain yield response to fertilizer N in first-year corn for these three trials (Yost et al., 2012) will not be summarized in detail here, but will be used to summarize EONR for both first- and second-year corn. The experimental design for these three trials was a randomized complete block design with four replications of fertilizer N treatments. Six fertilizer N rates (0, 0, 45, 67, 90, or 179 kg N ha^{-1}) were hand-applied 1 to 2 wk after corn planting as broadcast NH_4NO_3; one of the 0 kg N ha^{-1} plots received a sidedress application of 90 kg N ha^{-1} as NH_4NO_3 that was banded 4 cm deep midway between corn rows when the corn had reached the five to six leaf collar stage (Abendroth et al., 2011).

The remaining eight trials had stover management treatments applied at the end of first-year corn in 2011 in addition to fertilizer N treatments for second-year corn in 2012. First-year corn in these trials had received between 0 to 69 kg N ha^{-1} near planting (Table 5.3). A randomized complete block design with four replications of stover management and fertilizer N treatments was used for these trials. Main plots were removal and no removal of aboveground first-year corn stover following grain harvest and before fall tillage, and subplots were fertilizer N rates for second-year corn. At each location, stover was chopped, raked, and baled by cooperating growers for the stover removal treatments, while stover was chopped but not removed in the main plots with no stover removal. Stover remaining and removal rates were determined by sampling stover in three 1-m^2 quadrats in each main plot, drying samples at 60°C to constant mass, and weighing. Six of the 10 subplots were fertilizer N rates (0, 45, 78, 106, 134, or 269 kg N ha^{-1}) that were broadcast NH_4NO_3 immediately after planting. Two subplots were sidedress-only rates of 45 or 78 kg N ha^{-1} and the remaining two subplots were split applications of 17 or 33 kg N ha^{-1} as broadcast NH_4NO_3 immediately after planting followed by 45 kg N ha^{-1} as a sidedress. The sidedress applications were NH_4NO_3 that was banded 4 cm deep midway between corn rows when the corn had reached the five to six leaf collar stage (Abendroth et al., 2011).

In all 11 trials, soils were fertilized with recommended levels of required nutrients for corn production except for N in the first and second-year of corn (Kaiser et al., 2011). Growers selected, planted, and managed corn hybrids of appropriate relative maturity (Table 5.3). Second-year corn was planted in rows spaced 51 or 76 cm apart and corn plant density at harvest ranged from 65,000 to 94,200 plants ha^{-1} depending on the trial. Weeds were controlled using herbicides, which varied among trials.

Corn grain yield was measured in all 11 Minnesota trials, and corn silage yield also was measured in the eight trials in 2012. Physiologically mature corn ears were hand harvested from 3.0 and 6.1 m of row at the three and eight trials, respectively, within the center of each subplot, then dried at 60°C to constant mass, shelled, and weighed to determine grain yield adjusted to 155 g kg^{-1} moisture and cob dry matter yield. For the eight trials in 2012 only, corn stover was harvested 15 cm above the soil surface from 3 m of row within each subplot, weighed, chipped, and subsampled and weighed (about 1.0 kg) in the field. Stover subsamples were dried at 60°C to constant mass to determine stover dry matter yield. Silage yield was the sum of grain, cob, and stover yield expressed at 650 g kg^{-1} moisture. Dried grain, cob, and stover subsamples from the eight trials were ground to pass a 1-mm sieve and scanned with near-infrared reflectance spectroscopy at 1100-2500 nm (Foss Model 6500; Foss North America, Inc.) to estimate N concentration. Thirty samples of each plant tissue were selected with principal component analysis using WinISI version 3.0 (Intrasoft International, Port Matilda, PA) and analyzed by dry combustion with an Elementar varioMax (Elementar Americas, Mount Laurel, NJ) to develop calibration equations for N concentration. The near-infrared reflectance spectroscopy estimates of N concentration were calibrated to actual N concentration determined by dry combustion with linear regression (grain, $R^2 = 0.96$, $P < 0.001$; cob and stover were predicted with one equation, $R^2 = 0.88$, $P < 0.001$) using the REG procedure of SAS (SAS Institute, 2006). Aboveground plant N uptake was the sum of grain, cob, and stover N concentration multiplied by dry matter yield.

Presidedress Soil Nitrate Test

The PSNT was evaluated for plots that received no fertilizer N near planting for the 17 Iowa trials and for 13 of the 14 Minnesota trials (Table 5.3). Soil samples were collected when corn plants were at the five to six leaf collar stage (Abendroth et al., 2011). Six to eight soil cores (3.2 cm i.d.) were collected and composited to produce one soil sample from the surface 30-cm layer according to the PSNT sampling methods of Magdoff et al. (1984). Soil samples in Iowa were air dried and those in Minnesota were dried in a forced-air oven at 35°C until constant mass and all samples were pulverized to pass through a 2-mm sieve. The sieved soil was extracted in 2 *M* KCl using a 1:10 soil to extractant ratio and subsequently analyzed for exchangeable NH_4-N and NO_3–N by either the steam distillation procedure of Keeney and Nelson (1982) or by cadmium reduction with automated flow-injection analysis (Lachat QuickChem 8000, Hach Company, Loveland, CO; Methods 12-107-06-2-A and 12-107-04-1-B).

Corn Stalk and Residual Soil Nitrate-Nitrogen

In 13 of 17 trials in Iowa, basal corn stalk samples (20 cm long, beginning 15 cm above the soil surface) were collected 1 to 3 wk after physiological maturity according to methods of Binford et al. (1992). Ten stalks were collected from each subplot to form one composite sample, dried in a forced-air oven at 60°C until constant mass, and ground to pass a 0.5-mm sieve. Tissue NO_3–N was extracted with 0.025 *M* $Al_2(SO_4)_3$ with a 1:50 tissue to extractant ratio; 1 mL of 2 *M* $(NH_4)_2SO_4$ was added to each 50 mL of filtered extract to minimize differences in ionic strength. Extracts were analyzed with an Orion Model 93-07 nitrate specific ionic electrode (Orion Research Inc., Boston, MA) to determine tissue NO_3–N concentration.

In the eight Minnesota trials in 2012, soil samples were collected to a depth of 1.2 m for residual soil NO_3–N (RSN) in mid-April before corn planting and fertilizer N application and at 1 to 3 wk after corn harvest in mid- to late-October. Three cores were composited by 30-cm depth increments from each of three N rate subplots (0, 78, and 134 kg N ha^{-1}) in each main plot treatment that were fertilized near planting. Residual soil NO_3–N samples were processed like PSNT samples and analyzed for NO_3–N using automated flow-injection analysis. Soil bulk density was determined for each main plot at the time of RSN sampling from two 1.2 m-deep cores separated into 30-cm increments that were dried at 105°C and weighed. Residual soil NO_3–N content was the product of NO_3–N concentration and soil bulk density.

Statistical Analysis

Because experimental designs were not identical among experiments, the three groups of experiments (17 trials in Iowa, three Minnesota trials in 2011, and eight Minnesota trials in 2012) were analyzed separately at $P \leq 0.05$ using the MIXED procedure of SAS (SAS Institute, 2006) with fertilizer N rate as a fixed effect and trial, block (nested within trial), and interactions involving trial and block as random effects. For the eight Minnesota trials in 2012, stover management also was considered a fixed effect. The UNIVARIATE procedure of SAS (SAS Institute, 2006) was used to inspect residuals for normality and scatterplots of residuals vs. predicted values for homogeneity of variance (Kutner et al., 2004). The two-tailed log-likelihood ratio test was used to determine the significance of the random interaction between trial and N applications.

When the trial × N interaction was significant, best linear unbiased predictors were used to determine the effect of fertilizer N rate by trial. When multiple trials had a significant response to fertilizer N, the two-tailed log-likelihood test was used to determine which trials had a similar response to N and should be grouped together.

Linear and non-linear regression equations were developed using the MIXED and NLIN procedures of SAS (SAS Institute, 2006), respectively. Fisher's protected LSD test ($P \leq 0.05$) was used to compare means when response to fertilizer N was significant and no regression model significantly ($P \leq 0.05$) fit the data. When grain and silage yield response to fertilizer N adequately fit regression equations, the EONR was predicted by setting the first derivatives of the regression models to the average fertilizer N cost/corn price ratio from 2009 to 2011 (\$1.19 kg^{-1} N as urea, USDA-ERS, 2013; \$183 Mg^{-1} corn grain and \$39 Mg^{-1} corn silage, Center for Farm Financial Management, 2013). The EONR for trials from the literature was calculated using the regression model (linear, quadratic, or quadratic-plateau) that fit the mean yield by N rate with the smallest, normally and randomly distributed residuals (Kutner et al., 2004). The EONR for silage yield at the one responsive trial in New York (Lawrence et al., 2009) was reported at \$1.19 kg^{-1} N and \$35 Mg^{-1} corn silage. Sidedress-only and split fertilizer N application efficiency was estimated in comparison to the N rate required near planting to attain the same grain or silage yield, or aboveground plant N uptake.

RESULTS AND DISCUSSION

Precipitation in the Iowa trials in the 1989 growing season (April through September) was 100 mm below the 30-yr average (1981-2010) for trials 2 through 8 and 240 mm below average for trial 1 (Table 5.4). Growing season precipitation totals in 1990 and 1991 were 84 to 265 mm above the 30-yr average for trials 9 through 17. The above-average precipitation for trials 13 through 17 in 1991 was mainly due to excess precipitation in April (130-172 mm above average), whereas excess precipitation at trials 9 through 12 in 1990 was spread more evenly throughout the growing season.

In 2011, growing season precipitation was 46 mm below the 30-yr average precipitation across the three Minnesota trials and the deficit occurred primarily in August and September (Table 5.4). In 2012, growing season precipitation during the eight Minnesota trials was within 139 mm of the 30-yr average for six trials, whereas trials 22 and 27 had the highest growing season precipitation (338 mm above the 30-yr average; Table 5.4) and also were irrigated. Across the six non-irrigated trials, precipitation was 10 to 40 mm lower than average in April and 44 mm below average in June.

Corn Grain Yield

Eleven of the 17 Iowa trials (65%) did not respond to fertilizer N (Table 5.5), and mean grain yield across N rates in these 11 trials ranged from 8.3 to 12.0 Mg ha^{-1} (Supplemental Table S5.1). Each year of the study (1989, 1990, and 1991) had both responsive and nonresponsive trials. According to the two-tailed log-likelihood ratio test, the response to fertilizer N was consistent among the six responsive trials and the EONR was 130 kg N ha^{-1} (120-140 kg N ha^{-1} for net return to N within \$2.50 ha^{-1} of the maximum) (Table 5.6). Using the same fertilizer N cost and corn grain price values, the average EONR for continuous corn in Iowa was 203 kg N ha^{-1} according to the regional corn N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx) on 2 October 2013, indicating that the average alfalfa N credit would have been 73 kg N ha^{-1} for the six responsive trials and 203 kg N ha^{-1} for the 11 nonresponsive trials. These alfalfa N credits to second-year corn are higher than those from most land-grant universities in the midwestern United States (Table 5.1), especially for the nonresponsive trials.

Across the three Minnesota trials in 2011 (# 18-20), the response of corn grain yield to fertilizer N was consistent (Table 5.5), but the EONR could not be determined because no regression model fit the data. Across these trials, corn grain yield was 10.3 Mg ha^{-1} when no or 45 kg N ha^{-1} was applied and increased to 11.8 Mg ha^{-1} when 67 to 179 kg N ha^{-1} was applied near planting or when 90 kg N ha^{-1} was sidedressed (LSD = 1.3 Mg ha^{-1}). These data indicate that the EONR across trials was low (between 45 and 67 kg N ha^{-1}). The average EONR for continuous corn in Minnesota at \$1.19 kg N^{-1} and \$183 Mg^{-1} grain was 165 kg N ha^{-1} according to the regional corn N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx) on 2 October 2013, and the book value N credit for second-year corn with ≥43 alfalfa plants m^{-2} at termination is 84 kg N ha^{-1} (Kaiser et al., 2011). Thus, the recommended 81 kg N ha^{-1} was similar to the measured EONR in these three trials.

Despite the dry weather conditions that prevailed across much of the midwestern United States during the summer and fall of 2012, corn grain yield in the eight Minnesota trials was 10.2 to 15.1 Mg ha^{-1} (Supplemental Table S5.1). The effects of first-year corn stover management on second-year corn were evaluated in these trials, and the amount of first-year corn stover present after grain harvest ranged from 6.1 to 8.1 Mg dry matter ha^{-1}. Stover removal rates by the cooperating growers in the fall of 2011 ranged from 47 to 89%, resulting in residual stover amounts of 0.9 to 3.5 Mg dry matter ha^{-1}.

The interaction between stover management and fertilizer N rate was significant for corn grain yield across all eight trials (Table 5.5). However, three of eight trials (# 24, 25, and 27) did not respond to fertilizer N applied near planting, as a sidedress, or as a split application, and had a mean grain yield of 14.1 Mg ha^{-1}. Therefore, the stover management × fertilizer N interaction was tested only for the remaining five trials in which grain yield responded to N. In these five trials, the stover management × fertilizer N interaction was close to significant ($P = 0.055$), but the EONR for N applied at planting for stover removal (192 kg N ha^{-1}) and for stover retained (173 kg N ha^{-1}) had overlapping ranges for net return to N within \$2.50 ha^{-1} of the maximum. Therefore, stover management had only minimal effects on the EONR for grain yield of second-year corn in these trials.

Across stover treatments, the EONR for grain yield with N applied near planting across trials 21 and 26 was 81 kg N ha^{-1} (76-85 kg N ha^{-1} for net return within \$2.50 ha^{-1} of the maximum), whereas the EONR across trials 22, 23, and 28 was 196 kg N ha^{-1} (188-203 kg N ha^{-1} for net return within \$2.50 ha^{-1} of the maximum) (Table 5.6). In these two sets of trials, we estimated the relative fertilizer N efficiency of near planting and sidedressed N rates in terms of the resulting grain yield. Across trials 21 and 26, sidedress-only applications of 45 or 78 kg N ha^{-1} and the split application of 33 kg N ha^{-1} near planting and 45 kg N ha^{-1} at sidedressing improved fertilizer N efficiency by 1.2- to 1.4-fold compared to N applied near planting. In contrast, the split application of 17 kg N ha^{-1} near planting and 45 kg N ha^{-1} at sidedressing resulted in grain yield that was equivalent to that achieved with the same total N rate applied near planting (Fig. 5.3). Across trials 22, 23, and 28, both split applications (62 and 78 kg N ha^{-1}) and the sidedress-only application of 45 kg N ha^{-1} improved fertilizer N efficiency by 1.4-fold compared with N applied only near planting, whereas the efficiency of the sidedress-only rate of 78 kg N ha^{-1} was not improved. These results from five trials suggest that split and sidedress fertilizer applications to second-year corn after alfalfa may improve fertilizer N efficiency over N applied only near planting; but the effect was inconsistent. The variability in efficiency at these trials is reflected in the literature for corn after corn or soybean on medium- to fine-textured soils in the midwestern United States (Nelson and MacGregor, 1973; Bundy et al., 1992; Jokela and Randall, 1997; Randall et al., 2003; Terry et al., 2012). Future research should compare efficiencies for at-planting, split, and sidedress N applications with enough fertilizer N rates at each timing to calculate and compare EONR and relative efficiency, (Smith et al. 1987; Lory et al. 1995b), and the form of the fertilizer N should also be identical (Kyveryga et al., 2010).

The combined results of these 28 trials in Iowa and Minnesota indicate that in one-half of the cases, second-year corn after alfalfa did not respond to fertilizer N. These results were confirmed when the 28 trials from this study where combined with 39 trials of second-year corn from the literature, because the frequency response to fertilizer N was 55% (Fig. 5.1). Furthermore, the response of grain yield to fertilizer N in first-year corn was measured in 19 of our 28 trials; 10 of these trials showed no response of grain yield to fertilizer N for both first- and second-year corn after alfalfa and the remaining nine required fertilizer N only in second-year corn (Table 5.3). Therefore, terminated alfalfa often provides the entire N requirement for two subsequent corn crops.

Improved predictions of response to N in second-year corn would add more value to alfalfa in corn-based rotations and would greatly improve N management for second-year corn after alfalfa. Additionally, if the lack of N response could be predicted, growers could reduce fertilizer N applications by at least 168 kg N ha^{-1} for both first- and second-year corn in some fields, which could reduce fertilizer N costs by \$400 ha^{-1} (at \$1.19 kg N ha^{-1}). Conversely, growers using current university guidelines for second-year corn, which suggest using N credits ranging from 0 to 84 kg N ha^{-1} (Table 5.1), may apply large amounts of excess fertilizer N about 50% of the time.

Corn Silage Yield and Nitrogen Uptake

The three trials in Minnesota in 2012 with no response of grain yield to fertilizer N also had no response in silage yield or aboveground plant N uptake to fertilizer N; mean silage yield and N uptake across the three trials was 53.2 Mg ha^{-1} and 221 kg N ha^{-1}, respectively (Table 5.5). Aboveground plant N uptake likely did not increase with fertilizer N in these trials because N uptake in nonfertilized plots was 82 kg N ha^{-1} higher across the three nonresponsive trials than the other five responsive trials. Where grain yield increased with fertilizer N, silage yield also increased independent of stover treatments (Table 5.5); the EONR for N applied near planting for silage yield across these five trials was 184 kg N ha^{-1} (173-194 kg N ha^{-1} for net return to N within \$2.50 ha^{-1} of the maximum) (Table 5.6). The sidedress application of 45 kg N ha^{-1} as sidedress-only or as a split application with 17 or 33 kg N ha^{-1} applied near planting was 1.3- to 1.6-fold more efficient at increasing silage yield than N applied only near planting, whereas the sidedress-only application of 78 kg N ha^{-1} was only 1.1-fold more efficient. The EONR at planting for silage yield (184 kg N ha^{-1}) was 110 kg N ha^{-1} higher than the EONR for grain yield for two trials (# 21 and 26), but was similar to the EONR for grain yield (within 12 kg N ha^{-1}) across the other three trials (# 22, 23, 28). Previous research involving 25 trials of first-year corn after alfalfa in Minnesota also indicated that fertilizer N requirements can be higher for silage corn, but this occurred in only nine trials (36% of the time) (Yost et al., 2012, 2013a, 2013b). We suspect that differences in EONR for silage and grain corn are related to corn pricing differences (silage price can be affected by silage quality), corn hybrid type (silage- or grain-specific hybrid), and patterns in N availability and uptake during the growing season.

Across the five trials with silage response to N, stover management affected the response of aboveground plant N uptake to fertilizer N (Table 5.5). In the nonfertilized plots, N uptake was 18 kg N ha^{-1} higher where much of the stover had been removed (0.9 to 3.2 Mg ha^{-1} stover remaining) than with stover remaining (6.1 to 8.1 Mg ha^{-1}), but the slope for the increase in N uptake with N rate among stover treatments was not significantly different according to 95% confidence intervals (stover removed, $y = 142 + 0.666x - 0.00124x^2$, $R^2 = 0.77$, $P < 0.001$; stover not removed, $y = 124 + 0.749x - 0.00123x^2$, $R^2 = 0.78$, $P < 0.001$). Therefore, we evaluated the response of aboveground plant N uptake to fertilizer N across stover treatments. Aboveground N uptake increased from 146 kg N ha^{-1} in the nonfertilized plots to 243 kg N ha^{-1} when the highest N rate was applied, according to regression equations (Table 5.6). Across stover treatments, luxury consumption of N occurred in these five trials because aboveground plant N uptake increased linearly with fertilizer rates up to 269 kg N ha^{-1}, even though the EONR for silage was 184 kg N ha^{-1}. The sidedress-only rates of 45 and 78 kg N ha^{-1} and both split applications improved efficiency of aboveground plant N uptake by 1.4- to 2.0-fold compared to N applied only near planting in the 5 of 8 trials that required fertilizer N to increase grain yield. Enhanced N uptake efficiency of fertilizer N with split and sidedress applications has been reported for corn after corn or soybean in Minnesota (Jokela and Randall, 1997; Randall et al., 2003), but enhancements in N uptake were inconsistent among site-years. Therefore, more research is needed to identify weather and other conditions that cause improved N uptake efficiency in second-year corn after alfalfa and in corn grown in other crop rotations.

Presidedress Soil Nitrate Test

The PSNT concentrations in the 17 Iowa trials ranged from 4 to 24 mg NO_3–N kg^{-1} and concentrations were 6 and 11 mg NO_3–N kg^{-1} for two of three Minnesota trials with second-year corn in 2011 (Table 5.3). Across stover treatments, PSNT concentration was between 4 to 21 mg NO_3–N kg^{-1} for the eight Minnesota trials in 2012. Based on the critical concentration of 21 mg NO_3–N kg^{-1} (Magdoff et al., 1984; Fox et al., 1989; Bundy and Andraski, 1995), 17 of our 27 trials (63%) would have been correctly predicted as responsive or nonresponsive to fertilizer N. When our 27 trials were combined with 21 additional trials from Minnesota and Wisconsin in the literature (Randall and Vetsch, 1996; Schmitt and Randall, 1994; Bundy and Andraski, 1995; Andraski and Bundy, 2002), the accuracy of the PSNT at 21 mg NO_3–N kg^{-1} remained similar (65%; Fig. 5.2).

Of the 17 trials in the combined dataset that had incorrect PSNT predictions, 13 were incorrectly predicted as responsive and four were incorrectly predicted as nonresponsive (Fig. 5.2). The tendency of the test to over-predict response to fertilizer N was acknowledged by the developers (Magdoff et al., 1984; Magdoff, 1990). A lower critical concentration of 16 mg NO_3–N kg^{-1} when May precipitation exceeds 127 mm has been suggested by Blackmer et al. (1997) to account for losses of NO_3–N from high rainfall. However, the accuracy of the PSNT did not improve when this proposed lower critical concentration was applied in our study (trials 9-13, 17, 21, 24, 28; Table 5.4). Therefore, further research is needed to determine whether the PSNT and a combination of weather conditions can predict which fields of second-year corn after alfalfa will respond to fertilizer N. Combinations of other predictors such as soil characteristics, alfalfa stand age, alfalfa termination conditions, and weather conditions successfully identified which fields of first-year corn after alfalfa responded to fertilizer N (Yost et al., unpublished data, 2013) and these predictors also may help in second-year corn.

We expected stover removal to increase the PSNT concentration in the eight Minnesota trials in 2012 because stover removal decreased the EONR for continuous corn in Iowa, Illinois, and Minnesota (Coulter and Nazfiger, 2008; Pantoja et al., 2011; Sindelar et al., 2013). However, the PSNT concentration was affected by stover removal at only two trials and the response was bi-directional. Stover removal decreased the PSNT concentration from 24 to 19 mg NO_3–N kg^{-1} in trial 27, but increased the concentration from 7 to 12 mg NO_3–N kg^{-1} in trial 23. The difference in stover removal effects on PSNT concentration in these two trials likely was due to differences in soil moisture and soil texture; trial 27 had a loam soil and near-average precipitation in June and was irrigated, whereas trial 23 had silt loam soil and received 52 mm less precipitation in June than the 30-yr average (Table 5.4). Therefore, we speculate that stover removal exacerbated leaching of N below the 30-cm depth before PSNT sampling in trial 27. In this trial, stover removal decreased the PSNT concentration below the critical concentration of 21 mg NO_3–N kg^{-1}, indicating that this trial would have a response of grain yield to fertilizer N only when stover was removed. Stover management may impact the PSNT concentration only a portion of the time, but the effects are important when the PSNT concentration is close to the critical level, if growers are managing N with the PSNT.

Corn Stalk Nitrate Test

Elevated amounts of residual NO_3–N in soil or basal corn stalks in autumn can reflect excess fertilizer N application rates. Corn stalk concentrations of 0.7 to 2.0 g NO_3–N kg^{-1} have been defined as the optimum range for N sufficiency of corn in Iowa, while >2.0 g NO_3–N kg^{-1} is considered excessive (Binford et al., 1992; Blackmer and Mallarino, 1996). Corn stalk NO_3–N concentration was measured at 13 of 17 Iowa trials in 1989 to 1991. The seven trials in this study that did not have a response of grain yield to fertilizer N rate had a linear response of corn stalk NO_3–N concentration to fertilizer N (trials 7, 11-12, 14, 16-17). In these trials, corn stalk NO_3–N in the absence of fertilizer N (intercept) averaged 0.96 g kg^{-1} (Table 5.6), which is above the 0.7 g kg^{-1} lower limit for the optimum level for corn in Iowa. In contrast, the remaining six trials in which corn grain yield increased with fertilizer N had a quadratic response of corn stalk NO_3–N concentration to fertilizer N. In these trials, corn stalk NO_3–N averaged 0.25 g kg^{-1} without fertilizer (intercept), suggesting the possibility of inadequate N supply during the growing season. Although the average difference in stalk NO_3–N concentration between trials that were responsive and nonresponsive to N for grain yield were large, concentrations in nonfertilized plots among trials were highly variable, ranging from 0.07 to 0.97 g kg^{-1} in responsive trials and from 0.08 to 2.12 g kg^{-1} in nonresponsive trials. When considering concentrations in the nonfertilized plots and Iowa guidelines for the test (Binford et al., 1992; Blackmer and Mallarino, 1996), only 7 of 13 trials (53%) would have been correctly classified as being either responsive or nonresponsive to fertilizer N. These results support our conclusions of the test for first-year corn after alfalfa (Yost et al., 2013b), and indicate that the test should be used only with caution until further developed for second-year corn after alfalfa.

Soil Residual Nitrate-Nitrogen

Another indicator of N supply is soil nitrate before corn planting and after corn harvest. The range for RSN to 1.2 m at the beginning of second-year corn in the early spring of 2012 in the eight Minnesota trials ranged from 45 to 105 kg NO_3-N ha^{-1}. Although trials 21 and 28 had 67 and 69 kg N ha^{-1} applied by cooperating growers to first-year corn, respectively, RSN at these two trials (71 and 51 kg ha^{-1}, respectively) was within the range of RSN (45 to 105 kg NO_3-N ha^{-1}) for the remaining six trials that had only a starter N (0-7 kg N ha^{-1}) applied to first-year corn. Also, both trials were responsive to fertilizer N in second-year corn (EONR of 81 kg N ha^{-1} for trial # 21 and 196 kg N ha^{-1} for trial # 28). Therefore, it was highly unlikely that residual N from the fertilizer N application to first-year corn in these trials was sufficiently high to affect the EONR for second-year corn.

At the end of the second-year corn growing season in 2012, , RSN was affected by the interaction between stover management and fertilizer N rate (Table 5.5). However, fertilizer N had no effect on RSN at two of eight trials (trials 22 and 23) so the stover management × fertilizer N interaction was tested for the remaining trials (P = 0.005). Across these six trials, RSN increased linearly with fertilizer N rate for both stover treatments ($P \leq 0.005$, $R^2 \geq 0.82$) and RSN at the intercepts for stover removal (27 kg NO_3–N ha^{-1}) and no removal (29 kg NO_3–N ha^{-1}) were not different according to 95% confidence intervals. However, the slope of the increase in RSN with fertilizer N rate was nearly twice as rapid when stover was removed than when it was retained (0.305 vs. 0.157 kg NO_3–N ha^{-1} per kg N ha^{-1} applied, respectively) and was significantly different according to 95% confidence intervals. When 134 kg N ha^{-1} was applied, regression-predicted RSN was only 18 kg NO_3–N ha^{-1} greater when stover was removed, confirming that stover management may have minor effects on second-year corn fertilizer N requirements and RSN.

In the two Minnesota trials with no response of RSN to fertilizer N (trials 22 and 23), there was a relatively low mean RSN (16 kg NO_3–N ha^{-1}) when ≤134 kg N ha^{-1} was applied, which could be expected because the EONR for these two trials (192 kg N ha^{-1}) was higher than other trials. In the three trials that had no response of grain yield to fertilizer N (trials 24, 25, 27), RSN increased from 42 to 85 kg NO_3–N ha^{-1} when 134 kg N ha^{-1} was applied. The remaining trials (# 21 and 26 with an EONR of 81 kg N ha^{-1} for grain yield, and # 28 with an EONR of 192 kg N ha^{-1}) had lower levels of RSN and less accumulation of RSN in autumn of 2012; RSN increased from 15 to 36 kg NO_3–N ha^{-1} when 134 kg N ha^{-1} was applied.

CONCLUSIONS

Grain yield of second-year corn after alfalfa responded to fertilizer N only 50% of the time for our 28 trials and 55% of the time when our trials were combined with 39 trials from the literature. Based on these results, we conclude that current N credits from land-grant universities in the midwestern United States often over-predict and sometimes under-predict the need for fertilizer N in second-year corn. In 10 of our 19 trials where grain yield of first- and second-year corn after alfalfa was measured, there was no response of grain yield to fertilizer N in both corn crops. Across eight trials in 2012, stover removal in first-year corn affected the PSNT concentration in two trials, but had minor effects on corn yield or the EONR for grain and silage yield. In five Minnesota trials with response of grain yield to fertilizer N, most sidedress and split applications of fertilizer N were 1.2- to 2.0-fold more efficient at increasing aboveground N uptake and yield than N applied only near planting. However, some split and sidedress-only rates did not improve efficiency, so additional research is required to identify conditions that cause improved efficiency. In the absence of fertilizer N, seven Iowa trials with no grain yield response to fertilizer N had average corn stalk NO_3–N concentration (0.96 g kg^{-1}) in the optimal range (0.7-2.0 g kg^{-1}), whereas six responsive trials had concentration (0.25 g kg^{-1}) in the low range (0.25-0.7 g kg^{-1}). However, corn stalk NO_3–N concentration was highly variable in nonfertilized plots, and only 7 of 13 trials would have been correctly identified as responsive or nonresponsive to fertilizer N, confirming that more research is needed before the corn stalk NO_3–N test is reliable for second-year corn after alfalfa. The PSNT correctly predicted the responsiveness of second-year corn grain yield to fertilizer N only 65% of the time in the 48 trials presented and reviewed here. Therefore, improvements in the PSNT or additional predictors are needed to identify when second-year corn will respond to fertilizer N and the estimated EONR for these responsive fields.

Table 5.1. Current alfalfa N credit extension guidelines for first- and second-year corn after good stands of alfalfa (≥43-53 plants m^{-2} or ≥80% alfalfa) at termination on medium- to fine-textured soil from land-grant universities in the midwestern United States.

State	Alfalfa stand rating	First-year N credit	Second-year N credit	Citation
	plants m^{-2} or % alfalfa	---- kg N ha^{-1} ----		
IA	all situations	†	†	Blackmer et al., 1997
IL	>53	112	34	Fernández et al., 2009
IN, MI, OH	>53	157	-‡	Vitosh et al., 1995
KS	>53	134	-	Leikam et al., 2003
MN	>53	168	84	Kaiser et al., 2011
MO	≥80%	134-157	-	Killpack and Buchholz, 1993
ND	>53	168	84	Franzen, 2010
NE	>43	168	-	Shapiro et al., 2008
SD	>53	168	84	Gerwing and Geldermann, 2005
WI	>43	168	56	Laboski and Peters, 2012

† Iowa State University does not use N credits, but recommends that growers apply 0 to 34 kg N ha^{-1} for first-year corn and 0 to 67 kg N ha^{-1} for second-year corn.
‡ University extension guidelines do not list second-year N credits.

Table 5.2. Nearest town, year of trial, and soil series, subgroup, and texture for 28 on-farm trials of second-year corn after alfalfa conducted in Iowa from 1989 to 1991 and in Minnesota from 2011 to 2012.

				Soil		
Exp.	Trial	Nearest town	Year	Series	Subgroup	Texture†
IA	1	Waverly	1989	Kenyon	Typic Hapludolls	l
	2	Elkador	1989	Fayette	Typic Hapludalfs	sil
	3	Elkador	1989	Fayette	Typic Hapludalfs	sil
	4	Elkador	1989	Downs	Mollic Hapludalfs	sil
	5	Elkador	1989	Fayette	Typic Hapludalfs	sil
	6	Elkador	1989	Downs	Mollic Hapludalfs	sil
	7	Elkador	1989	Fayette	Typic Hapludalfs	sil
	8	Elkador	1989	Downs	Mollic Hapludalfs	sil
	9	Elkador	1990	Downs	Mollic Hapludalfs	sil
	10	Elkador	1990	Downs	Mollic Hapludalfs	sil
	11	Waverly	1990	Readlyn	Aquic Hapludolls	l
	12	Waverly	1990	Ostrander	Typic Hapludolls	l
	13	Waverly	1991	Readlyn	Aquic Hapludolls	l
	14	Elkador	1991	Fayette	Typic Hapludalfs	sil
	15	Elkador	1991	Fayette	Typic Hapludalfs	sil
	16	Elkador	1991	Downs	Mollic Hapludalfs	sil
	17	Waverly	1991	Dickinson	Typic Hapludolls	fsal
MN	18	Chatfield	2011	Tama	Typic Argiudolls	sil
	19	Emmons	2011	Clarion	Typic Hapludolls	l
	20	Montevideo	2011	Colvin	Typic calciaquolls	sicl

MN	21	Brewster	2012	Webster	Typic Endoaquolls	sicl
	22	Dennison	2012	Waukegan	Typic Hapludolls	sil
	23	Fountain	2012	Fayette	Typic Hapludalfs	sil
	24	Jeffers	2012	Clarion	Typic Hapludolls	l
	25	Le Center	2012	Le Sueur	Aquic Argiudolls	cl
	26	Medford	2012	Nicollet	Aquic Hapludolls	l
	27	Randolph	2012	Cylinder	Aquic Hapludolls	l
	28	Russell	2012	Hokans/Svea	Calcic Hapludolls	l

† cl, clay loam; fsal, fine sandy loam; l, loam; sicl, silty clay loam; sil, silt loam.

Table 5.3. Plant density, age, and termination (term.) timing and type for alfalfa, fertilizer N rate, tillage timing and type, and economically optimum N rate (EONR) for grain yield at \$1.19 kg N^{-1} and \$183 Mg^{-1} grain for first-year corn after alfalfa, and hybrid, starter fertilizer N rate, presidedress soil nitrate test (PSNT) concentration, and EONR for grain yield for second-year corn after alfalfa for 28 on-farm trials in Iowa and Minnesota.

		Alfalfa†			First-year corn			Second-year corn			
Exp.	Site	Density	Age	Term.	N rate	Tillage	EONR¶	Hybrid‡	Starter	PSNT§	EONR
		plants m^{-2}	yr		kg N ha^{-1}		kg N ha^{-1}		kg N ha^{-1}	mg kg^{-1}	kg N ha^{-1}
IA	1	59	≥ 3	SM	17	FC	0	T7500	17	20	0
	2	28	3	SC	0	FC	0	L648	0	24	0
	3	-	≥ 3	SM	0	FC	0	P3475	0	18	0
	4	-	≥ 3	SM	9	SM	0	P3475	10	20	0
	5	34	4	-	-	FC	-	ML616A	0	22	0
	6	-	≥ 3	SM	0	SM	0	P3475	0	19	0
	7	-	≥ 3	FC	0	SM	0	P3475	0	16	130
	8	-	≥ 3	FC	11	FC	0	P3475	11	20	0
	9	-	4	SM	0	FC	0	P3475	0	6	0
	10	-	3	SM	11	SC	0	P3751	11	9	0
	11	-	4	FM	0	FC	0	NK6330	0	6	130
	12	-	4	SC	0	FC	0	P3751	0	5	130
	13	-	3	SC	6	FC	0	P3615	6	9	0
	14	55	4	SM	0	FC	0	DKC535	0	8	130
	15	54	4	SM	13	FC	0	P3475	13	13	0
	16	32	5	SM	0	FC	0	P3417	0	6	130
	17	-	5	FM	0	FC	0	NK4545	0	4	130
MN	18	60	3	FC	22	FC	0	J7452	0	11	≤67

	19	47	6	FC	22	FC	0	CB201-16	7	6	≤67
	20	62	5	FC	22	FC	0	N8215	0	-	≤67
MN	21	43	3	FC	67	FC	-	P0392	0	4	81
	22	45	4	SC	0	FC	-	P34A89	0	8	196
	23	-	7	FNT	7	FC	-	DKC48-12	5	10	196
	24	-	4	FC	0	FC	-	GC95-15	0	4	0
	25	30	6	FM	0	FM	-	DKC55-09	0	11	0
	26	51	3	FM	0	FM	-	MC-5324	0	7	81
	27	63	2	FC	4	FM	-	T5ST682	5	21	0
	28	-	5	FST	69	FS	-	DKC42-72	7	6	196

† Stand density, stand age, and termination timing and type were not determined in every trial. Establishment year was included in alfalfa stand age. S, spring; F, fall; C, chisel plow tillage; M, moldboard plow tillage; NT, no tillage; S, strip tillage.

‡ CB, Channel Bio; DKC, DEKALB; GC, Gold County; J, Jung; L, Land O' Lakes; MC, Master's Choice; ML, Mallard; N, Nortec; NK, Northrup King; P, Pioneer; T, Trelay.

§ PSNT concentration is for the 0- to 30-cm soil depth in the nonfertilized control plots and is averaged across stover management treatments for trials 21-28.

¶ Grain yield response to fertilizer N in first-year corn was evaluated at $P \leq 0.05$.

Table 5.4. Precipitation totals for April through September with departures from the 30-yr average precipitation (1981-2010) in parenthesis for 28 on-farm trials in Iowa and Minnesota.†

Exp.	Trial	April	May	June	July	August	September
		------------	------------	------------ mm	------------	------------	------------
IA	1	68 (-26)	56 (-59)	39 (-87)	70 (-48)	53 (-55)	102 (35)
	2-8	72 (56)	76 (-28)	43 (-67)	33 (-72)	122 (22)	74 (-11)
	9,10	51 (35)	127 (23)	124 (14)	104 (-1)	185 (85)	13 (-72)
	11,12	83 (-11)	130 (15)	212 (86)	231 (113)	195 (87)	42 (-25)
	13,17	224 (130)	174 (59)	80 (-46)	98 (-20)	101 (-7)	100 (33)
	14-16	188 (172)	114 (10)	127 (17)	86 (-19)	100 (0)	128 (43)
MN	18	132 (46)	101 (2)	131 (9)	91 (-15)	31 (-92)	78 (-18)
	19	112 (25)	125 (16)	138 (11)	178 (60)	30 (-80)	46 (-40)
	20	42 (-21)	113 (36)	116 (12)	127 (33)	30 (-58)	15 (-64)
MN	21	84 (-12)	233 (130)	30 (-54)	53 (-2)	57 (20)	10 (-13)
	22	86 (-13)	173 (52)	313 (219)	115 (53)	91 (46)	14 (-14)
	23	89 (-23)	111 (-10)	45 (-52)	77 (17)	86 (32)	49 (15)
	24	75 (-19)	243 (155)	18 (-64)	21 (-34)	89 (53)	22 (1)
	25	69 (-38)	189 (74)	64 (-13)	47 (-17)	61 (16)	14 (-15)
	26	72 (-40)	183 (58)	160 (65)	80 (18)	64 (21)	21 (-9)
	27	84 (-14)	177 (56)	295 (201)	113 (50)	96 (51)	15 (-13)
	28	72 (-10)	266 (182)	50 (-35)	12 (-41)	74 (39)	26 (4)

† Monthly precipitation totals were obtained from the Utah Climate Center (http://climate.usurf.usu.edu).

Table 5.5. Significance of the *F* tests for the fixed effect of fertilizer N across 17 on-farm trials in Iowa during 1989 to 1991 and across three on-farm trials in Minnesota in 2011, and stover management (S), N, and their interaction across eight on-farm trials in Minnesota in 2012 on corn yield, aboveground plant N uptake, residual corn stalk NO_3–N, and residual soil NO_3–N. Interactions of the fixed effects with trial were evaluated with the two-tailed log-likelihood ratio test and significant outcomes of this test are noted in footnotes.

	Number	Source of	Yield			Residual NO_3–N‡	
Exp.	of trials	variation†	Grain	Silage	N uptake	Corn stalk	Soil
IA	17	N	<0.001§	-	-	<0.001§	-
MN	3	N	0.015	-	-	-	-
MN	8	S	0.639	0.542	0.185	-	0.105
		N	<0.001§	<0.001§	<0.001§	-	<0.001§
		S x N	0.015	0.100	0.004	-	0.004

† The 17 Iowa trials and three Minnesota trials in 2011 did not have stover management treatments.

‡ Corn stalk NO_3–N was measured only for 14 of 17 Iowa trials in 1989 to 1991. Residual soil NO_3–N is for the top 1.2 m of soil and was measured only in eight Minnesota trials in 2012.

§ The two-tailed log-likelihood ratio test for a given interaction between trial 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 trial.

Table 5.6. Parameter estimates, R^2 values, and model significance for linear and non-linear regression models relating fertilizer N application to corn grain and silage yields, corn stalk nitrate test (CSNT) concentration, aboveground plant N uptake, and residual NO_3–N (RSN) across on-farm trials conducted in Iowa and Minnesota. Trials not listed did not respond to fertilizer N except for trials 18, 19, and 20, which had a response of grain yield to N that did not significantly fit regression model.

Exp.	Dependent variable	Trials	Model†	Parameter estimates‡ $\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	X_0	R^2	Model significance
							kg N ha^{-1}		$P > F$
IA	Grain yield (Mg ha^{-1})	7, 11-12, 14, 16-17	QP	9.32	0.0195	-0.000050	211	-	***
	CSNT (mg kg^{-1})	7, 11-12, 14, 16-17	Q	0.246	0.00586	0.000037	-	0.42	*
		2-3, 8-10, 13, 15	L	0.955	0.0192	-	-	0.81	**
MN	Grain yield (Mg ha^{-1})	21, 26	QP	12.2	0.0500	-0.00027	93	-	***
		22-23, 28	QP	9.48	0.0378	-0.000080	237	-	***
	Silage yield (Mg ha^{-1})	21-23, 26, 28	QP	45.7	0.1080	-0.00021	256	-	***
	N uptake (kg N ha^{-1})	21-23, 26, 28	L	146.0	0.359	-	-	0.81	**
	RSN (kg N ha^{-1})	21, 26, 28	Q	15.3	0.00352	0.00115	-	0.66	*
		24-25, 27	L	42.0	0.317	-	-	0.76	*

*, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level.

† L, linear regression; Q, quadratic regression; QP, quadratic-plateau regression.

‡ $_{0,}$ intercept; $_{1}$, linear coefficient; $_{2}$, quadratic coefficient, X_0, fertilizer N rate at the junction of the linear or quadratic and plateau segments of the regression model.

§ The coefficient of determination is not listed for nonlinear regression models because residuals do not always sum to zero (Kutner et al., 2004).

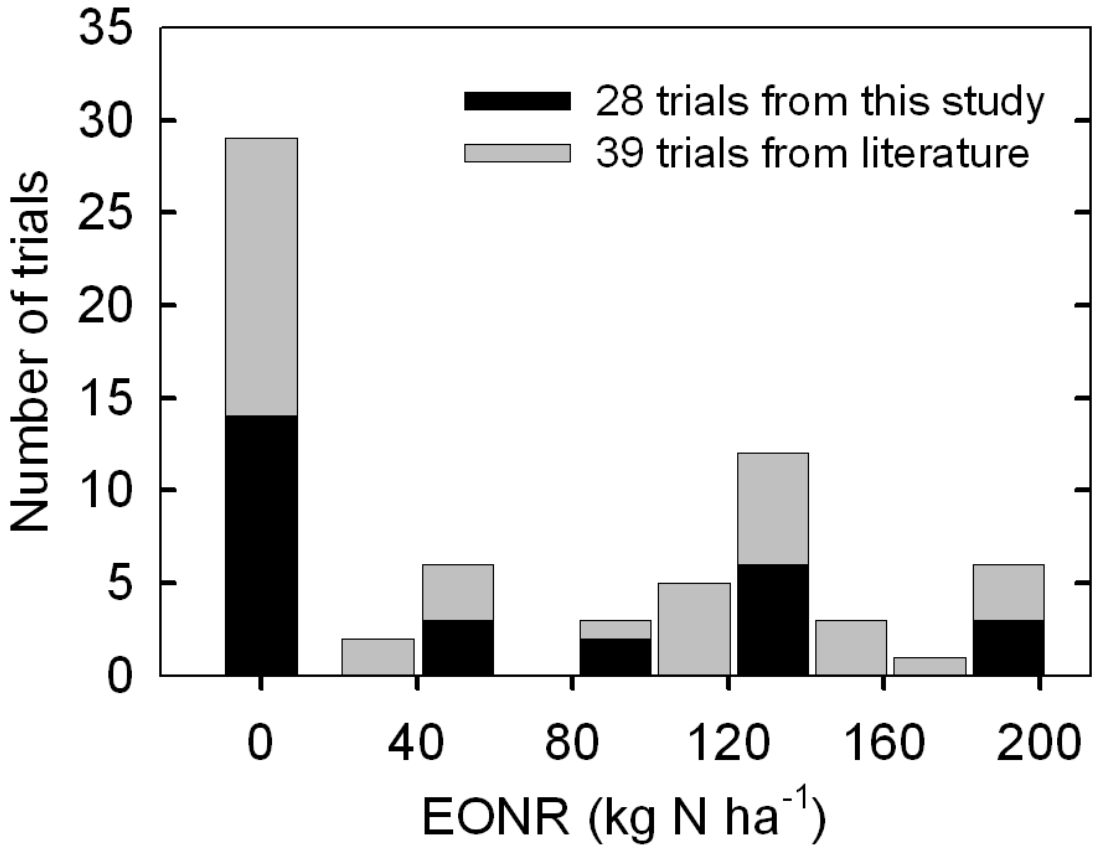

Fig. 5.1. Stacked histogram of the economically optimum N rate (EONR) based on the average fertilizer N cost/corn price ratio from 2009 to 2011 (\$1.19 kg N^{-1} as urea, USDA-ERS, 2013; \$183 Mg^{-1} corn grain, Center for Farm Financial Management, 2013) for 28 trials of second-year corn after alfalfa in this study and for 33 trials in the literature (Boawn et al., 1963; Levin et al., 1987; Fox and Piekielek, 1988; Moncrief et al., 1988, 1991; Aflakpui et al., 1993; Bundy and Andraski, 1995; Lory et al., 1995a; Randall and Vetsch, 1996; Schmitt and Randall, 1994; Andraski and Bundy, 2002; Katsvario et al., 2003) plus the corn silage EONR (\$1.19 kg N^{-1} and \$35 Mg^{-1} corn silage) for an additional six trials from the literature (Lawrence et al., 2009).

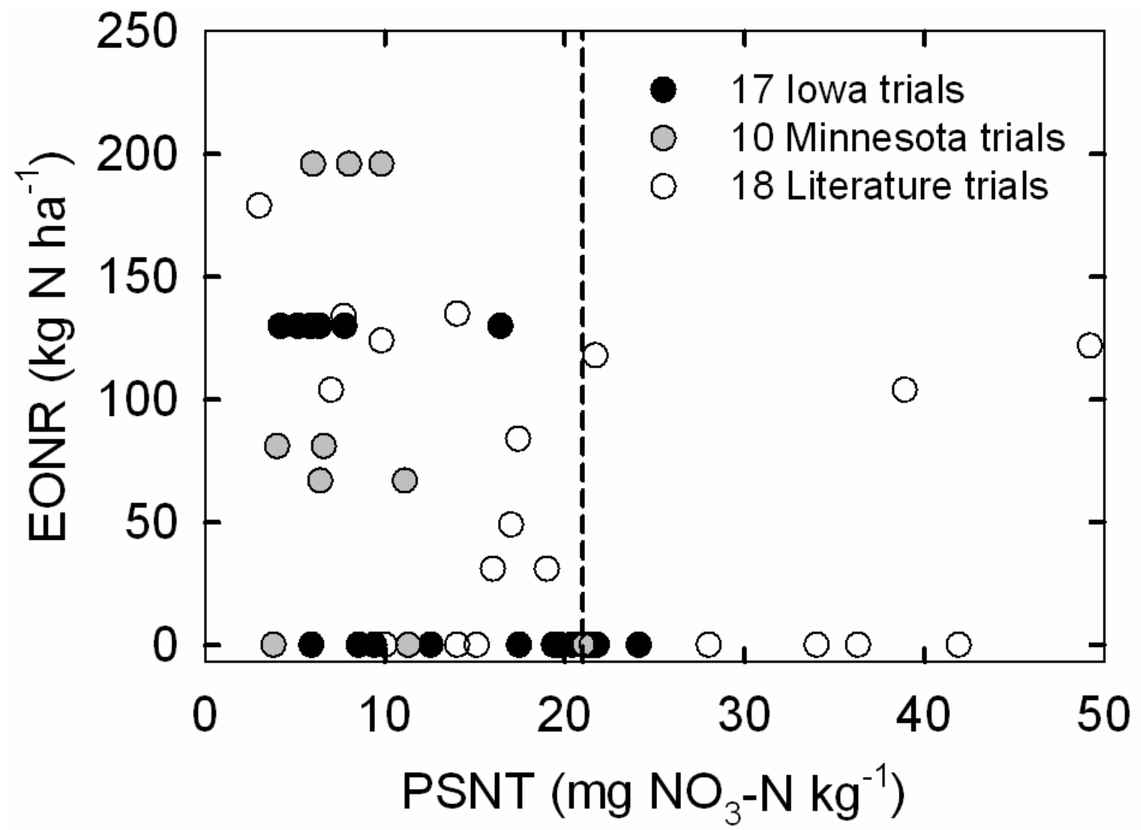

Fig. 5.2. Relationship between the presidedress soil nitrate test (PSNT) concentration and the economically optimum N rate (EONR) based on the average fertilizer N cost/corn price ratio from 2009 to 2011 (\$1.19 kg N^{-1} as urea, USDA-ERS, 2013; \$183 Mg^{-1} corn grain, Center for Farm Financial Management, 2013) for 27 trials of second-year corn after alfalfa in this study (solid symbols) and 21 trials from the literature (open symbols; Bundy and Andraski, 1995; Randall and Vetsch, 1996; Schmitt and Randall, 1994; Andraski and Bundy, 2002). The vertical dashed line represents the most widely accepted critical concentration of 21 mg NO_3–N kg^{-1} (Magdoff et al., 1984; Fox et al., 1989; Bundy and Andraski, 1995).

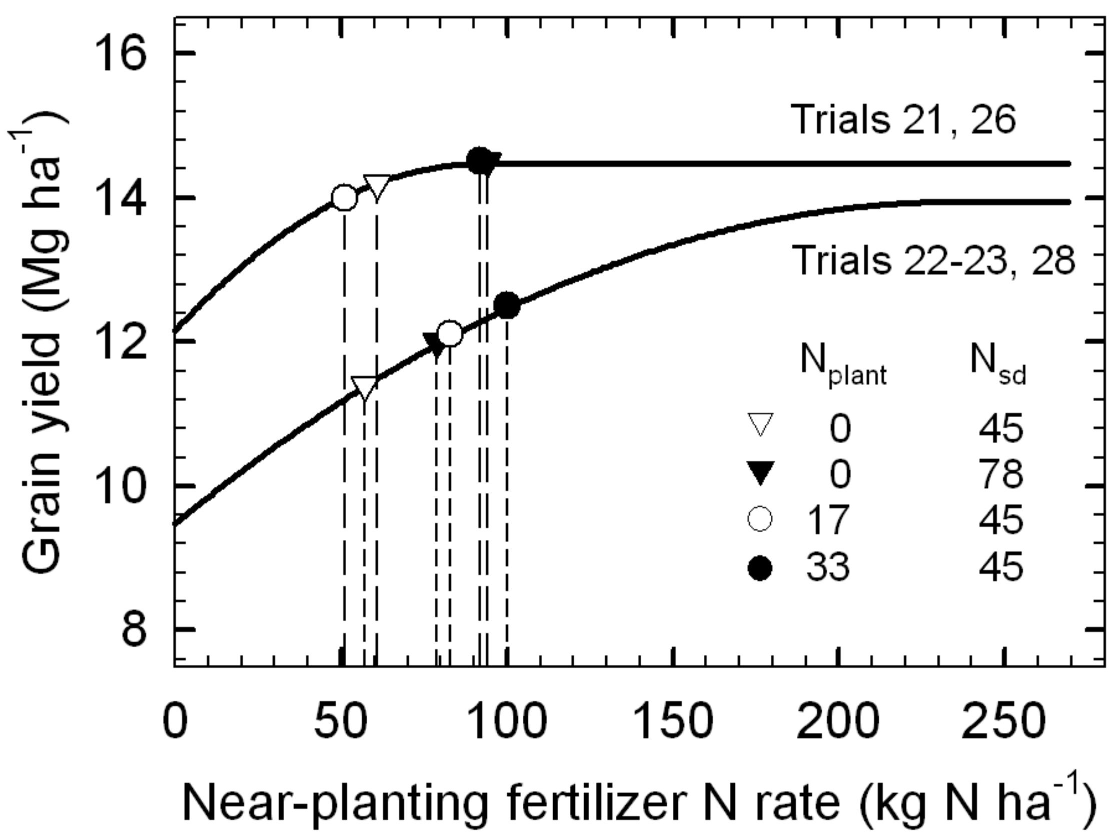

Fig. 5.3. The predicted fertilizer N equivalence of split (near planting [plant] and sidedress [sd]) and sd-only N applications to rates applied only near planting. Grain yield response to N applied only near planting was fit to quadratic plateau regression models (Table 5.6) for two groups of second-year corn trials in Minnesota in 2012 (trials 21 and 26, and trials 22-23, and 28) and these models were applied to grain yield from split and sidedress-only applications to estimate fertilizer N equivalence (at *x* for each drop line).

CHAPTER 6. Alfalfa-Annual Crop Rotation Patterns in the Upper Midwestern United States

INTRODUCTION

After corn, soybean, and wheat (*Triticum aestivum* L.), alfalfa is the fourth most widely grown and valuable crop in the United States in terms of hectarage and production value (USDA-NASS, 2013). From 2010 to 2012, USDA-NASS estimated that 7.6 million ha yr^{-1} of alfalfa was grown across the United States and that this production was valued at $7.5 billion. In addition to direct economic benefits of alfalfa production to the U.S. economy, alfalfa provides many environmental benefits to cropping systems (Olmstead and Brummer, 2008). During the alfalfa phase of crop rotations, soil quality and physical properties are often improved, in part because tillage does not occur in established alfalfa (Raimbault and Vyn, 1991; Russelle et al., 2006; Coulter et al., 2013). Other benefits of alfalfa in crop rotations include: i) soil NO_3-N losses that are much lower than crop rotations of corn and soybean only (Kanwar et al., 2005; Randall et al., 2007), in part because alfalfa provides continuous soil cover, requires no fertilizer N, and can extract soil NO_3-N to depths of at least 2.7 m without reducing biological N fixation (Kelner et al., 1997; Entz et al., 2001); and ii) weed seedbanks are often reduced and herbicide requirements are low for established alfalfa (Cosgrove and Barrett, 1987), except to eliminate noxious weeds from commercial hay (http://www.nawma.org/WeedFree.html).

Alfalfa also provides many benefits to subsequent crops. Alfalfa can reduce weed (Ominski, et al., 1999; Porter et al., 2003), pest, and disease pressure in following annual crops (Bullock, 1992; Pikul et al., 2005), which often leads to increased yield in subsequent crops. For example, grain yield of the first- and second-year corn following alfalfa often is at least 10% higher than adequately fertilized continuous corn (Crookston et al., 1997; Mallarino and Ortiz-Torres, 2006; Stanger and Lauer, 2008). One of the most widely documented benefits that alfalfa provides to subsequent crops is a large N supply. A recent literature analysis of 259 site-years concluded that the supplemental fertilizer N requirement of first-year corn following alfalfa was frequently eliminated or reduced (Yost et al., 2014a). Another summary of 67 site-years of second-year corn following alfalfa indicated that the second corn crop required supplemental fertilizer N in only one-half of the cases (Yost et al., 2014b). Wheat following alfalfa also benefits from the N supplied by alfalfa, but wheat can still require supplemental fertilizer N (Westerman and Crothers, 1993; Malhi et al., 2010), even though total N requirements of wheat are lower than corn. Wheat following alfalfa also can be sensitive to excessive N, which can increase lodging and reduce harvestable grain yield (Kelling et al., 2002). However, in water-stressed environments, wheat or other small grains following alfalfa may be preferable to corn due to lower water requirements (Pikul et al., 2005). The N benefit of alfalfa to subsequent crops is often severely underutilized when other N-fixing legumes such as soybean are grown as the two subsequent crops (Robbins and Carter, 1980; Meek et al., 1994).

Benefits of alfalfa in crop rotations are often dependent on the length of the alfalfa phase. For example, alfalfa phase length was related to the frequency and level of fertilizer N response in the first subsequent corn crop following alfalfa for most growing conditions (Yost et al., 2014a). Alfalfa phase length also affects net returns to alfalfa production, but optimal rotation lengths may vary by region. In Wisconsin and western Canada, 2- to 3-yr-old alfalfa stands (including the establishment year) maximized average annual net return during alfalfa production (Zentner et al., 1986; Barnett, 2006; Undersander and Barnett, 2008), whereas 4- to 5-yr-old stands were optimal in Manitoba (Jeffrey et al., 1993). Despite the importance of alfalfa phase length to N contributions to succeeding crops and overall alfalfa profitability, no geographic and only limited survey data exist on alfalfa phase lengths in agricultural fields in the upper midwestern United States (North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin), where about one-half (46% during 2010-2012) of the nation's alfalfa is produced (USDA-NASS, 2013). Additionally, no geographic data are available that describe patterns in which crops are grown following alfalfa termination. Patterns in the length of alfalfa production and in the succeeding crops may be related to geographic location, soil texture class, and year; both geographic location and year may reflect differences in crop market prices and weather patterns.

The USDA-NASS provides the most comprehensive estimates of crop hectarage in the United States, with agricultural census data collected every 5 yr and annual grower surveys. They also provide geographic annual crop hectarage estimates in CDLs by classifying satellite imagery into raster datasets of crop types with 30- or 56-m spatial resolution. With several years of CDLs now available for many states, crop rotation patterns can be examined. Recent studies have used CDLs to evaluate potato (*Solanum tuberosum* L.) production systems in Maine during 2008 to 2010 (DeFauw et al., 2012) and to monitor shifts from corn-soybean rotations towards increased monoculture cropping (four continuous years of either crop) of these two crops in the central United States during 2003 to 2010 (Plourde et al., 2013), but CDLs have not been used to examine rotation patterns of perennial and annual crops.

The objectives of this research were to: i) describe geographic trends in alfalfa phase length; ii) determine whether soil texture class is related to the length of the alfalfa phase; and iii) determine whether the length of the alfalfa phase, soil texture class, or year affect the crops grown during the 2 yr following alfalfa termination.

MATERIALS AND METHODS

Cropland data layers from USDA-NASS for six states (North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin) and 7 yr (2006-2012) were combined to analyze crop rotation patterns. Original raster CDLs were re-classified into six crop categories (alfalfa, corn, soybean, small grains, and other crops) and three other categories (noncropland, water, and a combination of perennial forages called ‘grass’) using Spatial Analyst of ArcGIS (ArcGIS 10.1, ESRI, Redlands, CA). The corn category included all types of corn, the small grains category included all major and minor small grains [all types of wheat, barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), millet (*Panicum liliaceum* L.), rye (*Secale cereale* L.), triticale (× *Triticosecale* Wittmack), spelt (*Triticum aestivum* L. emend. Thell.), and 'other small grains'], and the other crops category included all other field, fruit, and vegetable crop types classified in CDLs (http://nassgeodata.gmu.edu/CropScape/). Categories with two crops in a year (i.e., double cropping) were re-classified as the first of the two crops. All subsequent raster and vector data processing, smoothing, merging, selecting attributes, and mapping were conducted using ArcGIS.

In order to combine CDLs across 7 yr, CDLs with spatial resolution of 56 m (2006-2009) were split to 28-m resolution and then resampled at 30-m resolution with the nearest neighbor technique. The CDLs were generalized with two passes of an eight nearest neighbor majority filter to remove single or small clusters of pixels inside broader agricultural fields or other large areas. After generalization, CDLs from all 7 yr within a state were combined into a single raster using the Raster Calculator tool so that the crop category was identified for each of seven sequential years. The equation used to combine CDLs was: 2012 CDL + (2011 CDL x 10) + (2010 CDL x 100) + (2009 CDL x 1000) + (2008 CDL x 10,000) + (2007 CDL x 100,000) + (2006 CDL x 1,000,000). The combined 7-yr raster data were converted to vector data (polygons) for each state. Polygons with ≥1 yr of alfalfa and ≥0.5 ha in size were selected for further analyses of alfalfa phase length and following crop.

Hectares for each polygon were calculated by state using the World Geodetic System (1984) projected coordinate system for Minnesota and Iowa (Universal Transverse Mercator Zone 15 North) and for Nebraska, North Dakota, and South Dakota (Universal Transverse Mercator Zone 14 North), and the North American (1983) projected coordinate system for Wisconsin (High Accuracy Reference Network – Transverse Mercator). After hectares were calculated, the projected coordinate system of each state was changed to North America Lambert Conformal Conic using the 'North American Datum_1983 to High Accuracy Reference Network_Wisconsin' transformation for Wisconsin and 'North American Datum_1983_to_World Geodetic System_84_1' for the remaining five states in order to merge the six states into one shapefile.

Soil texture class attributes from the USDA-NRCS soil survey geographic database (Soil Survey Staff, 2011) vector data layer were categorized into three soil texture classes and spatially joined to CDL polygons. The coarse-textured category included sand and loamy sand soils. The fine-textured category included clay, clay loam, and silty clay loam soils. The medium-textured category included loam, silt loam, sandy loam, fine sandy loam, and sandy clay loam soils. Soils with a complex of multiple soil series were classified using the most prevalent soil in the complex.

Selection Methods

Two selection methods were used to determine alfalfa phase length and the crops grown for 2 yr following alfalfa termination. The first method for determining the length of the alfalfa phase was to select all polygons with ≥2 consecutive years of alfalfa that began with and were followed by a crop (corn, soybean, small grains, or other crops) for any set of years between 2006 and 2012. The ≥6 and ≥7 yr alfalfa phase lengths ended with alfalfa in 2012 and the ≥7 yr phase length began with alfalfa in 2006. This method is hereafter referred to as the 'generalized vector method.'

The second method, referred to as the 'adjusted vector method,' included all selections from the generalized vector method and followed the same set of rules for selecting a stand age, except that the category 'grass' was converted to 'alfalfa' if the probability of alfalfa being misclassified as grass was 10% higher than the reverse. The comparisons of alfalfa and grass probabilities were based on user's accuracy and commission error rates from USDA-NASS analyses with ground reference data by state (http://www.nass.usda.gov/research/Cropland/sarsfaqs2.html#Section1_11.0). For example, the user's accuracy of alfalfa in 2009 in North Dakota was 74% and the corresponding commission rate for grass was 19%. The probability of alfalfa being misclassified as grass for this example was calculated as 19 / (19 + 74) = 0.20. The product of probabilities for both types of misclassification was calculated for all combinations of two, three, or four consecutive years (2009-2012) of alfalfa or grass.

Probabilities could not be calculated for the 2006 and 2007 CDLs because full error matrices were not available from USDA-NASS. The full error matrix was available for the 2008 CDLs, but probabilities were not used for this year because USDA-NASS changed the definition of the 'alfalfa' category beginning in 2009 to include two additional types of alfalfa from USDA-Farm Service Agency reports (alfalfa-grass mixtures and alfalfa interseeded with small grains). Therefore, for the 2006 to 2008 CDLs, a single or double year of grass was converted to alfalfa if the majority of years for given alfalfa phase lengths were classified as alfalfa in generalized CDLs. For example, ‘grass’ in the code ‘corn-grass-grass-alfalfa-alfalfa-alfalfa-corn-corn’ for the 2006 to 2012 CDLs, respectively, were converted to alfalfa.

First- and second-year crops following alfalfa also were selected using both the generalized vector and the adjusted vector methods. First-year crops following ≥2 yr of alfalfa were selected for 2008 to 2012, and the same criterion was used for second-year crops in 2009 to 2012. In order to test the effect of alfalfa stand age on the type of following crop, the data were restricted to first-year crop in 2011 and second-year crop in 2012. Thus, first- and second-year crops following only 2- to ≥5-yr-old alfalfa could be determined for this analysis.

Statistical Analysis

Interactions between categorical variables were analyzed with chi-square statistics at $P \leq 0.05$ by state with $s \times r$ tables (Stokes et al., 2012) using the FREQ procedure of SAS (SAS Institute, 2006). Data were analyzed with alfalfa phase length and year as ordinal variables, and with selection method, soil texture class, and following crop as nominal variables. Spatial clustering in alfalfa stand age across the six states was evaluated with the Getis-Ord Gi* statistic at $P \leq 0.05$ using hot spot analysis in ArcGIS. The hot spot analysis was conducted with Euclidean distance as the distance method and fixed distance band as the conceptualization of spatial relationships; the default neighborhood threshold was set to 34,300 m.

RESULTS AND DISCUSSION

The user's accuracy was consistently high (91-99%) across years and states for row crops like corn and soybean, but was lower and more inconsistent for alfalfa in most states (30-95%; Fig. 6.1). Nebraska and Wisconsin had the highest user's accuracy for alfalfa across years (82-95%). Nebraska accuracy was high, likely because nearly one-third of alfalfa was irrigated compared to less than 4% in the other five states (USDA-NASS, 2013), making it easier to distinguish spectrally from other crops or noncropland. The high accuracy for Wisconsin may have been due to improved ground reference data, because a higher percentage of cropland was planted to alfalfa in Wisconsin than in the other states (USDA-NASS, 2013). For the remaining states, the lower accuracy of alfalfa classification relative to annual crops is a concern, especially because alfalfa is the fourth most widely grown crop in the nation. Overall, the lower accuracy for alfalfa is likely related to: i) difficulty in distinguishing alfalfa from other hay types, grassland, and pastures; ii) inadequate standards for determining how much alfalfa is necessary in a field to classify the field as alfalfa vs. other hay types or grassland; and iii) inadequate and inconsistent ground reference data from USDA-NASS and the USDA-Farm Service Agency for alfalfa, a non-federally-insured crop from 2006 to 2012.

Alfalfa hectares in original raster CDLs were severely under-represented in most years and states, compared to the USDA-NASS census/survey data, (Supplemental Table S6.1). Across the six states, only 38% of the alfalfa hectares in the census/survey were represented in original CDLs for 2006 to 2010. In 2011 to 2012, alfalfa hectarage estimates increased and 65% of the alfalfa hectarage in the census/survey data was accounted for in original raster CDLs. In contrast, hectarage estimates from original raster CDLs for corn and soybean were close to census/survey estimates across years and states (95 and 97% of census/survey hectares for corn and soybean, respectively).

To remedy the low classification accuracy of alfalfa in original raster CDLs, we generalized and converted the original raster to vector, and removed all polygons <0.5 ha in size. On average, the generalized vector CDL had two-thirds of the original raster CDL hectares across years in Nebraska and North Dakota and had one-half of the hectares in the remaining states (Supplemental Table S6.1). This decline likely occurred because: i) some alfalfa fields in original raster CDLs had more grass pixels than alfalfa, so the alfalfa field was generalized to grass; and ii) several alfalfa pixels in original raster CDLs were single or small clusters of pixels. Although generalized vector CDLs reduced alfalfa hectares, the number of alfalfa hectares were highly correlated to alfalfa hectares in original raster CDLs ($generalized = 18.0 + 0.458{*}original$, $R^2 = 0.92$, $P < 0.001$).

To further account for the lower classification accuracy of alfalfa in original raster CDLs, we adjusted generalized vector CDLs by converting some grass to alfalfa using classification error rates. This process increased alfalfa hectarage by 3 to 11% across years and states relative to generalized vector CDLs (Supplemental Table S6.1). Adjusted CDL alfalfa hectares also were highly correlated to the hectarage in original raster CDLs across years and states (*adjusted* = 25.8 + 0.451**original*, $R^2 = 0.92$, $P < 0.001$). For most cases, original raster, generalized vector, and adjusted vector CDLs were poorly correlated to the official census/survey alfalfa hectares, because representations of establishment year alfalfa and alfalfa/grass mixtures were inconsistent among years, states, and sources.

The effect of method (generalized vector vs. adjusted vector) was significant for alfalfa phase length in all states, but significantly affected the first-year crop type only in Minnesota and Iowa and the second-year crop type only in South Dakota (Fig. 6.2). The added alfalfa hectares and subsequent changes in alfalfa phase length from the adjusted vector method differed by state because adjustments were dependent on state and year classification error rates (Fig. 6.1). All alfalfa phase lengths were increased in states with lower alfalfa classification accuracy (North Dakota, South Dakota, Minnesota, and Iowa), whereas only longer alfalfa phases were affected in states with higher accuracy (4 to ≥7 yr phase lengths in Nebraska; ≥6 or ≥7 yr phase lengths in Wisconsin). In general, the proportion of longer alfalfa phases increased across most of the alfalfa production areas of the upper midwestern United States with the adjusted vector method (Fig. 6.3). Both selection methods resulted in all interactions for alfalfa phase length × soil texture class, alfalfa phase length × following crop, year × following crop, and soil texture class × following crop being significant at $P < 0.001$. Only the adjusted vector results are presented because the majority of results were consistent between methods and the adjusted vector method may partially remedy the relatively lower classification accuracy of alfalfa in original raster CDLs.

Alfalfa Phase Length

Geographic location. Alfalfa stands were maintained for ≤4 yr in a higher proportion of polygons in the eastern states of Iowa (82%), Wisconsin (67%), and Minnesota (62%) than in Nebraska (45%), South Dakota (38%), and North Dakota (12%) (Fig. 6.2), but there were significant differences within most states (Fig. 6.4). Shorter phases were typical in Iowa (except for the southern part of the state), the southeastern part of South Dakota, the eastern quarter of Nebraska, and nearly everywhere south of Interstate 94 in Minnesota. Longer alfalfa phases were typical across the entire state of North Dakota (except for the Red River valley), in western areas of South Dakota and Nebraska, and northern areas of Minnesota. Wisconsin had the greatest spatial complexity in alfalfa phase lengths, with three to four clusters of both shorter and longer alfalfa phases. The trend for longer alfalfa phases in some of the central sand plains of Wisconsin (http://wisconsingeologicalsurvey.org/geology/central_sand_plains.htm) may be partially related to a higher proportion of coarse-textured soils in that region relative to the remainder of the state. Coarse-textured soils may support longer alfalfa phases because the risk for soil compaction and disease may be lower.

Nearly a decade ago, a survey of 253 growers in Manitoba and Saskatchewan (Entz et al., 1995) found that forage (including alfalfa) phase length was dependent on climatic zone; phase lengths ranged from 3 to 5 yr in wet areas and from 6 to 9 yr in the driest areas. Their survey results also revealed that most growers did not rotate according to planned schedules but rather terminated forage when yield declined. A recent survey of 528 alfalfa growers in Minnesota confirmed these results; 98% of growers rotated alfalfa for reasons other than a planned schedule (Yost et al., unpublished data, 2013). Therefore, the patterns we identified in alfalfa phase length for the upper midwestern United States may be related more to climatic zones, which affect alfalfa productivity and over-wintering ability, and less to grower's sociological or crop management practices. Growers in the drier climates of this region (most areas outside the dominant Corn Belt) may be able to maintain alfalfa stands longer than wetter climates because the probability of soil compaction and alfalfa disease pressure can be lower for soils in drier climates. However, this analysis does not account for the complex weather variations within and among states that affect annual alfalfa productivity and winter-hardiness. Further analyses should determine the extent to which local weather affects alfalfa rotation frequency. Weather is not the only factor affecting alfalfa productivity and over-wintering ability; soil characteristics are also important.

Soil texture. Alfalfa phase lengths in the Dakotas and Iowa were relatively consistent for coarse- and medium-textured soils, but fine-textured soils had a higher frequency of shorter alfalfa phase lengths (Fig. 6.5). A similar trend occurred in Nebraska, Minnesota, and Wisconsin, with the exception that alfalfa phase lengths decreased with finer soil texture. Shorter alfalfa phases on fine-textured soils across states, coupled with survey results indicating that most growers do not follow planned crop rotations (Entz et al., 1995; Yost et al., unpublished data, 2013), suggests that fine-textured soils do not support alfalfa stands as long as medium- and coarse-textured soils. Machinery traffic required for multiple alfalfa harvests per year, together with the time pressure to remove hay from soils with greater water holding capacity (finer-textured soils; Hamza and Anderson, 2005) increases the likelihood of soil compaction, which often leads to decreased herbage yield and greater winter damage in alfalfa (Bélanger et al., 2005). Several other factors dealing with alfalfa management, such as variety winter-hardiness, fertilization, plant disease and pest tolerance, end use (feed on the farm or cash crop), hay market prices, other commodity crop market prices, and other sociological practices, likely affect alfalfa productivity and the rotation frequency in this region, but we do not have sufficient data to analyze how these complex factor interact with each other and with climate and soil conditions. Future research should seek to identify the most important factors regulating trends in alfalfa-annual crop rotation patterns.

First-Year Crops Following Alfalfa

Many of the complex interacting factors that potentially affect alfalfa rotation frequency also may affect the types of subsequent crops following alfalfa. Therefore, we defer extensive speculation about which of these complex factors regulated the types of first- and second-year crops that followed alfalfa in this region. Instead, we focus on statewide trends in crops that follow alfalfa to specify cumulative grower behavior, with the understanding that future research should identify reasons for these behaviors and how they might vary within and among states.

Corn was the most frequent first-year crop following alfalfa (61-92% of cases) in all states except North Dakota (40%). Soybean, which usually requires no supplemental fertilizer N (Salvagiotti, et al., 2008), was the first-year crop following alfalfa in 15% of the cases in the Dakotas, Minnesota, and Iowa. These results indicated that a substantial amount of growers in these states are underutilizing the large N supply from alfalfa. This analysis cannot determine why soybean was planted following alfalfa, but we suspect that it is related to water use requirements of soybean vs. other crops (Copeland et al., 1993). Future research should identify whether soybean as the first crop following alfalfa is economically and environmentally viable. Small grains were the first-year crop most frequently in the Dakotas (29% of the time) and Minnesota and Nebraska (10%), and North Dakota had the highest frequency of other crops as the first-year crop (8%).

Alfalfa phase length. Alfalfa phase length (2 to ≥5 yr) was significantly related to the type of first-year crop following alfalfa in 2011 across states (Fig. 6.6), with largest differences being found in North Dakota and Minnesota. In North Dakota, the longest alfalfa phase length was more frequently followed by soybean and corn, whereas shorter alfalfa phases were more frequently followed by small grains or other crops. In Minnesota, the frequency of small grains as the first-year crop following a 4-yr-long alfalfa phase was 31% compared to 7% frequency for the other phase lengths. There were smaller differences in first-year crop in the remaining four states, with small grains being slightly more frequent after longer alfalfa phases (4 or ≥5 yr) in South Dakota, Nebraska, and Iowa, and soybean being more frequent after shorter alfalfa phases in Nebraska. In Wisconsin, the frequency of other crops as the first-year crop increased by 5 percentage points when following 2-yr-long alfalfa phases compared to the other three phase lengths.

Soil texture. The first-year crop also changed with soil texture class (Fig. 6.6). In the Dakotas, the frequency of corn as the first-year crop was highest for coarse-textured soils; small grains were more frequent for finer textured soils. These trends likely occurred because much less alfalfa was grown on coarse-textured soils (4% of total hectares) than on other soil textures in these states. In Nebraska, soybean frequency as the first-year crop increased and small grains decreased in finer textured soils. Soil texture was less related to the type of first-year crop grown in Minnesota, Iowa, and Wisconsin. In Minnesota and Iowa, there was a higher frequency of corn and lower frequency of soybean on medium-textured soils relative to other textures and a slightly higher frequency of small grains and lower frequency of corn on coarse-textured soils relative to other textures in Minnesota. Wisconsin had a slightly higher frequency of small grains and lower frequency of other crops in medium- and fine- textured soils.

Year. The type of first-year crop was affected by the year in which the first-year crop was produced in all states, although differences were small in Nebraska and Wisconsin (Fig. 6.6). The frequency of corn as first-year crop decreased and other crop frequency increased in 2009 to 2011 for North Dakota. Corn frequency increased and small grains frequency decreased from 2008 to 2012 in South Dakota; the increase in corn frequency may be related to the increase in corn prices during this time period (USDA-NASS, 2013). Corn was grown as the first-year crop less frequently in 2009 and 2010 in Minnesota and Iowa compared to other years; soybean replaced much of these hectares in Iowa and small grains replaced much in Minnesota. It is likely that market prices of these crops influence the types of subsequent crops grown each year, but the spatial complexities in crop market prices and how they might influence grower's decisions about which crops to grow were not included in this analysis.

Second-Year Crops Following Alfalfa

Corn was the second-year crop following alfalfa in one-half to three-fourths of the cases in all states except North Dakota, where corn was the second-year crop in about one-third of the cases (Fig. 6.1). Soybean was the second-year crop in one-fourth to one-third of the cases in all states except Wisconsin, where soybean frequency was only 14%. The high frequency of soybean as the second-year crop following alfalfa in most states indicates that many growers may not be utilizing the increased N supply from alfalfa to the second-year crop; growing crops that require supplemental fertilizer N in these cases would utilize the 'free' N from alfalfa. Small grains were the second-year crop 5% of the cases in all states except North Dakota, where one-fourth of the second-year crop was small grains. North Dakota also had the highest frequency of other crops as the second-year crop (8%), and alfalfa was the second-year crop in 5% of the cases across states.

Alfalfa phase length. Second-year crop types in 2012 were affected by alfalfa phase length in each state (Fig. 6.7). Soybean frequency as the second-year crop in North

Dakota was higher when following alfalfa phases of ≥5 yr, and the frequency of alfalfa as the second crop increased for 4-yr phase lengths relative to the other lengths. In South Dakota, corn frequency increased from 38 to 53% when following alfalfa phases that were maintained for 3, 4, and ≥5 yr relative to 2 yr. The longest alfalfa phase in Nebraska had a higher frequency of other crops and a lower frequency of soybean than the shorter alfalfa phases. Corn frequency decreased for the longer alfalfa phases (4 and ≥5 yr) relative to shorter phase lengths in Minnesota. Second-year crops following 2-yr alfalfa phases in Iowa were more frequently soybean than after longer alfalfa phases, which were more frequently corn. The frequency of alfalfa as the second-crop was higher for shorter alfalfa phases (2 and 3 yr) in Wisconsin, and there was a slightly lower frequency of corn for the shortest alfalfa phases.

Soil texture. As with the first-year crop, the second-year crop following alfalfa was affected by soil texture class in each state (Fig. 6.7). In North Dakota, the frequency of other crops increased and corn frequency decreased as soil texture changed from coarse to fine. In contrast, coarse-textured soils in South Dakota had a higher frequency of corn and lower frequency of small grains than finer textured soils. These results were unexpected because coarse-textured soils have a lower water holding capacity than soils with finer texture and long-term fertilizer N rate trials in South Dakota indicated that when soil moisture is limited, the yield of first-year corn following alfalfa termination can be lower than corn in other rotations (Pikul et al., 2005). Conversely, increased irrigation on coarse-textured soils across South Dakota relative to finer-textured soils may explain why corn was more frequently grown as the first-year crop following alfalfa. As the soil texture changed from coarse to fine in Nebraska, soybean frequency increased, whereas the remaining crop types decreased in frequency. The frequency of corn as the second-year crop increased relative to other crop types for medium-textured soils in Minnesota and for coarse- or medium-textured soils in Iowa. Small grains frequency increased and other crops frequency decreased as soil texture changed from coarse to fine in Wisconsin.

Year. The types of second-year crops following alfalfa were affected by the year in which the second-year crop was produced in each state (Fig. 6.7). In North Dakota, Nebraska, and Minnesota, the frequency of corn as the second-year crop in 2010 and 2011 was lower relative to other years. North Dakota had a large increase in frequency of alfalfa as the second crop after alfalfa in 2011 (13 percentage points higher than other years) and soybean frequency decreased by 16 percentage points from 2009 to 2012. In South Dakota, there was a decrease in frequency of small grains with a corresponding increase in soybean frequency from 2009 to 2012. The frequency of other crops increased and small grains frequency decreased from 2009 to 2012 in Nebraska. Wisconsin had minor changes in all second-year crop types from year to year.

First- and Second-Year Crops Following Alfalfa

The eight most common sequences of both the first- and second-year crop following alfalfa were various combinations of corn, soybean, small grains, and alfalfa; sequences other than the eight most common are referred to as ‘secondary crop sequences' (Fig. 6.1). Two years of corn following alfalfa termination occurred in about one-fifth of the cases in the Dakotas, one-half of the cases in Nebraska, Minnesota, and Iowa, and about three-fourth of the cases in Wisconsin. Corn-soybean was the second most frequent two-year crop sequence following alfalfa termination in all states except North Dakota; this sequence occurred about one-fourth of the cases across states. As noted above, these data highlight the potential for better utilization of the N that alfalfa provides to the second subsequent crop by planting a non-legume crop in year two. The remaining six of the eight common sequences occurred in 0 to 17% of the cases across states. Secondary crop sequences were most frequent in Minnesota (15% of the time) and North Dakota (34%). These secondary crop sequences involved other combinations of corn, soybean, small grains, alfalfa, and other crops [most other crops in North Dakota and Minnesota likely were sunflower (*Helianthus annuus* L.), sugarbeet (*Beta vulgaris* L.), and potato].

Alfalfa phase length. Specific sequences of the first-year crop in 2011 and second-year crop in 2012 were affected by the preceding alfalfa phase length in each state (Fig. 6.8). In North Dakota, ≥5-yr-long alfalfa phases were followed less frequently by two years of small grains and secondary crop sequences than shorter alfalfa phases; these annual crop sequences were replaced mainly by increased frequency in corn-soybean and small grains-corn. South Dakota had a lower frequency of corn-corn, but no change in corn-soybean when following 2-yr-long alfalfa phases relative to longer phases, but the reverse occurred in Nebraska. In Minnesota, the frequency of corn-corn as following crops increased by 16 percentage points when following shorter alfalfa phases (2 and 3 yr) relative to longer alfalfa phases (4 and ≥5 yr), and the frequency of secondary crop sequences were variable among alfalfa phase lengths. Iowa had a lower frequency of corn-corn and a higher frequency of corn-soybean when following 2-yr-long alfalfa phases compared to longer phases. In Wisconsin, the frequency of corn-corn increased following 3- and 4-yr alfalfa phases relative to other phase lengths, and secondary crop sequences were more frequent following 2-yr phases relative to other phases.

Soil texture. Soil texture class also affected the frequency of specific 2-yr sequences of first- and second-year crops following alfalfa termination in each state (Fig. 6.8). The frequency of corn as both the first- and second-crop following alfalfa was higher in the Dakotas for coarse-textured soils relative to medium- and fine-textured soils. In Nebraska, the frequency of 2 yr of corn following alfalfa decreased and the frequency of corn-soybean increased as soil texture changed from coarse to fine. Minnesota and Iowa had similar trends in the frequency of corn as both subsequent crops; the frequency was higher for medium-textured soils than other soil textural classes. In Wisconsin, the frequency of secondary crop sequences decreased and the frequency of small grains-corn increased as soil texture changed from coarse to fine; otherwise the following crop types were relatively consistent across soil texture.

Year. The specific sequence of first- and second-year crops after alfalfa differed with year in each state, discussed here as the year of the second crop after alfalfa (Fig. 6.8). The frequency of corn-corn following alfalfa was lower for 2010 to 2011 compared to other years in North Dakota, Nebraska, Minnesota, and Iowa. In Minnesota and North Dakota, the lower frequency of corn-corn in 2010 to 2011 was replaced with a higher frequency of secondary crop sequences. In South Dakota, the frequency of corn-soybean increased and the frequency of small grains-corn and small grains as both following crops decreased from 2009 to 2012. In contrast, the frequency of secondary crop sequences increased from 2009 to 2012 in Nebraska. From 2009 to 2012 in Iowa, the frequency of corn-soybean as the following crops decreased by nine percentage points and soybean-corn increased by six percentage points. Wisconsin had a slightly higher frequency of corn-small grains in 2010 to 2011 relative to the other years, but was otherwise relatively consistent across years.

CONCLUSIONS

These are the first geographically-specific estimates that describe the broad scale behavior of crop rotation patterns of alfalfa and annual crops practiced by growers in the upper midwestern United States. Such spatial descriptions of alfalfa phase lengths and the first- and second-year crops that follow alfalfa in rotation should improve estimates of potential site-specific economic and environmental benefits of alfalfa in crop rotations, aid in planning of fertilizer need assessments for alfalfa and the crops that follow, and help focus the development of education and future research on crop rotation practices that maximize net return to alfalfa production and utilize the large N supply following alfalfa. Furthermore, these data may help improve water quality and soil erosion modeling at regional and watershed scales, promote more in-depth investigation of N cycling and loss when alfalfa is followed by crops other than corn, and support calculation of locally relevant crop production costs. This approach also may prove useful for examining rotation patterns of other annual and perennial crops. Future work should seek to identify and understand the complex effects of environmental, economical, and sociological factors on crop rotation patterns at large, spatial scales.

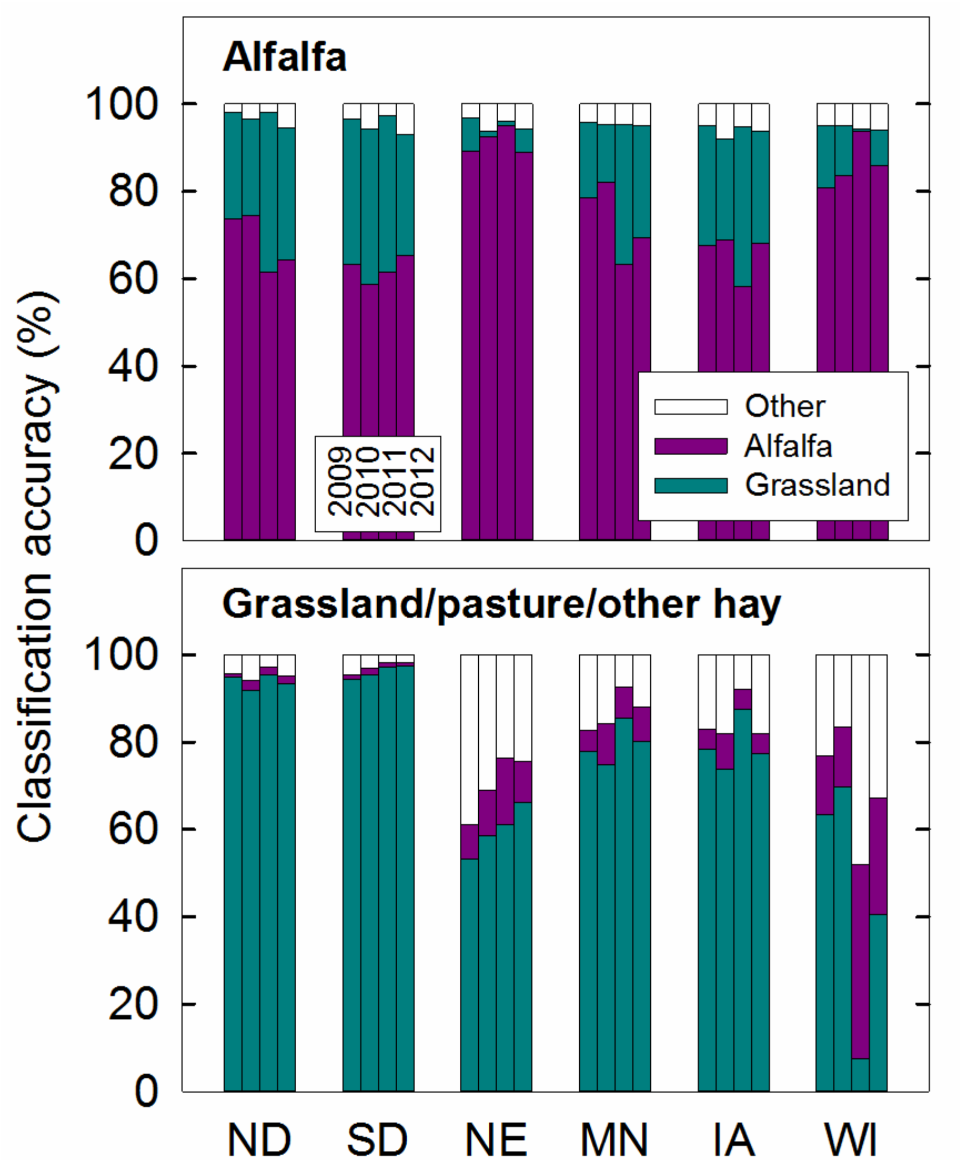

Fig. 6.1. The percent of the total pixels from original raster USDA-National Agricultural Statistics Service cropland data layers (2008-2012) that were correctly classified as either alfalfa (top) or grassland/pasture/other hay (bottom). User's accuracies and commission error rates were used to determine when to convert 'grass' to 'alfalfa' for the adjusted vector method described in text. Columns represent 2009 to 2012 in order from left to right within each grouping.

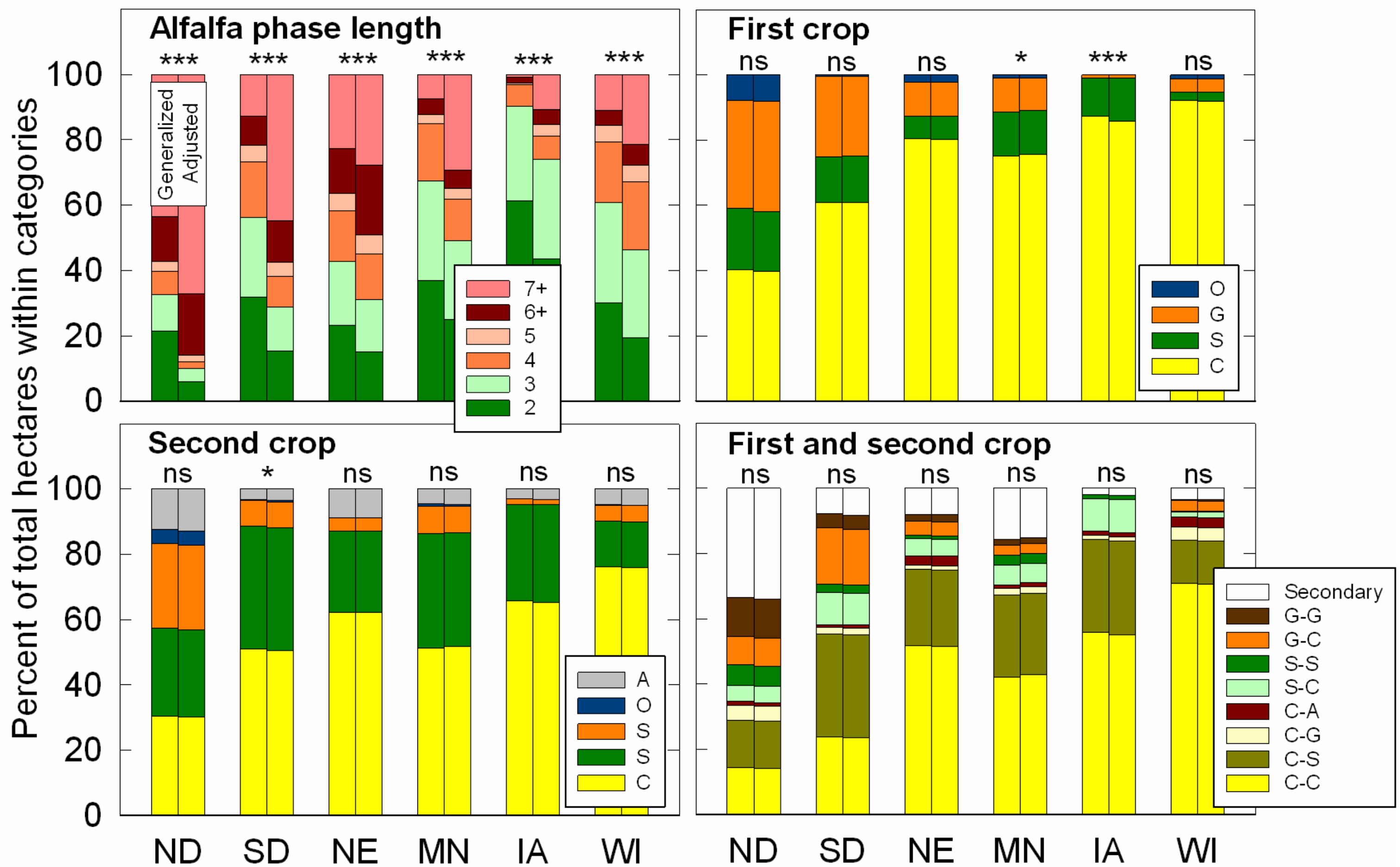

Fig. 6.2. The percent of the total hectares where alfalfa phase length (shading represents the number of years) could be determined from USDA-National Agricultural Statistics Service cropland data layers (2006-2012),

and the first-crop, second-crop, and specific first- and second-crop sequences [corn (C), soybean (S), small grains (G), alfalfa (A), other crops (O), and other secondary sequences of these crops] grown following alfalfa termination by state for two different selection methods described in the text (‘generalized’ vector results in the left-most column and ‘adjusted’ vector results in the right-most column). Differences in categorization between selection methods within states according to chi-squared tests were denoted with *, ***, ns for $P \leq 0.05$, ≤ 0.001, >0.05, respectively.

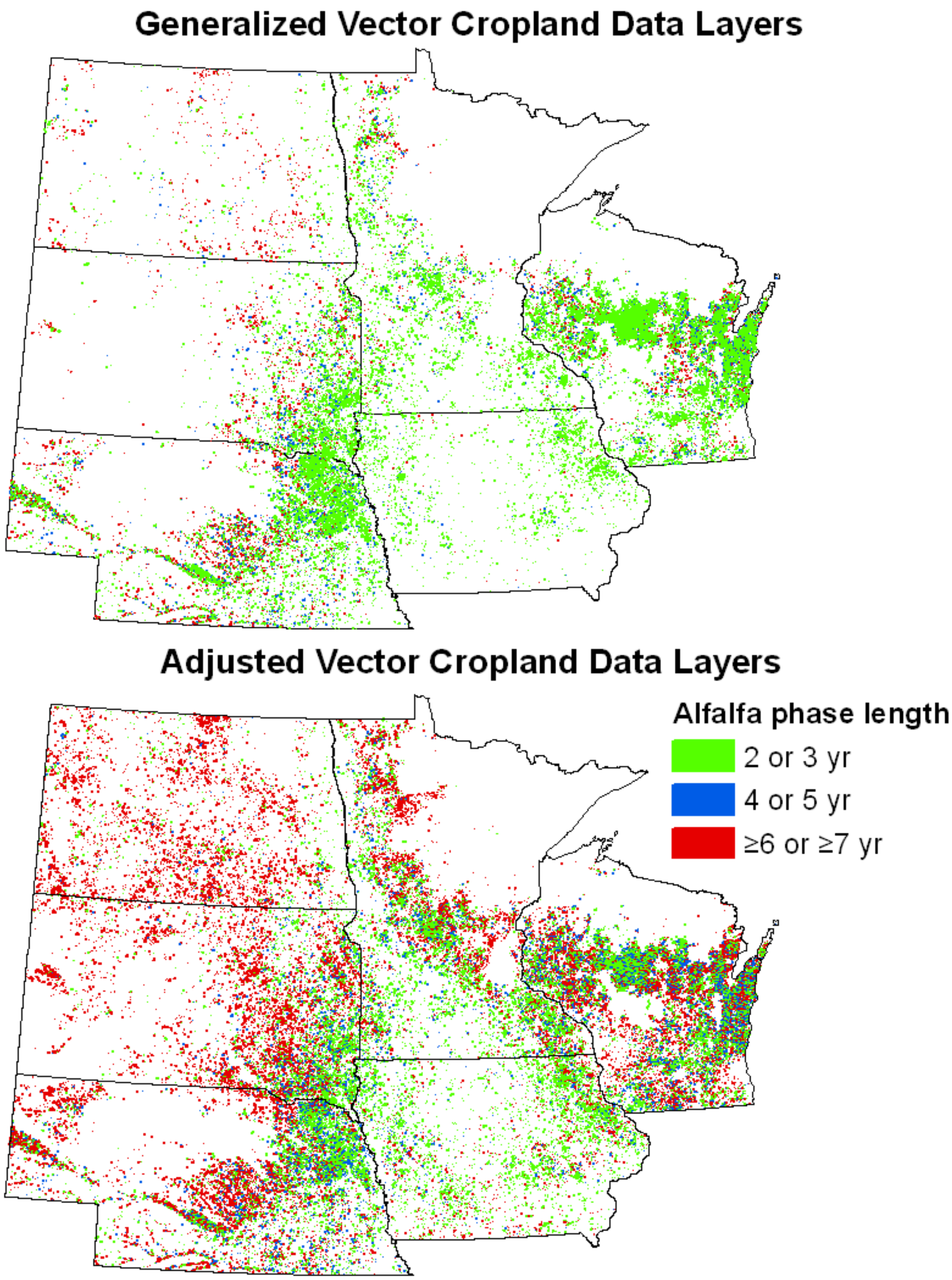

Fig. 6.3. Geographic location of polygons where alfalfa phase length (2 to ≥7 yr) could be determined from the generalized vector (top) and adjusted vector (bottom) USDA-National Agricultural Statistics Service cropland data layers (2006-2012). Polygons are enlarged to enhance visibility.

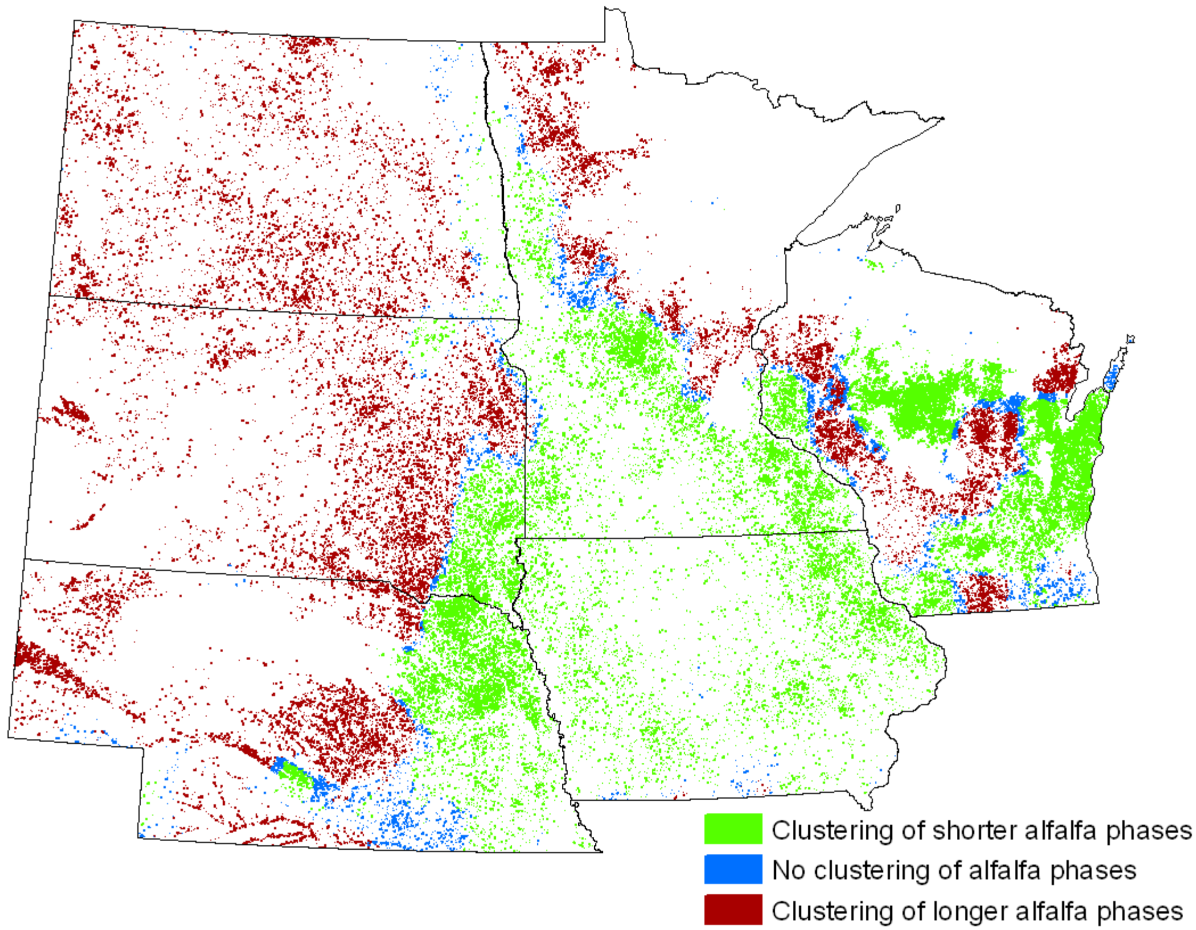

Fig. 6.4. Spatial clustering patterns of alfalfa phase length (2 to ≥7 yr) across the upper midwestern United States from the adjusted vector USDA-National Agricultural Statistics Service cropland data layers (2006-2012) according to Getis-Ord Gi* statistic at $P \leq 0.05$. Polygons are enlarged to enhance visibility.

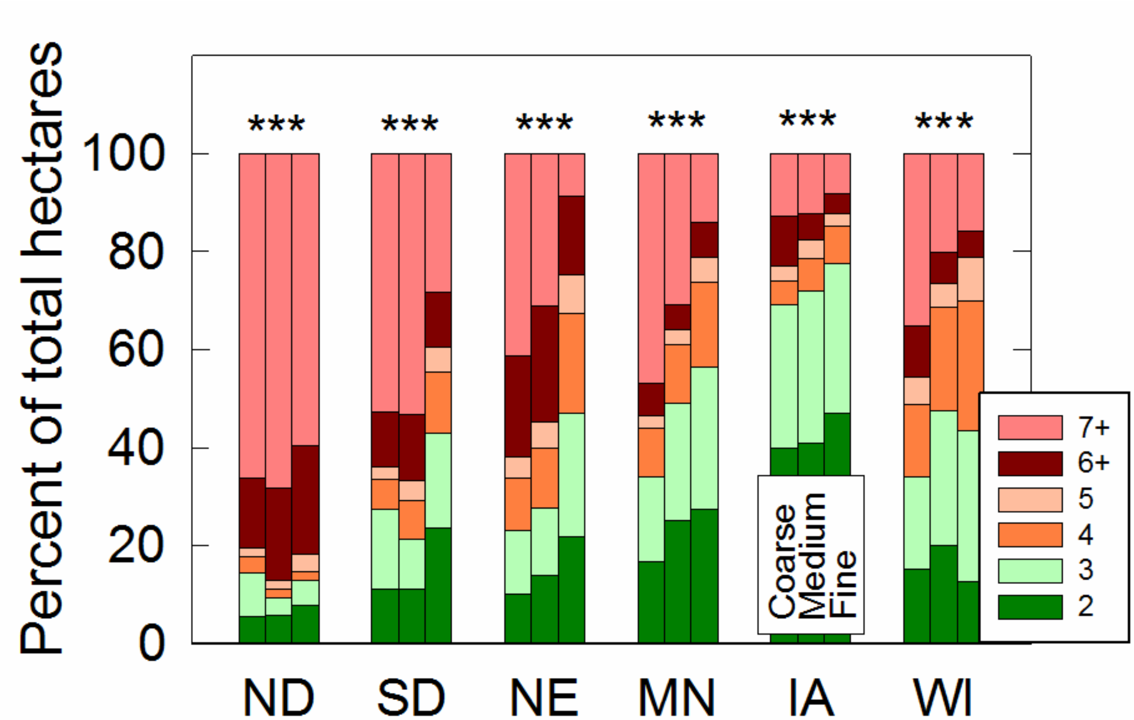

Fig. 6.5. The percent of total hectares where the phase length of alfalfa (shading represent years) could be determined from the adjusted vector USDA-National Agricultural Statistics Service cropland data layers (2006-2012) by state and soil texture class (coarse-, medium-, and fine-textured soils). Differences in alfalfa phase length categorization among soil texture class within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

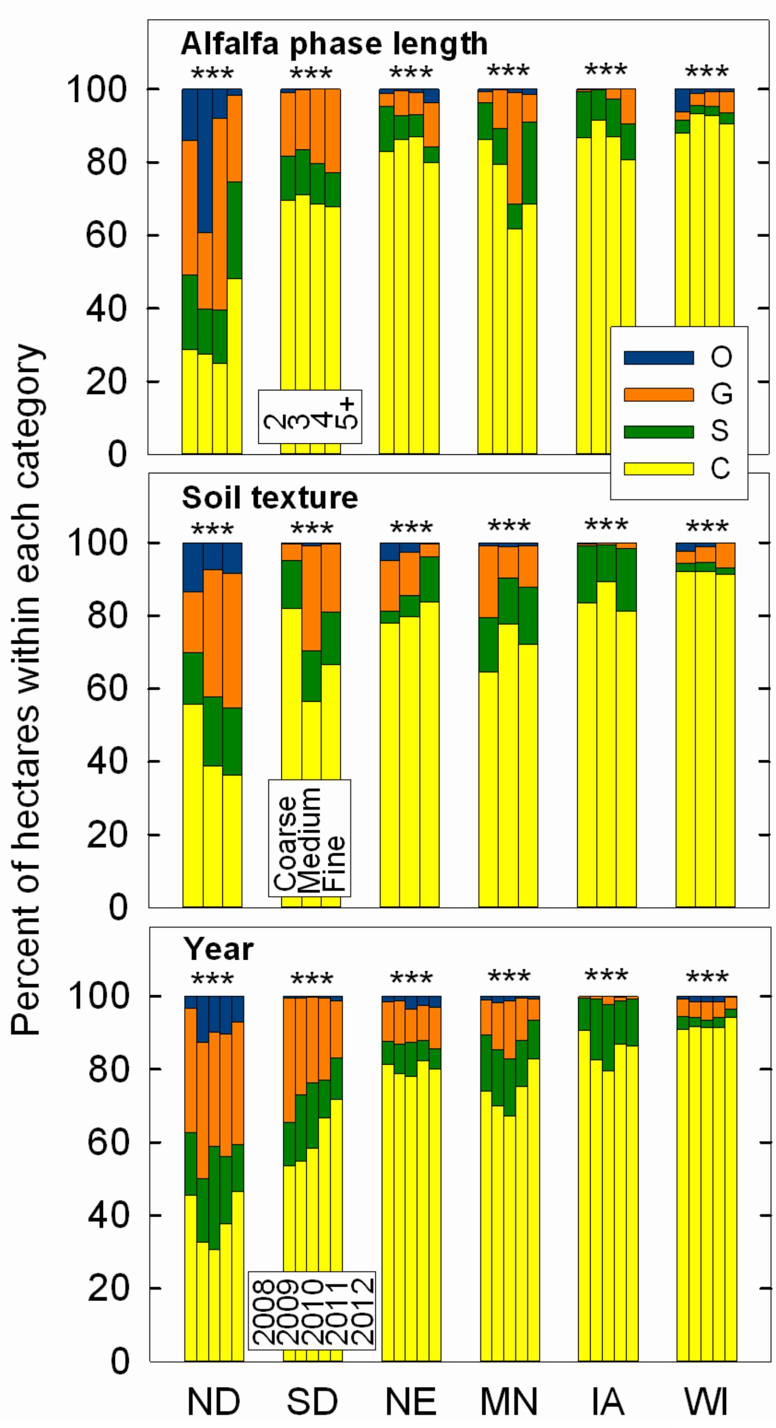

Fig. 6.6. The percent of the total hectares where the first-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector USDA-National Agricultural Statistics Service cropland data layers that were corn (C), soybean (S), small grains (G), or other crops (O) for each state by the length of the alfalfa phase (top graph, with lengths of 2 to ≥5 years proceeding from left to right in each group of columns), soil texture class (middle, with coarse-textured soils on the

left, medium-textured soils in the middle, and fine-textured soils on the right of each column group), and year when the indicated crops were grown (bottom graph, with years from 2008 to 2012 in sequence from the left-most column in each group). Differences in categorization among phase length, soil texture, and year within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

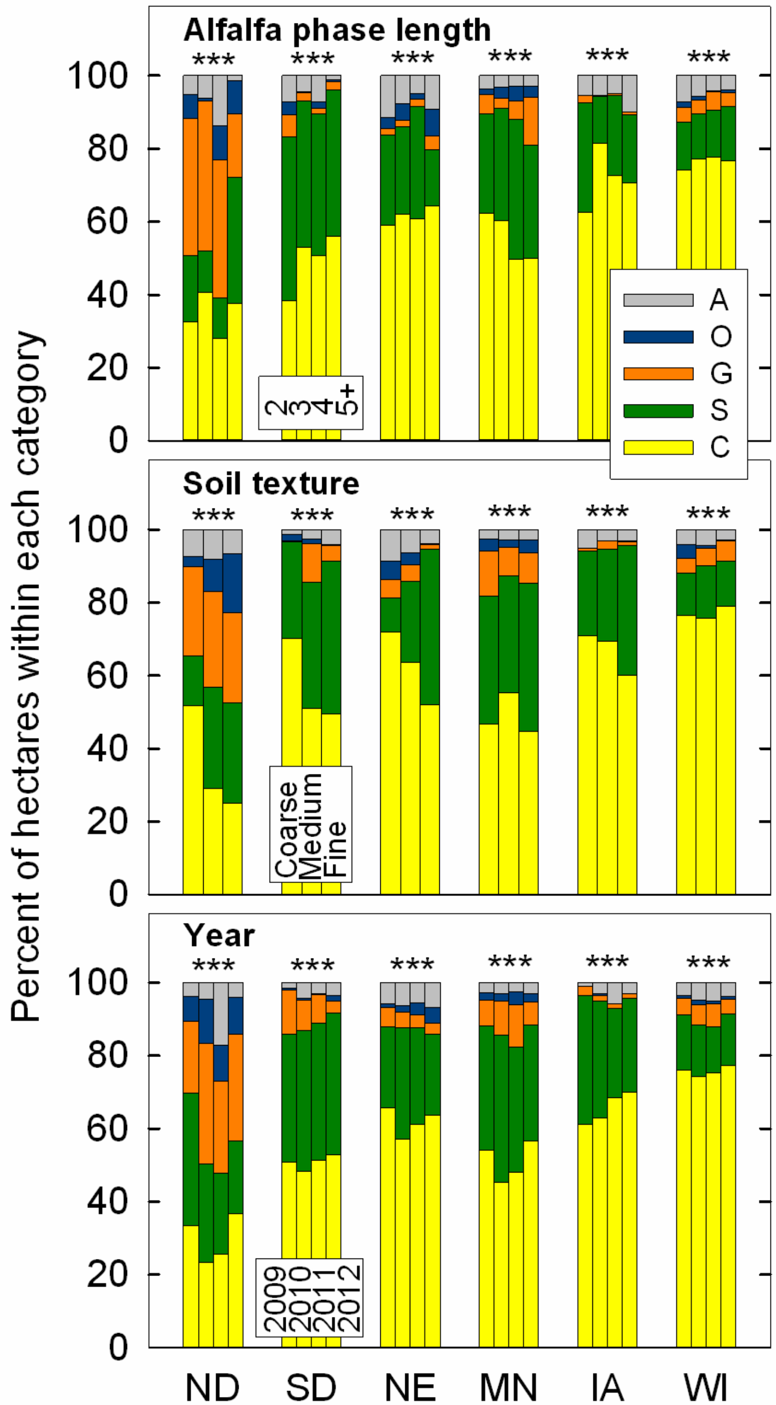

Fig. 6.7. The percent of the total hectares where the second-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector USDA-National Agricultural Statistics Service cropland data layers that were corn (C), soybean (S), small grains (G), other crops (O), or alfalfa (A) for each state by the length of the alfalfa phase (top graph, with lengths of 2 to ≥5 years proceeding from left to right in each group of columns), soil texture class (middle, with

coarse-textured soils on the left, medium-textured soils in the middle, and fine-textured soils on the right of each column group), and year when the indicated crops were grown (bottom graph, with years from 2009 to 2012 in sequence from the left-most column in each group). Differences in categorization among phase length, soil texture, and year within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

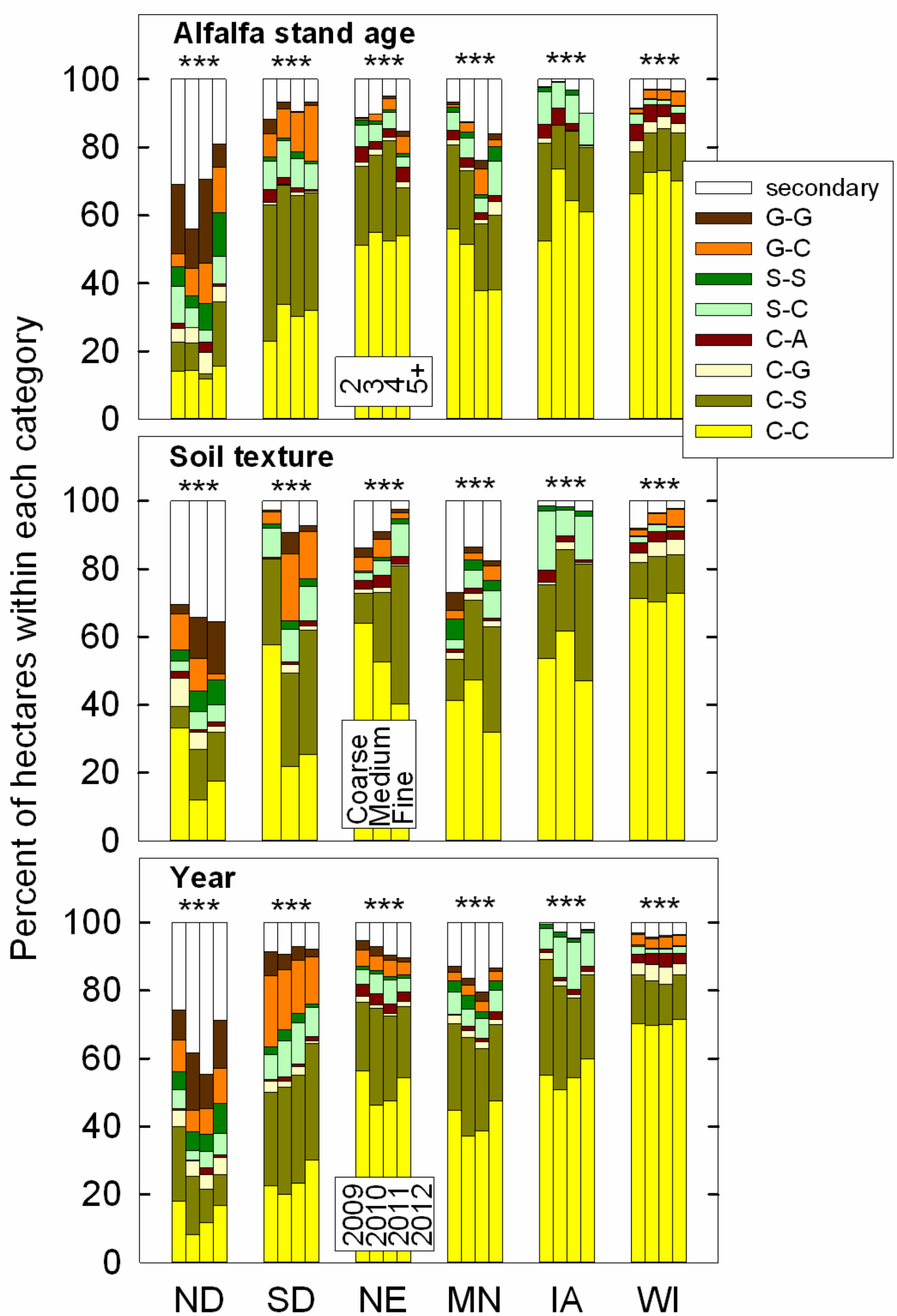

Fig. 6.8. The percent of the total hectares where both the first- and second-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector USDA-National Agricultural Statistics Service cropland data layers that were corn (C), soybean (S), small grains (G), alfalfa (A), or secondary combinations of these and other crops for each state by the length of the alfalfa phase (top graph, with lengths of 2 to ≥5 years proceeding from left to right in each

group of columns), soil texture class (middle, with coarse-textured soils on the left, medium-textured soils in the middle, and fine-textured soils on the right of each column group), and year in which the second-year crop was grown (bottom graph, with years from 2009 to 2012 in sequence from the left-most column in each group). Differences in categorization among phase length, soil texture, and year within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

CHAPTER 7. Nitrogen Management for First- and Second-Year Corn Following Alfalfa: A Summary

First-Year Corn Following Alfalfa

The results of seven on-farm trials indicated that alfalfa can provide the entire N requirement of first-year corn no-till planted following alfalfa termination in the fall. Results from eight on-farm trials demonstrated that manure N is not needed to increase grain or silage yield of corn following alfalfa when other soil nutrients are managed for optimal yield with fertilizer and soil pH is within the optimal range. Therefore, growers 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. The PSNT had limited success in identifying response to fertilizer N when trials from these two studies were combined with literature research; the test was accurate only 55% of 94 site-years. No accurate optimal CSNT range could be identified for 11 sites from these two studies plus 6 sites from previous research, because first-year corn following alfalfa had high relative yield and large variation in CSNT concentration at the EONR within and among locations. Based on these combined data, additional research or addition of other variables is needed before the PSNT or CSNT may accurately identify fertilizer N response in first-year corn following alfalfa.

A literature analysis conducted to identify site-specific conditions that cause first-year corn following alfalfa to respond to N indicated that soil texture was a significant covariate. On medium-textured soils, alfalfa termination timing also was a significant covariate. First-year corn following alfalfa rarely required fertilizer N when alfalfa harvested for ≥2 yr was fall-terminated on medium-textured soils; corn following alfalfa harvested 1 yr responded more frequently.. The frequency of response to fertilizer N increased greatly when alfalfa was grown on coarse- or fine-textured soils and when alfalfa was terminated in the spring on medium-textured soils. For these conditions, combinations of alfalfa stand age and weather conditions (air temperature and precipitation) explained much of the variation in whether a site would respond to N and the EONR at various PRs. Although the regression models developed to predict fertilizer N response appear robust, additional site-years of research are needed to include more weather conditions and to provide independent validation. Additional research is required to develop regression models to identify responsiveness to fertilizer N for first-year corn following alfalfa on coarse-textured soils and for first-year corn following young alfalfa stands (1-yr-old and 2-yr-old alfalfa not harvested in the first year) on medium- and fine-textured soils. Future research also should investigate whether alfalfa termination timing affects fertilizer N response in first-year corn on coarse- and fine-textured soils.

The geographic analysis of perennial-annual rotation patterns across six states (North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin) in the upper midwestern Unites States revealed that alfalfa is rotated more frequently within the dominant Corn Belt area than in other areas of this region. The analysis also indicated that corn is the most frequent first-year crop following alfalfa in all states except North Dakota and that the type of first-year crop following alfalfa is affected by the length of the preceding alfalfa phase, soil texture, and year in all states. This geographic analysis could be used to further evaluate the application of the regression models developed from the literature analysis. Furthermore, spatial descriptions of alfalfa-annual crop rotations should improve estimates of: i) potential site-specific economic and environmental benefits of alfalfa in crop rotations, ii) water quality and soil erosion modeling at regional and watershed scales; iii) investigations of N cycling and loss when alfalfa is followed by crops other than corn; iv) locally relevant crop production costs; and v) future education and research needs for crop rotation practices that maximize net return to alfalfa production and utilize the large N supply following alfalfa

Second-Year Corn Following Alfalfa

The results from 28 on-farm trials in Minnesota and Iowa revealed that second-year corn required no fertilizer N one-half of the time. The same trend occurred when these trials were combined with 39 trials in the literature. First-year corn residue removal had minimal impact on the fertilizer N response of second-year corn following alfalfa. Sidedress fertilizer N application to second-year corn was sometimes more efficient at increasing grain yield than N applied only near planting. Future work should identify which site-specific conditions cause sidedress N to be more efficient. Research is also needed to determine how the EONR differs between at-planting and sidedress applications, because most studies on fertilizer N efficiency have not used enough N rates to simultaneously determine the EONR for multiple N application timings. The PSNT had higher accuracy at predicting responsiveness to fertilizer N for second-year corn (65%) than for first-year corn, but the low accuracy for both corn crops following alfalfa indicates the need for further work. Future research also should identify site-specific conditions that cause second-year corn following alfalfa to require supplemental fertilizer

N. Factors affecting second-year corn following alfalfa response to fertilizer N are likely to be similar to factors causing response to N in first-year corn.

The geographic analysis of second-year crops following alfalfa in the upper midwestern Unites States revealed that in states other than Wisconsin, corn is the second-year crop one-half of the time or less. These results highlight the need for further research and education about the large N supply from alfalfa to the second, subsequent crop. In most states, soybean was the second crop following alfalfa one-third of the time, indicating that second-year alfalfa N supply may be underutilized. This geographic analysis could be used for a variety of other applications concerning improvements in alfalfa production and rotation practices and examining rotation patterns of other perennial and annual crops.

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