Identification of Nitrogen Management Categories by Corn Stalk Nitrate Sampling Guided by Aerial Imagery

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Nitrogen Management

ABSTRACT

Past studies on N management in corn (*Zea mays* L.) have shown insurmountable difficulties predicting N supply from soil and fertilizer sources. New tools are needed for collecting feedback about the N status of corn from large areas at a low cost. We used adaptive management to compare major N management practices by organizing many grower groups across Iowa and conducting a guided corn stalk nitrate survey of 683 fields in 2006 and 824 in 2007. Aerial images of corn canopy taken in late August were used to select three sampling areas, one within each predominant soil type within a field. Ordinal logistic regressions (OLRs) were used to calculate the cumulative probability of a stalk sample to test in a higher stalk test category and to identify important factors affecting stalk test values. The analyses revealed significant differences in corn N status among management categories based on combinations of forms and timing of fertilizer and manure applications, previous crop, and soil drainage classes. In both years, fields receiving spring anhydrous ammonia (AA) were more likely to test higher than fields receiving fall liquid swine (*Sus scrofa*) manure (LSM), spring urea-ammonium nitrate (UAN) solution, or fall AA. The large amounts of rainfall in June 2006 and cumulative spring rainfall in 2007 significantly decreased the likelihood to test in a higher stalk test category. A guided corn stalk nitrate survey as part of an adaptive management program allows documenting relatively efficient management practices within large areas of spatially variable soils and rainfall patterns.

Nitrogen management in corn production has been intensively scrutinized since the 1990s. The scrutiny has involved economic and environmental issues, energy and sustainability considerations, and more recently nutrient management regulations. However, N management is a challenge because much of the research has shown insurmountable difficulties predicting N supply from the soil and fertilizer sources.

Soils in the Midwest of the United States usually supply more than half of the N needed for producing maximum corn yields (Martens et al., 2006; Sanchez and Blackmer, 1988), but estimating this N supply is difficult because of unpredictable effects of weather on soil microbial activity and soil N availability (Jansson and Persson, 1982; Mulvaney et al., 2001). For example, soil moisture content, one factor alone, has a large influence on N availability in the soil by affecting rates of mineralization of soil organic matter, corn growth and development, timing and rate of N uptake by plants, and by promoting losses of N through leaching and denitrification. Our knowledge about the effect of site-specific soil and weather factors on N availability is limited (Kay et al., 2006; Sogbedji et al., 2001). The problem is complicated by the lack of reliable and practical methodologies for quantifying factors that affect N availability on both temporal and spatial scales (Hatfield, 2000). Transferring N availability research data into a N recommendation is further complicated by the assumption built into N recommendations that management practices (e.g., form and timing of N applications) perform equally in a wide range of weather and soil conditions. Classifying N response data into management categories based on factors known at the time of fertilizer application has been suggested as a possible approach to minimize variability in economic optimum N rates and to improve N fertilizer recommendations (Kyveryga et al., 2007).

Management practices known to have large effects on N availability include previous crop (Blackmer et al., 1997), timing of N fertilization (Scharf et al., 2002; Vetsch and Randall, 2004), and methods of application (Fox et al., 1986; Stecker et al., 1993). Previous crop is the only practice commonly used to adjust N recommendations in the Corn Belt. Establishing relationships between management practices and N availability to form N management categories requires a large number of observations. For example, 54 replicated small-plot trials were not sufficient for establishing a reliable relationship between N availability and the previous crop in a corn–corn and corn–soybean rotation (Kyveryga et al., 2007).

The number of N management categories commonly used by growers in Iowa is at least 27, and the categories are combinations of three times of N application (fall, spring, or sidedress), three forms of N (AA, urea-ammonium nitrate solution [UAN], or granular urea), and three methods of application (broadcast,

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Abbreviations: AA, anhydrous ammonia; CSR, corn suitability rating; LSM, liquid swine manure; OLR, ordinal logistic regression; SD, sidedress; UAN, urea-ammonium nitrate solution.

injected, or dribble). When N management categories include manure applications, the number of categories becomes too large and too expensive for traditional small-plot research methods. The traditional small-plot research also would not typically be completed at enough different locations to account for variability in weather and soil conditions. New methods are needed to describe and quantify N availability to corn if scientists are to develop more reliable N recommendations.

Adaptive management may provide ways to describe and quantify the variability in N availability in corn fields. Adaptive management was first developed to describe and manage variability in complex forest and water ecosystems (Holling, 1978; Lee, 1993) caused by human and environmental factors. The concept of adaptive management is based on two main ideas. One is that complex systems need to be managed in iterative cycles of action, which include choosing one management action from many alternatives, monitoring and evaluating results of that action, and using feedback from the evaluations to create and implement a new action. The other main idea is that users of recommended practices developed from data collected in the iterative cycles of action, in our case growers, need to be included as colleagues in the adaptive management process. The end users need to understand the rationale for new recommended practices if the end users will be expected to adopt the new practices.

The EPA 2008 Science Advisory Board Report stressed the importance of adaptive management as part of an overall strategy to reduce N loads to the Gulf of Mexico (http://www.epa.gov/msbasin/actionplan.htm, p. 120–123). A critical component of an adaptive management program is feedback from evaluation of results. One way to improve N recommendations is to use feedback about the accuracy of the recommendations as part of a systematic process for developing and refining recommendations. Current N fertilizer recommendations are not designed to use feedback for improving the recommendations with time. Even one of the most innovative N recommendation systems based on a large number of research trials (Sawyer et al., 2006) does not specify collecting feedback information to improve the recommendation.

The end-of-season corn stalk nitrate test can provide reliable feedback information of corn N status (Brouder et al., 2000; Fox et al., 2001; Wilhelm et al., 2005). The test is based on measuring stalk nitrate concentration in the lower portions of corn plants. The test has been calibrated to express N sufficiency as four categories: deficient, marginal, optimal, and excessive (Binford et al., 1990, 1992). The stalk nitrate test was used in a recent survey of >3200 fields over 12 yr in two major watersheds in Iowa. The results showed that the stalk nitrate test can effectively identify major factors affecting N availability in large-scale studies (Balkcom et al., 2003). The study identified spring rainfall as the primary factor influencing N availability and losses of nitrate to two rivers in Iowa. However, only a few factors were considered and the relationship between stalk nitrate values and rainfall data were studied only for the data averaged over the years of the study and for individual years, and not for individual fields.

Precision farming technologies, remote sensing, and aerial imagery are other relatively new tools to collect feedback information of the N status of many corn fields. Aerial images taken at the end of the growing season can guide sampling for the corn stalk nitrate test (Blackmer and Kyveryga, 2008). Stalk nitrate results collected in this manner could be used to identify N management categories at a relatively low cost when used in an adaptive management program with corn growers. The growers would provide management histories of their fields and help interpret the spatial patterns observed on the imagery.

The objective of this study was to identify major factors affecting N supply to corn as measured by nitrate–N concentrations in lower corn stalk sections collected from many fields and groups of growers across Iowa. Specifically, we estimated relative differences between N management practices (categories) commonly used for corn at different scales (across Iowa and within the Des Moines Lobe Landform Area) based on a survey of the N status of corn fields using aerial imagery and information about soil types from Soil Survey maps to guide the collection of samples for the corn stalk nitrate test.

MATERIALS AND METHODS

A survey of the N status of corn fields in Iowa was conducted during 2006 and 2007 by collecting samples of lower corn stalk sections at the end of the season (Binford et al., 1990, 1992). The target population of the survey was all corn fields that represented major N management practices in Iowa based on timing, forms, and method of N fertilizer and manure applications. The sample population consisted of 683 fields sampled in 2006 and 824 fields in 2007 (Fig. 1). The fields were located in nearly all counties in each year and selected based on the interest of participating growers or based on locations of customers associated with independent crop consultants or agronomists from local cooperatives. The fields in the latter case were often clustered in groups, which ranged from 20 to 60 fields located in one or more counties.

Potential participants (growers, crop consultants, or agronomists) were identified 2 or 3 mo before stalk sampling by sending survey forms to the potential participants. The exact field locations were identified on legal maps that show land ownership based on growers' descriptions, or the locations were based on field boundaries created using Google Earth (Google Inc, Mountain View, CA) or ArcView 3.3 software (Environ. Syst. Res. Inst., Redlands, CA).

The spatial files (i.e., shapefiles generated using GIS software) showing field boundaries were used to develop a flight plan for taking color-infrared digital aerial images of the fields in late August or early September of each year. This time for image collection was selected because spatial patterns in corn N stress within fields are often the most pronounced as corn plants deplete the supply of N from the soil and fertilizer toward the end of the growing season (Blackmer and White, 1998). The images were taken from a height of about 2400 m above the ground with four-band digital cameras with about 1-m resolution. The wavelengths captured included: the blue band (410–490 nm), the green band (510–590 nm), the red band (610–690 nm), and the near-infrared band (800–900 nm). The cameras were 12-bit but the images were converted to 8-bit data. Several images were taken for each field along the flight path and then the images were mosaiced into one photo. The image mosaics were orthorectified by using the USGS 7.5 min digital elevation models.

Each image was overlaid with digital soil maps downloaded from the Iowa Cooperating Soil Survey (2003) using ArcView 3.3. The green band was used to separate the variability in corn N stress (yellow corn) from the variability created by other management factors such as fertilizer and manure applicator skips or double fertilizer applications, different hybrids, weed

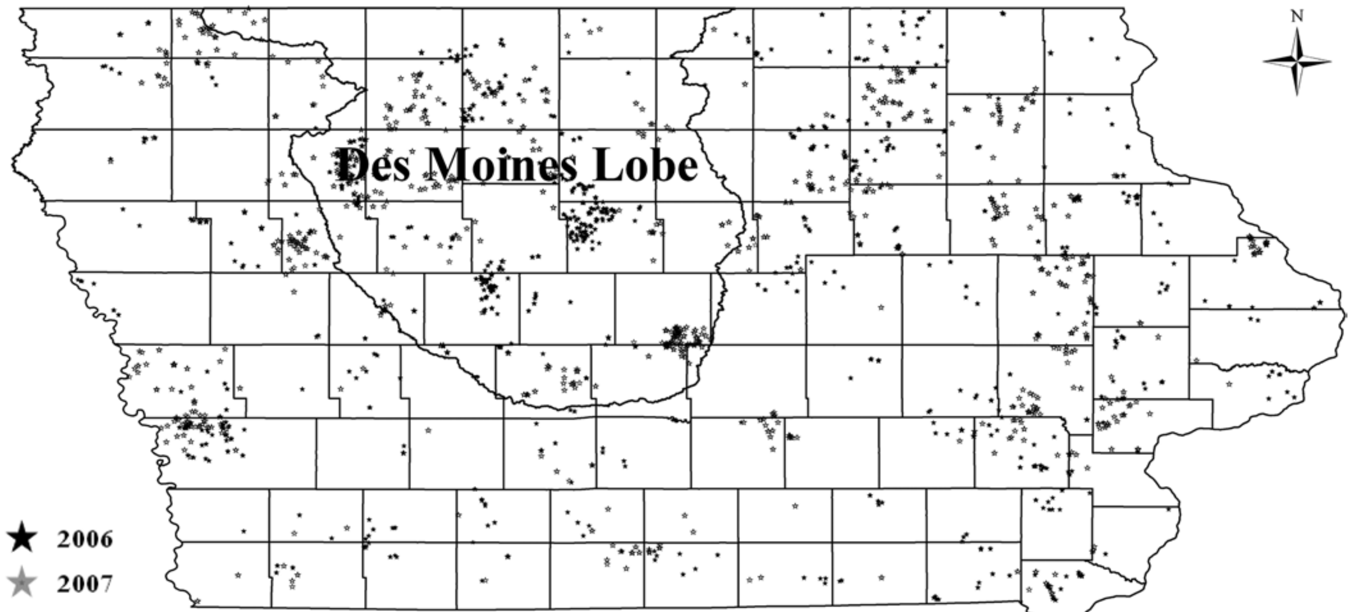

Fig. 1. Locations of 683 corn fields in 2006 and of 824 in 2007 sampled in a guided corn stalk nitrate survey in Iowa.

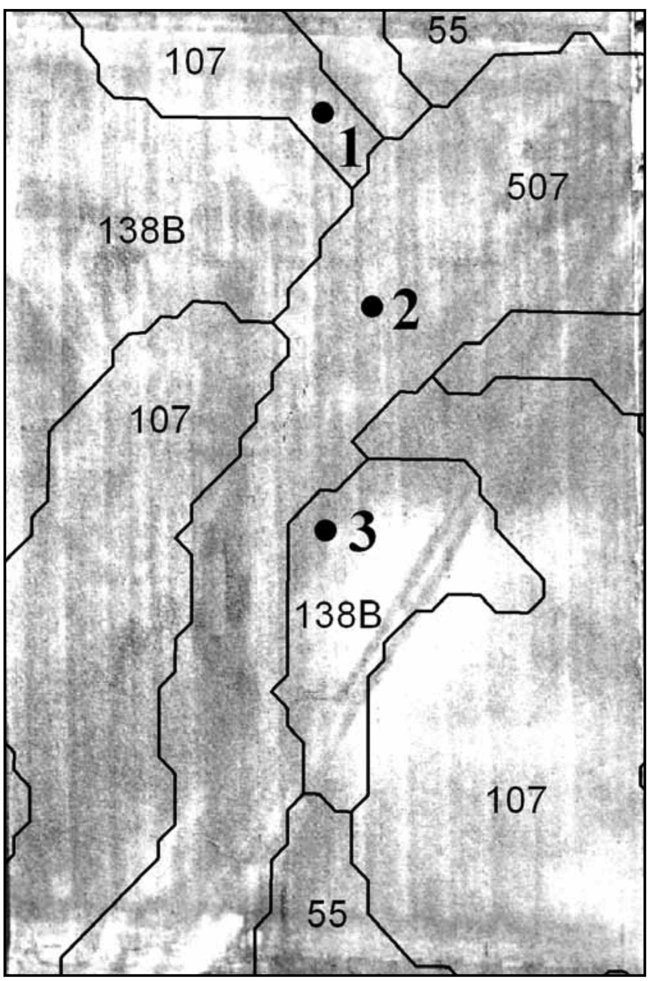

Fig. 2. Schematic illustration of a corn field with three predetermined sampling areas for taking corn stalk nitrate samples located within three predominant soil types within the field, and selected based on color aerial imagery (green band reflectance here) of corn canopy taken in late August or early September. The sampling areas were located with the help of a handheld GPS.

infestation, standing water during the growing season or by water and grassways within the fields. Also, the aerial images were used to ensure that the sampling areas were located in representative areas that had uniform corn color.

Three sampling areas were selected within each field: one within each predominant soil type (Fig. 2). A fourth sampling area (not shown) was selected within an area that appeared deficient or yellow (i.e., greater canopy reflectance) on the imagery to confirm that the stressed area was attributed to N stress but not other factors such as soil moisture stress, early senescence, or disease damage. The exact coordinates were recorded for each sampling area and were uploaded to a Magellan eXplorist handheld GPS (Magellan Navigation Inc., Santa Clara, CA) that was used to navigate to the sampling areas within a field.

Corn stalk samples were collected after corn plants reached the black layer stage or immediately before the harvest as recommended by Blackmer and Mallarino (1996). Ten individual stalk segments of 0.20-m long were collected from each of the three sampling areas within each field. The stalks were collected along two corn rows from an area of 6 to 8 m. Each composite sample had 10 individual stalks with leaves stripped from the stalks. Coordinates were recorded by the handheld GPS to verify exact sampling locations. The samples were placed into cloth bags and shipped to the laboratory on the sampling day or on the next day by the postal service. In the laboratory, the samples were dried at 65°C and ground to pass a 1-mm mesh. Stalk NO_3–N was extracted from the plant samples with 2 mol L^{-1} KCl, and the solutions were filtered and analyzed with a Lachat flow-injection analyzer (Lachat Instruments, Milwaukee, WI).

Management Information, Soil, and Rainfall Data

Survey forms were sent to growers and technical providers (i.e., independent crop consultants or agronomists) to collect management information for fields to be sampled in this study. The management information requested was previous crop {soybean [*Glycine max* (L.) Merr.]} or corn, timing of

Table 1. Descriptive statistics for explanatory variables used for identifying important factors affecting N sufficiency levels found in the guided corn stalk nitrate surveys of 683 fields in 2006 and of 824 fields in 2007 across Iowa.

Factor	Management category†	Percentage of total‡	Mean total N rate	Corn stalk test category			
				Deficient	Marginal	Optimal	Excessive
				2006 (2007)§			
		%	kg N ha^{-1}	%			
Year		45 (55)		27 (41)	15 (18)	26 (19)	31 (22)
N form¶	AA Fall	28 (22)	177 (182)	20 (41)	17 (19)	28 (19)	34 (20)
	UAN SD	7 (10)	150 (151)	42 (49)	12 (19)	18 (18)	27 (14)
	UAN Spring	16 (21)	152 (166)	36 (43)	18 (17)	26 (18)	20 (22)
	LSM Fall	17 (12)	198 (218)	27 (45)	14 (16)	23 (13)	36 (26)
	AA Spring	23 (20)	175 (172)	20 (35)	13 (18)	32 (21)	35 (26)
Previous crop	Soybean	82 (66)	170 (167)	28 (46)	16 (19)	27 (18)	30 (17)
	Corn	17 (33)	204 (201)	24 (30)	13 (16)	27 (21)	37 (33)
Soil drainage	Well	40 (47)	170 (179)	27 (36)	13 (16)	26 (20)	34 (27)
	Poor	55 (47)	179 (178)	27 (46)	17 (18)	27 (18)	29 (18)
	Tillage	80 (80)	178 (180)	28 (40)	16 (18)	26 (18)	31 (24)
Tillage	No-till	20 (20)	164 (168)	29 (47)	14 (18)	27 (19)	30 (16)
		Mean	SD#	Minimum	Maximum		
Total N rate, kg N ha^{-1}		173 (177)	38 (42)	34 (34)	336 (403)		
CSR††		75 (75)	16 (15)	5 (5)	100 (100)		
June rainfall, cm		5 (9)	2 (5)	1 (1)	14 (24)		
March through May rainfall, cm		22 (29)	4 (7)	10 (11)	39 (50)		
March through August rainfall, cm		45 (80)	6 (19)	32 (34)	74 (127)		

† Reference management categories are underlined.

‡ The total number of samples includes samples from management categories that had <3% of samples (e.g., urea, beef, or poultry manure applications).

§ Data in parenthesis indicate percentages of stalk samples collected in 2007.

¶ AA, anhydrous ammonia; LSM, liquid swine manure; SD, sidedress; UAN, urea-ammonium nitrate solution,

SD, standard deviation.

†† CSR, corn suitability rating.

application [fall, spring, or sidedress], forms of N fertilizer (AA, UAN, or LSM), total N rates applied with all N sources, and tillage type. The management information from the growers was processed and, in some cases, verified by follow-up phone calls. Total amount of N applied (kg N ha^{-1}) with the animal manure was calculated based on manure analysis provided on the survey forms by growers and technical providers.

Because growers in Iowa usually apply most of their N fertilizer at one time and with one N fertilizer or manure form, we formed N management categories based on a combination of forms and timing of N fertilizer and manure applications. Some example categories are: UAN applied in spring (UAN Spring) and AA applied in the fall (AA Fall). Fields that received multiple fertilizer and manure applications and had two or more N fertilizer and manure forms were assigned to management categories based on the largest amount of N applied (Table 1).

The digital soil maps for each county were downloaded from the Iowa Cooperating Soil Survey (2003). The soil maps included soil types, soil drainage classes, and corn suitability rating values (CSR). The CSR is an index of production composed of potential crop productivity, soil drainage, and soil erosion (Miller, 2005). Each corn stalk sample was assigned individual information for soil type, soil drainage class, and CSR value by overlaying sampling areas with the soil maps in ArcView 3.3.

Spatially interpolated daily rainfall data for the 2 yr of the study were obtained from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/rainfall/). The rainfall data were recorded by multisensors (radar and rainfall gauges) hourly or at 6-h intervals, processed, and interpolated at 4-km grids by the Environmental Modeling Center of the National Weather Service (http://wwwt.emc.ncep.noaa.gov). The daily rainfall values were aggregated to monthly cumulative rainfalls, cumulative spring (March through May), and cumulative growing season (March through August) rainfalls. Each field was assigned one rainfall value from the nearest located grid by overlaying the rainfall grids and the field boundaries and performing spatial join in ArcGIS Desktop 9.3 software (Environ. Syst. Res. Inst., Redlands, CA).

Statistical Analysis

Stalk NO_3–N values were expressed as four test categories: deficient (<0.25 g kg^{-1}), marginal (0.25–0.70 g kg^{-1}), optimal (0.70–2.0 g kg^{-1}), and excessive (>2.0 g kg^{-1}) as defined in previous studies (Binford et al., 1992; Blackmer and Mallarino, 1996). Ordinal logistic regressions were used to identify explanatory variables (i.e., N management categories, rainfall, or total N rate) that affected stalk nitrate test outcomes and to estimate the magnitude of the effects. Ordinal logistic regressions, often called the cumulative or proportional odds logistic models, are used when the response variable is expressed as several ordered categories (Hosmer and Lemeshow, 2000; McCullagh, 1980). Analyzing stalk nitrate values as ordered categories (deficient, marginal, optimal,

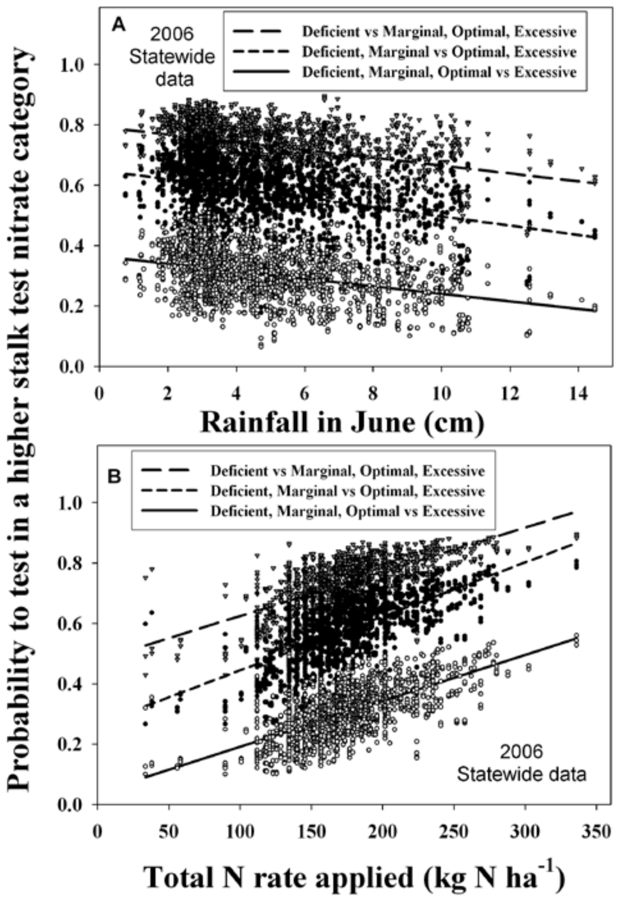

Fig. 3. Predicted probabilities for corn stalk samples to test in a higher stalk test nitrate category as affected by (A) rainfall in June and (B) total N rate applied for 683 fields sampled across Iowa in 2006.

and excessive) enabled us to maintain the original categories of N status reported for the test, make easier interpretation of regression coefficients, and use stalk NO_3–N data that were not normally distributed and did not have constant variance.

In logistic regression, the odds of an outcome or event are defined as the ratio of the probability of the event to the probability of a nonevent. The essence of OLR is to estimate the probability that a stalk sample will test in a higher stalk nitrate category with a change in one explanatory variable of interest while holding all other variables constant. The magnitude of the effect is expressed as an odds ratio which indicates the chance of any stalk sample to test in a higher stalk test category when a continuous explanatory variable increases by one unit or the chance to test in a higher stalk test category for a categorical explanatory variable when its categories are compared with a reference management category. When an odds ratio is >1, there is a higher chance to test in a higher stalk test category. When an odds ratio is <1, there is a smaller chance of a sample to test in a higher stalk test category. When an odds ratio is 1, a category in question and the reference category are equally likely to test in a higher stalk test category.

A unique feature of OLR is that the direction of the response variable (i.e., deficient vs. excessive) does not change the magnitude of the effect but only changes the sign of the regression coefficients (Bender and Benner, 2000). With four ordered stalk response categories, the regression model calculates three different equations. The first equation estimates the probability of a sample to test in the marginal, optimal, and excessive categories relative to the deficient category (Fig. 3A and B). The second equation estimates the probability to test in the optimal and excessive categories relative to the deficient and marginal categories. The last equation specifies the probability to test in the excessive category relative to the other three categories. The analysis is valid only when the assumption of parallel regressions or equal slopes for the three equations is met.

The stratified survey sampling design was used when analyzing data. Three individual stalk samples collected within each field were considered as the primary sampling units. The fields were specified as strata because the exploratory analyses showed that fields varied widely in stalk test outcomes. The PROC SURVEYLOGISTIC procedure of SAS software (SAS Institute, 2005) was used to estimate parameters for OLRs (An, 2002). The LOGIT link was used to specify a function that links the probability in response to the linear predictors in the OLRs. The overall significance of the regression models was tested by the likelihood ratio test, which tests that at least one explanatory variable has a statistically significant effect. Odds ratios were expressed as 95% Wald confidence intervals. The equal slope assumption was tested by the Chi-square test and the slopes were considered different at $P < 0.05$. Because the test for the assumption of equal slopes in OLR was found to be sensitive to the sample size by often showing significant slope differences for data with a large number of observations (Scott et al., 1997), a visual technique was also used to test the equal slope assumption for some OLRs.

The predictive accuracies of OLRs were summarized by using Sommers' D statistics and c-c values. The Sommers' D statistic is the ratio of difference between concordant and disconcordant pairs divided by the total numbers of pairs used in the models. Two samples are considered as a pair if they test in different stalk test categories. A pair was concordant when the model predicted a sample testing in a higher stalk test nitrate category to have a higher predicted probability than the sample testing in a lower stalk test category. A pair was discordant when the model predicted a sample testing in a lower stalk nitrate test category to have a higher predicted probability than the sample testing in a higher stalk test category. The c-c values show how well models predicted the observed stalk test categories, and the values range from 0.5 (random prediction) to 1 (perfect prediction).

We started the model selection process by evaluating complete models that included all categorical and continuous explanatory variables. The best or reduced OLR models had the smallest values for Akaike Information Criteria and the largest values for Sommers' D and c-c statistics while satisfying the equal slope assumption. For average monthly, cumulative spring, and growing season rainfalls, only one rainfall variable was evaluated at a time in the regression model. The interaction terms were not included because not all combinations of one categorical explanatory variable (e.g., N form and timing) could be evaluated at different levels of another categorical variable (e.g., soil drainage class), and because of the difficulty in interpreting statistically significant interaction effects for OLRs. The data were analyzed separately for a sample of fields collected across Iowa and for the Des Moines Lobe Landform Area during each year of the study (Fig. 1).

Sample size analysis was performed to estimate how many stalk samples should be collected in similar studies in the future. The calculations were completed as described in health-related studies using OLRs (Julious et al., 1997; Walters, 2004).

RESULTS AND DISCUSSION

Descriptive Statistics for Statewide Data

Table 1 shows the percentage of samples collected in each management category for factors studied in the survey, the percentage of samples tested in different stalk test nitrate categories, descriptive statistics for total N rates applied and rainfall estimates across Iowa in 2006 and 2007. Although the fields sampled were not randomly selected from all hypothetically possible fields, the data provide a relatively good representation of all major N management practices currently used by growers in Iowa (Nunez and McCann, 2008). About one-quarter of the fields were fertilized with AA in fall, one-fifth with AA and UAN in spring, one-sixth with injected LSM in fall, and one-10th with sidedress UAN during 2 yr. Fields that had poultry manure, beef manure, and urea applications were not used in the analyses because of a relatively small number of fields sampled (<3% of the total). The majority of the fields were corn after soybean, 82% in 2006 and 66% in 2007, but a substantial number of the fields were corn after corn, 17% in 2006 and 33% in 2007. The soil drainage classes were similar in distribution to Iowa corn land with the most land in either the poor or well-drained categories. Eighty percent of the fields were tilled (e.g., minimum tillage, strip tillage, or chisel tillage) and 20% were no-till each year.

Mean total N rates applied differed among various management categories for each factor studied (Table 1). Fields receiving LSM were more heavily fertilized than fields receiving only commercial N fertilizers (e.g., UAN and AA). Fields receiving fall-applied AA had slightly higher N rates than fields receiving spring and sidedress N applications of UAN. Fields planted to corn after corn received on average 34 kg N ha^{-1} more total N than fields planted to corn after soybean in 2006 and 2007.

There was a large difference in percentages of samples tested in different stalk test nitrate categories between the 2 yr when averaged across all of the management categories (Table 1). In 2007, 59% of the samples were in the deficient and marginal categories while only 42% were in the deficient and marginal categories in 2006. For the fourth sample collected in the target deficient area (data not shown), about 65% of the samples in 2006 and 80% in 2007 were in the deficient and marginal categories. These differences are likely due to different amounts of rainfall and subsequent differences in N availability from the soil and fertilizer to corn plants. The cumulative average growing season rainfall, from March through August, for the fields surveyed was 35 cm greater in 2007 than in 2006. The cumulative average spring rainfall, from March through May, was 21 cm in 2006 and 29 cm in 2007. The fields studied in 2007 received on average 4 cm more rainfall in June than the fields in June of 2006.

Statewide Differences between Nitrogen Management Categories

Table 2 shows odds ratios calculated from the best OLRs for testing effects of explanatory variables on stalk nitrate distributions across the state in 2006 and 2007. The odds ratios were calculated within each categorical variable (factor) relative to a reference management category. The reference management categories were the following: AA Spring for the N form and timing category, corn for previous crop category, poorly drained soils for soil drainage class category, and no-till for tillage category.

In both years, all factors, except previous crop and tillage in 2006, had statistically significant effects on the cumulative probability to test in a higher stalk test nitrate category (Table 2). Within the factor of N form and timing, there were significant effects of all management categories compared with AA Spring. All the categories had odds ratios much <1. For example, the category AA Fall had an odds ratio of 0.84 in 2006 and 0.60 in 2007. For AA Fall, the interpretation is that the OLR predicted that fields receiving AA in the fall 2006 were 0.84 times as likely to test in a higher stalk test category compared with fields receiving AA spring 2006 and only 0.60 times as likely to test higher from applications in fall 2007 compared with applications in spring 2007.

Sidedress applications of UAN also had odds ratios <1 in both years. The relative lower efficiency of the sidedress N applications in 2006 is consistent with inadequate moisture for the sidedressed N to become available for plant uptake, which was probably caused by lower-than-normal rainfall in June and July of 2006.

For fields receiving UAN Spring, the likelihood of testing in a higher stalk category was 0.53 times as great as fields receiving AA Spring in 2006 and 0.58 times in 2007. The lower relative efficiency of UAN Spring compared with AA Spring could be explained by the presence of nitrate in UAN (25% of total N) that can be easily lost with rainfall immediately after spring applications, and the presence of urea in UAN that can be lost by volatilization if it is applied on the soil surface, and because urea converts to nitrate much more rapidly than AA. Another reason for lower relative efficiency of UAN is that many growers try to reduce the cost of application by using weed-and-feed spring N applications (before or immediately after planting), where a large portion of the total N is broadcast with herbicides on the soil surface; therefore, this N is more likely to be lost by volatilization or leaching (Viswakumar et al., 2008).

For injected swine manure in the fall, the odds ratio was 0.72 in 2006 and 0.28 in 2007, suggesting that LSM Fall was much less efficient in supplying N to the plant compared with AA Spring. This finding is not surprising because results from controlled studies on 205 manured fields in Iowa showed large variability in N availability and N losses from injected LSM (Hansen et al., 2004). A contrast between AA Fall and LSM Fall categories indicated that fields receiving fall-applied AA were 1.17 times more likely to test in a higher test category than those receiving LSM in 2006 and 2.17 times more likely in 2007, which suggests that N applied in swine manure was probably nitrified and lost at much higher rates than AA applied in the fall.

Previous crop had a statistically significant effect only in 2007. The finding that fields planted to corn after soybean in 2007 were only 0.72 times as likely to test in a higher stalk test category compared with those planted to corn after corn was unexpected. The mean values for total N rates applied for corn after soybean was 167 kg N ha^{-1} and for corn after corn was 201 kg N ha^{-1} (Table 1). This difference in total N rates (34 kg N ha^{-1}) is slightly less than is usually observed (45–56 kg N ha^{-1}) in economic optimum N rates recommended for corn after corn in comparison with corn after soybean in

Table 2. Effects of explanatory variables on the cumulative probability of corn stalk samples to test in a higher stalk test nitrate category as observed in the guided corn stalk nitrate survey of 683 fields across Iowa in 2006 and of 824 fields in 2007.

Factor	Management category†	2006 Odds ratio‡	2006 95% Confidence interval	2007 Odds ratio	2007 95% Confidence interval
N form§	AA Fall	0.84*	0.71–0.99	0.60**	0.50–0.72
	UAN SD	0.54**	0.42–0.68	0.54**	0.48–0.67
	UAN Spring	0.53**	0.43–0.65	0.58*	0.48–0.71
	LSM Fall	0.72**	0.68–0.87	0.28**	0.22–0.35
	AA Spring				
AA Fall vs. LSM Fall		1.17¶	1.00–1.38	2.17**	1.72–2.83
UAN SD vs. UAN Spring		1.01	0.78–1.32	0.93	0.74–1.15
Previous crop	Soybean	1.15	0.96–1.37	0.72**	0.62–0.83
	Corn				
Soil drainage	Well	1.32*	1.10–1.59	1.62*	1.34–1.45
	Poor				
Tillage	Tillage	1.05	0.89–1.24	1.37*	1.15–1.64
	No-till				
Total N rate, 10 kg ha^{-1} increments		1.07**	1.05–1.09	1.11**	1.08–1.13
CSR#		1.00	0.99–1.01	0.99¶	0.98–0.99
June rainfall, cm		0.93**	0.91–0.96		
Cumulative spring rainfall, cm				0.97**	0.96–0.98

* Significant at $p < 0.05$ level.

** Significant at $p < 0.01$ level.

† Reference categories are underlined.

‡ An odds ratio calculated from ordinal logistic regression (OLR) indicates the chance of a stalk sample to test in a higher stalk test category when a continuous explanatory variable increases by one unit or relatively to a reference category for a categorical explanatory variable. When an odds ratio is 1, stalk nitrate test results are independent from explanatory variables. When an odds ratio is >1, the chance of a sample being in a higher stalk nitrate category increases, and when it is <1, the chance of a sample being in a higher stalk test category decreases.

§ AA, anhydrous ammonia; LSM, liquid swine manure; SD, sidedress; UAN, urea-ammonium nitrate solution.

¶ Significant at $p < 0.1$ level.

CSR, corn suitability rating.

Iowa (Blackmer et al., 1997; Sawyer et al., 2006). Possible reasons for the lower likelihood of corn after soybeans testing in a higher stalk test category are: (i) corn after corn may be planted on more productive fields because some growers try to plant their best fields to corn after corn, but the two categories of fields had almost identical mean CSR values of 73; (ii) corn after corn fields could have a greater frequency of animal manure applications in the past; (iii) corn after soybean fields may be more susceptible to losses of N from rainfall due to a shift in the carbon–nitrogen cycle compared with corn after corn (Blackmer and Green, 1995); (iv) growers could be using hybrids with greater N fertilizer use efficiency in the corn after corn fields. This result is an example of how survey data of the N status of corn fields can suggest where additional controlled studies may be needed.

Including soil drainage class in the analysis enables us to estimate the effect of soil specific characteristics on corn N status for each sample collected within a field. In 2006, the well-drained soils were 1.32 times more likely to have samples test in a higher stalk test category compared with the reference category of poorly drained soils, and in 2007 well-drained soils were 1.62 times more likely to test in a higher stalk test category (Table 2). This could be due to greater amounts of denitrification in the poorly drained fields or the result of a greater number of poorly drained fields with tile drainage compared with the well-drained fields. Tile-drained soils are more likely to leach more N below the plant root zone than soils without artificial drainage (Dinnes et al., 2002). Unfortunately, we did not have information about how many poorly drained soils had artificial drainage.

In 2007, fields that had different types of tillage were about 1.4 times more likely to test in a higher test category than no-till fields, which could be due to larger potential N losses, greater N immobilization, and smaller N mineralization from soil organic matter in the no-till fields.

The odds ratio for total N rate applied was 1.07 in 2006 and 1.11 and 2007, meaning that with each additional 10 kg N ha^{-1} the probability to test in a higher stalk test nitrate category increased by 7% in 2006 and 11% in 2007 (Table 2). This is in agreement with the original studies to calibrate the stalk nitrate test that showed a positive relationship between total N fertilizer rates and corn stalk nitrate values (Binford et al., 1990; Hooker and Morris, 1999).

The small negative effect of CSR on stalk nitrate values in 2007 (Table 2) could be attributed to the fact that the soils with greater productivity (i.e, higher soil organic matter content, poorly drained with artificial drainage, less prone to erosion) tended to lose more soil and fertilizer derived-N than soils with low CSR values.

In 2006, the amount of rainfall in June had a significant odds ratio of 0.93, which reflects the fact that large amounts of rainfall in June can reduce N availability to corn by either leaching or dentrification. There was a small but highly significant negative effect of cumulative spring rainfall in 2007. The average cumulative spring rainfall was 29 cm across the state (Table 1), that is 4

Table 3. Effects of explanatory variables on the cumulative probability of corn stalk samples to test in a higher stalk test nitrate category as observed in the guided corn stalk nitrate survey of 202 fields within Des Moines Lobe in 2006 and of 242 fields in 2007.

Factor	Management category†	2006		2007	
		Odds ratio	95% Confidence interval	Odds ratio	95% Confidence interval
N form‡	AA Fall	1.13	0.80–1.55	0.46*	0.32–0.67
	UAN SD	0.10**	0.07–0.15	0.57*	0.19–0.37
	UAN Spring	0.84	0.55–1.30	0.36**	0.23–0.88
	LSM Fall	0.48*	0.33–0.70	0.11**	0.07–0.19
	AA Spring				
AA Fall vs. LSM Fall		2.31**	1.78–3.00	4.05**	2.61–6.31
UAN SD vs. UAN Spring		0.12**	0.08–0.14	1.59*	1.12–2.27
Previous crop	Soybean	0.86	0.62–1.18	0.89	0.65–1.21
	Corn				
Soil type	Canisteo	0.95	0.55–1.62	0.77	0.44–1.36
	Clarion	1.31	0.77–2.23	1.37	0.78–2.41
	Nicollet	0.64§	0.39–1.05	2.79**	1.64–4.73
	Webster				
Total N rate, 10 kg ha^{-1} increments		1.06*	1.02–1.09	1.15**	1.10–1.20
CSR¶		1.05*	1.02–1.09	0.93§	0.89–0.97
March through May rainfall, cm		1.10	1.05–1.15	0.96*	0.93–0.98

* Significant at $p < 0.05$ level.

** Significant at $p < 0.01$ level.

† Reference categories are underlined.

‡ AA, anhydrous ammonia; LSM, liquid swine manure; SD, sidedress; UAN, urea-ammonium nitrate solution.

§ Significant at $p < 0.1$ level.

¶ CSR, corn suitability rating.

cm greater than the long-term average spring rainfall (data not shown). However, fields in the southern half of the state received from 30 to 40 cm of spring rainfall in 2007 (data not shown).

The significant effects of spring rainfall observed in both years (Table 2) deserve special attention. Excessive early season rainfall can affect N supply to the crop during the entire growing season in three ways by: (i) decreasing availability of soil-derived N through leaching or denitrification, (ii) inhibiting the mineralization potential of soil organic matter if rainy weather is coupled with lower soil and air temperatures (Kay et al., 2006), and (iii) causing direct losses of fertilizer N from high intensity rainfall occurring after fertilization (Balkcom et al., 2003; van Es et al., 2006). Rainfall received in May has been previously proposed to adjust estimated optimal N rates based on the late-spring soil nitrate test (Blackmer et al., 1997). Recently, real time weather data (rainfall and air temperatures) observed before sidedress fertilizer applications has been proposed to adjust N fertilizer rates for corn in New York (Melkonian et al., 2008). Because early season rainfall seems to be an important factor influencing N availability to corn, more research is needed to clarify how N rates should be adjusted for the rainfall.

Analysis of Data from the Des Moines Lobe

The Des Moines Lobe Landform Area has a smaller number of soil types than the statewide data, and that allowed the OLR to identify the effects of soil types on stalk nitrate test results. Our analysis of the Des Moines Lobe data demonstrates how OLR can be used for data collected on a smaller geographic scale to answer more specific questions that cannot be answered at larger geographic scales. The Des Moines Lobe includes the Central and North Central parts of Iowa (Fig. 1), and is characterized by gently rolling landscapes and soils developed on calcareous glacial till. Fields in this landform area often have soils that can vary substantially in soil organic matter and calcium carbonate content, soil drainage class, and soil pH values (Brevik et al., 2006; Rogovska et al., 2009).

The data analyzed for the Des Moines Lobe were only fields that had sampling areas within the Clarion-Nicollet-Webster (Clarion, fine-loamy, mixed, superactive, mesic Typic Hapludolls; Nicollet, fine-loamy, mixed, superactive, mesic Aquic Hapludolls; Webster, fine-loamy, mixed, superactive, mesic Typic Endoaquolls) or Canisteo-Nicollet-Webster (Canisteo, fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) soil associations, which are the dominant soil associations in the landform. These fields include about 77% of all samples collected within the Des Moines Lobe Area in 2006 and 86% of all samples collected in 2007. Compared with statewide data (Table 1), a slightly larger percentage of fields received LSM and AA in the fall and a slightly smaller percentage of fields received AA in the spring (data not shown).

Stalk nitrate test results were significantly different among the major soil types (Table 3). In 2006, the somewhat poorly drained Nicollet soils were less efficient in supplying N to corn than the poorly drained, high soil organic matter Webster soils, but in 2007 the Nicollet soils were more efficient in supplying N to corn. The first finding indicates that in relatively dry years corn grown on poorly drained soils within Central Iowa would be expected to test in a higher stalk nitrate test category because poorly drained soils have a large water holding capacity and larger mineralization potential. The second finding

Table 4. Statistics for the association between predicted and observed probabilities calculated from ordinal logistic regressions (OLRs) of corn stalk nitrate data collected during 2 yr across Iowa and within the Des Moines Lobe Landform Area.

Year	Scale	Concordant (discordant) pairs†	Somers'D‡	c-c value§
		%		
2006	Statewide	59.4 (39.9)	0.20	0.60
	Des Moines Lobe	64.2 (35.3)	0.29	0.65
2007	Statewide	63.4 (36.1)	0.27	0.64
	Des Moines Lobe	67.7 (31.8)	0.36	0.68

† A pair (two stalk samples tested in two different stalk test categories) was considered concordant when an OLR predicted a stalk sample testing in a higher stalk test category to have the higher predicted probability. A pair was discordant when the sample testing in a higher stalk test category was predicted to have the lower predicted probability.

‡ It indicates the strength and direction of the relationship between stalk tested outcomes and explanatory variables. It ranges from –1 (all pairs disagree) to 1.0 (all pairs agree).

§ It ranges from 0.5 to 1, with 0.5 indicating that regression models randomly predicted stalk test categories and with 1 indicating the model perfectly predicted all stalk test categories.

suggests that the poorly drained soils may have lost a larger percentage of N in 2007, which was a relatively wet year.

The primary difference between the Des Moines Lobe data (Table 3) and statewide data (Table 2) was more distinct differences among the management categories of N forms and timing. The effect of previous crop, however, was not significant in either year for the Des Moines Lobe, whereas in 2007 the statewide data showed a much lower probability of corn after soybean to test in a higher stalk test category. This suggests that the stalk nitrate test results for the statewide data were affected by the unusually large amount of rainfall in the southern half of the state (30–40 cm compared with an average of 29 cm for the entire state), and supports our previous discussions that a large amount of rainfall was the main reason for the effect of previous crop in 2007.

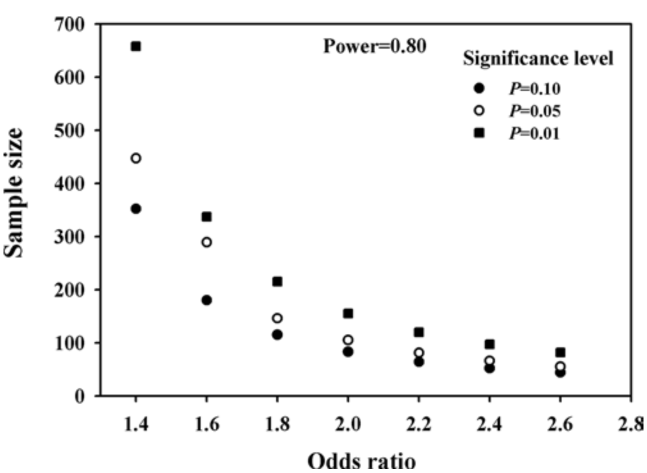

Fig. 4. Example of calculating a number of corn stalk samples to be collected in similar studies in the future for detecting predetermined differences between two N management categories at different levels of statistical significance. The calculations were based on stalk test results from fields receiving anhydrous ammonia and liquid swine manure in fall across Iowa in 2007.

Performance of Ordinal Logistic Regressions for Data at Different Scales

Table 4 shows statistics for the association between observed and predicted probabilities calculated from OLRs fit to the statewide data (Table 2) and to the Des Moines Lobe data (Table 3) collected in 2006 and 2007. About 60% of the pairs were concordant for the statewide data in 2006 and about 64% in 2007. The pairs within the Des Moines Lobe had slightly greater concordance, with about 64% in 2006 and 68% in 2007.

The strength and direction for the relationships between stalk outcomes and explanatory variables are indicated by Somer's D values. All observed and predicted pairs disagree when the Somer's D value is –1, and all the observed and predicted pairs agree when the value is 1. The Somer's D values ranged from 0.20 for the statewide data in 2006 to 0.36 for the Des Moines Lobe area in 2007. The OLR performance also was evaluated by c-c values. A perfect prediction has a c-c value of 1 and a random prediction has a value of 0.5. The c-c values ranged from 0.60 for the statewide data in 2006 to 0.68 for the Des Moines Lobe in 2007. These analyses show that the predictive accuracy was slightly better in a relatively wet year when N availability was greatly influenced by rainfall and N management categories. Also, the OLRs performed slightly better for the data collected within the Des Moines Lobe, probably because of less variability in management practices and the smaller range in total N rates applied.

In our analyses of the survey data, we ignored possible spatial correlations among fields clustered in groups as shown in Fig. 1. Other factors not considered that may affect the stalk test outcomes within individual groups of growers included similarities in N fertilizer recommendations delivered to the growers within one group by local cooperatives and agronomists, and availability of similar N fertilizer products or equipment for fertilizer applications. Competition among the local cooperatives and fertilizer dealers may also have influenced the N fertilizer recommendation delivered to growers and the stalk test results within fields located in one geographic area (Nowak and Cabot, 2008).

Sample Size for Future Similar Studies

Figure 4 shows sample size calculation based on corn stalk samples for AA Fall and LSM Fall categories in 2007 for statewide data (Table 1). The sample size was calculated for the different odds ratios at different levels of statistical significance with a power of 0.8 (Type error II = 0.20) when using OLRs (Julious et al., 1997; Walters, 2004). The sample size exponentially decreased as the odds ratios increased. The effect of the odds ratio was much larger than the effect of choosing the critical probability levels at which the differences would be claimed statistically significant. The sample size ranged from about 650 samples (about 216 fields) with relatively small odds ratios to about 50 samples (about 16 fields) with relatively large odds ratios. By controlling sample size and choosing the desired odds ratio, we can reasonably estimate whether we can detect a meaningful difference between management categories for different geographic and landform areas, and different groups or clusters of fields within the state (Fig. 1).

CONCLUSIONS

The study described how the end-of-season stalk nitrate test guided by aerial imagery of the corn canopy and information about soil types from Soil Survey maps can be used to identify major factors affecting N sufficiency for corn. The factors were identified in a survey of >1500 fields across Iowa during 2006 and 2007. Groups of growers provided critical field information needed for the identification of the factors. We used OLRs to estimate the cumulative probability of a stalk sample to test in a higher stalk nitrate test category at different levels of explanatory variables. Significant explanatory variables included: N management categories based on a combination of N forms and timing of N fertilizer and manure applications, previous crop, soil drainage class, CSR, and variability in early season rainfall across Iowa and within the Des Moines Lobe Landform Area. Future studies should concentrate on analyses of data collected from individual groups of growers (i.e., clusters of fields) where fields have similar soil and weather conditions but different management practices. This should lead to more accurate estimation of relative differences in N supply to corn among specific N management practices used by growers within relatively small and uniform geographic areas.

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