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NITROGEN RECOMMENDATION SYSTEMS, WEATHER EFFECTS
ON NITROGEN RESPONSE, AND THE PREDICTION OF
NITROGEN RESPONSE IN ILLINOIS

BY

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THESIS

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ABSTRACT 1

Nitrogen rate determination by corn producers entails both environmental and economic risk. Over-application increases production costs and causes environmental damage, whereas under-application reduces food production and farm revenue. Several recommendation methodologies have been proposed to provide fixed N recommendations to maximize profits. The maximum return to nitrogen (MRTN) system, currently in use in Illinois and other Corn Belt states, fits an appropriate function (linear, quadratic, or quadratic + plateau) to each N response, calculates a predicted return to N at each N rate, then averages these net return responses over all responses in the database. The MRTN rate is that rate producing the predicted maximum return to N across all responses. This is a departure from previous approaches, in which yield data were typically averaged across a set of experiments to form a single response function, from which an optimum N rate was derived. Using data from N rate trials run on corn following corn and corn following soybeans at seven sites in Illinois over 10 years (1999-2008), we evaluated this approach in comparison to both the conventional approach and one using different functional forms of N response. It was determined that the logistic function is the most suitable model for corn N response in Illinois. MRTN rates derived from the logistic function did not perform better than those derived from the quadratic + plateau function. MRTN recommendations from averaged annual response curves generally resulted in higher revenue than those derived from a single response curve.

ABSTRACT 2

Nitrogen application in intensive corn production systems is a source of both environmental and economic risk. Over-application of N is economically wasteful, and is a source of point and nonpoint pollution affecting the health of humans and ecosystems alike. Under-application of N decreases yield and profitability. While advances have been made in the development of guidelines for N rates, the ability to predict site-specific economically optimal N rates (EONR) that change based on expected or observed weather remains elusive. Being able to predict N response will allow producers to adjust N application to be closer to economically optimal given expected growing conditions, increasing profitability while reducing environmental impact. N rate studies were conducted at seven sites in Illinois for 10 years, from 1999 to 2008. Weather variables were evaluated for their ability to predict the parameters governing N response over the experimental period. Average precipitation in July, average soil temperature at 10 cm depth during silking, and average soil temperature at 20 cm depth during June were most predictive of N response. Early season weather variables were also evaluated for their ability to predict N response parameters. Average soil temperature at 20 cm depth during April, simulated average soil moisture at 135 cm depth during April, and average precipitation in January were most predictive of N response. However, when significant selected variables were entered into simple linear regression, use of predicted EONR for corn following soy resulted in lower revenues than the maximum return to nitrogen (MRTN) system, while results were mixed for corn following corn.

To the band, Sodom

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TABLE OF CONTENTS

| | |
|--|----|
| CHAPTER 1: AN EVALUATION OF MODELS FOR NITROGEN RESPONSE IN ILLINOIS AND THE REVENUES OF THE MAXIMUM RETURN TO NITROGEN SYSTEM | 1 |
| 1.1 INTRODUCTION | 1 |
| 1.2 MATERIALS AND METHODS | 6 |
| <i>Experimental design and site soil characterization</i> | 6 |
| <i>Statistical Modelling of Yield Response</i> | 7 |
| 1.3 RESULTS AND DISCUSSION | 13 |
| <i>N response in Illinois</i> | 13 |
| 1.4 CONCLUSION | 17 |
| 1.5 REFERENCES | 18 |
| 1.6 TABLES | 22 |
| CHAPTER 2: PREDICTING NITROGEN RESPONSE: THE EFFECT OF WEATHER ON CORN NITROGEN RESPONSE IN ILLINOIS | 30 |
| 2.1 INTRODUCTION | 30 |
| 2.2 MATERIALS AND METHODS | 35 |
| <i>Weather data and creation of biometeorological and meteorological weather variables</i> | 36 |
| <i>Selection of pre-season variables most predictive of N response</i> | 40 |
| 2.3 RESULTS AND DISCUSSION | 42 |
| <i>Effect of weather and site on N response</i> | 42 |
| <i>Early season weather variables as predictors of N response</i> | 45 |
| <i>Predictive ability of selected weather variables on N response parameters</i> | 47 |
| 2.4 CONCLUSION | 49 |
| 2.5 REFERENCES | 50 |
| 2.6 FIGURES AND TABLES | 57 |

CHAPTER 1: AN EVALUATION OF MODELS FOR NITROGEN RESPONSE IN ILLINOIS AND THE REVENUES OF THE MAXIMUM RETURN TO NITROGEN SYSTEM

1.1 INTRODUCTION

N fertilization is necessary for profit maximization in intensive corn production systems in Illinois. Under-application of N causes losses due to lower yields (Black, 1993; Pan et al., 1997; Scharf and Lory, 2000) and with increasingly high N to corn price ratios, over-application of N also reduces net income by increasing the total costs of production beyond the point where the profit maximum is attained (DuPont, 2014; Sheriff, 2005). In addition to the economic penalties felt directly by the individual producer, over-application of N imposes economic-environmental costs on both local and national areas. On the local scale, groundwater nitrate pollution harms the health of local residents and eutrophication of local watersheds negatively impacts ecosystems. On the national scale, nitrate loading to the Mississippi river from corn acreage causes the ultimate hypoxiation of large swathes of the Gulf of Mexico in previously productive shrimp fisheries off the coast of Louisiana, the economic cost of which is in the millions (Donner and Kucharik, 2008; Goolsby et al., 1999; Jaynes et al., 2001; Meisinger and Randall, 1991; Rabelais et al., 2001; Turner et al., 1991). Determining profit-maximizing N rates for corn is vital to reducing the costs associated with over-application, both environmental and economic (Hong et al., 2007; McSwiney and Robertson, 2005; Seungdo and Dale, 2008; Stanford, 1973).

N response and, concomitantly, economically optimal N rates (EONR) vary tremendously both spatially and temporally. Differences in crop demand, soil N amounts,

preceding crop, and N losses between sites interact to produce different N responses (Bundy and Andraski, 1995; Fiez et al., 1995; Hergert et al., 1995; Schmidt and Randall, 1994). Choice of functional form for yield response to N has a great effect on the estimated EONR as well. Modelling nitrogen response as linear, quadratic, or quadratic + plateau can shift the determined optimal rate up or down by several dozen kilograms per hectare depending on the one selected (Cerrato and Blackmer, 1990; Bullock and Bullock, 1994; Belanger et al., 2000). Year-to-year fluctuations in expected weather patterns complicate assessment of average N response site-to-site by interacting with spatial variability (Eghball and Varvel, 1997; Mamo et al., 2003). Unusual weather events, such as droughts, can bias short term N rate experiments by inflating standard error and shifting the true mean N response. Accurate assessment of spatial and temporal variation in N response is paramount to determining the distribution of economically optimal N rates and providing accurate N recommendations.

Historically there have been many attempts to produce recommendation systems that provide the optimal nitrogen rate. One of the first attempts was a mass-balance approach, where the recommended rate is the total N content of the grain minus all accountable sources of N from the soil, adjusted for inefficiency of N recovery by the crop (Meisinger, 1984; Stanford, 1973). This approach was modified and implemented by most corn-producing states (Illinois, Indiana, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Pennsylvania, and South Dakota) into a yield goal recommendation system, where N was incrementally applied according to the expected or desired yield for a given field (Beegle and Wolf, 2000; Dahnke et al., 1992; Gerwig and Gelderman, 1996; Hergert et al., 1995; Hoefl and Peck, 2001; Lory and Scharf, 2003; Schmidt et al., 1998; Vitosh et al., 1995). So widespread and influential were the yield

goal recommendation systems that they also became incorporated into both regulatory and technical regimes (USDA-NRCS, 1999; USEPA, 2001).

However, numerous studies have found that yield, and therefore yield goal, does not correlate with EONR (Bundy, 2000; Fox and Piekielek, 1995; Kachanoski et al., 1996; Vanotti and Bundy, 1994). Much of this lack of correlation is due to the fact that yield goal recommendation systems generally have one simple incremental rate for the entire state, while soil N supply (which is a significant component in mass balance approaches) is expected to vary widely with location (Lory and Scharf, 2003). In addition to this, producers over-estimate yield potential, inflating the recommendation and resulting in over-application (Goos and Prunty, 1990; Schepers and Mosier, 1991). These factors motivated many states to suspend yield goal based recommendations in favor of recommendation systems based on regional differences in yield and soil type (in the case of Wisconsin) or recommendations based simply on the type of cropping and rotation system (in the case of Iowa), with adjustments for estimates of soil N as well (Blackmer et al., 1997; Bundy, 2000; Vanotti and Bundy, 1994;).

University agronomists, endeavoring to create a unified system of N recommendations across the corn-belt which corrected the problems associated with the yield goal system, held discussions over the apparent differences in N recommendation methodologies among the different states (Sawyer et al., 2006). The result of this discussion, the Maximum Return to N (MRTN) system, is an attempt to create a uniform system of EONR determination based on regional N response data (Nafziger et al., 2004, Sawyer et al., 2006). Site level response data are grouped according to geographic location within the state, as well as by preceding crop to account for increases in soil N due to use of a legume (Barber and Stiver, 1962; Mulvaney et al., 2005; Stranger and Lauer, 2008). Quadratic + plateau, quadratic, or linear response curves are fit

to each site-year of data and the financial returns of these curves are averaged across site-years by N rate. The N rate corresponding with the maximal return over all responses included in the database for a given N to corn price ratio is the recommended rate for that specific regional grouping and corn price ratio. Implicitly, this methodology recognizes heterogeneity of N response by site and has the added benefit of responding to actual or anticipated changes in the ratio of N cost to corn prices. Additionally, as more N response trials are conducted, they are easily integrated into the MRTN determination. As the number of N response trial locations increases, geographical specificity of recommendations will become more granular. Thus, recommendations are specific to each regional site-year grouping but the methodology and analysis is constant across the entire Corn-Belt, adding credibility to the guidelines.

While intuitively this system is a great improvement over past attempts, its performance must be financially evaluated and compared with that of other recommendation systems in order to both encourage its adoption and to affirm it as an improvement. Differences between fitting response curves to individual years and then averaging the returns and fitting a single response curve to all the data are not yet known. In addition to this, different functional forms for N response data in Illinois need to be evaluated against quadratic + plateau for suitability and fit, as choice of functional form can affect the simulated EONR by large margins.

Using experimental data over 10 years and across 7 sites in Illinois, we tested the linear + plateau, quadratic, quadratic + plateau, Mitscherlich, logistic, and Gompertz functional forms using the Bayesian information criteria as well as normality of the residuals within a mixed effects model framework. The revenues (crop value minus N cost) and the recommended rates from the MRTN system using both individual site-year response curves and aggregate site response curves using both quadratic + plateau and the chosen functional form, the yield goal

system, and the *ex post* EONR and maximal revenue for each growing season and site for corn following corn and corn following soy using a fixed N to corn price ratio were compared.

1.2 MATERIALS AND METHODS

Experimental design and site soil characterization

Experimental plots were in place by 1999 as a split plot arrangement of two levels of rotation (corn-corn and corn-soybean) and six levels of N fertilizer rates (0, 50, 101, 151, 202, and 252 kg hectare⁻¹) in a randomized complete block design with four replications at each of seven sites in Illinois: Monmouth, DeKalb, Urbana, Perry, Dixon Springs Bottomland, Dixon Springs Upland, and Brownstown. Two sites were used at Dixon Springs in order to reflect the two different soils and terrains prevalent in that region of Illinois. Soils at the Bottomland site were moderately well-drained, level Inceptisols, whereas the soils of the Upland site were somewhat poorly-drained, somewhat-sloped Alfisols. At all sites, the experiment was conducted for 10 years, from 1999 to 2008. Four blocks split into corn following corn, with N rate kept in place each year, and corn following soybean (alternating with soybean following corn) were treated with six different N rates. Grain yield and moisture were recorded using a plot combine, and grain yields converted to equivalent yield at 150 g H₂O kg⁻¹.

Soil types were characteristic of the types found in regions surrounding the experimental sites. Descriptions of the soils at each experimental site as well as expected yields are summarized in Table 1.1 (Olson and Lang, 2000; USDA, 2014).

The Monmouth, DeKalb, Urbana, and Perry experimental sites were located in USDA Plant Hardiness Zone 5b between 200 and 270 m above sea level, while the Dixon Springs Bottomland and Upland, and Brownstown experimental sites were located in zones 6b and 6a respectively, roughly 170 m above sea level. Soils at the Monmouth, DeKalb, and Urbana experimental sites were poorly-drained Mollisols high in organic matter content. The soil at the Perry experimental site was a somewhat poorly-drained Alfisol with moderate organic matter content. The Dixon

Springs Upland and Brownstown experimental sites were also Alfisols, albeit moderately well-drained and low in organic matter for the former and poorly-drained and low in organic matter for the latter. The Dixon Springs Bottomland experimental site was a somewhat poorly-drained Inceptisol low in organic matter content.

Experimental plots at the Brownstown site were more negatively affected by unusually high precipitation than typical fields in the rest of the county in which it was located. Three data sets (2000 corn following soy, 2002 corn following corn, and 2002 corn following soy) were discarded from this location due to very low yields.

Statistical Modelling of Yield Response

Several functional forms were evaluated for their suitability in modelling N response across Illinois. The simplest of the functional forms is the linear + plateau function. In this functional form, crop yield is assumed to be a linear function of N until a point where another unknown nutrient becomes the limiting factor and growth reaches a plateau (Anderson and Nelson, 1975; Babcock and Blackmer, 1994; Lanzer and Paris, 1981).

The linear + plateau response function is defined by Eq. [1] and [2] as

$$Y = a + bX \text{ if } X < C \text{ [1]}$$

$$Y = P \text{ if } X \geq C \text{ [2]}$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the intercept representing the yield with no added N, b is the linear coefficient representing the marginal increase in yield per added kilogram of N, C is the critical N rate beyond which the response is a plateau, and P is the plateau yield.

With the quadratic representation, yield is assumed to be increasing in N at a decreasing rate until a maximum point is reached, after which the response is a decreasing function of N rate (Cerrato and Blackmer, 1990).

The quadratic response function is defined by Eq. [3] as

$$Y = a + bX + cX^2 \quad [3]$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the intercept representing the yield with no added N, b is the linear coefficient representing the marginal increase in yield per added kilogram of N, and c is the quadratic coefficient representing the diminishing yield increase per added kilogram of N. A negative response to N application has been observed in some yield studies (Mortensen and Beattie, 2003). However, in typical N response trials that show no such yield penalty from excessive N application, use of the quadratic function overstates yields at the optimum because it is fitting the plateau area with a curvilinear concave function (Cerrato and Blackmer, 1990). The aforementioned authors also found that residuals for the fitted quadratic model were non-normally distributed, indicating it was not the correct functional representation for their corn yield response data set.

A modification of the quadratic functional form, the quadratic + plateau model, is defined by Eq. [4] and [5] as

$$Y = a + bX + cX^2 \text{ if } X < C \quad [4]$$

$$Y = P \text{ if } X \geq C \quad [5]$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the intercept representing the yield with no added N, b is the linear coefficient representing the marginal increase in yield per added kilogram of N, c is the quadratic coefficient representing the diminishing yield increase per added kilogram of N, C is the critical N rate beyond which the

response is a plateau, and P is the plateau yield. Cerrato and Blackmer in 1990 evaluated 5 different models (linear plateau, quadratic plateau, quadratic, exponential, and square root) for estimating corn yield response found that quadratic + plateau was the most appropriate given the data in question, producing a model fit with a high coefficient of linear determination as well as normally distributed residuals (Cerrato and Blackmer, 1990).

The Mitscherlich production function when applied to N response has a negative-exponential increase to a yield plateau (Mitscherlich, 1909; Mitscherlich, 1913; Von Liebig, 1855). It is defined by Eq. [6] and [7] as

$$Y = a (1 - \exp(-b (X + c))) \quad [6]$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the asymptote representing the yield plateau, b is the coefficient representing the marginal increase in yield per added kilogram of N, and c is the yield of the field at zero kilograms N.

The logistic response function is defined by Eq. [7] as

$$Y = a / (1 + \exp((b - X)/c)) \quad [7]$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the asymptote representing the yield plateau, b is the N rate where the value of yield is halfway between zero and the yield plateau (referred to as the “inflection point”), and c is a scale parameter for the X axis affecting the rate of increase of N response (referred to as “scale”) (Overman et al., 1994). The inflection point parameter can also be interpreted as controlling the yield-intercept of the response function, that is, the yield with no N applied (Wilcutts et al. 2008).

The Gompertz response function is similar to the logistic though more flexible due to the N rate being an exponent, and is defined by Eq. [8] as

$$Y = a \exp(-b c^X) \text{ [8]}$$

where Y is the corn yield (kg/ha), X is the N application rate (kg/ha), a is the asymptote representing the yield plateau, b is the yield at zero kilograms of N, and c is a scale parameter for the X axis affecting the rate of increase of N response. This function has previously been used to model changes in yield as a percentage of the maximum against the number of weed-free growing degree days (Evans et al. 2003).

Six functional forms – linear + plateau, quadratic, quadratic + plateau, Mitscherlich, logistic, and Gompertz – were tested for suitability in modelling N response in Illinois by fitting a mixed effects model to each using R version 3.1.0 (R Core Team, 2014) and package nlme (Pinheiro et al., 2013). Random effects included in the models are site and block nested within site, as well as all interactions with preceding crop, parameters, and N rate in the case of the linear mixed effects model used for the quadratic functional form. Random effects were assumed to be independent from one another and have a diagonal covariance structure. In cases where a quadratic + plateau function could not be fit due to the site-year response not reaching a plateau or having no response to N, those data points were fit with a linear function. After complete models were run for each functional form, statistically insignificant terms were removed and the model was rerun until a final model was obtained and residuals were examined for normality. Because models were non-nested, a likelihood ratio test could not be used to obtain a p value for comparing the models (Kutner et al., 2004). Instead, the Bayesian information criteria (BIC) for the final models for each functional form were compared, and the functional form of the model with the lowest BIC was selected as the most satisfactory model of N response for the

experiment (Hong and Preston, 2012). Additionally, BIC weights were computed to estimate the probability that each model was the best model (Burnham and Anderson, 2002)

A fixed N to corn price ratio of 1:10 (\$/lb:\$/bu) (5.6:1 \$/kg:\$/kg) was used for all equations. The *ex ante* MRTN rate was determined for each site and each preceding crop by averaging the revenues from the fitted quadratic + plateau yield response regressions for all individual years, by taking the revenues from the fitted quadratic + plateau yield response for the aggregate experiment by site, by averaging the revenues from the chosen functional form based on BIC and residual analysis fit for all individual years, or by taking the revenues from the chosen functional form based on BIC and residual analysis fit for the aggregate experiment by site and then selecting the profit maximizing rate.

Yield goal based recommended rates were determined by the following equation prescribed by the University of Illinois Agronomy Handbook (Hoefl and Nafziger, 2004):

$$N = 0.0214 E_{Yield} - SC$$

where N is the recommended rate in kg/ha, E_{Yield} is the yield goal for the site in question, and SC is the N credit when soybean is the preceding crop which in this case was 45 kg/ha (Ruffo et al., 2006). Revenues and rates for the yield goal recommendation method were then determined for each site-preceding crop combination. Expected yield values listed in Table 1.1 were used as yield goals (Olson and Lang, 2000).

Because the choice of functional form used to fit each site year has an effect on the overall shape of N response and EONR, we use a LOESS regression to model each site year. LOESS regression is a non-parametric regression technique with much greater flexibility than linear or nonlinear regression, and is ideal for modelling data for which no theoretical models exist

(Kutner et al., 2004). Though there are several existing models of N response, selecting one or a subset of them to determine EONR introduces bias to our evaluation.

Average differences in revenue between the rates of MRTN derived from both averaged annual responses and a single response for all years for the quadratic + plateau and selected functional response and from the *ex post* EONR derived from the quadratic plateau and selected functional form were calculated and compared. In instances where the regression calculation for either functional form failed to converge, a linear function was fit instead. When the *ex post* EONR or MRTN exceeded the maximum rate applied in the experiment (252 kg/ha), the maximum rate was used instead.

1.3 RESULTS AND DISCUSSION

N response in Illinois

Bayesian information criteria (BIC) for the mixed effects models with different functional forms are listed in Table 1.2. The logistic model had the smallest BIC value, followed by the Mitscherlich production function and the quadratic + plateau model. This selection method is sufficient when comparing nonnested models (Burnham and Anderson, 2002; Hong and Preston, 2012), and residuals for the chosen logistic mixed effects model were normally distributed, adding weight to the BIC selection method. The BIC weights indicate that the logistic model has a 65% chance of being the best model, whereas the quadratic + plateau has a 0.4% chance of being the best model. When comparing the two, the logistic model is 162.75 times more likely to be the best model than the quadratic + plateau. However, the Mitscherlich function was also close to being chosen as the best model, with a 34.5% chance of being the best model and the logistic being 1.88 times more likely to be the best model than the Mitscherlich.

The chosen logistic mixed effects model for N response in Illinois had significant fixed main effects for the asymptote, inflection point, and scale parameters and fixed interaction effects with previous crop and asymptote and inflection point parameters at $p < 0.001$, which are shown in Table 1.3. Variance components of the final model are shown in Table 1.4. The random interaction effect of asymptote and site accounted for the most variation in N response in Illinois, followed by the random interaction effect of site, asymptote, and previous crop. While the random interaction effect of site and the inflection point was included, the random interaction of site and scale was negligible and was dropped from the final model. Estimates of the best linear unbiased predictors (BLUPs) of the random interaction effects of site with parameters and

previous crop are listed in Table 1.5.

The result of our evaluation of several different functional forms supports the choice of past researchers in using the logistic function to model corn yield response to N (Overman et al., 1994). While the logistic function has not been used very often to describe N response, some previous research indicates that it is best able to describe yield response to N in lettuce (Wilcutts et al., 2008). Our results add to the small corpus of literature suggesting that the logistic function is best able to model N response not just for corn, but for a variety of crops.

Financial performance between EONR assuming a logistic N response and the MRTN rates derived from using both annual averages of logistic response and a single logistic regression fit over the entire experiment for corn following corn and corn following soybean are detailed in Table 1.6. Not surprisingly, revenues from both logistic MRTN techniques were significantly lower than those from the yearly EONR for the majority of sites and previous crop. Performance between yearly EONR and MRTN rates derived from using both annual averages of quadratic + plateau response and a single quadratic + plateau regression fit over the entire experiment for corn following corn and corn following soybean are detailed in Table 1.7. As with revenues from logistic MRTN rates, revenues from quadratic + plateau MRTN rates were significantly lower than those from yearly EONR for the majority of sites and preceding crop. Differences in revenues between the logistic MRTN and quadratic + plateau MRTN were not significant for any site and rotation. The logistic function is therefore not an improvement over the quadratic + plateau function for MRTN determination. However, given the evidence that it is best able to model nitrogen response in Illinois, as well as the fact that convergence failed for fewer site-rotation-years, it is a useful addition to the small array of functions utilized by the MRTN database.

Differences in revenue between deriving MRTN rates from yearly N response curves and from a single N response curve for all the data for corn following corn and corn following soybean using logistic and quadratic + plateau response curves was not significant for any site. However, deriving MRTN rates using a single N response curve performed more poorly than deriving MRTN rates from the average of yearly response functions for nearly all sites and functional assumptions, though of varying degrees. The net change in N application from using MRTN rates derived from a single N response curve vs use of MRTN rates derived from yearly N response curves varied significantly by site, but was typically negative. Intuitively, this was because unusual N response observations were not that influential on the ultimate response curve when fitting all the data together, whereas in an average the effect of an unusual year is given more weight. These results correspond with econometric research showing that the average of statistical models is a better predictor than a single model (Stock and Watson, 2004; Winkler and Makridakis, 1969).

Differences between yield goal based rates and logistic MRTN rates for corn following corn and corn following soybean varied greatly between sites, and are shown in Table 1.8. The yield goal system resulted in lower revenues than the MRTN system for the majority of sites and rotations, though of varying degrees by site, but both over and under-recommended N rates. When comparing sites that were recommended too much N and sites that were recommended too little N, it is clear that the yield goal system tends to recommend producers over-apply N in fields with high expected yield and tends to recommend producers under-apply N in fields with low expected yield. The likely result of this application regime is to cause excessive nitrate leaching and nitrous oxide production in highly productive areas of Illinois while simultaneously

lowering productivity in less productive areas (Bouwman et al., 2002; Hong et al., 2007). Since the yield goal methodology generally over-estimates N rates for high yielding sites while underestimating them for low yielding sites, revenue losses at high yielding sites are likely because of wasted N, whereas revenue losses at low yielding sites are a result of forfeited yield.

1.4 CONCLUSION

Use of the logistic function to derive MRTN rates did not result in an improvement over use of the quadratic + plateau function. However, given the statistical evidence in favor of the logistic function for N response modelling in Illinois as well as smaller number of convergence failures vs the quadratic + plateau, the logistic function will prove a valuable addition to the MRTN toolbox.

In comparing revenues and rate recommendations between MRTN derived from single N response curves and averaged annual N response curves, some sites showed very small revenue reductions associated with reduced N usage. For example, at Dixon Springs Upland for corn following corn, a reduction in N usage of 15 kg/ha cost an average of \$0.68/ha in lost revenue. While making N recommendation systems closer to economically optimal may help reduce over-application of fertilizer, the relatively small penalties associated with lower N usage indicate that if N were subject to taxation and made more expensive, EONR rates would fall, reducing environmental degradation.

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1.6 TABLES

Table 1.1. Location, hardiness zone, soil series, soil taxonomy, draining ability, organic matter content, and expected yield of experimental sites.

| Site | Approximate Site Coordinates (latitude and longitude) | USDA Hardiness Zone | Soil Series | Classification Soil Taxonomy | Draining Ability | Organic Matter | Expected Yield (kg/ha) |
|--------------------------|--|---------------------------|-------------------------|------------------------------------|-------------------------|-------------------|---------------------------|
| Monmouth | 40° 55' 60" and -90° 43' 25" | 5b | Sable silty loam | Mollisol | Poor | High | 11,301 |
| DeKalb | 41° 50' 29" and -88° 51' 4" | 5b | Flanagan silt loam | Mollisol | Somewhat poor | High | 10,987 |
| Urbana | 40° 5' 2" and -88° 14' 25" | 5b | Drummer silty clay loam | Mollisol | Poor | High | 10,673 |
| Perry | 39° 48' 21" and -90° 49' 26" | 5b | Clarksdale silt loam | Alfisol | Poor | Moderate | 8789 |
| Dixon Springs Bottomland | 37° 26' 13" and -88° 40' 2" | 6b | Belknap silt loam | Inceptisol | Somewhat poor | Low | 8789 |
| Dixon Springs Upland | 37° 26' 13" and -88° 40' 2" | 6b | Grantsburg silt loam | Alfisol | Moderately well drained | Low | 7534 |
| Brownstown | 38° 56' 57" and -88° 57' 34" | 6a | Cisne silt loam | Alfisol | Poor | Low | 7220 |

USDA, United States Department of Agriculture.

Table 1.2 Bayesian information criteria (BIC), delta BIC, relative likelihoods, and BIC weights for different functional forms of nitrogen response in Illinois

| Function | BIC | $\Delta \text{BIC}_i^\dagger$ | $\exp(-0.5 \Delta \text{BIC})^\ddagger$ | w_i^\S |
|---------------------|-----------|-------------------------------|---|----------|
| Linear + plateau | 58,840.85 | 47.88 | 0.000 | 0.000 |
| Quadratic | 58,809.88 | 16.91 | 0.000 | 0.000 |
| Quadratic + plateau | 58,803.12 | 10.15 | 0.006 | 0.004 |
| Mitscherlich | 58,794.24 | 1.27 | 0.530 | 0.345 |
| Logistic | 58,792.97 | 0.00 | 1.000 | 0.651 |
| Gompertz | 58,816.71 | 23.74 | 0.000 | 0.000 |

BIC, Bayesian information criterion.

$^\dagger \Delta \text{BIC}_i = \text{BIC}_i - \min(\text{BIC})$.

‡ Relative likelihood.

$^\S w_i = \Delta \text{BIC}_i / \sum (\Delta \text{BIC}_i)$

Table 1.3. Estimates of fixed effects for logistic nitrogen response parameters for the mixed effects model of nitrogen response in Illinois containing all experimental sites and rotations.

| Parameter | Corn following corn | Corn following soy |
|------------------|---------------------|--------------------|
| Asymptote | 9926.98*** | 10,718.005*** |
| Inflection point | 26.66*** | -21.238*** |
| Scale | 50.68*** | - |

*** Significant at the 0.001 probability level.

Table 1.4. Estimates of the standard deviations of random main and interaction effects of logistic nitrogen response parameters with site and block within site for the mixed effects model of nitrogen response in Illinois containing all experimental sites and rotations.

| Random effect | Parameter | | | |
|-------------------|------------------------|-----------------------|------------------------|-----------------------|
| | Asymptote | | Inflection point | |
| | Corn following corn | Corn following soy | Corn following corn | Corn following soy |
| Site | 1673.14 | 508.96 | 6.11 | 15.06 |
| Block within site | 359.58 | 338.52 | 2.45 | 0.01 |
| Residual | 1953.035 | | | |

Table 1.5. Best linear unbiased predictions (BLUPs) of combined fixed and random effects for parameters of the logistic nitrogen response model for the mixed effects model of nitrogen response in Illinois containing all sites and rotations.

| Site | Parameter | | | |
|--------------------------|---------------------|--------------------|---------------------|--------------------|
| | Asymptote | | Inflection point | |
| | Corn following corn | Corn following soy | Corn following corn | Corn following soy |
| Monmouth | 11,955.47 | 13,555.23 | 24.00 | -55.71 |
| DeKalb | 11,187.11 | 12,174.75 | 21.91 | -21.85 |
| Urbana | 11,175.40 | 11,927.41 | 20.32 | -22.74 |
| Perry | 9329.88 | 9369.63 | 29.14 | -14.26 |
| Dixon Springs Bottomland | 10,667.74 | 11,556.99 | 34.93 | -0.49 |
| Dixon Springs Upland | 7432.17 | 7950.32 | 27.75 | -13.76 |
| Brownstown | 7741.10 | 8491.71 | 28.57 | -19.85 |

Table 1.6. Differences in revenues between maximum return to nitrogen (MRTN) rates determined using logistic regression and yearly economically optimal nitrogen rates (EONR) rates derived from LOESS regression for corn following corn and corn following soy.

| Location | Corn following corn | | | | | Corn following soy | | | | |
|--------------------------|---------------------------|--|--|--|--|---------------------------|--|--|--|--|
| | Average EONR rate (kg/ha) | Yearly logistic response curves for MRTN determination | | Single logistic response curve over entire experiment for MRTN determination | | Average EONR rate (kg/ha) | Yearly logistic response curves for MRTN determination | | Single logistic response curve over entire experiment for MRTN determination | |
| | | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus</i> | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus</i> | | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus</i> | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus</i> |
| | | | <i>yearly EONR return</i> | | <i>yearly EONR return</i> | | | <i>yearly EONR return</i> | | <i>yearly EONR return</i> |
| Monmouth | 195 | 215 | -\$18.86 | 210 | -\$18.00* | 127 | 134 | -\$21.29** | 131 | -\$20.56** |
| DeKalb | 218 | 253 | -\$13.21* | 249 | -\$11.66* | 167 | 171 | -\$22.08** | 164 | -\$22.21** |
| Urbana | 203 | 224 | -\$21.40** | 214 | -\$22.09*** | 168 | 184 | -\$13.60 | 178 | -\$14.42 |
| Perry | 171 | 193 | -\$28.27** | 190 | -\$26.25** | 142 | 159 | -\$28.43 | 151 | -\$28.37* |
| Dixon Springs Bottomland | 210 | 196 | -\$52.19** | 200 | -\$49.57** | 200 | 194 | -\$35.35* | 195 | -\$35.42* |
| Dixon Springs Upland | 183 | 212 | -\$21.26** | 197 | -\$20.06* | 151 | 191 | -\$46.33 | 159 | -\$43.13 |
| Brownstown | 206 | 252 | -\$19.59 | 200 | -\$54.56* | 181 | 170 | -\$16.62 | 166 | -\$17.19 |

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

MRTN, maximum return to nitrogen rate; EONR, economically optimal nitrogen rate

Table 1.7. Differences in revenues between maximum return to nitrogen (MRTN) rates determined using quadratic + plateau regression and yearly economically optimal nitrogen rates (EONR) rates derived from LOESS regression for corn following corn and corn following soy.

| Location | Corn following corn | | | | | Corn following soy | | | | |
|--------------------------|---------------------------|---|---|---|---|---------------------------|---|---|---|---|
| | Average EONR rate (kg/ha) | Yearly quadratic + plateau response curves for MRTN determination | | Single quadratic + plateau response curve over entire experiment for MRTN determination | | Average EONR rate (kg/ha) | Yearly quadratic + plateau response curves for MRTN determination | | Single quadratic + plateau response curve over entire experiment for MRTN determination | |
| | | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus yearly EONR return</i> | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus yearly EONR return</i> | | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus yearly EONR return</i> | MRTN rate (kg/ha) | <i>average ex ante MRTN return minus yearly EONR return</i> |
| | | | | | | | | | | |
| Monmouth | 195 | 204 | -\$17.64* | 195 | -\$17.95* | 127 | 135 | -\$21.56** | 127 | -\$19.81** |
| DeKalb | 218 | 246 | -\$10.69* | 231 | -\$8.33** | 167 | 157 | -\$22.74** | 152 | -\$23.43** |
| Urbana | 203 | 208 | -\$22.94*** | 201 | -\$24.36*** | 168 | 175 | -\$14.96 | 169 | -\$16.27 |
| Perry | 171 | 198 | -\$31.67** | 181 | -\$20.81** | 142 | 152 | -\$28.32* | 148 | -\$28.55* |
| Dixon Springs Bottomland | 210 | 212 | -\$41.51** | 202 | -\$48.23** | 200 | 190 | -\$35.13* | 183 | -\$35.09* |
| Dixon Springs Upland | 183 | 239 | -\$32.56* | 197 | -\$20.06* | 151 | 191 | -\$46.33 | 159 | -\$43.13 |
| Brownstown | 206 | 253 | -\$19.59 | 222 | -\$40.47** | 181 | 178 | -\$16.26 | 175 | -\$16.29 |

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

MRTN, maximum return to nitrogen rate; EONR, economically optimal nitrogen rate

Table 1.8. Differences in revenues and rates between maximum return to nitrogen (MRTN) rates derived from the average of yearly logistic nitrogen response curves and rates derived from the yield goal, and differences between yield goal revenues and yearly economically optimal nitrogen rates (EONR) rates derived from LOESS regression for corn following corn and corn following soy.

| Location | Corn following corn | | | | | | Corn following soy | | | | | |
|--------------------------|---------------------|---|---|-----------------------------------|---|--|--------------------|---|---|-----------------------------------|---|--|
| | Yield goal | | Yearly logistic response curves used for MRTN | | | | Yield goal | | Yearly logistic response curves used for MRTN | | | |
| | Nitrogen Rate | <i>average ex ante yield goal return minus yearly EONR return</i> | MRTN rate (kg) | Yield goal N rate minus MRTN rate | <i>average ex ante MRTN return minus yearly EONR return</i> | <i>Yield goal returns minus MRTN returns</i> | Nitrogen Rate | <i>average yield goal return minus yearly EONR return</i> | MRTN rate (kg) | Yield goal N rate minus MRTN rate | <i>average ex ante MRTN return minus yearly EONR return</i> | <i>Yield goal returns minus MRTN returns</i> |
| Monmouth | 242 | -\$31.80 | 215 | 27 | -\$18.86 | -\$12.95 | 197 | -\$48.80* | 134 | 63 | -\$21.29** | -\$27.51 |
| DeKalb | 235 | -\$8.57** | 253 | -18 | -\$13.21* | \$4.64 | 190 | -\$22.78** | 171 | 19 | -\$22.08** | -\$0.70 |
| Urbana | 228 | -\$21.36** | 224 | 4 | -\$21.40** | \$0.05 | 183 | -\$13.71 | 184 | -1 | -\$13.60 | -\$0.11 |
| Perry | 188 | -\$24.95** | 193 | -5 | -\$28.27** | \$3.32 | 143 | -\$29.06* | 159 | -16 | -\$28.43 | -\$0.63 |
| Dixon Springs Bottomland | 188 | -\$57.31** | 196 | -8 | -\$52.19** | -\$5.12 | 143 | -\$48.74 | 194 | -51 | -\$35.35* | -\$13.39 |
| Dixon Springs Upland | 161 | -\$37.80* | 212 | -51 | -\$21.26** | -\$16.54 | 116 | -\$44.92 | 191 | -75 | -\$46.33 | \$1.41 |
| Brownstown | 155 | -\$81.23** | 253 | -98 | -\$19.59 | -\$61.64 | 110 | -\$68.75 | 170 | -60 | -\$16.62 | -\$52.13 |

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

MRTN, maximum return to nitrogen rate; EONR, economically optimal nitrogen rate

CHAPTER 2: PREDICTING NITROGEN RESPONSE: THE EFFECT OF WEATHER ON CORN NITROGEN RESPONSE IN ILLINOIS

2.1 INTRODUCTION

Weather and price volatility aside, management of N application is the greatest source of financial risk for corn producers in Illinois. Whereas under-application of N fertilizer forfeits revenue stemming from increased production (Black, 1993; Pan et al., 1997; Scharf and Lory, 2000), over-application reduces net income from the economic optimum and increases the amount of N that enters local watersheds, contributing to the degradation of marine ecosystems through hypoxia (Donner and Kucharik, 2008; Goolsby et al., 2001; Jaynes et al., 2001 ; Meisinger and Randall, 1991; Rabalais et al., 2002; Sogbedji et al., 2000). Despite reducing profitability, producers are more likely to over-apply N under the assumption that the aggregate cost of over-application in most growing seasons is far outweighed by the cost of under-application during “the good years” (Babcock, 1992; Sherriff, 2005).

There have been many attempts in the past century to determine economically optimal N rates in corn production systems in order to maximize profitability while minimizing environmental impact (Blackmer et al., 1997; Hoefl and Peck, 2001; Stanford, 1973; Vanotti and Bundy, 1994). While the recently introduced MRTN recommendation system (Nafziger et al., 2004), especially in tandem with soil N testing, are close to economically optimal (Sawyer et al., 2006), inter-annual variability in N response can result in recommended rates being too high or too low by 10 to 10² kg/ha (Bundy, 2000; Fox and Piekielek, 1995; Kachanoski et al., 1996;

Vanotti and Bundy, 1994). This is because N response in corn displays large spatiotemporal variation (Eghball and Varvel, 1997; Mamo et al., 2003).

Whereas spatial variation is primarily due to differences in landscape and soil properties (Broadbent, 1984; Fiez et al., 1994; Hergert et al., 1995; Ritchie, 1984; Stanford, 1982; Swan et al., 1987), temporal variation is due to differences in planting date and weather between growing seasons (Nafziger, 1994; Swanson and Wilhelm, 1996). Early-season rainfall when soils are dry and warm enough for planting has been shown to influence corn yield response to N (Gupta, 1985; Sogbedji et al., 2001). The timing and frequency of rain during the growing season can also affect the N response curve (Thompson, 1988). Extreme temperatures reduce yield due to corn's sensitivity to temperatures above 30 C (Lobell and Asner, 2003). While extreme temperatures can affect yield by stopping crop growth, yield reduction is more attributable to the increase in vapor pressure deficit and the depletion of soil moisture induced by high temperatures (Baier, 1973; Lobell et al., 2013; Ray et al., 2002). In fact, soil moisture explains a greater proportion of yield variability than raw climatic variables (Baier and Robertson, 1968). However, temperatures up to a certain threshold can actually increase crop growth and yield (Baier, 1973). Understanding the complex and layered effects of weather on N response in corn throughout the growing season may lead to a quantitative adjustment of application rates based on expected weather outcomes.

The accumulation of thermal units throughout the growing season, commonly measured as growing degree days (GDD), has been found to be closely associated with corn crop development (Cross and Zuber, 1972; Cutforth and Shawkewich, 1989; Gilmore and Rogers, 1958; Pruess, 1983; Russelle et al., 1984; Tollenaar et al., 1979). Analysis of weather effects on yield and N response over the specific developmental stages of the crop has yielded more

significant results than calendar averages in wheat for many weather variables (Baier and Robertson, 1968). Since N response in corn is more sensitive to weather during reproductive growth (such as silking and afterwards), biometeorological time (weather variables measured during discrete growth-stage periods of the crop) explains more of the variation in N response than meteorological time (weather variables measured during discrete time intervals independent of crop phenology) (Harder et al., 1982; Robertson, 1968). Heat stress during and after silking negatively affects a host of reproductively vital processes in corn (Fonseca and Westgate, 2005; Lobell et al., 2013). Water stress during and around silking reduces yield significantly, and can be greater than 50% when the stress is prolonged (Barnabas et al., 2008; Çakir, 2004; Denmead and Shaw, 1960; Fonseca and Westgate, 2005; Harder et al., 1982; Otegui et al., 1995; Ray et al., 2002; Shaw, 1974). However, while water stress during any biometeorological period of corn can affect yield, stress during grain filling is the most harmful next to stress during silking (Claasen and Shaw, 1970 a, b; Denmead and Shaw, 1960; Grant et al., 1989; NeSmith and Ritchie, 1990).

Too much water can be as detrimental as too little with corn. Unusually high rainfall can flood soils, drowning plants and increasing incidence of disease. The effect of flooding is much more pronounced in young corn plants than more mature ones, reinforcing the need to study N response within a biometeorological framework (Ashraf and Rehman, 1999; Meyer et al., 1987; Mason et al., 1987). In contrast to the large body of evidence supporting the need for examining weather within a biometeorological framework, meteorological variables averaged over monthly and longer time scales have recently proved successful in modelling weather effects on yield (Lobell et al., 2013; Lobell et al., 2014; Ray et al., 2002). However, weather variables alone cannot describe N response, as weather effects on N response are not uniform across locations,

and weather interacts with soil and location (Grant et al., 1989; Mamo et al., 2003; Scharf et al., 2005).

Even though EONR values may be dependent on weather realized during the growing season (Mamo et al., 2003), N management decisions are typically made before planting. A USDA survey of producer practices found that 75% of N is applied before planting, while only 25% occurs after planting (Cassman et al., 2002). This is in lieu of the fact that pre-plant N efficiency decreases in proportion to the size of the application (Reddy and Reddy, 1993), and that in-season N has higher N use efficiency (Miller et al., 1975; Olson et al., 1986; Randall et al., 2003; Randall and Vetsch, 2005; Welch et al., 1971). Though producers have the ability to test N concentration in the soil and adjust application rates to account for soil N supply (Magdoff, 1991; Magdoff et al., 1984; Schroder et al., 2000; Wibawa et al., 1993), the recommendation systems that they follow are weather invariant. The dynamic nature of weather and its effect on yield and N response proscribe static rate recommendations from ever being economically optimal. To reduce N waste, adjusting N application in response to expected environmental conditions is as important as delaying application.

Predicting N response (and therefore, economically optimal N rates (EONR)) before N application will increase profitability of corn production systems and may also reduce environmental impact. Long term, multi-site N response experiments are necessary to reveal weather variables with the greatest effect on N response. Using a ten year and seven site N response experiment conducted in Illinois from 1999 to 2008, we examined the effects of a variety of biometeorological and monthly meteorological variables as well as simulated soil moisture data on N response. A regression tree algorithm was used to determine which subset of the variables was best able to predict the parameters of fitted site-year N response equations.

Influential variables were added to a nonlinear mixed effects model for N response across the entire experiment and tested for significance. Finally, we restricted the variables to only include pre-planting ones and performed the analysis again. Variables identified as significant in the regression tree and the nonlinear mixed effects model were then entered into linear regression. The regression model was fit to the parameters of the logistic function and the predictive ability of the model was tested using 2-fold cross validation.

2.2 MATERIALS AND METHODS

Experimental plots were in place by 1999 as a split plot arrangement of two levels of rotation (corn-corn and corn-soybean) and six levels of N fertilizer rates (six levels: 0, 50, 101, 151, 202, and 252 kg per hectare) in a randomized complete block design with four replications at each of seven sites in Illinois: Monmouth, DeKalb, Urbana, Perry, Dixon Springs Bottomland, Dixon Springs Upland, and Brownstown. Two sites were used at Dixon Springs in order to reflect the two different types of soil and terrain prevalent in that region of Illinois. Soils at the Bottomland site were moderately well draining and level Inceptisols, whereas the soils of the Upland site were somewhat poorly draining and sloped Alfisols. At all sites, the experiment was conducted for 10 years from 1999 to 2008. Four blocks split into corn following corn and corn following soybean were treated with six different N rates – 0, 50, 101, 151, 202, and 252 kilograms per hectare. Grain yield, in kilograms per hectare, was recorded for each treatment.

Soil types were varied but characteristic of the types found in regions surrounding the experimental sites and indeed of the most common types in Illinois. Descriptions of the soils at each experimental site as well as expected yields are summarized in Table 2.1 (Olson and Lang, 2000; USDA, 2014).

The Monmouth, DeKalb, Urbana, and Perry experimental sites were located in USDA Plant Hardiness Zone 5b between 200 and 270 m above sea level, while the Dixon Springs Bottomland and Upland, and Brownstown experimental sites were located in zones 6b and 6a respectively, roughly 170 m above sea level. Soils at the Monmouth, DeKalb, and Urbana experimental sites were poorly drained Mollisols high in organic matter content. The soil at the Perry experimental site was a somewhat poorly drained Alfisol with moderate organic matter content. The Dixon Springs Upland and Brownstown experimental sites were also Alfisols, albeit moderately well-

draining and low in organic matter for the former and poorly draining and low in organic matter for the latter. The Dixon Springs Bottomland experimental site was a somewhat poorly drained Inceptisol low in organic matter content.

Experimental plots at the Brownstown research station were more negatively affected by unusually high precipitation than typical fields in the rest of the county in which it is located. Three site years (2000 corn following soy, 2002 corn following corn, and 2002 corn following soy) were removed from the Brownstown data set due to the experiment being compromised by innate difficulties regarding the aforementioned.

Weather data and creation of biometeorological and meteorological weather variables

Daily weather data was collected at each of the seven experimental sites by the Illinois State Water Survey as part of the Illinois Climate Network program (<http://www.isws.illinois.edu/warm/datatype.asp>). Data collected by the program and used by this research were solar radiation, maximum air temperature, minimum air temperature, average air temperature, average dew-point temperature, precipitation, maximum soil temperature at 10 cm depth, minimum soil temperature at 10 cm depth, average soil temperature at 10 cm depth, maximum soil temperature at 20 cm depth, minimum soil temperature at 20 cm depth, and average soil temperature at 20 cm depth. Cumulative rainfall (CRF) at the end of an early-season phenological interval (200 to 700 GDD) has been shown to strongly influence plant-available N, though the effect of CRF was tested for all growth stages (Kay et al. 2006). As such, a variable for CRF was also created as the cumulative sum of average daily precipitation from the beginning to the end of each of the phenological periods of interest.

Soil moisture data were not collected for the experiment. As such, soil moisture was estimated using the STM2 soil temperature and moisture model from the USDA-ARS (Spokas et

al. 2007). Researchers in Quebec, Canada examined the predictive ability of the STM2 model for gravelly, sandy, loamy, and clayey soils. Model predictions were accurate for the loamy and clayey soils in question, though less accurate for clayey (Perreault et al. 2013). As the soils in question for this study lie somewhere between the loamy and clayey ones used for evaluation of the STM2 model, it is likely STM2 simulations were generally accurate for our analysis.

The depth at which soil moisture measurements (or in this case simulations) are taken is just as important as the measurement itself. One study in Argentina examined the effects of drought on corn growth, water uptake, and kernel abortion around silking and found that during the 20 days leading to silking, irrigated corn plants drew 70% of their water from the first 40 cm of soil, whereas plants under water stress drew only 40%. During the 20 days after silking, irrigated plants still drew a similar amount of their water from the first 40 cm of soil, whereas plants under water stress drew 64% of their water from the 90 – 180 cm soil profile (Otegui et al. 1995). Post emergence, the complete saturation of soil is most impactful on the developing corn plant with regards to oxygen stress (Meyer et al. 1987; Mason et al. 1987). Clearly, soil moisture at different depths have different levels of import to the corn plant depending on the phenological period of interest. To account for this, and to limit the possibility of false positives by testing too many variables, we used simulated soil moisture at 1 cm, 20 cm (the midpoint of the 0 – 40 cm depth), and 135 cm (the midpoint of the 90 – 180 cm depth). Unfortunately, soil moisture simulations from the STM2 model become more inaccurate as depth increases (Perreault et al. 2013). Averages were created for these depths from January through September, and averages of soil moisture at these depths were also created for the phenological periods of interest.

While vapor pressure deficit (VPD) measurements were not collected by the Illinois State Water Survey, they can be calculated from dewpoint temperature and relative humidity (RH). Vapor pressure deficit is saturation vapor pressure (SVP) – RH The relationship is determined by:

$$SVP = \exp\left(\frac{17.269 T}{237.3 + T}\right)$$

$$VPD = \left(1 - \frac{RH}{100}\right) SVP$$

where T is assumed to be the dewpoint temperature (Lobell et al. 2013). Daily VPD estimates were calculated and monthly averages from January to September, as well as averages for all the phenological periods of interest, were created.

GDD were calculated using the following formula, as described in the 2014 Illinois Agronomy Handbook:

$$GDD = \left[\frac{(T_{max} + T_{min})}{2}\right] - T_{base}$$

where T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature, and T_{base} is the baseline temperature where growth does not occur, which for corn is 10° C (50° F). When daily maximum temperatures are above 30° C (86° F), $T_{max} = 30$, and when daily minimum temperatures are below 10° C (50° F), $T_{min} = 10$. A variable for cumulative GDD is then created as the cumulative sum of the GDD from the planting date for each site-year.

Phenological periods of interest were defined using ranges of GDD for each growing season. Based on previous work on plant available N, we defined biometeorological periods of interest as the following ranges of GDD: 0 – 700 (planting, emergence, and vegetative growth), 700 – 1350 (vegetative growth), 1350 – 2000 (reproductive growth), and 2000 to 2600 (physiological maturation)(Kay et al. 2006). Based on previous work on the importance of stress

around silking and during grain fill, in combination with the approximate GDD needed for corn plants in Illinois to reach each growth stage, we defined additional biometeorological periods of interest as the following ranges of GDD: 1220 – 1400 (V17 to R1(silk), corresponding with the 20 days leading up to silking), 1400 – 1660 (R1 (silk) to R2 (blister), corresponding with the 20 days after silking), 1220 – 1660 (V17 to R2 (blister), corresponding with the 20 days before and after silking), and 1350 – 1450 (VT (tassel) to R1 (silk), corresponding to actual silking) (Hoeft and Nafziger, 2014; Kay et al. 2006; Denmead and Shaw 1960; Otegui et al. 1995; Çakir 2004).

In addition to the aforementioned phenological periods, monthly averages for all the utilized variables were created from January through September for each site, as September is the latest month that corn plants reach maturity in Illinois (Illinois Agronomy Handbook 2014). This resulted in a total of $17 \times 15 = 255$ variables examined for weather effects on N response, and $5 \times 15 = 75$ variables examined for suitability as predictive pre-season weather effects.

Selection of growing season variables most explanatory of N response

Logistic N response curves were fit using R version 3.1.0 (R Core Team, 2014) and package function `nls{stats}`, part of the package `nlme` (Pinheiro et al., 2013). for all site-years where data allowed convergence of the algorithm, as this function was identified as the most suitable function for N response in Illinois (Febrer et al., 2014). Parameters of the logistic response function for each site-year (asymptote, N-midpoint, and scale) were then stored as variables. A regression tree algorithm was used to determine which variables were best able to predict each parameter using R function `rpart {stats}` part of the package `rpart` (Therneau et al., 2014). Using the “1 – se” method, the trees were pruned by choosing the smallest tree for which the RMSE was within one standard error of the lowest RMSE obtained by any of the trees produced (Breiman et al. 1984).

Variables identified as the best predictors by the regression tree algorithm were entered into a nonlinear mixed effects model for the entire experiment as random effects varying with site. Main effects of identified variables as well as significant interactions were included, and the resulting model was tested for significance vs the original model using a log-likelihood ratio test.

Selection of pre-season variables most predictive of N response

The scope of weather variables for examination was restricted monthly averages up until planted crops have experienced 555 GDD (growth stage V6), which was typically in May. Averages up until V6 are chosen because this is identified as the latest possible time N can be side-dressed without potentially reducing yield (Illinois Agronomy Handbook 2014). A regression tree algorithm was again used to determine which variables were best able to predict each parameter of the logistic N response regressions using R function `rpart {stats}`. Trees were pruned using the “1 – se” method.

Pre-season variables identified as the best predictors by the regression tree algorithm were entered into a nonlinear mixed effects model for the entire experiment as random effects varying with site. Main effects of identified variables as well as significant interactions were included, and the resulting model was tested for significance vs the model without weather variables using a log-likelihood ratio test. Influential variables were entered into a linear regression for each site for the asymptote parameter. Interactions were excluded due to the low number of degrees of freedom (5), and predictive ability tested using 2-fold cross validation.

Predictive ability was also tested by identifying variables and interactions that were significant in the mixed effects model and using them as candidate variables for linear regression of the asymptote parameter for the full data set. Variables identified as significant at 0.20 were entered into the model, with previously entered variables with less than 0.20 significance

removed, using a stepwise algorithm. Predicted asymptote values, as well as estimated BLUPs for the random and main effects of site, previous crop, and site with previous crop, were used to engineer predicted nitrogen response curves. Predicted EONR were derived from these curves. Revenues were compared against actual EONR and maximum return to nitrogen (MRTN) recommendations.

2.3 RESULTS AND DISCUSSION

Effect of weather and site on N response

For the asymptote parameter, the smallest tree chosen by the 1 – se method had a cross validated error of 76.4%. This tree was of size 5 and is shown in Figure 2.1. The first split indicates that site is the most predictive variable for the asymptote of the logistic N response function. For DeKalb, Dixon Springs Bottomland, Monmouth, and Urbana, average soil temperature at 10 cm depth during silking (S) was most predictive of the asymptote parameter, which supports the body of literature on the amplified vulnerability of corn yield to stress during silking (Denmead and Shaw, 1960; Harder et al. 1982). Given low soil temperatures at 10 cm depth during silking, the average soil temperature at 20 cm depth during June was most able to predict the asymptote parameter. For Brownstown, Dixon Springs Upland, and Perry, average precipitation during the month of July (a meteorological variable) was most predictive of the asymptote parameter.

While biometeorological variables can be important, they are not necessarily the most influential time periods when studying weather effects on yield (Harder et al., 1982; Robertson, 1968). Selection of meteorological variables by the regression tree supports the choices of modern researchers in examining yield response in a meteorological framework (Lobell et al., 2013; Lobell et al., 2014), and supports the findings of Baier and Robertson, who showed that correlations between yield and monthly precipitation amounts were higher than correlations between yields and biometeorological precipitation totals in wheat (Baier and Robertson, 1967). The variables chosen, being measurements of water availability and heat during the growing season, reinforce the body of research demonstrating the detrimental effects of water stress and

heat stress on yield and N response (Baier, 1973; Barnabas et al., 2008; Fonseca and Westgate, 2005; Harder et al., 1982; Lobell and Asner, 2003; Lobell et al., 2013; Ray et al., 2002).

Soil moisture variables for any period, biometeorological and meteorological, were not selected by the regression tree algorithm. This contradicts previous research showing that soil moisture variables are more influential than climatic variables (Baier and Robertson, 1968). However, because soil moisture values were simulated using a model and not measured in situ, introduced error and/or bias may have caused the variables to not be as influential as climatic variables which were accurately measured. Cumulative rainfall (CRF) was also not selected by the regression tree for any phenological period, in contrast to previous results (Kay et al. 2006). Asymptotes of the logistic N response regressions for each site year plotted against the observations of the selected weather variables are shown in Figure 2.2 for corn following corn and Figure 2.3 for corn following soy.

For the N-midpoint parameter, the smallest tree chosen by the 1 – se method had a cross validated error of 75.2%. This tree was of size 2 and is shown in Figure 2.4. The only split for the N-midpoint parameter is by previous crop, indicating that rotation is the most predictive variable of the N-midpoint for the logistic N response function. Since the N-midpoint parameter affects the y-intercept (yield at 0 kg N/ha), this supports the body of literature showing increases in soil N from using a legume as a previous crop (Barber and Stiver, 1962; Mulvaney et al., 2005; Stranger and Lauer, 2008).

For the scale parameter, the smallest tree whose cross validated error, 101.2%, was within one standard error of the smallest cross validated error was of size 1. Given that this tree amplifies the standard error of the scale parameter instead of reducing it, the smallest tree for the

scale parameter is actually a tree of size 0, that is, no variables are well suited to predict the scale parameter of logistic N response in Illinois.

Weather variables selected by the regression tree algorithm as predictive of the asymptote parameter were included as random interaction effects with site in a nonlinear mixed effects model for N response in Illinois. Interactions with previous crop and among each other were tested. Fixed effects of the model were the asymptote, the interaction effect of asymptote with previous crop, N-midpoint, the interaction effect of N-midpoint with previous crop, and the scale parameter. All fixed effects were significant at $p < 0.0001$ except for the asymptote fixed effect, which was not statistically significant. This, however, is due to the fact that the asymptote parameter was captured in interactions with weather and previous crop. The random effects of July average precipitation, the average soil temperature at 10 cm depth during silking, and the average soil temperature at 20 cm depth during June explained significant amounts variation with site on N response in Illinois and were included in the final mixed effects model. The random interaction effects of July average precipitation with previous crop, July average precipitation with average soil temperature at 10 cm depth during silking, July average precipitation with average soil temperature at 20 cm depth during June, and average soil temperature at 10 cm depth during silking with average soil temperature at 20 cm depth during June explained significant amounts of variation with site on N response in Illinois and were included in the final mixed effects model.

A log likelihood ratio test indicated that the model with weather effects was statistically significant at $p < 0.0001$ when compared to the model without weather effects. Residuals were centered around 0, homoscedastic, and normally distributed for all sites. Estimates of BLUPs were normally distributed for random interaction effects, with the exception of the random

interaction effect of N-midpoint with previous crop and site and the random interaction effect of soil temperature at 10 cm depth during silking with average soil temperature at 20 cm depth during June and site.

Early season weather variables as predictors of N response

For the asymptote parameter, the tree selected by the 1 – se method had cross validated error of 73.5%. This tree was of size 5 and is shown in Figure 2.5. The first split also indicates that site is the most predictive variable for the asymptote of the logistic N response function. For Brownstown, Dixon Springs Upland, and Perry, average soil temperature at 20 cm depth for April was most predictive of the asymptote parameter. Given high average soil temperatures at 20 cm depth for April, average precipitation for January was the most predictive of the asymptote parameter. For DeKalb, Dixon Springs Bottomland, Monmouth, and Urbana, average soil moisture at 135 cm depth for April was most predictive of the asymptote parameter. Given low average soil moisture of the 135 cm depth for April, average precipitation for January was the most predictive of the asymptote parameter. Asymptotes of the logistic N response regressions for each site year plotted against the observations of the chosen predictive weather variables are plotted in Figure 2.6 for corn following corn and Figure 2.7 for corn following soy.

The fact that no biometeorological variables were chosen by the regression tree algorithm as predictive of N response is unusual, as previous research found that early-season, post-planting weather variables have a strong effect on yield (Kay et al. 2006). However, these researchers did not include pre-planting variables in their analysis, which may indicate that they are more valuable than post planting ones. It is unclear why precipitation in January and soil temperatures in April can predict N response. Water from January snow melting would likely exit through tile drainage long before the crop could take advantage of it. While soil temperature

in April can be an indicator of planting date, the split chosen by the regression tree is counter intuitive, showing that high April soil temperatures (which would accelerate planting) result in lower maximum yields than low April soil temperatures (Gupta, 1985). However, soil moisture at the 135 cm depth in April is intuitively rational as an explanatory variable, likely acting as an indicator of soil moisture at this depth during reproductively vital periods of crop growth (Kay et al. 2006).

For the N-midpoint parameter, the tree selected by the 1 – se method had a cross validated error of 74.2%. This tree was of size 2 and is shown in Figure 2.8. The only split for the N-midpoint parameter is by previous crop, also indicating that rotation is the most predictive variable of the N-midpoint of the logistic N response function.

For the scale parameter, the tree selected by the 1 – se method had a cross validated error of 101.8% and was of size 1. Given that this tree amplified the standard error of the scale parameter instead of reducing it, the smallest tree for the scale parameter was actually a tree of size 0; that is, no variables are able to predict the scale parameter of logistic N response in Illinois.

Predictive weather variables selected by the regression tree algorithm for the asymptote parameter were included in a nonlinear mixed effects model for N response in Illinois as random effects. Interactions with previous crop and among each other were tested. Fixed effects of the model were the asymptote, the interaction effect of asymptote with previous crop, N-midpoint, the interaction effect of N-midpoint with previous crop, and the scale parameter. All fixed effects were significant at $p < 0.0001$ except for the asymptote fixed effect, which was not statistically significant. This, however, is due to the fact that the asymptote parameter was captured in interactions with weather and previous crop. The random effects of average soil temperature at

20 cm depth for April, the average soil moisture at 135 cm depth for April, and the average precipitation for January explained significant amounts variation with site on N response in Illinois and were included in the final mixed effects model. The random interaction effects of average soil temperature at 20 cm depth for April with previous crop, average soil temperature at 20 cm depth for April with average soil moisture at 135 cm depth for April, average soil temperature at 20 cm depth for April with average precipitation for January, average soil moisture at 135 cm depth for April with average precipitation for January, average soil temperature at 20 cm depth for April with average soil moisture at 135 cm depth for April with average precipitation for January, and average soil temperature at 20 cm depth for April with average soil moisture at 135 cm depth for April with average precipitation for January with previous crop explained significant amounts of variation with site on N response in Illinois and were included in the final mixed effects model.

A log likelihood ratio test indicated that the model with weather effects was statistically significant at $p < 0.0001$ when compared to the model without weather effects. Residuals were centered around 0, homoscedastic, and normally distributed for all sites. Estimates of BLUPs were normally distributed for random interaction effects, with the exception of random interaction effect of N-midpoint with previous crop and site.

Predictive ability of selected weather variables on N response parameters

R square values between the predicted and actual asymptote parameters, mean square errors (MSE) of the residuals, and average value of the residuals for the cross validation results by site are listed in Table 2.2. Despite the fact that cross validated regression using the predictive weather variables for each site had very low degrees of freedom (5) compared to the number of variables entered (2), predictive ability was very good for several sites. Monmouth and Urbana

had R square values above 40%, relatively low MSE, and residuals centered near 0. However, other sites, such as Brownstown and DeKalb, had R square values near 0 and biased residuals.

The average difference in revenues between the predicted and actual EONR and the quadratic + plateau MRTN and actual EONR when using the full data set are listed in Table 2.3. Performance of the predicted EONR was mixed and inconclusive. While predicted EONR resulted in higher revenues than the quadratic + plateau MRTN at some sites for corn following corn, at other sites it resulted in lower revenues. However, for corn following soybean, the predicted EONR resulted in lower revenues than the quadratic + plateau MRTN for all sites.

Though the results were mixed, the fact that regressions had very low degrees of freedom, predictive ability may be improved with a longer term experiment. However, given that the regressions performed poorly for all sites with corn following soybean, it may be the case that the predictive variables chosen are more influential on nitrogen response in corn following corn and that using soybean in rotation with corn acts as a buffer against weather-related stress.

The range of predictive ability and MSE across sites reinforces the high amount of inter-site variability in N response (Mamo et al., 2003). This also indicates that though variables selected were effective at improving the mixed effects model of N response in Illinois, sites should be examined independently of each other using the CART algorithm in order to select the influential weather variables particular to that site and thus increase forecasting ability of N response. However, due to the much lower number of degrees of freedom involved when restricting the scope of the CART analysis to individual sites, the number of variables examined must be reduced from the amount used in this study in order for the algorithm to function.

2.4 CONCLUSION

The exhaustive nature of the weather variables analyzed provides a good filter for future researchers seeking to examine the effect of weather on both yield and N response in corn. Variables during early phenological growth stages were shown to not be relevant to ultimate yield response, while soil temperatures during silking and precipitation during July were determined to be most predictive. Though cross validated predictions for many sites were not accurate enough to make confident estimates of N response by the optimal side-dressing time, the techniques presented herein lay the groundwork for successful attempts at EONR prediction.

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2.6 FIGURES AND TABLES

Figure 2.1. Regression tree produced from biometeorological and meteorological weather variables for the asymptote parameter of logistic nitrogen response in Illinois.

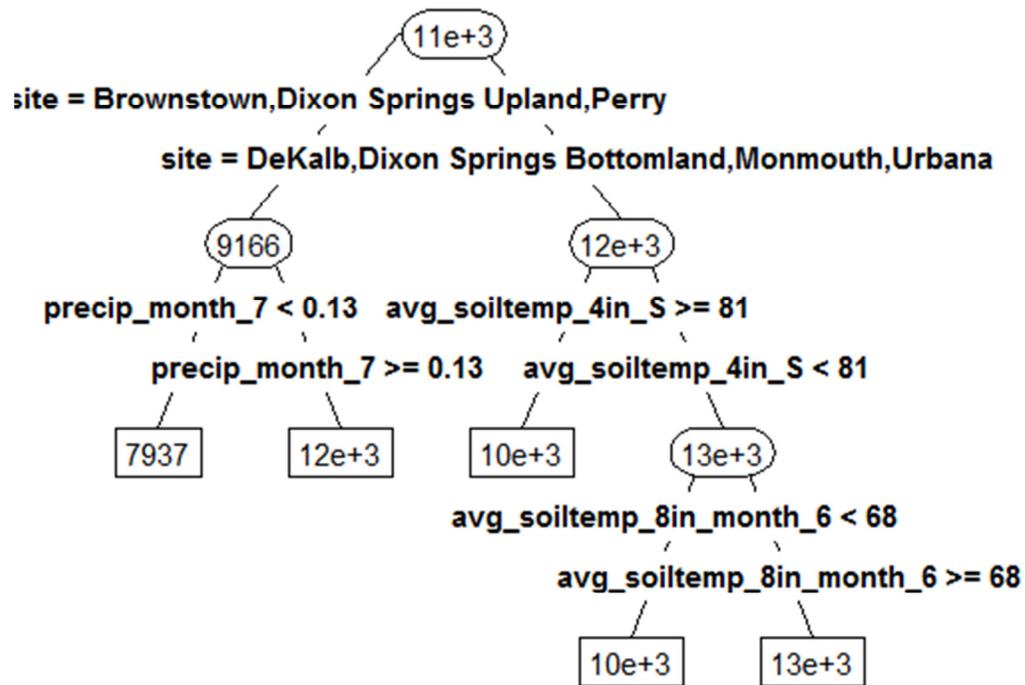


Figure 2.2. Asymptotes of fitted logistic nitrogen response regressions for each site year plotted against selected biometeorological and meteorological weather variables for corn following corn

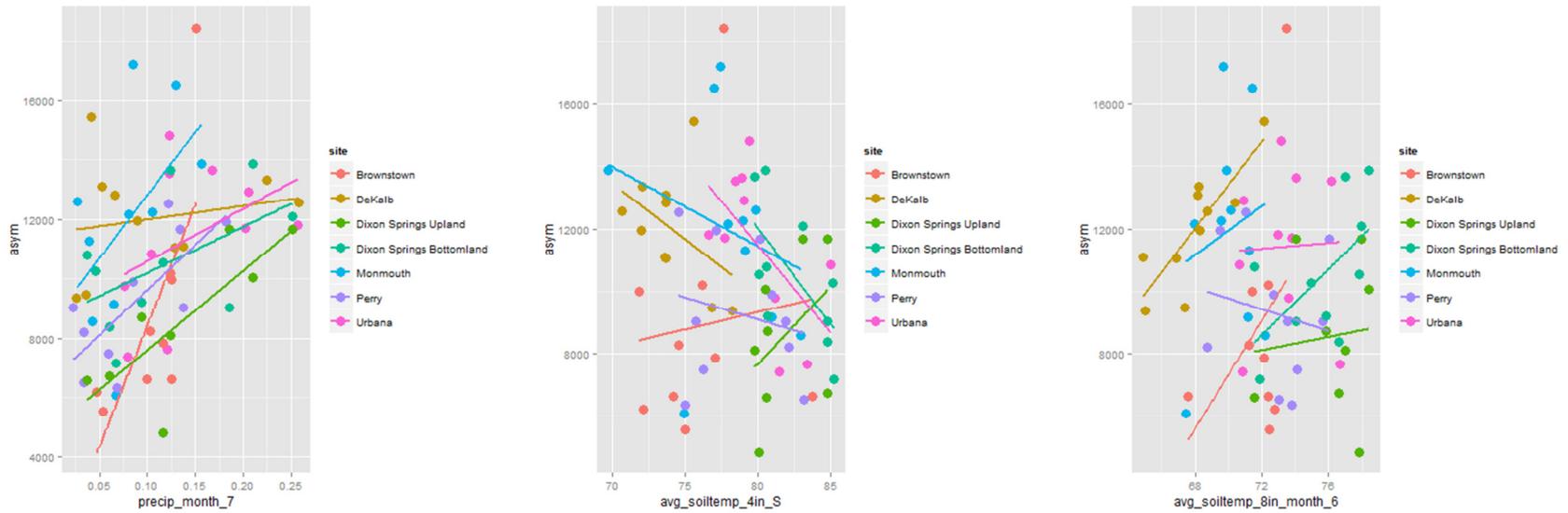


Figure 2.3. Asymptotes of fitted logistic nitrogen response regressions for each site year plotted against selected biometeorological and meteorological weather variables for corn following corn

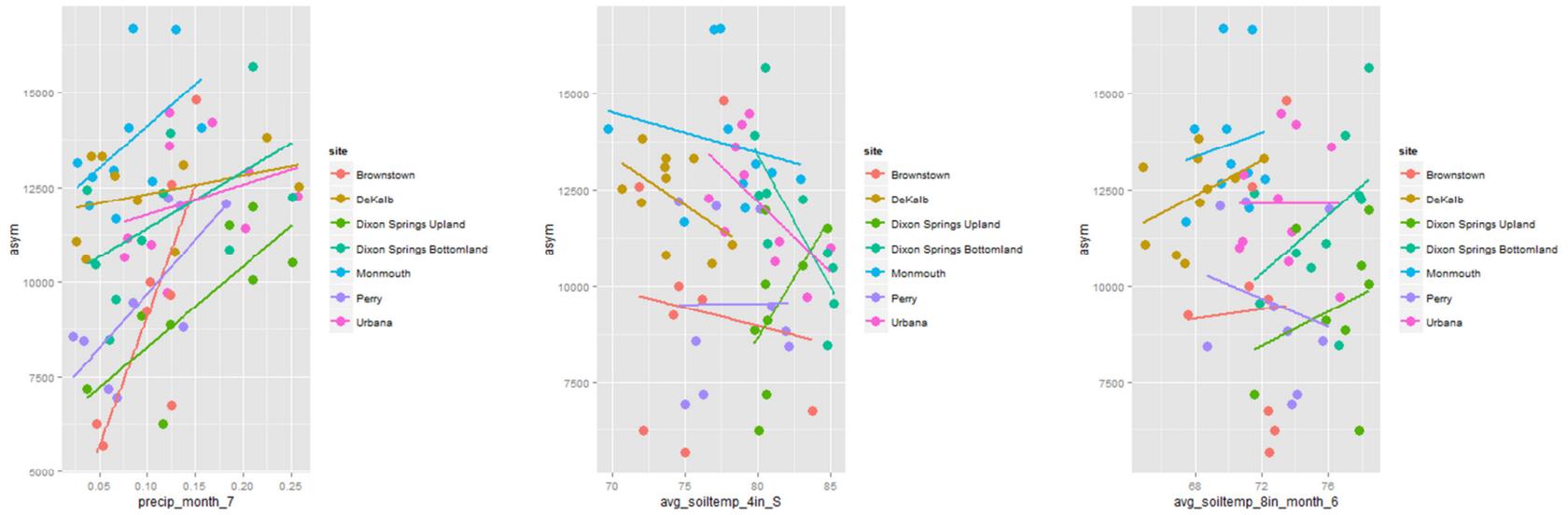


Figure 2.4. Regression tree produced from biometeorological and meteorological weather variables for the N-midpoint parameter of logistic nitrogen response in Illinois.

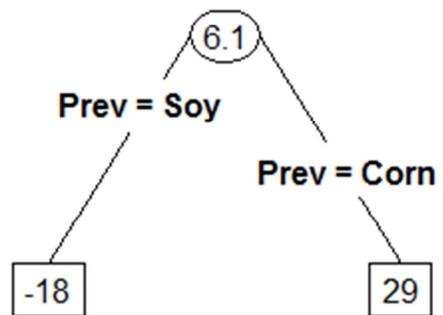


Figure 2.5. Regression tree produced from early season biometeorological and meteorological weather variables for the asymptote parameter of logistic nitrogen response in Illinois.

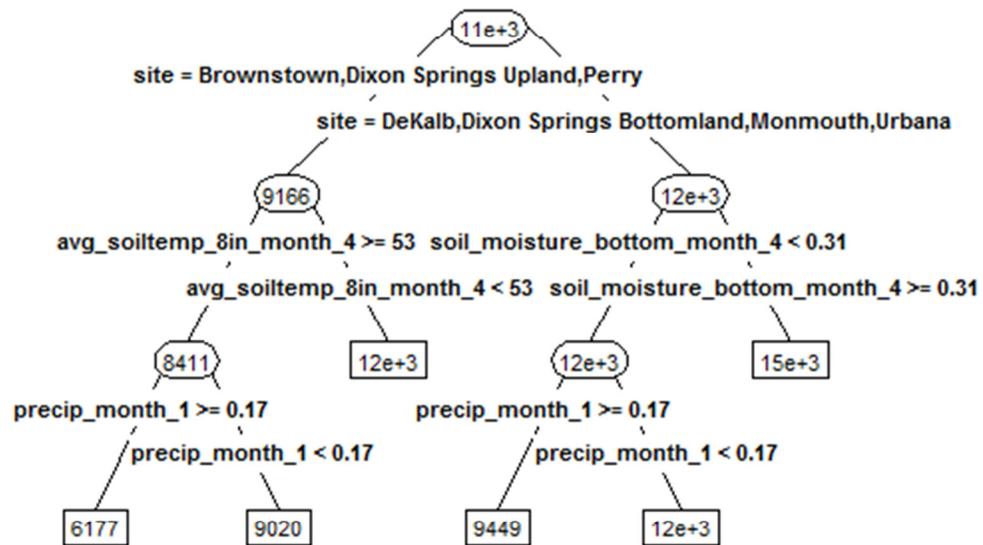


Figure 2.6. Asymptotes of fitted logistic nitrogen response regressions for each site year plotted against selected early season biometeorological and meteorological weather variables for corn following corn.

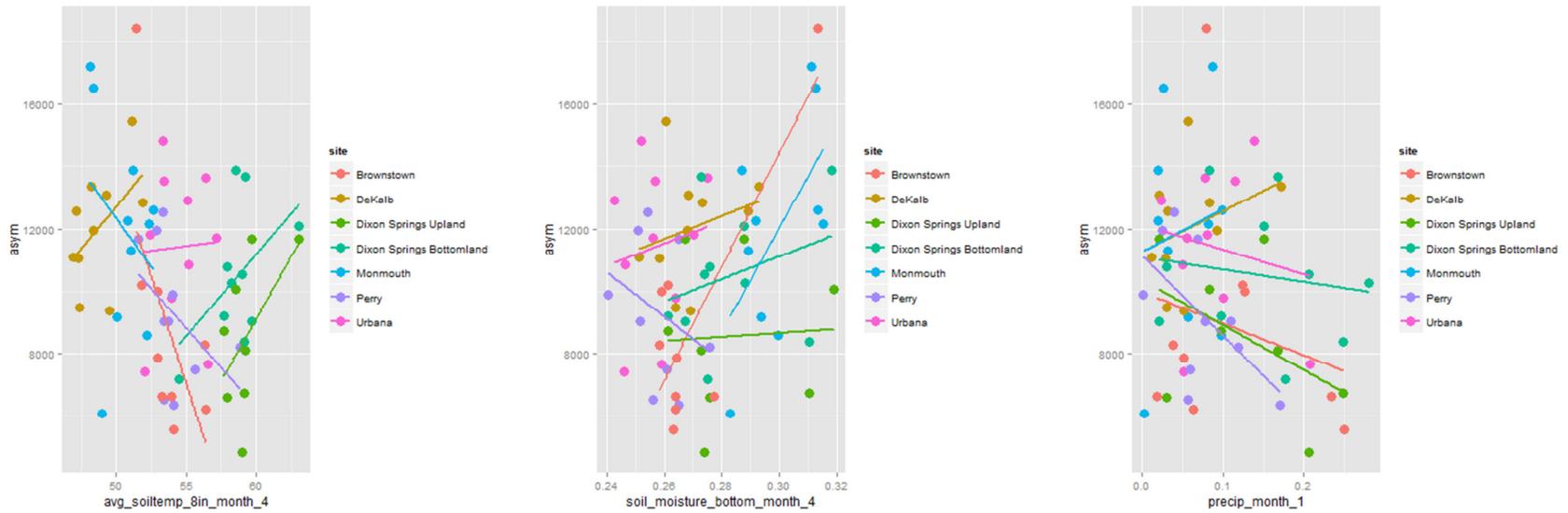


Figure 2.7. Asymptotes of fitted logistic nitrogen response regressions for each site year plotted against selected early season biometeorological and meteorological weather variables for corn following corn.

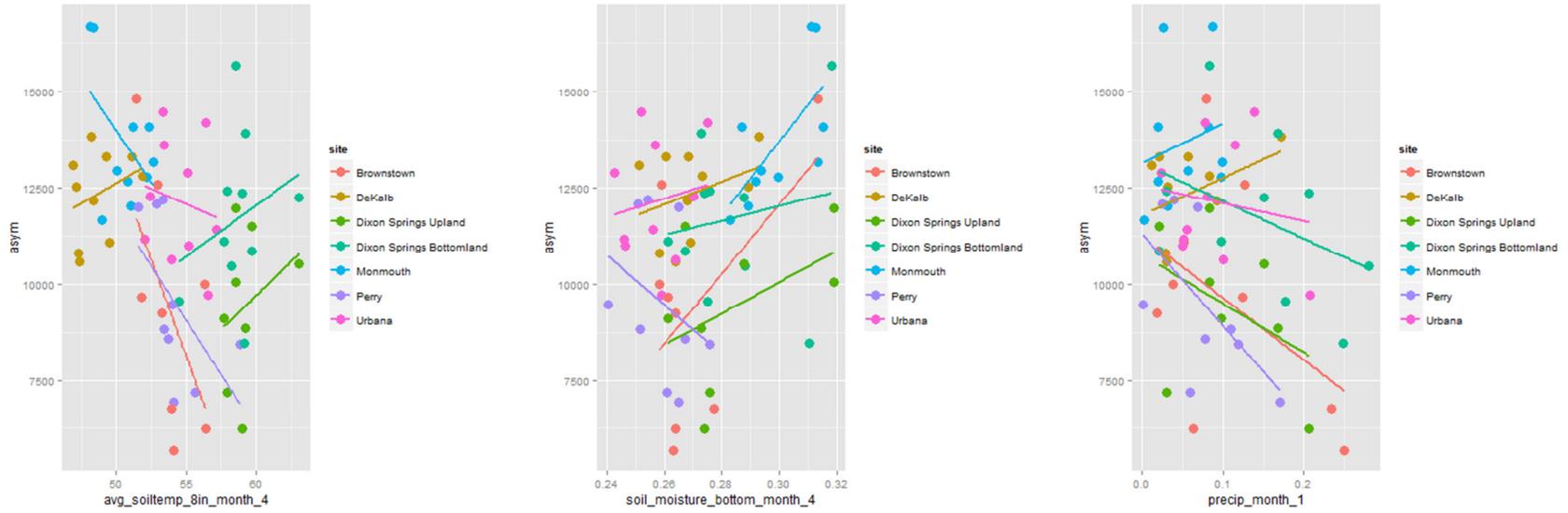


Figure 2.8. Regression tree produced from early season biometeorological and meteorological weather variables for the N-midpoint parameter of logistic nitrogen response in Illinois.

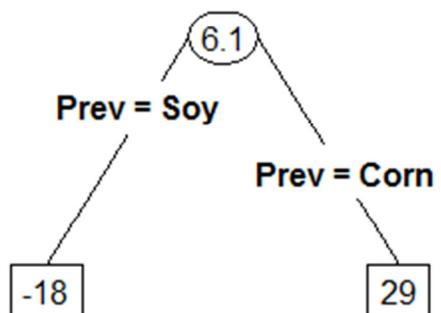


Table 2.1. Soil characteristics of the experimental sites used for examining nitrogen response in Illinois

| Site | Soil Type | Draining Ability | Organic Matter | Expected Yield (kg/ha) |
|--------------------------|-------------------------|--------------------------|----------------|------------------------|
| Monmouth | Sable Silty Loam | Poor | High | 11301 |
| DeKalb | Flanagan Silt Loam | Somewhat Poor | High | 10987 |
| Urbana | Drummer Silty Clay Loam | Poor | High | 10673 |
| Perry | Clarksdale Silt Loam | Poor | Moderate | 8789 |
| Dixon Springs Bottomland | Belknap Silt Loam | Somewhat Poor | Low | 8789 |
| Dixon Springs Upland | Grantsburg Silt Loam | Moderately Well Draining | Low | 7534 |
| Brownstown | Cisne Silt Loam | Poor | Low | 7220 |

Table 2.2. R squares between predicted and actual asymptote values, mean square error of residuals, and average value of residuals for regression with early season biometeorological and meteorological weather variables included.

| Location | R square | MSE | Mean of residuals |
|--------------------------|----------|----------|-------------------|
| Monmouth | 45% | 4.18E+06 | -144 |
| DeKalb | 1% | 4.60E+06 | -130 |
| Urbana | 44% | 1.66E+07 | -438 |
| Perry | 9% | 8.75E+06 | 210 |
| Dixon Springs Bottomland | 26% | 2.01E+07 | 2140 |
| Dixon Springs Upland | 19% | 6.65E+06 | 852 |
| Brownstown | 9% | 2.97E+08 | -2960 |

Mean square error, MSE.

Table 2.3. Average differences between predicted economically optimal nitrogen rate (EONR) revenues, quadratic + plateau maximum return to nitrogen (MRTN) revenues, and actual EONR revenues by location for corn following corn and corn following soybean.

| Location | Corn following corn | | | Corn following soybean | | |
|--------------------------|--|--|--|--|--|--|
| | Average predicted EONR revenues minus actual EONR revenues | Average quadratic + plateau MRTN revenues minus actual EONR revenues | Predicted revenue difference minus MRTN revenue difference | Average predicted EONR revenues minus actual EONR revenues | Average quadratic + plateau MRTN revenues minus actual EONR revenues | Predicted revenue difference minus MRTN revenue difference |
| Monmouth | -20.15 | -17.64 | -2.52 | -39.56 | -21.56 | -18.01 |
| DeKalb | -16.59 | -10.69 | -5.89 | -34.35 | -22.74 | -11.61 |
| Urbana | -21.52 | -22.94 | 1.42 | -25.18 | -14.96 | -10.22 |
| Perry | -15.68 | -31.67 | 16.00 | -34.21 | -28.32 | -5.89 |
| Dixon Springs Bottomland | -55.25 | -41.51 | -13.75 | -60.22 | -35.13 | -25.09 |
| Dixon Springs Upland | -32.10 | -32.56 | 0.46 | -65.14 | -46.33 | -18.81 |
| Brownstown | -69.26 | -19.59 | -49.67 | -31.48 | -16.26 | -15.22 |

Economically optimal nitrogen rate, EONR; maximum return to nitrogen rate, MRTN.