Integrating Field and Climate Data for Nitrogen Risk Management

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ABSTRACT

In-field data collected over time using precision agriculture technologies are becoming common in the US Midwest. We illustrate how long-term data can be used to quantify seasonal weather and climate risks for nitrogen fertilizer risk management for corn (Zea mays). We developed a probability model for estimating the risk of deficient corn nitrogen status using within-field late-season plant measurements, field information about previous crop, nitrogen rate, application timing and nitrogen form in combination with weather data. Using three grower risk perspectives (risk-tolerant, risk-neutral, risk-averse) we demonstrate the use of deficient corn nitrogen status probability values for making decisions for seasonal logistics and multi-year investments in more efficient and less risky fertilizer management practices. We find these probabilities could enable growers to explore different alternative management scenarios (rates, timing and fertilizer forms) for in-season nitrogen management for each risk perspective. We conclude that annual evaluations surveys of corn nitrogen status across Iowa may be useful not only for field-level logistic decisions but also to build new monitoring tools for seasonal weather and business tools for climate risk assessments.

1 Introduction

Climate risk management in agricultural production is entering a new era in which it is possible to use field-level management and crop performance data to quantify changes in production and environmental risk. Precision agriculture technology has enabled researchers and farmers to record outcomes of specific management practices within fields. These data now have sufficiently long records to be relevant in climate risk evaluations. We demonstrate that precision agriculture data viewed from a climate risk perspective can inform decisions with horizons of months to decades.

Nitrogen fertilizer management is a necessary element of crop production. As crops will not grow without nitrogen, farm profitability depends on finding the balance between the cost of nitrogen application (including capital cost of machinery) and crop revenue (Rosas et al. 2015, Babcock and Pautsch 1998). An additional risk element is environmental risk. This is the possibility that applied nitrogen will not be completely removed by the crop uptake and will negatively impact water quality, and, therefore, will harm ecosystems (e.g., causing hypoxia) and will increase external costs to communities (e.g., water treatment) and businesses built upon vulnerable ecosystems.

The Iowa Soybean Association evaluated late-season corn stalk nitrogen status (i.e., crop demand vs soil and fertilizer nitrogen supply) in ~3,500 corn fields across Iowa during 2006-2014. We use these data to illustrate how crop nitrogen status data can be used in climate risk management by farmers and agronomists. Specifically, we have estimated probabilities of deficient corn nitrogen status given field management practices, cropping system, and rainfall variability. We demonstrate that these data can be used to inform within-season decisions as well as multi-year business investment decisions, under a range of risk preferences.

2 Methods

2.1 Rainfall Data

Rainfall data were used to develop equations for quantifying the probability of corn nitrogen deficiency. We use rainfall data that coincident with nitrogen management information collected for each individual field (see Section 2.2). Rainfall data from the Stage IV quantitative precipitation estimate distributed by the National Center for Environmental Prediction were obtained from the Iowa Environmental Mesonet archive (http://mesonet.agron.iastate.edu/rainfall). Six-hourly Stage IV rainfall data were aggregated for May through June period.

We illustrate the use of these data in risk management with weather station data. The station data were from the National Climatic Data Center Global Historical Climate Network and were obtained from the Iowa Environmental Mesonet Climodat archive (http://mesonet.agron.iastate.edu/climodat/).

2.2 Late-Season Corn Nitrogen Deficiency

An annual statewide nitrogen feedback survey was conducted to determine which combination of management factors resulted in excessive, optimal, and deficient nitrogen status. The management factors included nitrogen rate, timing of application, and nitrogen form. Data were collected within ~3,500 corn fields across Iowa from 2006 to 2014 (Figure 1). Data collection included late-season digital aerial imagery of the corn canopy and measurement of corn plant nitrogen status using plant post mortem corn stalk nitrate test (CSNT). The CSNT was used to classify nitrogen status into deficient (0-250 mg NO_3-N), marginal, optimal, and excessive categories (Blackmer and Mallarino, 1996). Three stalk samples (10 individual plants in each sample) were collected within the three predominant soil types in each production corn field to characterize the field-average corn nitrogen status (Kyveryga et al., 2010; Kyveryga et al., 2011). Farmers provided information about nitrogen rate applied, timing of application, nitrogen fertilizer form, and previous crop.

Farmers are keenly interested in the risk of yield reduction from insufficient nitrogen (deficient CSNT status) and of excessive nitrogen application. The data were used to develop a probability model of deficient nitrogen status. Binary multiple logistic regression analysis was used to estimate the probability of deficient nitrogen status. Four categories of nitrogen status were divided into two binary pairs (two regression equations): Deficient vs Sufficient (all samples in Optimal and Excessive). Multiple logistic regression equations were developed using the R statistical software (R Development Core Team, 2004). The site locations were considered random factors (though site characteristics such as soil type could be considered a fixed factor in subsequent development). Fixed factors were nitrogen management, a combination of timing application and fertilizer form, previous crop, and several aggregates of rainfall estimates. Data analysis and model comparison revealed the best rainfall predictor was May-June rainfall. Two risk equations (one for corn after corn and another for corn after soybean) were developed for each of three major Iowa landforms: Northwest plus Des Moines Lobe, North East and Southern Iowa (Figure 2).

3 Results

3.1 Nitrogen Risk Context: Rainfall Change

Spring rainfall is a primary risk factor for nitrogen loss and deficient CSNT status (see Section 2.2). One management strategy for reducing nitrogen loss is post-spring (i.e. sidedress) application. This means a secondary risk factor is early and mid-summer rainfall, because it could prevent post-spring application of nitrogen. The Iowa average (1893 – 2014)

May-June (spring) and July-August (summer) rainfall are similar with slightly more rainfall in spring (21.7 cm) than in summer (18.7 cm). A climate risk context is given by separating the data into the current climate normal period (1981 – current; World Meteorological Organization current climate normal period is 1981 - 2010) and past period (1893 – 1980). Spring and summer rainfall are uncorrelated in Iowa (Figure 3). This means that the joint distribution of the spring and summer rainfall may be approximated as a bivariate normal distribution. Using this approximation, the 95th percentile is used to identify extreme rainfall. Prior to 1981, seven years fall outside the 95th percentile. This is higher than expected from the bivariate normal distribution (4.4 is 5% of 88 years; whereas, 7 of 88 years is 7.9%), and it indicates the true distribution may have a heavy tail. Nevertheless, the change in extremes during 1981 – 2015 is clear with 13 years (37.1%) outside the 95th percentile.

Change in frequency of extreme spring rainfall has implications for nitrogen risk management. Growers may reduce the risk for of nitrogen loss by applying relatively stable nitrogen forms prior to spring or by using post-spring applications. The 13 extreme years identified in 1981 - 2015 can be grouped by whether the excessive rainfall occurred in the spring, summer, or both. Years with excessive rainfall in the spring but not summer (4 of 13 years) would imply higher primary risk for nitrogen loss from pre-spring application. Years with excessive rainfall in the summer but not spring (3 of 13 years) would imply higher secondary risk of inability to apply post-spring nitrogen. Finally, years with excessive spring and summer rainfall (3 of 13 years) would imply primary and secondary risk.

3.2 Nitrogen Risk Management

Interpretation of weather-dependent probability for deficient CSNT status will depend on risk perspectives. We define three risk perspectives to illustrate interpretation in the context of growing season logistical decisions (seasonal weather risk) and business investment decisions (climate risk). A risk-tolerant grower is willing to accept a higher likelihood of deficient nitrogen status. A risk-neutral grower will seek nitrogen practices that are balanced by crop revenue. A risk-averse grower is unwilling to accept yield losses from inadequate nitrogen. An economic context is provided by using the result from Kyveryga et al. (2012) who report 60-70% likelihood of economic yield response given additional 56 kg N ha^{-1} to corn with deficient CSNT status. We use the upper end of this range as a rough guideline. Interpretation is made within the context of a nitrogen management framework. The 4R nitrogen management framework (**r**ight amount, **r**ight rate, **r**ight time, **r**ight form) has been developed to reduce environmental impact of nutrient management (IPNI, 2012). This framework is flexible and allows the possibility to switch practices.

3.2.1 Seasonal Weather Risk

Nitrogen management includes at least two seasonal decisions. Prior to the growing season, the grower must determine the nitrogen practice and application rate. Within the growing season, the grower must decide whether additional nitrogen may be needed. A risk management approach for nitrogen management enables growers to evaluate “What If” scenarios (Haige et al. 2015). This is facilitated by using the probability models developed from CSNT data.

In a seasonal weather risk management framework, the grower would be provided prior to the growing season the probability of CSNT deficient status for each possible combination of nitrogen practice, May-June rainfall, and nitrogen application time (Fall or Spring application), form, and rate. In addition, the grower would be given the range of rates for CSNT results classified as optimal (Figure 4). A pre-season CSNT deficient status probability table is illustrated using the station at Webster City, Iowa (in the region for Northwest Iowa and Des Moines Lobe; Table 1). The range of nitrogen rates is obtained from field data with optimal nitrogen status by selecting 25th, 50th, and 75th percentiles (box edges in Figure 4). For illustration, the 25th percentile is the rate for a risk-tolerant grower, 50th percentile for a risk-neutral grower, and 75th percentile for a risk-averse grower.

The Webster City deficient CSNT status probability values shows May-June rainfall greater than the 75th percentile would result in probability of CSNT deficient status exceeding 50% for the majority of practices and application rates (Table 1). The economic yield response, however, is >50% only for CSNT deficient status >70% (0.7 x 0.7 = 0.49), and a minority of practices and application rates cross this threshold for 95th percentile May-June rainfall. The risk perspective would determine the interpretation of these products to select application timing and rate for a given practice (Table 2). Once a nitrogen practice has been implemented, the grower would monitor the probability of deficient CSNT status during May-June as it is updated with each rainfall event in order to determine whether additional nitrogen application could result in economic gain.

3.2.2 Climate Risk

Change in rainfall may motivate change in nitrogen practice. The grower's decision requires considerations of capital investment, new application rate and timing, new combinations of different forms, combinations of these, or entirely new technology. A rational basis for evaluating the investment payoff would need historical measurements of CSNT status to determine change in likelihood. These data do not exist. To obtain an estimate, the CSNT deficient status probability model can be used to simulate historical data.

The simulated historical CSNT deficiency status probability for risk-neutral application rate (50th percentile for nitrogen rates producing the optimal nitrogen status; Figure 4) near Webster City, Iowa shows that the probability of nitrogen deficiency for all practices since the early 1990s has been unusually high (Figure 5a). For instance, for C-S rotation with Spring UAN applied at 157 N kg ha^{-1}, the 10-yr average CSNT deficiency probability exceeded 0.6 for the first time on record in 1993 and since then has remained near 0.6. Additionally, the maximum CSNT deficiency probability in a 10-yr period has exceeded 0.8 since 1993 (Figure 5b). The reason for higher risk with spring UAN is that 25% of this fertilizer is NO_3-N, leaching relatively easily. Additionally, urea comprises 50% of the nitrogen mix, and it can be volatilized as NH_3 if it is not incorporated into the soil. This means growers near Webster City face nitrogen management conditions unlike any before, and it suggests nitrogen stress caused by excessive water could be reducing yield.

The possible choices each risk perspective could make are summarized in Table 3. The most disruptive decisions would be associated with spring-applied UAN. A risk-averse grower would be required to choose one of four options: (1) substantially increase nitrogen rate, (2) switch to anhydrous ammonia (NH_4-N form is attached to negatively charge soil particles and less vulnerable to leaching compared with UAN), (3) participate in innovative technology development, or (4) accept a different risk perspective. Each decision carries with it a different investment cost. The cost of (1) would be dependent on fertilizer prices and may be substantially less than the cost of (2) that would require equipment purchase. The return on investment of (3) may be unclear. By comparison, risk-neutral and risk-tolerant growers may not need to adjust their nitrogen practice.

It is important to recognize the uncertainty that rainfall will remain at this high level. The cost of the investment must be balanced against the possibility that the rainfall could shift to previous levels and not require a nitrogen investment at all. This identifies an important gap in climate information for agricultural business risk management that a climate forecast could fill.

5 Conclusions

We have examined the possibility to use archives of precision agriculture data to inform seasonal weather and climate risk management decisions. We have used weather data, data collected from farmers, and within-field measurements of yield and late-season CSNT deficiency to develop a probability model for nitrogen deficiency status. We have used three risk perspectives for nitrogen risk management within the context of 4R nitrogen management to determine if new decisions could be made given the nitrogen deficiency probability model. We have determined the model can lead to different decisions in before-season nitrogen form and application and within-season nitrogen application rate. We have found the change in rainfall over the past 25 years has increased the probability of CSNT deficient status in northwest Iowa. Risk-averse growers will need to make investments for some practices to return to lower probability levels of previous years. We conclude precision agriculture data may be useful not only for in-field logistic decisions but also as a means to build new monitoring tools for seasonal weather risk and business tools for climate risk.

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Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 255–316, doi:10.1017/CBO9781107415324.010.

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Table 1. Probability of deficient CSNT status by combination of timing, form and rate of N application, and May-June rainfall for corn after soybean field located near Webster City, within the Des Moines Lobe. Fall AA=fall-applied anhydrous ammonia; Fall SM=fall-injected swine manure; SD N=side-dress UAN solution or anhydrous ammonia; Spring AA=spring-applied anhydrous ammonia; Spring UAN=spring-applied UAN. May through June rainfall 5th, 25th, 50th, 75th, and 95th percentiles are, respectively, 7.5, 16.0, 22.1, 28.4, and 38.0 cm.

Total rate, kg N ha^{-1}	May through June Rainfall, percentile				
	5th	25th	50th	75th	95th
	Fall AA				
168	0.19	0.28	0.36	0.46	**0.60**
190	0.16	0.24	0.32	0.41	**0.56**
207	0.14	0.22	0.29	0.38	**0.52**
	Fall SM				
185	0.26	0.37	0.47	**0.57**	***0.70***
207	0.23	0.33	0.42	**0.52**	**0.66**
235	0.19	0.28	0.37	0.46	**0.61**
	SD N				
140	0.30	0.42	**0.52**	**0.61**	***0.74***
157	0.27	0.39	0.48	**0.58**	***0.71***
168	0.26	0.37	0.46	0.56	**0.69**
	Spring AA				
151	0.16	0.24	0.32	0.41	**0.55**
168	0.14	0.22	0.29	0.38	**0.52**
185	0.13	0.20	0.26	0.34	0.49
	Spring UAN				
146	0.35	0.47	**0.57**	**0.66**	***0.78***
157	0.33	0.45	**0.55**	**0.64**	***0.76***

185	0.28	0.39	0.49	**0.59**	***0.71***

Table 2. Producer risk tolerance and in-season weather-based decisions.

Risk Perspective	Seasonal Weather Risk Decision	
	Prior to Growing Season Decision	In- Season Decision
Risk-Averse	Select nitrogen rate with low CSNT deficient probability given 95th percentile rainfall. For instance, C-S rotation Spring AA rate >185 kg N ha^{-1}.	None
Risk-Neutral	Select nitrogen rate within range of optimal CSNT status (Figure 3).	Monitor May-June rainfall to determine if selected nitrogen rate has reached 70% probability CNST deficient status. If so, apply 56 kg N ha^{-1}.
Risk-Tolerant	Select nitrogen rate with ~50% likelihood CSNT deficient status at 50th percentile rainfall. For instance, C-S rotation Spring AA rate <151 kg N ha^{-1}.	Monitor May-June rainfall to determine if selected nitrogen rate has reached 70% probability CSNT deficient status. If so, apply 56 kg N ha^{-1}.

Table 3. Producer risk tolerance and climate-based decisions.

Risk Perspective	Climate Risk Decision		
	Spring UAN	Spring AA	Fall AA
Risk-Averse	Switch to AA Apply Higher Rate New Technology	Apply Higher Rate Use nitrification Inhibitor	Apply Higher Rate Switch to Spring AA Use nitrification Inhibitor
Risk-Neutral	Switch to AA Apply Higher Rate	No Changes	No Changes
Risk-Tolerant	Switch to Spring AA	No Changes	No Changes

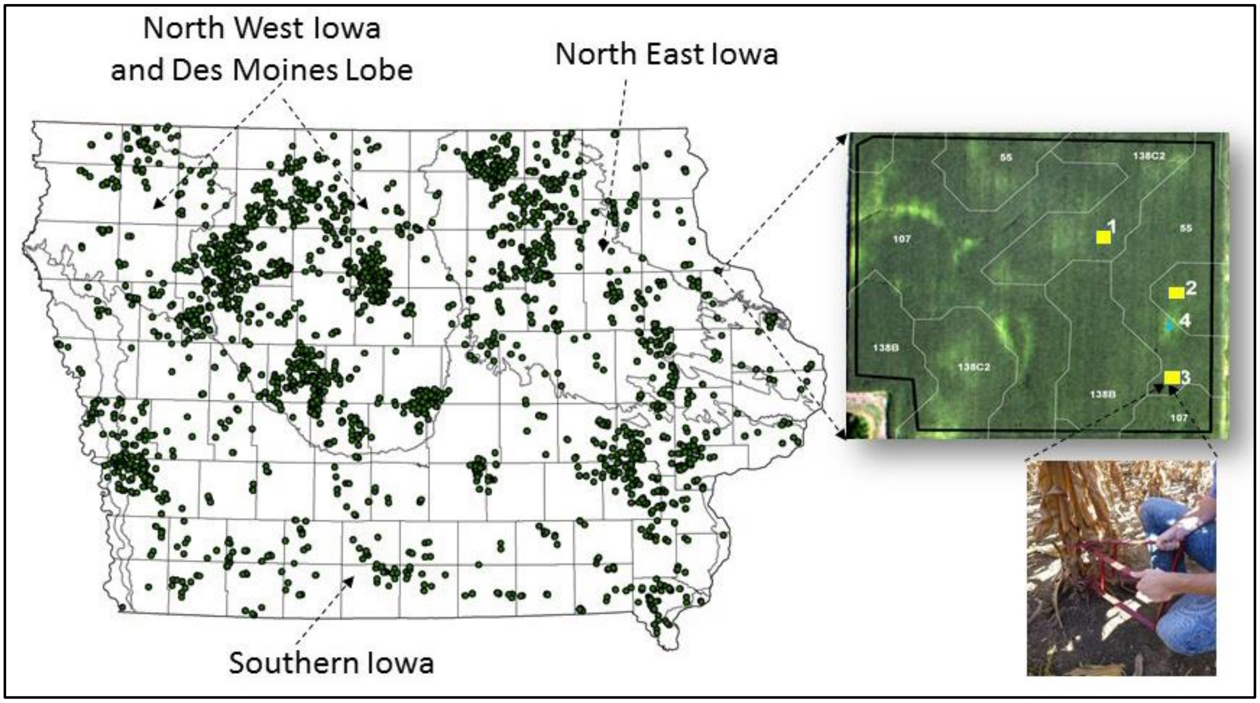

Figure 1. Locations of >3500 corn fields evaluated for post-season corn N status during a period from 2006 through 2014. The digital color aerial imagery of the corn canopy was used to select three sampling areas (1, 2, and 3) within three predominant soil types to characterize the average field N status. Corn stalk sample 4 was collected within a target deficient area with yellow appearance. Observations from sampling area 4 were not used in analyses of this study.

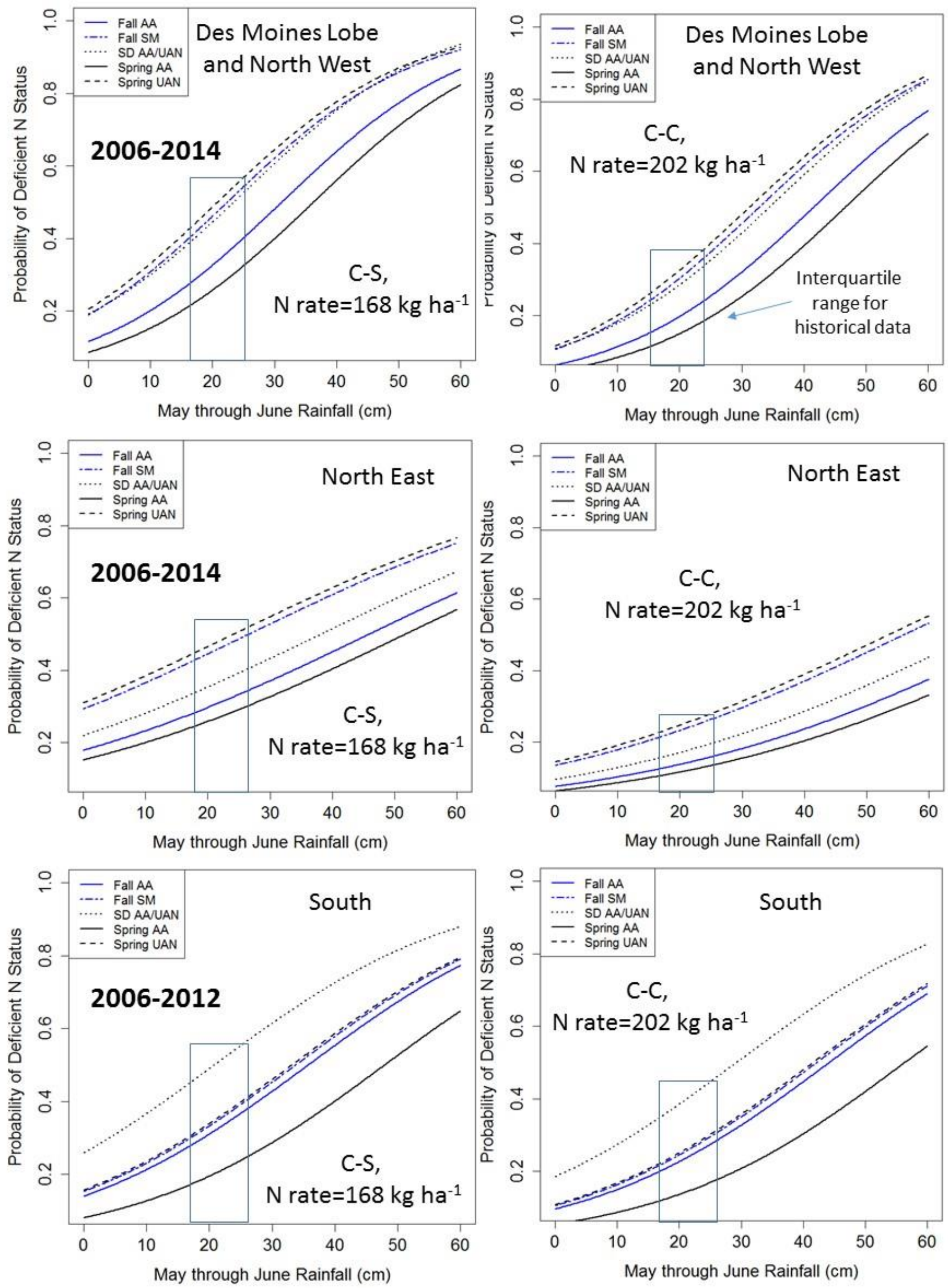

Figure 2. Effect of May through June rainfall on the probability of late-season corn deficient nitrogen status for different combination of timing and forms applications for the landform regions of Des Moines Lobe plus North West Iowa, Eastern Iowa, and Southern Iowa (data collected 2006 through 2014). Fall AA=fall-applied anhydrous ammonia; Fall SM=fall-injected swine manure; SD AA/UAN=side-dress anhydrous ammonia or urea ammonium nitrate solution; Spring AA=spring-applied anhydrous ammonia; Spring UAN=spring-applied UAN. Edges of the rectangles indicate 25th and 75th percentiles of long-term May through June rainfall for each landform area.

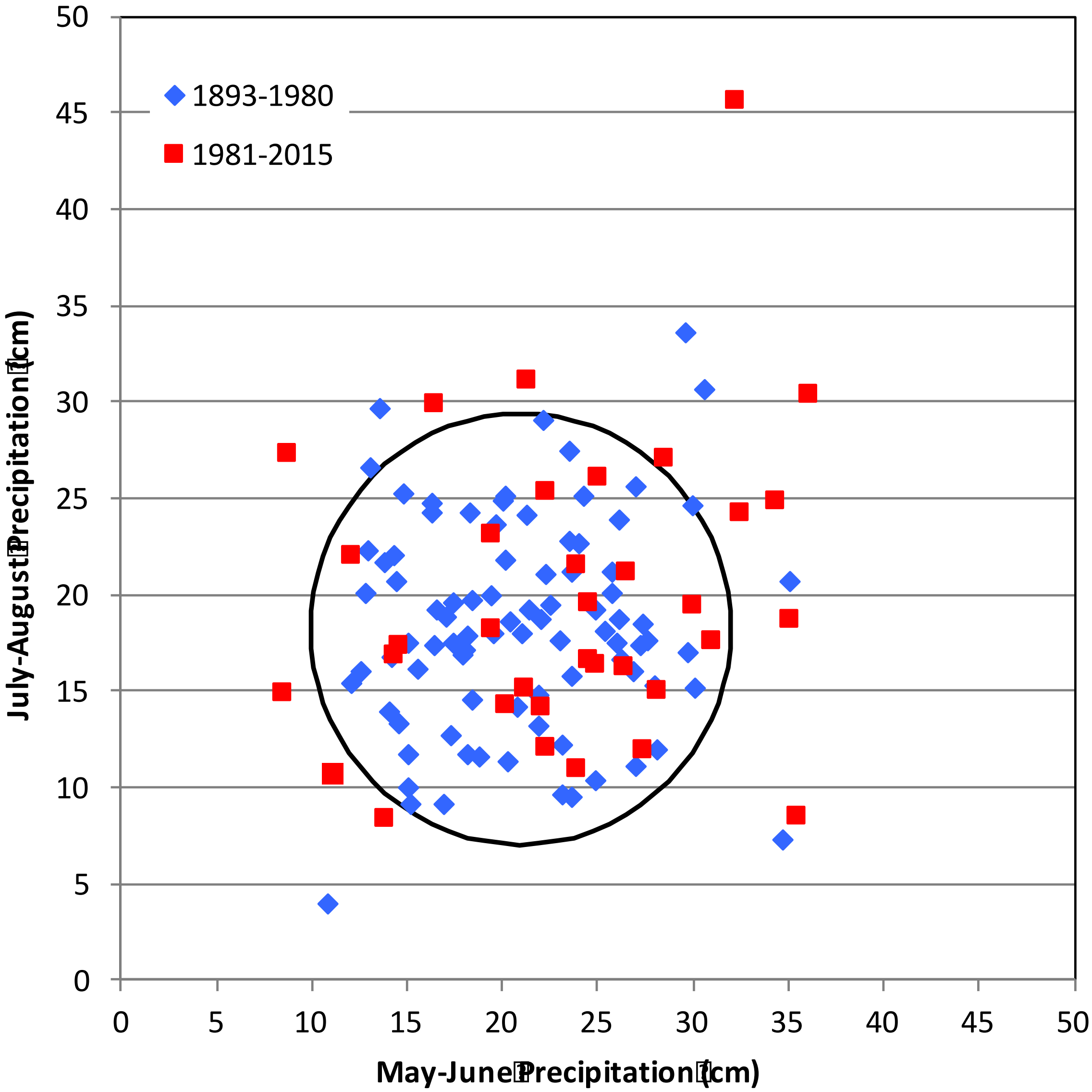

Figure 3. Scatterplot of May-June and July-August Iowa rainfall. The black circle indicates the theoretical 95th percentile of the bivariate normal distribution.

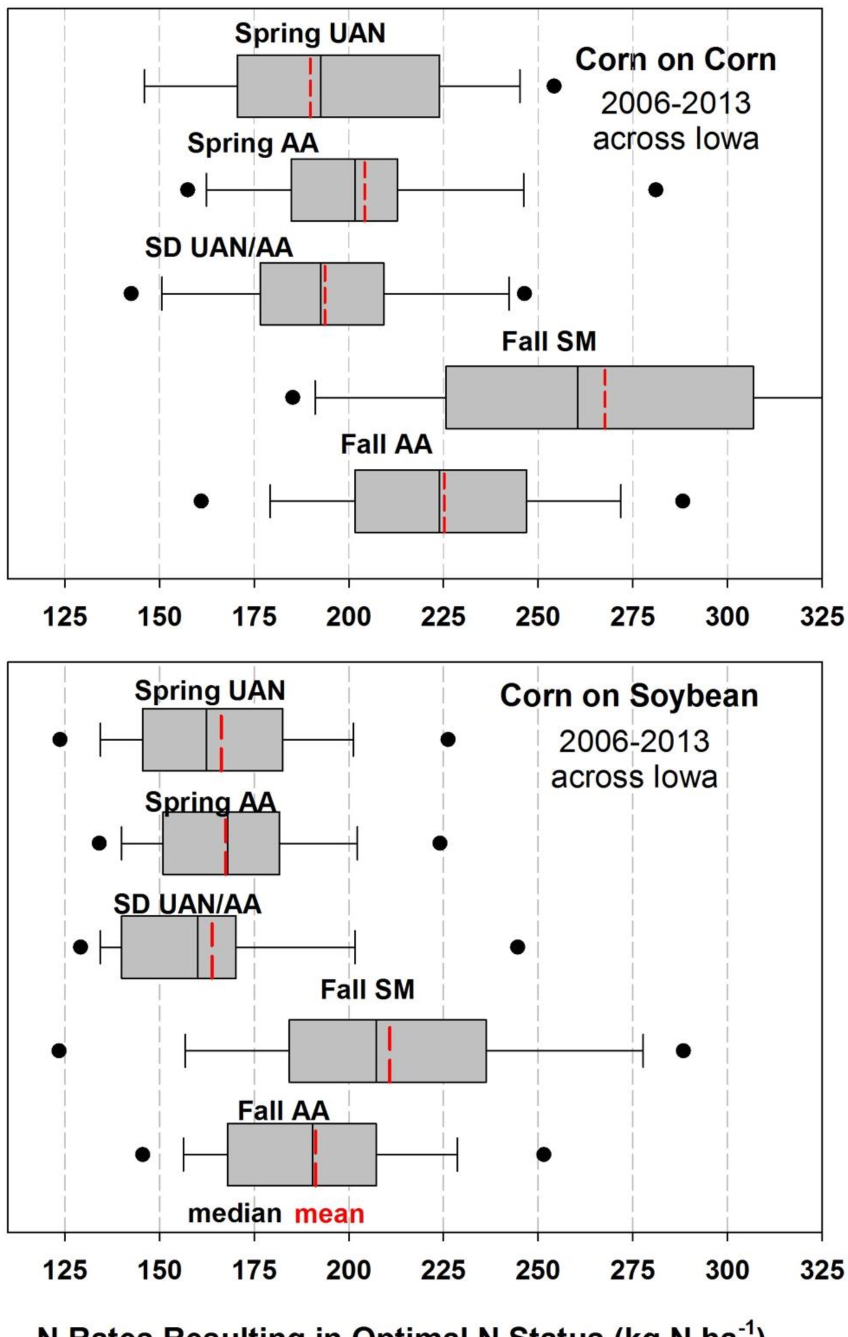

Figure 4. Distribution of nitrogen rates that produced the field-level optimal corn nitrogen status for 410 fields evaluated within the landform of Des Moines Lobe plus North West Iowa (data collected 2006 through 2013). Fall AA=fall-applied anhydrous ammonia; Fall SM=fall-injected swine manure; SD UAN/AA=sidedress urea ammonium nitrate solution or anhydrous ammonia; Spring AA=spring-applied anhydrous ammonia; Spring UAN=spring-applied UAN.

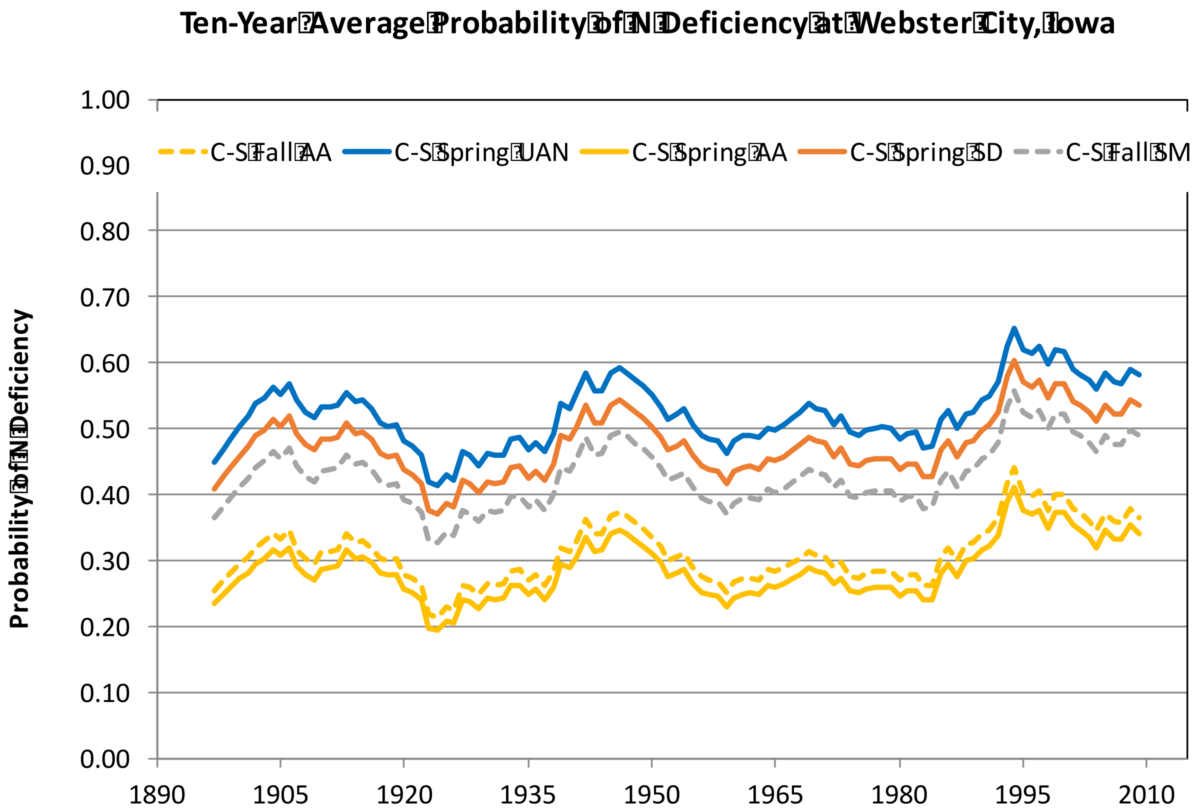

Figure 5a. Average probability of nitrogen deficiency (10-yr moving average) for 1893 – 2014 using rainfall data from Webster City, Iowa. C-S=corn after soybean; Fall AA=fall-applied anhydrous ammonia; Fall SM=fall-injected swine manure; SD UAN=side-dress urea ammonium nitrate solution or anhydrous ammonia; Spring AA=spring-applied anhydrous ammonia; Spring UAN=spring-applied UAN.

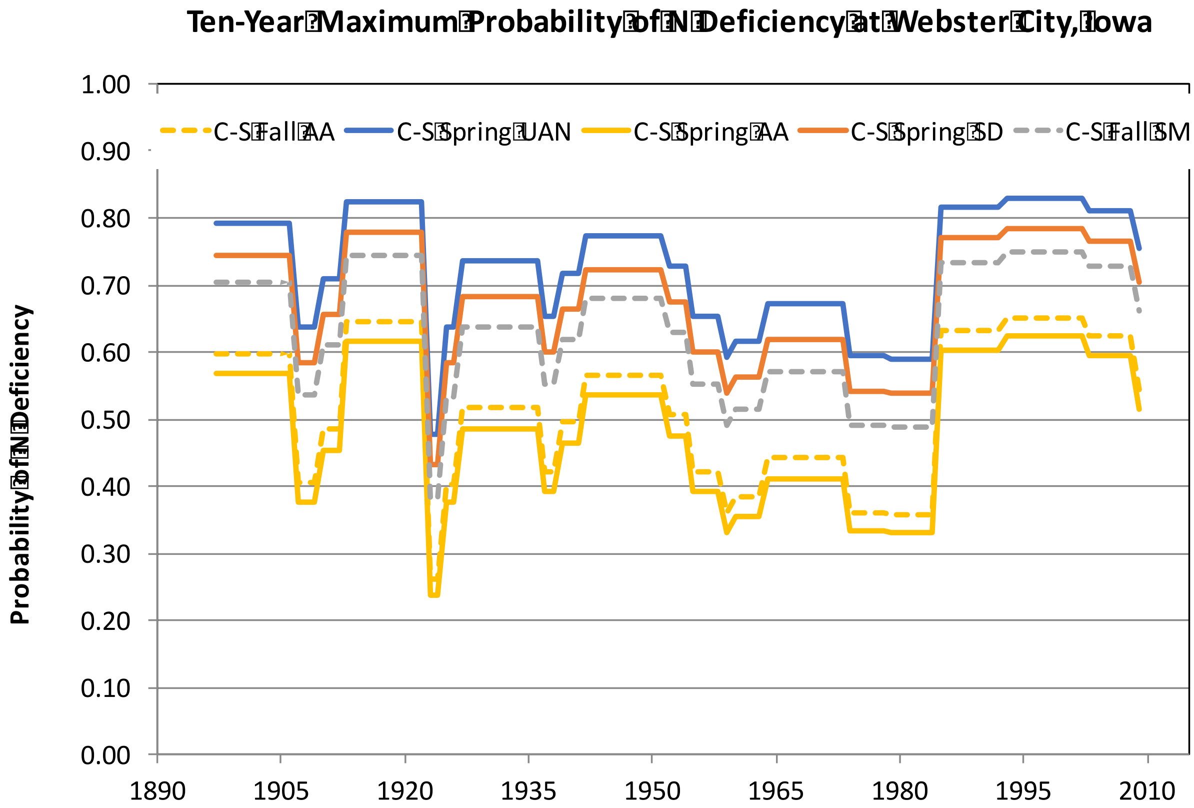

Figure 5b. Maximum probability of nitrogen deficiency within 10-yr period (moving window) for 1893 – 2014 using rainfall data from Webster City, Iowa. C-S=corn after soybean; Fall AA=fall-applied anhydrous ammonia; Fall SM=fall-injected swine manure; SD UAN=side-dress urea ammonium nitrate solution or anhydrous ammonia; Spring AA=spring-applied anhydrous ammonia; Spring UAN=spring-applied UAN.

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